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α_s(2019) discussions summary

S. Alekhin
Institut für Theoretische Physik, Universität Hamburg, D-22761 Hamburg, Germany
Institute for High Energy Physics,142281 Protvino, Russia
E-mail: sergey.alekhin@ihep.ru

Fernando Barreiro
Facultad de Ciencias, Universidad Autónoma de Madrid, 28049 Madrid
E-mail: fernando.barreiro@uam.es

Siegfried Bethke
Max-Planck-Institut für Physik, Munich
E-mail: bethke@mppmu.mpg.de

Nora Brambilla
Physik Department, Technische Universität München, D-85748 Garching, Germany
E-mail: nora.brambilla@ph.tum.de

Daniel Britzger
Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
E-mail: daniel.britzger@desy.de

Stanley J. Brodsky
SLAC National Accelerator Laboratory, Stanford University, California, USA
E-mail: sjbth@slac.stanford.edu

Stefano Camarda
CERN, EP Department, CH-1211 Geneva 23, Switzerland
E-mail: stefano.camarda@cern.ch

David d'Enterria
CERN, EP Department, CH-1211 Geneva 23, Switzerland
E-mail: david.d'enterria@cern.ch

Mattia Dalla Brida
Dipartimento di Fisica, Università di Milano-Bicocca, and INFN, Sezione di Milano-Bicocca, 20126 Milan, Italy
E-mail: mattia.dalla.brida@desy.de

Maarten Golterman
Department of Physics & Astronomy, San Francisco State University, San Francisco, CA 94132, USA
E-mail: maarten@sfsu.edu

Joey Huston
Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-1116, USA
E-mail: huston@pa.msu.edu

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Stefan Kluth
Max-Planck-Institut für Physik, D-80805 Munich, Germany
E-mail: skluth@mpp.mpg.de

J. H. Kühn
Institut für Theoretische Teilchenphysik, KIT, 726128 Karlsruhe, Germany
E-mail: johann.kuehn@kit.edu

Ramon Miravitllas
IFAE, BIST, Campus UAB, 08193 Bellaterra (Barcelona), Catalonia (Spain)
E-mail: rmiravitllas@ifae.es

Redamy Pérez-Ramos
DRII-IPSA, Bis, 63 Boulevard de Brandebourg, 94200 Ivry-sur-Seine, France
Sorbonne Universités, UPMC Univ Paris 06, UMR 7589, LPTHE, F-75005, Paris, France
E-mail: redamy.perez-ramos@ipsa.fr

Santiago Peris
Dept of Physics and IFAE-BIST, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Catalonia (Spain)
E-mail: peris@ifae.es

Peter Petreczky
Physics Department, Brookhaven National Laboratory, Upton (NY)
E-mail: petreczk@quark.phy.bnl.gov

João Pires
CFTP, Instituto Superior Técnico, Universidade de Lisboa, P-1049-001 Lisboa, Portugal
LIP, Avenida Professor Gama Pinto 2, P-1649-003 Lisboa, Portugal
E-mail: joao.ramalho.pires@tecnico.ulisboa.pt

Andres Põldaru
MPI, Munich, D-85748 Garching
E-mail: andres.poldaru@cern.ch

K. Rabbertz
KIT, Karlsruhe, Germany
E-mail: klaus.rabbertz@cern.ch

Felix Ringer
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
E-mail: fmringer@lbl.gov

Stefan Sint
School of Mathematics and Hamilton Mathematics Institute, Hamilton building, Trinity College Dublin, Dublin 2, Ireland
E-mail: sint@maths.tcd.ie

R. Sommer
Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany
John von Neumann Inst. for Computing (NIC), DESY, Platanenallee 6, 15738 Zeuthen, Germany
E-mail: rainer.sommer@desy.de

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Gábor Somogyi
MTA-DE Particle Physics Research Group, University of Debrecen, 4010 Debrecen, Hungary
E-mail: somogyi.gabor@science.unideb.hu

Hiromasa Takaura
Department of Physics, Kyushu University, Fukuoka 819-0395, Japan
E-mail: takaura@phys.kyushu-u.ac.jp

Andrii Verbytskyi
Max-Planck-Institut für Physik, D-80805 Munich, Germany
E-mail: andriish@mpp.mpg.de

A summary of the main points of discussion raised during the talks and their follow-up questions, as well as in the round table of the last day of the α_s(2019) workshop, is presented. The discussions not only focused on particular issues affecting each one of the individual α_s extractions, but also on the current PDG categorization of α_s measurements and on the methods used to average them into a single $\alpha_s(m_Z)$ value. Most of the listed points are open and sources of potential controversies, which we highlight here as one might expect that ongoing progress in the field will lead to their clarification and resolution.

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The results of the discussions during the presentations and round-table session on the last day of the workshop, are summarized here ordered according to α_s extraction category. An important point of discussion was the organization of α_s determination categories, the incorporation of new developments, and the methodology used for the $\alpha_s(m_Z)$ averaging in the PDG review [1]. The last point of this contribution deals with those latter issues. We note that the topic of α_s determinations was also discussed in a 2018 workshop [2] where complementary details can be found.

- **Lattice QCD:**

  The lattice-QCD practitioners suggested the PDG α_s review to include an expert member of this community. Alternatively, the $\alpha_s(m_Z)$ average of the FLAG collaboration report [3] could be incorporated into the lattice-QCD PDG chapter and propagated as input into the world-average value. Despite the fact that it is difficult to reach full agreement on the averaging of a very broad range of observables, FLAG has gathered the expertise of a large fraction of the lattice collaborations in its team in order to reach a rough consensus. The fact that the most recent FLAG report provides subaverages for the various different α_s extractions, helps to carry out reanalyses of these results if desired. It was pointed out that several lattice results are now dominated by higher-order uncertainties in the pQCD counterpart observables mostly computed at NNLO accuracy, except for the static QCD energy that uses a N^{3}LO result [4]. Thus more efforts should be put on the perturbative side of the calculations in the coming years in order to understand and reduce these uncertainties, in parallel to evaluating observables non-perturbatively at higher energy scales. It was emphasized that the lattice community considers that their α_s subcategories are as different from each other as e.g. the category of τ-decay is from DIS. Therefore it was suggested that the PDG average includes the results of the lattice QCD subcategories as categories parallel to τ-decays, DIS, etc.

- **Hadronic τ decays:**

  It was proposed to collect the latest results from τ decays as well as the novel low-energy e^+e^- annihilation ($R_{e^+e^-}$) extraction [5] under one single α_s group labelled "τ and e^+e^- continuum below charm" (or similar) as they share many theoretical and experimental coincidences. The α_s extraction from hadronic τ decays is significantly affected by the spectral functions measured with limited precision by ALEPH and OPAL in e^+e^- collisions at LEP [6]. It was stressed the need to discuss with the BaBar/BELLE-II communities the use of large τ decays data samples from B-factory experiments to improve on the $\alpha_s(m_\tau)$ determination. Although, up until now, all recent extractions of α_s have been based on the same data, they differ mainly in the treatment of non-perturbative physics. In particular, there is the need to resolve the duality violation treatment and pinching strategy in connection with the properties of the Operator Product Expansion.

- ***e*-p scattering and fits of parton distribution functions:**

  First, it was pointed out that the current "Deep inelastic lepton-nucleon scattering (DIS)" label of this extraction category should be changed to "e-p scattering and global PDF fits" (or similar) to properly include all available α_s determinations in this domain. In particular, to take into account the fact that there are new α_s determinations from HERA data, e.g. based on NNLO jets in DIS and in (anticipated) photoproduction studies, which will be included into the world average. A discussion followed on how to properly merge the novel DIS jets $\alpha_s(m_Z)$ result together with the more inclusive structure function results [7]. The question was raised on what to do with novel NNLO hadron collider extractions, e.g. based on jet or electroweak boson production at the LHC, that have a strong explicit PDF dependence. It seemed that the inclusive W, Z cross sections should go under the "hadron collider" category, as those are *total* cross section like the $t\bar{t}$ ones that are not explicitly included into the global PDF fits, whereas any extraction based on *differential* jet cross sections at NNLO should be rather included as part of the α_s determinations derived in parallel with the future global PDF fits that include these jet spectra too.

It was reminded that there is currently no consensus on how to reliably estimate theoretical uncertainties of α_s extractions, from missing higher-order corrections in NNLO PDF+α_s fits. This complicates not only the comparison with other categories, but also comparisons within this category to some extent.

- **Hadronic final states in e^+e^- annihilation:**

  The novel results from e^+e^- annihilation based on energy-energy correlations (EEC) and jet rates (R2) [8], further justify organizing the α_s subgroup extractions of this category based on the hadronization correction method employed, i.e. based on Monte Carlo event generators or on analytic models for the non-perturbative effects. New developments in jet substructure techniques [9] applied to e^+e^- studies will reduce the hadronization corrections and, once they reach NNLO accuracy, will allow to reanalyze the LEP data with smaller non-perturbative uncertainties. These latest more precise results open up the potential substitution of older LEP analyses, with larger uncertainties, from the world average. New applications of the Principle of Maximum Conformality (PMC) for determining renormalization scales in α_s extractions via e^+e^- event-shape variables were discussed during the workshop [10]. The PMC renormalization scales depend on the event-shape kinematics, reflecting the virtuality of the underlying QCD subprocess. Work is ongoing to provide a systematic evaluation of the theory uncertainties of the PMC predictions for pQCD at high orders.

- **Hadronic Z and W boson decays:**

  Why does the PDG world-average for this category prefer the α_s value derived from the global electroweak (Gfitter) SM fit, rather than the value derived from stand-alone analysis of the pseudo-observables directly measured at the Z boson pole? The result from the global SM fit, $\alpha_s(m_Z) = 0.1194 \pm 0.0029$ with a $\sim$2.4% uncertainty, is only slightly more precise than the latter, $\alpha_s(m_Z) = 0.1203 \pm 0.0028$ with $\sim$2.5% uncertainty, but the former is more prone to potential biases from new physics present in other sectors of the SM [11].

- **Hadronic final states at pp, $p\bar{p}$ colliders:**

  The breadth of LHC data and the associated recent NNLO pQCD theoretical developments have provided various new α_s extractions from pp collisions, including inclusive pp $\rightarrow t\bar{t}$, W, and Z [12] production cross sections, as well as differential jets cross sections. The question was raised whether adding more measurements could lead to not improving the world average with the currently used linear pre-averaging method. To be able to fully exploit all the experimental data, via e.g. a χ^2-based BLUE-type average [13, 14], the correlation matrices among measurements must be provided by the experimental collaborations. It has also been stressed that (future) systematically improved parton showers, if possible including corrections at NLL (or beyond) accuracy, are essential to fully gain control of the MC uncertainties involved in these analyses and also for α_s determinations based on e^+e^- data.

One of the strengths of the LHC data is the possibility to test asymptotic freedom at high energy scales, in the TeV regime, never explored before. In this context, it was pointed out that e.g. some ATLAS analyses of data from pp collisions covering scales at large total event energy (H_T) seem to run (evolve with scale) faster than expected. This effect can depend on the choice of renormalization scale setting in the extraction of α_s, and this should be carefully checked for each chosen observable. The α_s running plots in the PDG summary should incorporate the pp $\rightarrow$ jets results at NNLO that extend the range up to about 2 TeV at the proper scale of each observable (leading jet p_T, sum of jet p_T's,...). For the α_s running in the low energy range, the lattice results should be added. Last but not least, it was not clear, i.e. not explicitly documented in the publications, if all analyses at scales above the top quark production threshold used the proper number of active free flavours $n_f = 6$ in the prediction and the evolution calculations.

- **α_s categorization, combination and averaging of $\alpha_s(m_Z)$ results:**

The current $\alpha_s(m_Z)$ PDG world-average [1] is derived from different measurements grouped, first, into subcategories that are subsequently combined into six overall categories. The individual subcategories are grouped following experimental measurements and theoretical methods (e.g. sharing a similar treatment of hadronization corrections), and the overall categories share basically the same underlying physical process. Suggestions were made to change some of the labels of the categories and/or to rearrange them to include newly available α_s extractions (see more detailed cases discussed above). In order to enter into the world average, the current conditions are that the α_s analysis has at least an NNLO theoretical accuracy, includes reliable estimates of experimental, systematic, and theoretical uncertainties, and the results are published in a peer-reviewed journal. It was discussed the possibility to drop relatively old analyses (e.g. from LEP e^+e^- final states), because the same data have been reanalyzed in newer studies and/or because old hadronization corrections may have been superseded. Although the large $\alpha_s(m_Z)$ uncertainties of the oldest results likely have a small numerical impact on the final world-average, the results of more recent developments could be considered instead. In any case, it was emphasized, as done now in the PDG, that one should clearly study and define *beforehand* the rules for the selection of the analyses to be incorporated into the world average, and then follow them strictly to avoid any bias.

It was highlighted that the individual lattice-QCD results have total 0.5 to 1% uncertainties, which are a factor of 2–4 smaller than all other $\alpha_s(m_Z)$ individual extractions (with 1.5–4% uncertainties). What does this imply for averaging, which will be driven by the most precise result? One way to control this (as already performed in recent α_s combinations) is to drop categories from the average and check the consistency of the results by explicitly quoting $\alpha_s(m_Z)$ averages without a subset of the measurements. The possibility to eventually use the lattice extraction as *the single* $\alpha_s(m_Z)$ PDG world-average, as it is the most precise value, it is based on experimental data (hadron masses and decays), and now contains also the running up to high scales, was considered. Some people expressed concerns on that proposal, given the need to always cross-check the lattice-QCD extraction with hadronic data in the explicitly perturbative regime. It was also pointed out that there are a number of dedicated high-precision determinations of the strong coupling from various methods that may eventually be inconsistent with the lattice-QCD results (if their derived central $\alpha_s(m_Z)$ values do not change, and the uncertainties shrink). In addition to the discussion on the averaging, where concrete decisions on the weight of these analysis have to be made, future average analyses should also point out these discrepancies factually to motivate further studies and progress.

The technical averaging procedure was also discussed. Currently it uses linear preaverages for the subcategories, then χ^2-average with floating correlation with the PDF "χ^2 reweighting" prescription (enlarged uncertainties, if needed, until $\chi^2/\mathrm{dof} = 1$). Alternative averaging methods, e.g. a χ^2 average in the groups with a correlation model following the BLUE or CONVINO approaches [13, 14], were suggested, in particular to combine LHC measurements (see above). Values obtained with alternative methods should be provided together with the "default" world-average to check the overall robustness and stability of the final $\alpha_s(m_Z)$ averaging procedure.

All in all, the meeting featured lively and stimulating discussions among different experts on controversial issues, as well as on technical details, whose clarification will ultimately have an impact on more accurate and precise α_s determinations. Novel ideas to extract α_s, estimation of expected reductions in the theoretical and experimental uncertainties of each method, as well as issues to be addressed in the coming future to improve the combination of all results, were discussed. There was a common agreement of the usefulness of organizing similar dedicated α_s workshops every $\sim$2 years, following the 2011 [15] and 2015 [16] meetings. Whereas the strong force decreases with energy, the scientific interest in the QCD interaction clearly increases with time.

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