

Letter of intent: ALPHA-S@LHC

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1. Research objectives

The strong interaction is theoretically described by quantum chromodynamics (QCD), and the strength of the interaction between quarks and gluons is encoded in the QCD coupling, $\alpha_s(Q)$, which depends on the energy scale Q . The strong coupling is usually given at the reference scale of the Z-boson mass ($Q=m_Z$), at which the current PDG world-average is: $\alpha_s(m_Z) = 0.1180 \pm 0.0009$ (0.8% total relative uncertainty), and its value at any other energy can be predicted by the QCD Renormalisation Group Equations. If one ignores the quark masses, α_s is the only free parameter of the theory, and it remains the least well-known interaction coupling in the standard model (SM) of particle physics. Knowing $\alpha_s(m_Z)$ precisely is crucial in particle physics: going from precision calculations of virtually all processes at the LHC, including precision studies of the Higgs sector, to the energy evolution of the electroweak vacuum stability. Short of a quantitative improvement in its determination, the ultimate precision of physics results from the high-luminosity phase of the LHC will be limited by QCD.

The goal of the ALPHA-S@LHC project is to provide the most precise determination of $\alpha_s(m_Z)$ using multiple observables collected in proton-proton (pp) collisions by the CMS experiment at the LHC. Multi-jet ($pp \rightarrow N_j + X$) and jet+gauge-boson ($pp \rightarrow j + V$) production are well understood theoretical processes with improved experimental and theoretical uncertainties. Multi-jet processes have allowed probing the running of α_s up to multi-TeV scales. The determination of α_s relies on the factorisation at an arbitrary energy scale μ_F of the hadronic cross section σ_{pp} into collinear parton densities (PDFs) of the protons and a partonic cross section σ_{ij} : $\sigma_{pp} = \text{Sum PDF}_i(\mu_F) \otimes \sigma_{ij}(\mu_F) \otimes \text{PDF}_j(\mu_F)$, with α_s entering in the partonic cross section and in the PDF evolution. Currently, σ_{ij} is calculated from first principles pQCD up to NNLO accuracy using the NNLOJET code, with the PDFs determined at the same (or better) level of pQCD accuracy from experimental electron-proton and pp data. The existing studies demonstrate that combined fits of multiple $pp \rightarrow N_j + X$ and $pp \rightarrow j + V$ distributions can lead to $\alpha_s(m_Z)$ extractions with sub-percent precision at the LHC. Achieving such improvements requires, however, a new approach in the treatment of uncertainties and correlations across measurements as well as theoretical predictions. The plans of ALPHA-S@LHC are: (a) to perform a simultaneous measurement in pp collisions of a large number of differential observables sensitive to $\alpha_s(Q)$, (b) to improve the treatment of non-perturbative (NP) effects in the theoretical predictions, mainly due to multi-parton interaction (MPI) and hadronisation (HAD) effects, (c) to implement a novel treatment of the large number of systematic uncertainties that accounts for their respective accuracy in the extraction of α_s , and (d) to provide an analysis framework that allows further extensions of the experimental analyses beyond the time frame of ALPHA-S@LHC, combination with other LHC extractions (mostly from ATLAS), and thus further future reductions of the $\alpha_s(m_Z)$ uncertainty.

State of the art

The extraction of α_s from the experimental data typically proceeds in two sequential steps:

(i) The raw data is calibrated and corrected for experimental effects (data analysis or data reduction). Simulated data obtained with Monte Carlo (MC) methods, including a simulation of the detector with GEANT4, are used for this purpose. After calibration at event level, analogue distributions obtained from real and simulated data are directly comparable. Distributions are corrected from any residual distortions, which often consists in a matrix (pseudo) inversion or least-squares minimisation. All experimental uncertainties are derived in this step.

(ii) The $\alpha_s(m_Z)$ value and any additional parameters (e.g. PDF parameters, theory nuisance parameters) are fitted to the data simultaneously (QCD interpretation or QCD analysis). The uncertainties are usually assumed to be Gaussian, so that this fit consists of a least-squares minimisation. The strong coupling and the PDF parameters are best extracted from a simultaneous fit, typically implemented as a least-squares minimisation with nuisance parameters. An additional factor accounting for NP effects may be included in this approach, depending on the level at which the interpretation is done: at particle level (e.g. protons, pions) or at parton level (quarks and gluons). Following this strategy, the precision reachable can be illustrated with the most precise value obtained so far at CMS at 13 TeV with 2016 pp data: $\alpha_s(m_Z) = 0.1166 \pm 0.0014(\text{fit}) \pm 0.0007(\text{model}) \pm 0.0004(\text{scale}) \pm 0.0001(\text{param}) = 0.1166 \pm 0.0017$, where

- the fit uncertainty accounts for experimental effects and the model dependence in step (i) as well as NP uncertainties in step (ii);
- the model uncertainty in the QCD interpretation accounts for the value of certain initial parameters (e.g. bottom and charm quark masses);
- the scale uncertainty accounts for the truncation in the pQCD expansion at NNLO;
- and the parametrisation uncertainty accounts for the dependence in the analytical shape of the PDFs arbitrarily defined at a given scale.

Plan

1. Simultaneous measurement of many differential observables: high-pileup proton-proton collision data recorded by the CMS detector at $\sqrt{s}=13.6$ TeV during LHC Run 3 (2022–2025) will be exploited to perform a simultaneous measurement of standard and novel differential observables, such as multi-differential cross sections as a function of the jet kinematics and cross section ratios. Combinations with similar Run-2 measurements at other $\sqrt{s}$ will be also considered.
2. Upgrade of the fitting tool: First, two open-source fitting frameworks for QCD interpretation (xFitter and NNPDF) will be compared. One of them will be chosen to perform the ALPHA-S@LHC fits. The so-called “errors on errors” will be implemented to account for the different levels of accuracy of the systematic uncertainties themselves and preserve the constraining power of the systematic uncertainties while mitigating the risk that some of them introduce artificial tensions. Then, the treatment of NP effects will be revisited to be better motivated physically by (a) breaking down the uncertainties for HAD and MPI separately, and (b) describing them using a transfer matrix rather than bin-to-bin corrections.
3. Determination of the strong coupling: The preparation of theoretical predictions requires a significant amount of computing power, hence it the effort should start as early as possible. In the last six months, the data and the tools will be used to perform the ultimate determination of α_s , following a blinding strategy where only a fraction of the data will be used to set up the fit.

2. Connection to Transnational Access infrastructures (TAs) and/or Virtual Access projects (VAs)

TA infrastructure: CERN as hosting institute, as host for the LHC and the CMS experiment

VA infrastructure: Powerful computing clusters (e.g. in Baden-Württemberg with Klaus Rabbertz or in Brussels with Laurent Favart)

3. Estimated budget request

Total: 200kEUR (includes administrative overheads, plus CHF-EUR conversion)

- Personnel: 130kCHF per year to contribute to the funding of a two-year postdoc contract from CERN TA (fellowship or LD)

We will also request support from CERN TA for workshops / invitations over the 4 years at a rate of 140CHF/day/participant, anticipating 20 participants for 5 days for a total of 14kCHF.

4. Participating and partner institutions:

- CERN Theory: Pier Monni, Alex Huss
- KIT, Germany: Klaus Rabbertz team
- University of Ioannina, Greece: Panagiotis Kokkas team
- HIP, Finland: Mikko Voutilainen team
- ULB-IIHE, Belgium: Laurent Favart team
- DESY Hamburg, Germany: Frank Tackmann, Giulia Marinelli
- Zhejiang University, China: Xiao Meng team
- LPNHE Paris, France: Bogdan Malaescu team
- MPI Munich, Germany: Giulia Zanderighi, Stefan Kluth
- Jyväskylä University, Finland, Felix Hekhorn