Brussels, 23 June 2017

COST 012/17

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "Unraveling new physics at the LHC through the precision frontier" (PARTICLEFACE) CA16201**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action Unraveling new physics at the LHC through the precision frontier approved by the Committee of Senior Officials through written procedure on 23 June 2017.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA16201
UNRAVELING NEW PHYSICS AT THE LHC THROUGH THE PRECISION FRONTIER (PARTICLEFACE)

The COST Member Countries and/or the COST Cooperating State, accepting the present Memorandum of Understanding (MoU) wish to undertake joint activities of mutual interest and declare their common intention to participate in the COST Action (the Action), referred to above and described in the Technical Annex of this MoU.

The Action will be carried out in accordance with the set of COST Implementation Rules approved by the Committee of Senior Officials (CSO), or any new document amending or replacing them:

a. “Rules for Participation in and Implementation of COST Activities” (COST 132/14);
b. “COST Action Proposal Submission, Evaluation, Selection and Approval” (COST 133/14);
c. “COST Action Management, Monitoring and Final Assessment” (COST 134/14);
d. “COST International Cooperation and Specific Organisations Participation” (COST 135/14).

The main aim and objective of the Action is to Shifting the precision frontier in Quantum Field Theory to a new level of accuracy with the quest for discovery at high-energy colliders, LHC and future colliders, as the main motivation. Creating new resources of networking and innovation, and encouraging advances in related areas of pure mathematics and computer science.. This will be achieved through the specific objectives detailed in the Technical Annex.

The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 52 million in 2016.

The MoU will enter into force once at least five (5) COST Member Countries and/or COST Cooperating State have accepted it, and the corresponding Management Committee Members have been appointed, as described in the CSO Decision COST 134/14.

The COST Action will start from the date of the first Management Committee meeting and shall be implemented for a period of four (4) years, unless an extension is approved by the CSO following the procedure described in the CSO Decision COST 134/14.

TECHNICAL ANNEX

OVERVIEW

Summary

Elementary particle physics is currently described by the Quantum Field Theory (QFT) called the Standard Model (SM). The SM, being an apparent success, is well known to be theoretically incomplete. **Fundamental questions** underlying the quantum structure of Yang-Mills theories are still unanswered. The SM does neither account for mass hierarchies nor for dark matter or dark energy. Most importantly it cannot remain valid to arbitrarily high energies and does not include gravity. After the confirmation of the Higgs boson's existence, entirely new questions come into the focus in the field.

The key to address those questions is to **confront experimental data to theoretical predictions with the highest possible precision**. The current LHC data do not show a clear signal of new physics. Therefore, any evidence is expected to appear as a gentle deviation from the SM. **Precision phenomenology** is the necessary prerequisite for theory and collider physics in the coming years and it will be the driving element in the development of new and innovative tools and algorithms to perform a meaningful comparison between theory and data.

The aim of this Action is to **shift the precision frontier to a new level of accuracy and to create new resources of networking and innovation, with the quest for discovery as the main motivation**. It is designed to work through long-standing challenges on the basis of the most encouraging advances in QFT and related areas of pure mathematics and computer science by **uniting the leaders of the field in a coherent effort**.

Areas of Expertise Relevant for the Action	**Keywords**
● Physical Sciences: Particle physics (theory) ● Physical Sciences: Fundamental interactions and fields (theory) ● Physical Sciences: Mathematical physics ● Computer and Information Sciences: Theory of scientific computing and data processing	● LHC ● Quantum Field Theory ● Fundamental Interactions

Specific Objectives

To achieve the main objective described in this MoU, the following specific objectives shall be accomplished:

Research Coordination

- Development of novel computer algebra algorithms to achieve efficient analytical simplifications that can lead to relevant breakthroughs and can be applied to other fields.
- Deepen the knowledge about fundamental questions underlying the quantum structure of Yang-Mills theories.
- Establishment of a standard formalism for NNLO computations in QFT, and detailed comparison among different schemes and methods from different groups.
- Extension of the standardised formalism beyond NNLO for multi-particle and multi-scale scattering processes.
- Achievement of a unified approach to precision phenomenology of electroweak and strong interactions, which could be considered separately up to now, and ask for new approaches to the identification of particle dynamics in high-multiplicity environments.
- Maximising the discovery potential at the LHC, and assessment of the discovery potential of future high energy colliders.
- Providing support for refined experimental analysis at collider experiments by developing user-friendly and standardised high precision simulation tools.

● Coordination of specialised research training in the field.
● Dissemination of research results to the general public and potential stakeholders.
● Exploration of the potential commercial applications of the developed methods, algorithms, cutting-edge software and modelling tools in other fields, e.g. big data analysis or risk assessment

Capacity Building

● Consolidating and extending the scientific collaboration among the major European and non-European experts in formal aspects of QFT, precision phenomenology, development of Monte Carlo event generators, and model building.
● Promoting the communication and collaboration of theoretical and experimental physicists with mathematicians, to achieve breakthroughs that require an interdisciplinary approach.
● Acting as stakeholder platform and developing a joint research agenda to achieve a common training framework and standardised research methodologies.
● Fostering the development of the field in COST NNC Countries by attracting to Europe talented researchers through STSM and participation in training events.
● Involving newly established research groups from COST ITC and IPC Countries.
● Improving the gender balance of the Action, particularly involving more women in leading positions.
● Increasing the number of ECI researchers to promote their career prospects, scientific maturity and leadership, thus maximising their employability opportunities.
● Involving potential stakeholder in scientific communication and scientific journalism.
● Attracting industry partners from the software and consulting sectors.

1) S&T EXCELLENCE

A) CHALLENGE

I) DESCRIPTION OF THE CHALLENGE (MAIN AIM)

The primary tool in particle physics research is the exploration of the particle's interactions in colliders at the **high-energy frontier**. Particle collisions at the highest possible energies are currently probed by the LHC, which is the largest and most complex single experiment ever performed in the history of mankind in a joint enterprise of most of the European and many other States. The LHC is now running with upgraded collision energy of 13 TeV (14 TeV soon) and the high-quality LHC data is providing a unique window of opportunity to search for new physics.

Elementary particle physics is currently described by the Quantum Field Theory (QFT) called the Standard Model (SM). The SM, being an apparent success story, is well known to be theoretically incomplete. **Fundamental questions** underlying the quantum structure of Yang-Mills theories are still unanswered. The SM does neither account for hierarchies of particle masses nor for dark matter or dark energy. Most importantly it cannot remain valid to arbitrarily high energies and does not include gravitational interactions. Therefore, after the confirmation of the Higgs boson's existence, entirely new questions come into the focus of the scientific community, e.g. the nature of the Higgs boson, its implications for our Universe at very early times or the possible connections of the Higgs boson with inflation driven by new forces.

The key to address those questions is to **confront current knowledge and experimental data to theoretical predictions with the highest possible precision**. The current LHC data do not show a clear signal of new physics. Therefore, any evidence of new physics is expected to appear as a tiny deviation from the SM. **Precision phenomenology** is thus the necessary prerequisite for theory and collider physics in the coming years and it will be the driving element in the development of new and innovative tools and algorithms to perform a meaningful comparison between theory and data.

The transfer of knowledge to the experimental collaborations proceeds through provision of suitable **simulation tools**, which are omnipresent in all aspects of the experimental measurements. Their further development is continuously ongoing. Studies of the Higgs boson and searches for new particles beyond the SM all rely on an intricate separation of potential signals from background processes, which both need to be predicted to high precision. Providing precision predictions of high multiplicity processes in the SM and beyond at the energy frontier calls for new innovative approaches in theoretical particle physics.

Challenging the precision frontier requires also to deepen our understanding of the quantum structure of Yang-Mills theories and might lead to relevant **breakthroughs not only in theoretical particle physics but also in mathematics**. Perturbative calculations in QFT are based on the universality and factorization properties of Yang-Mills theories, which are generally assumed but not yet proven. Only by going to higher orders we can gain a deeper insight. Another example for major novelties in analytical computations and the interdisciplinary approach of this Action are the use of e.g. symbol calculus for multi-loop problems together with the systematic application of differential and difference equations. As a virtue, the symbol map captures to a good extent the main combinatorial and algebraic properties of certain transcendental functions, e.g. harmonic polylogarithms, by exploiting the underlying Hopf algebra structure, thus allowing for efficient and systematic simplifications of large analytic expressions. Progress in higher order computations also leads to progress in mathematics.

The physics programme of a proton-proton collider at energies a factor of 10 above the reach of the LHC is presently being discussed. Such a machine will test particle physics in an entirely new regime. Up to now, only very little theoretical work has been done in this direction, and many of the challenges ahead have not yet been identified. At energies well above the scale of electroweak symmetry breaking (EWSB), the hierarchy of the strong and electroweak interactions is no longer present, and will demand a variety of new precision calculations. Hadronic final states with **ultra-high multiplicity** will pose new challenges for the identification of resonances, and predictions of their kinematic properties will likely be decisive for the design of accelerator and detectors.

II) RELEVANCE AND TIMELINESS

The aim of this COST Action is to **shift the precision frontier to a new level of accuracy and to create new resources of networking and innovation, with the quest for discovery as the main motivation**. It is designed to work through long-standing challenges on the basis of the most encouraging advances in QFT and related areas of pure mathematics and computer science by **uniting the leaders of the field in a coherent effort**. This action will have unique impact on the physics programme of current and upcoming collider experiments at the high-energy frontier, and will directly **contribute to shaping the future of particle physics** by establishing a distinguished framework with excellent conditions for collaboration and training of the next generation of researchers in the field.

The research programme of this Actions is built on the accumulated experience and the current leadership in elementary particle physics and collider phenomenology. The initial list of proposers includes a **multidisciplinary group** consisting of the leading specialists in theoretical physics and new perturbative methods, experts in the phenomenology of the SM and beyond, mathematicians, experimentalists and developers of Monte Carlo event generators, With the focus on the high-energy/high-precision frontiers, this Action has identified the areas in the field where breakthroughs and discoveries are expected in the coming years.

The **LHC is currently in a crossroad** where a clear signal of new physics has not yet been evidenced in the data. Based on the LHC results the particle physics community will face **important strategic choices** on the future research directions in high-energy collider physics during the next five years. The decision on the construction of a linear electron-positron collider, hosted in Japan, and operated by a worldwide consortium effort will likely be made soon. In outlining particle physics at long-term, CERN, and now also the Chinese physics community, are seriously considering the construction of a new 80km-long ring tunnel, which could be instrumented with either an electron-position collider optimised for the study of the Higgs boson, or with a 100 TeV proton-proton collider. It is therefore of paramount importance to scrutinize the available LHC data and to leave no stone unturned when assessing the potential of directions for future research at high energy colliders. In this context, the **European Strategy for Particle Physics** will be updated in in 2019 or 2020, and this Action is t**imely** with all the decisions that will determine the **future in the field**.

B) SPECIFIC OBJECTIVES

I) RESEARCH COORDINATION OBJECTIVES

The Action central goal is to coordinate the transfer of knowledge and know-how among the participant groups, such that existing collaborations are strengthened and new synergies are created in order to achieve the following research objectives:

- Development of novel computer algebra algorithms to achieve efficient analytical simplifications that can lead to relevant breakthroughs and can be applied to other fields.
- Deepen the knowledge about fundamental questions underlying the quantum structure of Yang-Mills theories.
- Establishment of a standard formalism for NNLO computations in QFT, and detailed comparison among different schemes and methods from different groups.
- Extension of the standardised formalism beyond NNLO for multi-particle and multi-scale scattering processes.
- Achievement of a unified approach to precision phenomenology of electroweak and strong interactions, which could be considered separately up to now, and ask for new approaches to the identification of particle dynamics in high-multiplicity environments.
- Maximising the discovery potential at the LHC, and assessment of the discovery potential of future high energy colliders.
- Providing support for refined experimental analysis at collider experiments by developing user-friendly and standardised high precision simulation tools.
- Coordination of specialised research training in the field.
- Dissemination of research results to the general public and potential stakeholders.
- Exploration of the potential commercial applications of the developed methods, algorithms, cutting-edge software and modelling tools in other fields, e.g. big data analysis or risk assessment.

II) CAPACITY-BUILDING OBJECTIVES

The following objectives are entailed to increase the critical mass of the Action in driving scientific progress, thereby strengthening the European Research Area:

- Consolidating and extending the scientific collaboration among the major European and non-European experts in formal aspects of QFT, precision phenomenology, development of Monte Carlo event generators, and model building.
- Promoting the communication and collaboration of theoretical and experimental physicists with mathematicians, to achieve breakthroughs that require an interdisciplinary approach.
- Acting as stakeholder platform and developing a joint research agenda to achieve a common training framework and standardised research methodologies.
- Fostering the development of the field in COST NNC Countries by attracting to Europe talented researchers through STSM and participation in training events.
- Involving newly established research groups from COST ITC and IPC Countries.
- Improving the gender balance of the Action, particularly involving more women in leading positions.
- Increasing the number of ECI researchers to promote their career prospects, scientific maturity and leadership, thus maximising their employability opportunities.
- Involving potential stakeholder in scientific communication and scientific journalism.
- Attracting industry partners from the software and consulting sectors.

C) PROGRESS BEYOND THE STATE-OF-THE-ART AND INNOVATION POTENTIAL

I) DESCRIPTION OF THE STATE-OF-THE-ART

The LHC data is characterized by the production of **complex multi-particle final states** and its description requires higher order radiative corrections. NLO calculations in QFT have been automatized in the recent past to a very high degree in several computer codes (e.g. aMC@NLO, Rocket, CutTools, GoSam, BlackHat). This achievement has only been possible due to important recent theoretical breakthroughs in understanding better the analytic structure of loop amplitudes. Merging with Parton Showers, which effectively resum large logarithmic contributions from collinear configurations as implemented in Monte Carlo event generators, has also been achieved at NLO. A similar level of understanding is currently lacking at higher orders (NNLO and beyond), where calculations are made on a **case-by-case basis**, and are limited to processes with low multiplicities.

Overcoming the current **theoretical precision frontier** becomes significant not only for an accurate comparison with a variety of relevant scattering processes that will be measured with the highest precision at the LHC, it is also a major challenge because it might shed light on relevant information about the deep quantum structure of Yang-Mills theories and will require the introduction of fundamental new ideas both in physics and mathematics. Moreover, QCD computations are also important for the **cosmic frontier** and other research fields, for example in evaluating cross sections for the direct detection of **dark matter**.

II) PROGRESS BEYOND THE STATE-OF-THE-ART

The QFT calculations required to provide **precision phenomenological predictions** for multi-particle final states at the LHC pose formidable challenges, both conceptually and technically. Their completion requires substantial innovation and progress in the formal understanding of perturbative field theory, new tools and algorithms in computer algebra, highly efficient and innovative approaches to the simulation of particle collisions, and a variety of proof-of-concept calculations to validate these new approaches. In many of those aspects, the **interaction with mathematicians will be instrumental for success**. With ever increasing computational power, one may also envisage to shift more formal parts of these calculations from purely **algebraic manipulations to numerical evaluation**, thereby facilitating **automation at higher orders**. In this Action, we will develop new innovative concepts for precision QFT and its application to collider physics, thereby providing the tools to address the frontiers in precision and energy of the LHC and of future colliders.

The LHC is producing a large set of data from proton-proton collisions at the highest energies. These data push the boundaries of knowledge on elementary particles in several directions: energy, precision and sensitivity. They could provide **exciting observations of new physics effects** at the highest energies ever attained in a laboratory. The large production rates for known particles (especially top-quarks, EW and Higgs bosons) will allow for **improved precision measurements** of particle properties and interactions. The large amount of data collected will push the sensitivity for the observation of **ultra-rare processes**. Evidence for new physics effects beyond the SM could become manifest, through direct observation in particle production, or indirectly in precision observables. The interpretation of the new LHC data is limited by the theoretical accuracy, and demands new innovative concepts for reliable predictions and their adaptation to quickly changing experimental boundary conditions. (e.g. possible reported evidence of new signals). The Action will address these challenges, and will confront state-of-the-art innovation in applied QFT with precision data from the LHC.

On the **energy frontier**, the High-Luminosity LHC and future colliders will probe final states of increasing complexity in its search for new short-lived states, thereby demanding innovation in the analysis techniques and reliable predictions for anticipated signals and their background.

Readiness for the interpretation of new effects in a model-independent context is very much in demand, and requires novel approaches for the description of particle dynamics at the highest energies.

III) INNOVATION IN TACKLING THE CHALLENGE

The Action will address the challenge with a novel approach from several parallel directions:

- The research challenge of the Action, in theoretical particle physics, requires relevant input, exchange of new ideas and development of efficient tools from **mathematicians**. Likewise, the physics motivated challenge can potentially lead to breakthroughs in mathematics. This interdisciplinary approach is central for the success of the Action.
- The establishment of a **standard formalism for NNLO** computations will overcome the fragmentation in the field, where concurrent groups are developing and competing with different methods. If the standardisation at NNLO is achieved, it will pave the path beyond NNLO for multi-particle processes.
- Scattering amplitudes of **spontaneously broken gauge theories** like EW are less singular in the IR than massless gauge theories like QCD, but their gauge and UV structures are more complex. Reaching a unified approach of electroweak and strong interactions, which could be considered separately up to now, requires novel approaches to achieve the required accuracy without compromising the computation complexity.
- While most of the proposers and future stakeholders are quite skilled in delivering public talks, and organising outreach activities, they are less experienced in the interaction with the **mass media**. In fact, there is a certain degree of distrust towards journalists due to the fear of scientists to the loss of rigor in the press articles. The Action is prepared to overcome this distrust and to build the necessary bridges in order to increase the visibility of the field in the mass media.
- Although the research goals are on fundamental physics, the Action will promote the potential exploitation of the methods and algorithmic achievements following an **Open Innovation** strategy. In addition, the training of young researchers goes beyond the purely scientific knowledge and has the purpose to provide them with the necessary tools to compete successfully with the acquired analytical skills also in the private sector. The connection with **industry** is mostly made through former PhD candidates from the proposers´ institutions to assure a fluent communication.

D) ADDED VALUE OF NETWORKING

I) IN RELATION TO THE CHALLENGE

The initial list of proposers includes all the relevant stakeholders necessary to consolidate a larger community of researchers that will persist after the end of the Action:

- The Actions involves all the **relevant experts in new perturbative methods and precision phenomenology**. Networking will allow to break fragmentation in the field by creating a common framework to confront the different methods developed by their respective groups.
- The close collaboration between **mathematicians and theoretical physicists** will guarantee a multidisciplinary approach to the challenge.
- Monte Carlo event generator developers participating in the Action will profit from the research results, that will also directly benefit the experimental analysis. Among the proposers there are also a few experimentalists that will provide advice and will act as the bridge with other experimentalists from the LHC experiments, ATLAS, CMS and LHCb. The Action counts also with the additional collaboration of model building experts. Overall, it is well prepared for a **fast reaction to quickly changing experimental boundary conditions** boosted by possible evidences of new signals.
- The **network-wide training activities** are designed to provide dedicated and broad research competences that are difficult to obtain locally. Moreover, besides specialised and

technical training in research, the Action schools will offer also training in **transferable and complementary skills** provided by a dedicated team of trainers.

- Networking also offers to ECI the possibility to strengthen their **management skills** by assuming leading responsibilities within the Action, with the promotion of women researchers as target stakeholders.
- The Action will offer new opportunities of development to researchers from COST ITC, NNC and IPC Countries, particularly to ECI.
- During the recent years of LHC operations and in the context of the Higgs boson discovery the proposers have gained significant experience in the communication of fundamental science to the general public. The Action will **improve the communication capacity** of the participants, and will extend their influence towards till today less chartered audiences, e.g. mass media.
- The Action will create synergies between **academic and industry research**, while keeping identity and diversity. Former PhD candidates now working in industry are essential for the success of this strategy.

II) IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

Several European and international initiatives, with emphasis in related areas, are currently in place. The MC and WGL will promote the collaboration with the following existing Actions and networks when a mutual benefit is expected to occur and will invite the relevant experts to participate in the Actions activities:

- The recently approved COST Action **CA16108** “Vector Boson Scattering Coordination and Action Network” is focused in the measurement of Vector Boson processes. The potential for two-way theory-experiment transfer of knowledge is high.
- The COST Action **CA15108** “Connecting insights in fundamental physics” (http://connecting-insights-cost.eu). A collaboration in the interpretation of possible signals beyond de SM will be advantageous.
- The **HiggsTools** MSCA Training Network (http://higgstools.org) is focused in the physics of the Higgs boson; while PARTICLEFACE is broader in scope, a combined effort in the Higgs boson sector will be beneficial for both.
- The **MCNet** MSCA Training Network (http://www.montecarlonet.org) deals with Monte Carlo event generators. Results produced within this Action can be used to feed and improve the accuracy of these event generators.
- The **LHC EWK and Higgs Cross-Section Working Groups** lead by CERN. They produce high-quality review reports. This Action can contribute with new results to their future reports.

2) IMPACT

A) EXPECTED IMPACT

I) SHORT-TERM AND LONG-TERM SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS

The physics program of the LHC is currently foreseen for a period of 15 years and the experimental data are expected to lead to exciting new discoveries. Thus, the research activities at the LHC will be in the focus of the entire high-energy community for, at least, the next decade. Short-term impacts concern milestones and deliverables that will be achieved during the lifetime of the Action. Long-term impacts are those that are expected to persist after the end of the Action.

Short-term impacts:

- Overcome the current precision frontier in theoretical particle physics to achieve a successful interpretation of data and contribute to potential discoveries at the LHC.
- Train young researchers on the most interesting topics at the forefront of fundamental research and cutting-edge computing, as well as reinforcing their soft skills.
- Strengthen the individual potential and enhancing the career perspectives and employability of ECI researchers in academia and industry.
- Increase the communication skills and public engagement of the participants, and the visibility of the field among the general public.
- Explore potential applications in industry, and create new sources of Open Innovation.
- Promote the creation of spin-offs and entrepreneurship to exploit the research results.

Long-term impacts:

- Contribute to shape the future in the field.
- Create a multidisciplinary network of physicists, mathematicians and software developers that will remain active and will continue to collaborate closely beyond the end of this Action.
- Strengthen Europe's leadership in fundamental physics, and extend its area of influence to COST NNC and IPC Countries.
- Promote the career development of ECI researchers such that they can take leading positions in research, management and evaluation of European projects (MSCA, COST, ERC).
- Counteract the current gender imbalance in the field, particularly in leading positions.
- Promote the vocational enrolment of women in scientific and technological studies at the university, and pursuing careers in research.
- Create an innovation-friendly environment that makes easier the communication between fundamental research and industry.

B) MEASURES TO MAXIMISE IMPACT

I) PLAN FOR INVOLVING THE MOST RELEVANT STAKEHOLDERS

The proponents of this Action comprise already a **multidisciplinary community** of the most relevant experts in the field, ranging from specialists in theoretical physics, mathematicians, phenomenologists of the SM and beyond, experimentalists and developers of Monte Carlo event generators. They count with an extensive list of personal contacts, international collaborations and are involved in the organization of multiple activities. They have sufficient **capacity to attract and recruit** to the Action additional experts in the field.

The **Kick-off Meeting** represents the best opportunity to enlarge the number of participants from the beginning. An intense advertisement campaign by the usual means in the field will be undertaken to make from the Kick-off Meeting a success and to involve in the activities of the Action the maximal number of experts and stakeholders. The subsequent Yearly Workshops, in particular the Mid-Term Meeting where the progress of the Action will be reviewed, represent further opportunities to effectively gather new participants. All the Actions events will be **open to the scientific community** and will widely advertised to maximise the impact and involvement of additional participants.

The Action will organise four **Training Schools** providing a common environment for training of **Master, PhD candidates and ECI** in the most advanced state-of-the-art techniques, and also in complementary skills. On one side, the TS will serve to involve in the Action young researchers that can later apply for a STSM. On the other side, ECI will be given leading responsibilities in the organisation of these events, and also in the other Action events, giving them visibility and the opportunity to promote their managerial skills.

There is already a representative sample of **COST ITC and IPC** proposers that can play an active role in attracting further participants from those countries and extending the Action to other neighbouring countries. To maximise the inclusiveness policy of the Action and the participation of students and researchers with budgetary constraints, at least **one Yearly Workshop and two Training Schools** will be organised in these countries. With the exception of Russia, already involved in this Action, the field is not sufficiently developed in most of the COST NNC Countries. The Action will target supporting young researchers from NCC, in particular concerning STSM, to create the seed for future involvement.

Industry partners will be involved thanks to well-established collaborations built in previous European training networks, and through former PhD candidates of the proposers that moved to industry, mostly in the software and consulting sectors. They will be invited to participate in the Action events to foster the exchange of professional experience and enlarge the employment perspectives of the young researchers.

A variety of targeted **outreach and dissemination activities** will be implemented to maximise the impact of the public engagement strategy of the Action. In order to overcome those aspects in which the proposers are less strong, such as the interaction with the mass media, a journalist has already been involved in the Action. His involvement is also relevant to attract the interest of other **scientific journalists**.

The effectiveness of the **inclusiveness and gender policies** of the Action will be reviewed every six months. Having in mind that the number of women in the field is low, particularly at the faculty level, the Action is built with the aim of counteracting this imbalance. Besides assigning leading responsibilities to the women proposers from the beginning, the main goal of the gender policy is to increase the number of women participating in the Action.

II) DISSEMINATION AND/OR EXPLOITATION PLAN

The dissemination of the research results will follow the most **efficient and well-tested procedures in the field**. A website based on WordPress (http://wordpress.org), a free and open source blogging tool allowing for a **collaborative management and content administration** will be setup. The Action website will provide information on the participant researchers and teams, research and training events, reports, training material, open source computer codes, and highlight most relevant achievements. The WGLs will be responsible to update the information on the progress in their respective tasks.

All the scientific papers produced by the members of the Action will be self-archived in the arXiv (http://arxiv.org) repository for electronic preprints. The arXiv, started in 1991 as a preprint repository in particle physics, has now been extended to include many other disciplines and its existence has been one of the precipitating factors that led to the current **Open Access** movement in scientific publishing. **The journals in the field with the highest impact factors** (JHEP, Eur. Phys. J.C, Nucl. Phys. B, Phys. Lett. B and Acta Phys. Polon. B), are our target journals for publication of results, and are presently Open Access funded by SCOAP3 (http://scoap3.org), an innovative project lead by CERN which is designed to bring open access to the high-energy physics community at no cost for authors. Since January 2014, arXiv also links the published articles through SCOAP3. Moreover, a **network preprint repository** will be created and linked to the website and the arXiv, allowing to **increase the visibility of the Action**, and facilitating the reporting of the scientific results. A **Review Handbook** summarizing the research achievements will be prepared for the final conference and will be published by the end of the Action.

The **Indico System** (http://indico.cern.ch) has become the standard web application in our field for the management and organisation of workshops, conferences, and training events. It provides an easy to use tool to manage registration of participants, to attach multimedia files and to store the resulting agendas in a multi-level hierarchical tree, keeping copies of all lectures and talks. All the **Action events** will be based on Indico and will be linked from the Action website. The Action will also exploit web video tools for the organisation of **webinars and on-line lectures**. The **Hepforge** (http://www.hepforge.org) as a development environment for high energy physics software projects, and the Durham **HepData** (http://hepdata.cedar.ac.uk), as a public available reaction data database, are also of common use by members of our network. The full set of **online documentations, and training materials** available through these web applications and repositories linked at the Action website will also create a very useful library for future training programs.

Besides the Action events, research results will be disseminated through oral presentations at the **most relevant international conferences in the field**, such as the upcoming and future editions of HEP-EPS 2017, RADCOR 2017 and ICHEP 2018, and other external workshops, and will be published in the corresponding proceedings.

The recent discovery of the Higgs boson and the award of the Nobel Prize in Physics 2013 to François Englert and Peter Higgs has attracted a lot of attention and interest from the general public to particle physics. Numerous dedicated press articles and TV documentaries have been released. **Proposers of the Action have delivered public talks** (a few of them have been recorded and are available on-line), and have been interviewed by the media. Based on the previous experience of the participants, the Action will organise two kind of **outreach activities during the Action events**: general public talks by renowned scientists, and more focussed educational events for secondary school students in order to develop their interest in science. Most of the institutions of the proposers have also their own outreach programme that include among other activities open days and visits to schools. Promoted by the Action, the participants will also profit from the local infrastructure by actively participating in these **local outreach activities**.

Today, the most effective way to impact and engage the general public is by exploiting the potential of the web and the **social networks**. A section in the Action website targeted to the general public will be created. It will link short news on the research activities and results of the network, in the form of press-notes, outreach materials, Action leaflet, short articles and videos, such that non-specialists can understand them. A short video summarising the main achievements will be issued at the end of the Action. The **press-notes** will be prepared with the help of the journalist involved in the Action, who will distribute them through national news agencies. Specialised scientific blogs are also among the target stakeholders. A Twitter account will be created, and will be linked to the Action website. It will be used to highlight the achievements and news of the network for non-specialists.

The main motivation of our research programme is to provide support for refined experimental analysis at collider experiments. Consequently, the generated publications and simulation tools are designed to be disseminated and used as much as possible among the research community following the principles of **Open Access and Open Source,** provided the authors get credit for their work. However, the development of sophisticated and cutting-edge software and modelling tools might find applications in other fields, like e.g. big-data. Commercially exploitable **Intellectual Property Rights (IPR)** such as systems, methods and algorithms generated by the Action will be legally protected. Advice on how to exploit foreground IPR will be sought from specialists through the MC. This information will be treated as confidential and as such its use will be restricted in early dissemination activities like publications until it is fully protected. Some of the proposers have already experience in this subject.

C) POTENTIAL FOR INNOVATION VERSUS RISK LEVEL

I) POTENTIAL FOR SCIENTIFIC, TECHNOLOGICAL AND/OR SOCIOECONOMIC INNOVATION BREAKTHROUGHS

The Action unites in a coherent effort the leaders of the field through a highly challenging project. With the quest for discovery as the main motivation, overcoming the current precision frontier requires to achieve significant scientific breakthroughs with potential high impact in particle phenomenology, purely theoretical physics and mathematics. Significant scientific progress is expected as the outcome of the Action.

The training program is designed to develop outstanding analytic skills of highly motivated young researchers. These valuable skills can further be exploited either in academia or industry.

The Action will create an innovation-friendly environment to facilitate the communication between fundamental research and industry. Although socioeconomic innovation breakthroughs cannot be anticipated, the fact of opening this way of communication, maintaining the identity and diversity of the parties, is an innovative asset of the Action.

3) IMPLEMENTATION

A) DESCRIPTION OF THE WORK PLAN

I) DESCRIPTION OF WORKING GROUPS

The implementation of the Action is organised in five Working Groups (WG). The first three WG are focused on the scientific objectives with clear interdependences among them. Progress achieved in WG1 will be used to produce new results in WG2, which will be extrapolated at higher-energies in WG3. The WG4 is devoted to internal management and coordination of the Action activities, while WG5 is aimed at the implementation of the Action policies and external communication.

WG1: Innovative Tools, Algorithms and Methods for precision calculations and the deep quantum structure of Yang-Mills Theories	
Objectives	Development of innovative cutting edge algorithms to push the precision frontier forward, development of computational tools, computer algebra implementations, and proof-of-concept computations.
Tasks	1.5 Development and standardisations of new computational methods in Quantum Field Theory based on 1.4 new four-dimensional regularization and renormalization algorithms, generalized unitarity and eikonal methods; 1.3 computation of master integrals for multi-leg multi-loop scattering amplitudes; and 1.1 the development of novel computer algebra algorithms to achieve efficient analytical simplifications. 1.2 Factorisation properties of Yang-Mills theories and connection with gravity through the recent investigations on the colour-kinematics duality.
Milestones	▪ New Special Functions, efficient algorithms for asymptotic expansions, recurrence relations and computer algebra simplifications. ▪ Solving the infrared/ultraviolet structure and factorisation properties of Yang-Mills theories at higher orders. ▪ Scattering amplitudes in gravity. ▪ Master integrals and tensor reduction for higher-order computations. ▪ Development of novel higher-order methods in four space-time dimensions. ▪ Establishment of a standard formalism for NNLO computations, and

	comparison among different schemes. Extension beyond NNLO.
Deliverables	▪ Publications in high-impact journals and open-source software (D1-D4). ▪ Reports of the WG activities (D8, M12, 24, 36, 48).
WG2: Precision Phenomenology at the energy frontier with high-quality LHC data	
Objectives	Precise theoretical predictions for LHC in the high-energy run to push the frontiers regarding precision and sensitivity. Computation of cross sections for Higgs boson production (single and multiple Higgs boson production), EW gauge bosons, heavy-quark, multi-jet and ultra-rare processes in differential kinematics.
Tasks	2.1 Precise predictions for exclusive single and multiple Higgs boson production, EW boson and heavy-quark (top-quark) production at hadron colliders, 2.2 multi-jet, jet substructure physics, and ultra-rare processes. The methodology includes the computation of perturbative corrections as well as 2.3 the application of effective field theories such as soft-collinear effective theory (SCET) and all-order resummation in particular kinematical regions, e.g. for transverse momentum. 2.4 High-quality LHC data will also be used to determine non-perturbative quantities such as parton distributions. Based on the innovative tools, algorithms and methods developed in WG1, the projects aim at the NNLO accuracy in QCD for the precision of the theoretical predictions, and combined with EW contributions at NLO.
Milestones	▪ Fully exclusive theoretical predictions for Higgs boson, EW bosons, top quark, multi-jet and ultra-rare processes at NNLO in the SM and beyond. ▪ Resummation of multi-scale processes in hadro-production. ▪ New substructure techniques in jet physics at higher orders. ▪ Improved Parton distribution functions with EW corrections.
Deliverables	▪ Publications in high-impact journals (D1-D4). ▪ Implementation of result in Monte Carlo events generators for direct comparison with data (D1-D4). ▪ Reports of the WG activities (D8, M12, 24, 36, 48).
WG3: Assessing the discovery potential of future high energy colliders	
Objectives	Assessment of the discovery potential of future high energy colliders based on the experimental results from the high-energy run of the LHC combined with progress in theoretical research.
Tasks	Study of EW gauge-boson production at the highest energies at 3.2 fixed order in perturbation theory and 3.3 resummation. The scattering of EW gauge-bosons at high energies is particularly important for further investigations of the EWSB at future colliders and the determination of the scale of new physics. Studies of heavy-quark properties and couplings in the SM and beyond (3.2) as well as applications of effective field theories to jet observables at hadron colliders (3.3). 3.1 As a particular strong point the research approach towards new physics phenomena is largely independent of particular model assumptions and driven by precision comparisons to SM predictions for well-defined signals. This maximizes the discovery potential.
Milestones	▪ Prospects for the physics of the Higgs boson, EW bosons, top quarks, and high-energy jets at future colliders with ultra-high multiplicities. ▪ Combined EW and QCD predictions at the highest energies. ▪ Resummation techniques for multi-scale processes at the highest energies.

Deliverables	▪ Publications in high-impact journals (D1-D4). ▪ Recommendations for the European strategy discussion of high-energy physics, to be updated in 2019-2020 (D5, M24). ▪ Reports of the WG activities (D8, M12, 24, 36, 48).
WG4: Management, Reporting, Organisation of Events, Training Activities and Short-Term Scientific Missions	
Objectives	Efficient coordination of the Action activities, transparent administration, and reliable reporting.
Tasks	4.1 Overall management of the Action, setting up of the management structure (MC, CG, WG), website, efficient communication with partners and COST Association, preparation of scientific and financial reports, 4.2 harmonisation of Action events, 4.3 coordination of Short-Term Scientific Missions (STSM) and 4.4 publication of Final Review Handbook.
Milestones	▪ MC, CG and WG Meetings. ▪ Kick-off Meeting, Yearly Workshops, Mid-Term Review and Final Conference. ▪ Training Schools. ▪ Successful implementation of STSM.
Deliverables	▪ Setting up of the overall management structures and procedures, website contents, and implementation of internal communication tools (D6, from M1). ▪ Opening of calls, coordination and follow-up of STSM (D7, every six months). ▪ Scientific and financial reports based on WG reports (D8, M12, 24, 36, 48). ▪ On-line documentation from webinars, training schools and presentation of research results at workshops and final conference (D9, throughout, M48). ▪ Final Review Handbook (D10, M48).
WG5: Inclusiveness and Gender Policies, Dissemination and Exploitation of Results, and Public Engagement	
Objectives	Implementation of the Action policies. Industrial dimension. Communication of the Action results to the wider public; attraction of public awareness to fundamental research in particle physics.
Tasks	5.1 Monitoring the successful implementation of inclusiveness and gender policies. Boosting ECI careers and employability through management responsibilities, promotion of entrepreneurship and potential exploitation of results in industry. 5.2 Coordination of the communication and public engagement strategy of the Action, such as general public talks by renowned scientists at the Action events, educational events for secondary school students, and participation in local outreach activities. Generating content for the general public section of the Action website, exploiting the potential of the social networks, preparation of press notes and distribution to press agencies and blogs of scientific news.
Milestones	▪ Extension of the Action to other COST ITC, NNC and IPC Countries. ▪ Organisation of events at COST ITC, NNC and IPC Countries. ▪ Gender balance above 30% overall, 40% in management responsibilities. ▪ Collaborative public website, open lectures for general public and school students, and participation in local outreach programs.
Deliverables	▪ Review of the effectiveness of inclusion and gender policies (D11, every six months starting M6). ▪ Outreach materials and press notes at the public website and social media (D12, throughout starting M1). ▪ Training on IPR and entrepreneurship, non-disclosure agreements with industry, and patent applications. (D13, M12).

II) GANTT DIAGRAM

PARTICLEFACE		Y1				Y2				Y3				Y4			
Working Group Activities		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
WG1	1.1 Mathematical developments																
	1.2 IR and UV at higher-orders																
	1.3 Master multi-loop integrals																
	1.4 Four dimensional methods																
	1.5 NNLO/N^{n}LO Standardisation																
WG2	2.1 Fully exclusive predictions																
	2.2 Multi-jet and jet substructure																
	2.3 Resum. of multi-scale processes																
	2.4 Improved parton densities																
WG3	3.1 Prospects ultrahigh multiplicities																
	3.2 Predictions at highest energies																
	3.3 Multi-scale resum highest energ.																
WG4	4.1 Website setup and contents																
	4.2 Organisation of events																
	4.3 Coordination of STSM																
	4.4 Final Review Handbook																
WG5	5.1 Monitoring of Inclusiveness and Gender policies																
	5.2 Coordination of Outreach and Exploitation of Results																
Action Activities																	
Events and Training	Workshops	K							M								
	Final Conference																E
	Training Schools (TS)																
	STSM																
	WG Meetings																
Management	MC Meetings																
Dissemination and public engagement	Dissemination																
	Public engagement																

K = Kick-off Meeting
M = Mid-Term Scientific Meeting
E = End of the Action and Final Conference

III) PERT CHART (OPTIONAL)

IV) RISK AND CONTINGENCY PLANS

All the proposers of this Actions belong to prestigious research institutions with a well-demonstrated record in the implementation of international projects. Remarkable risks in the overall management of the Action and the organisation of the Action events are not expected, due to the extended experience of the participants. Prospective risks are listed in the following table, and will be monitored by the MC and WGLs to react quickly according to the corresponding mitigation plan. The proposers are also well prepared to diminish the impact of other unforeseen risks.

Description of Risk	Probability	Impact	Proposed mitigation measures
Underperformance of the LHC.	Very low	Medium	This is an external risk with a very low likelihood. The theoretical goals of the Actions remain unaffected and are still valid, although effective comparison with data would be at risk.
Theoretical goals not achieved as scheduled, and affecting interdependences among WG, e.g. standardisation of NNLO techniques in WG1 applied to physical processes in WG2 and WG3.	Medium	High	The proposers count with a well demonstrated track record of achievements and have the capacity to afford the challenging goals of the Action. In case a given goal that is necessary to achieve the next step is delayed, results will be produced with the most sophisticated tools available at the time. The WGL will coordinate the redefinition of the research program, if necessary.
Insufficient expertise among the participants to achieve specific goals.	Low	Low	The initial list of proposers involves a multidisciplinary team of relevant experts. Although no single member is essential, the Action has enough critical mass for a successful implementation. If necessary, the WGL will involve external experts, also as lecturers at training schools, and will integrate them in the Action.
Involvement of COST NCC Countries.	High	Medium	The field is insufficiently developed in most of the COST NNC Countries. The Action will prioritise supporting young researchers from these countries, including STSM, to create the seed for future involvement.
Gender imbalance.	High	Medium	The number of women in the field is low, particularly at the faculty level. The Action is built with the aim of counteracting this imbalance. Leading responsibilities will be assigned from the start to women proposers. Priority will also be given to support women participants. The MC will monitor the progress every six months.
Low attendance to training schools and workshops, in particular from COST ITC, NNC and IPC Countries.	Medium	Medium	Targeted campaigns will be undertaken to advertise the Action events. Priority will be given to participants from COST ITC, NCC, and IPC Countries.
Insufficient attendance to public outreach activities. Low impact and visibility of dissemination materials and press notes in the media, social networks and blogs of scientific news measured by the number of clicks.	Medium	Medium	The dissemination strategy will be redefined with the help of the media and communication experts involved in the Action. Website materials and press notes will be revised to make them more accessible to the general public. Advertisement of public events will be strengthened.
Insufficient involvement of industry partners.	Medium	Medium	A recruitment campaign among former PhD candidates not yet contacted will be undertaken.

B) MANAGEMENT STRUCTURES AND PROCEDURES

The Action organisation and management structure will follow the COST rules. The Action will be governed by the **Management Committee (MC)**, chaired by the Action Chairperson (Ch) and assisted by the ViceChair (VCh), who will be responsible for the overall coordination of the Action and the communication with the COST Association. The MC will be responsible for the coordination, implementation and management of the Action activities and for supervising the appropriate allocation and use of the grant with a view to achieving the Action scientific and technological objectives. The operative management of the Action will be executed by a **Core Group (CG)** within the MC. It will be composed of the Chair, the ViceChair, and the **Working Group (WG)** Leaders. The CG will be responsible for the preparation of the MC meetings.

Each WG will be coordinated by a WG Leader (WGL) and assisted by a WG ViceLeader (WGVL). They will be in charge of developing the scientific activities needed to achieve the Action objectives, in line with the Action strategy defined by the MC. The Leader of the WG4 will coordinate the Action events and STSM within the MC and CG. The Leader of the WG5 will coordinate the Action policies, outreach and external relations.

The MC Members will be nominated by the COST National Coordinators, while the Chair, ViceChair, and WGL will be elected during the Kick-off Meeting. The Action will ensure a wide participation and distribution of responsibilities among ECI, women researchers and representatives from COST ITC, NCC and IPC Countries in all the management and coordination bodies. The MC will meet twice a year, during the Action events or by virtual means. WGs will meet likewise at least twice a year. Meetings might be organised more frequently if necessary. Mailing lists will also be created to smoothen the internal communication, the organisation of events and the advertisement of job opportunities for ECI.

C) NETWORK AS A WHOLE

The initial consortium is optimized to have the critical mass, expertise and geographical distribution to successfully address the challenge and objectives of the Action by **exploiting the synergies and complementarities among all the stakeholders**. It involves a multidisciplinary community of leading experts in the field with well-established international collaborations that will be advantageous to enlarge the number of future participants of the Action, following the principle of inclusiveness and gender promotion. The Action offers **high-level training,** including training in **complementary skills**, for Master students and PhD candidates, and is focussed towards the career promotion and employability of ECI. The **dissemination and outreach activities** of the Action count with the support of experts in Media and Communication. This is probably a distinctive feature of this Action, and will help not only to maximise the visibility of the Action but it is also aimed at improving the public engagement skills of the participants.

The connection with **industry** is made mostly through former PhD candidates from the proposers´ institutions, acting as encouraging example for ECIs wishing to pursue a career in industry, and ensuring a successful communication path for **Open Innovation**. A risk management and financial consultancy company has already joined the Action. Two major world-leading scientific software companies, which are also heavily involved in training programs, and with which close ties of collaboration already exist, will join the Action.

The Action has targeted **Latin-American countries as IPCs**, supported by long-term collaborations with senior researchers. Former PhD candidates and ECI researchers from those countries revealed a high degree of competences and mature skills. The region has also a great potential growth in the field, and the Action could be extended to further countries easily. Other proposers from IPCs and NNCs are involved because of the relevance of their expertise to achieve the goals of the Action.