PhotonPortal

Shedding light on physics beyond the Standard Model at the LHC Run 2 using photons

ANR – Appel à projet générique 2016

Overview

Summary of the project

Higgs boson *LHC Run 2* *new physics searches* *Higgs precision studies* *exotic scenarios with photons* *$H+X$* *$H\to\gamma\gamma$* *diphoton excess* *final states with photons*

The discovery of a Higgs boson at the LHC Run 1 represents a milestone of particle physics. On the other hand, no clear sign of new phenomena beyond the Standard Model was found in the proton-proton (pp) collisions collected at 7 and 8 TeV at the LHC. The LHC Run 2 started in 2015, and ATLAS already collected and analyzed 3.2 fb^{-1} of pp collisions at 13 TeV. The increased center of mass energy with respect to Run 1 has allowed ATLAS to search for new physics directly by looking for new particles, and will permit, in the years to come, to reveal New Physics through precision studies in the Higgs boson sector. In this context, final states involving photons will play an crucial role: di-photon events will be used to search additional Higgs-boson-like particles, while topologies with non-resonant photon pairs or single photons in presence of missing transverse energy will probe more exotic scenarios. In parallel, the study of the production of the Higgs boson associated with other objects represents an excellent opportunity to discover new physics: by exploiting the di-photon decay channel it will be possible to cleanly isolate the Higgs boson signal in events with additional objects, and to explore the possibility of its resonant or non-resonant production in association with new particles. In December 2015, ATLAS presented preliminary results on the search for diphoton final states, and these results were recently updated. A modest but intriguing excess of diphoton events with respect to the SM expectations was observed, corresponding to a mass of about 750 GeV, and the CMS collaboration also reported a similar excess. With the data collected in 2016, 8-to-10 times more than in 2015, it will be possible to establish the origin of the excess, while with the full Run 2 dataset, about 100 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV, the consortium plans to complete a rich and diverse program of searches and precision measurement exploiting photons in the final state as unifying element.

La découverte du boson de Higgs, lors de la première campagne du LHC du CERN, représente un jalon de la physique des particules. Cependant, aucune indication de phénomène au delà du Modèle Standard n'a été observée pendant cette même période où le LHC a délivré des collisions proton-proton (pp) à 7 et 8 TeV d'énergie dans le centre de masse. La seconde campagne du LHC a débuté en 2015: ATLAS a déjà collecté et analysé 3.2 fb^{-1} de données à 13 TeV d'énergie dans le centre de masse. Un nouveau domaine de recherche est désormais ouvert avec la recherche directe de signaux de nouvelle physique. Il va permettre des mesures de précision du secteur du boson de Higgs. Les états finaux avec des photons auront un rôle privilégié: la signature en paire de photons permettra de rechercher un éventuel nouveau boson de type Higgs, alors que les topologies avec des paires de photons non résonantes, ou des photons uniques, en présence d'énergie transverse manquante permettront de sonder des scénarios plus exotiques. L'étude de la production du boson de Higgs, en association avec d'autres objets, constituera aussi un terrain propice à la découverte de nouvelle physique. En exploitant le canal de désintégration en une paire de photons, il sera possible alors d'isoler la production d'événements où le boson de Higgs est accompagné d'autres objets, et ainsi d'explorer la possibilité de sa production résonante ou non associée à des nouvelles particules. La collaboration ATLAS a, en particulier, présenté le résultat de recherche de résonances dans le canal di-photon, où un excès de paires de photons, modeste mais intriguant par rapport aux prédictions du Modèle Standard, à une masse d'environs 750 GeV, est observé. La collaboration CMS a aussi présenté un excès similaire. Avec les donnés collectés en 2016, 8 à 10 fois plus qu'en 2015, il sera possible d'établir l'origine de l'excès; avec tous les données collectés au Run 2, environs 100 fb^{-1} de collisions à 13 TeV d'énergie, le consortium prépare un programme riche et complète de recherches et de mesures de précision, en utilisant les photons dans les états finaux comme fil conducteur.

Table 1: Consortium composition, person-power and implications. Acronyms in the last columns refer to the *Collaborative Axes* and *Transverse Tasks* discussed in details in the *Scientific program* section starting on page 9.

Partner	Last name	First name	Abbr.	Position	p·m	Main role in the project ([axis/task coordinator]).
LAPP	Delmastro	Marco	MD	CR	38	**Coordinator of the project and for LAPP**. **Coordinator of CA1**. Contributor to CA1.a, CA1.b, CA4.a, CA4.b, TT1.a, TT2.a, TT2.b.
LAPP	Berger	Nicolas	NB	CR	38	**Coordinator of CA3**. Contributor to CA3.a, CA1.b, CA4.a, CA4.b, TT2.a, TT2.b.
LAPP	Koletsou	Iro	IK	MC	19	Contributor to CA4.a, CA4.b.
LAPP	Grevtsov	Kirill	KG	PHD	12	Contributor to CA1.b, CA4a, CA4.b, TT2.a, TT2.b.
LAPP	Guillemin	Thibault	TG	CR	24	Contributor to CA4.a, CA4.b, TT2.a, TT2.b.
LAPP	Lafaye	Remi	RL	DR	10	Contributor to CA1.a, CA1.b.
LAPP	Leveque	Jessica	JL	CR	7	Contributor to CA1.a.
LAPP	Raspopov	Sergii	SR	PHD	24	Contributor to CA3.a, CA1.a.
LAPP	Wingerter	Isabelle	IW	DR	14	**Coordinator of TT1**. Contributor to CA1.a, CA1.b, CA4.a, CA4.b, TT1.a, TT2.a, TT2.b.
LAPP	Vallier	Alexis	AV	PD	19	Contributor to TT1.a and CA1.a
LAL	Fayard	Louis	LF	DR	38	**Coordinator for LAL**. **Coordinator of TT2**. Contributor to CA4.b, CA4.c, TT2.c.
LAL	De Vivie	Jean-Baptiste	JDV	CR	10	**Coordinator of CA2**. Contributor to CA2.b, CA2.c, TT3.b.
LAL	Escalier	Marc	ME	CR	38	Contributor to CA3.a, CA1.a.
LAL	Fournier	Daniel	DF	DR	14	Contributor to CA2.b, CA2.c.
LAL	Goudet	Christophe	CG	PHD	12	Contributor to CA4.b, CA4.c, TT2.c.
LAL	Kado	Marumi	MK	DR	10	Contributor to CA3.a, CA2.b, CA2.c.
LPNHE	Marchiori	Giovanni	GM	CR	24	**Coordinator for LPNHE**. **Coordinator of TT3**. Contributor to CA1.c, CA2.a, TT3.a.
LPNHE	Lopez Solis	Alvaro	ALS	PHD	12	Contributor to CA3.b, TT1.b.
LPNHE	Laforge	Bertrand	BL	PR	19	Contributor to CA3.b, TT1.b.
LPNHE	Laplace	Sandrine	SL	CR	38	**Coordinator of CA4**. Contributor to CA4.b, TT3.b.
LPNHE	Luzi	Pierre	PL	PHD	12	Contributor to CA1.a, CA4.d, TT2.c.
LPNHE	Manzoni	Stefano	SM	PHD	12	Contributor to CA1.a, CA1.c, CA2.a., TT3.a.
LPNHE	Nikolic	Irena	IN	MC	7	Contributor to CA1.b.
LPNHE	Ocariz	José	JO	PR	19	Contributor to CA4.d, TT2.c.
LPNHE	Roos	Lydia	LR	DR	29	Contributor to CA1.a, CA1.b.
LPNHE	Tarek	Ahmed	AT	PHD	36	Contributor to CA1.a, CA4.b, TT3.b.

CR	Chargé de Recherche CNRS	PR	Professeur	p·m	person–months implication over the project period (2016-2020, 48 months)
DR	Directeur de Recherche CNRS	PD	PostDoc		
MC	Maître de Conférences	PHD	Ph.D. Student		

People involved

Consortium The Consortium is composed of three groups of experimentalists working on the ATLAS experiment in the following French laboratories:

- **LAPP** (*Laboratoire d'Annecy-Le-Vieux de Physique des Particules*), Annecy-Le-Vieux; CNRS/IN2P3 and Université de Savoie Mont-Blanc.
- **LAL** (*Laboratoire de l'Accélerateur Linéaire*), Orsay; CNRS/IN2P3 and Université Paris Sud.
- **LPNHE** (*Laboratoire de Physique Nucléaire et des Hautes Energies*), Paris: CNRS/IN2P3, Université Pierre et Marie Curie and Université Paris Diderot.

person-power main roles Table 1 lists all members of the consortium, the allocated person-power and their main roles in the project. Acronyms, in the last columns, refer to the *Collaborative Axes* and *Transverse Tasks* which are presented in the *Scientific program* section starting on page 9.

Context, goals and positioning of the project

Scientific landscape

Particle physics after the discovery of the Higgs boson at the LHC Run 1

$H(125)$ discovery LHC SM The discovery of a new particle, $H(125)$, with properties compatible with those of a Higgs boson at the Large Hadron Collider (LHC) Run 1 [1,2] represents a milestone of particle physics. The $H(125)$ boson perfectly completes the framework of the Standard Model (SM), crowning with success more than 50 years of experimental and theoretical efforts. On the other hand, during its activities at $\sqrt{s}$ = 7 TeV and 8 TeV, the LHC explored the energy range up to about 1 TeV without finding clear signs of *BSM* phenomena beyond the SM (BSM). This situation has left the discipline in an unprecedented situation, with no clear indication as to the regime in which the SM should break down and new physics could be discovered. Ignoring gravity, the SM with a 125 GeV Higgs boson could in principle be extended *fine-tuning* to an arbitrarily high scale [3]. However, if this scale were close to the Planck scale, a fine-tuning of more than 26 orders of magnitude would be required to explain the observed Higgs boson mass, *NP* and many hints suggest that New Physics (NP) should occur below the Planck scale [4]. While it is *EW scale* natural to expect that this NP should appear not far above the electroweak (EW) scale, the absence of any observed deviation from the SM and of any direct detection of new physics in LHC Run 1 data suggests that NP has a more complicated nature than what was initially thought. The initial phase of *LHC Run 2 $\sqrt{s} = 13$ TeV* the LHC Run 2, providing in 2015 about 3 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV, has brought some intriguing hint of possible NP phenomena [5,6]. The rest of the LHC Run 2, scheduled to begin in Spring 2016 and to provide up to about 100 fb^{-1} at $\sqrt{s} = 13$ TeV until 2018, will be marked at the same time by searches for signals of NP, and by precision studies in the Higgs boson sector to investigate possible deviations from the SM predictions.

Solving the SM problems: extending the Higgs boson sector

Higgs boson sector As one of the less studied part of the SM, the Higgs boson sector could reserve a few surprises, and needs to be studied in an open way. Among the possibilities, this sector could show to be more populated than expected. Many models of BSM physics require a second scalar particle at higher mass to fulfill unitarity conditions in the WW and ZZ scattering amplitudes at high-energy [7]. Other models, *2HDM NMSSM* in particular in the two-Higgs doublet models (2HDM, [8]) and Next-to-Minimal-Supersymmetric extensions of the SM (NMSSM, [9]), predict new states lighter than the $H(125)$, which would have evaded detection at LEP [10]. In many BSM models, the coupling values of the second boson to the SM particles are constrained by the existence of the $H(125)$ particle. In the specific case of the 2HDM, *narrow resonances $\gamma\gamma$ final states* the couplings of the second scalar particle to the W and Z bosons can be very small [11]. Under these assumptions, the second resonance is expected to be also narrow, and sizable branching fractions in the $\gamma\gamma$ final states are possible. Using an approach similar to that used for the discovery of the Higgs *Higgs-like particles* boson in its $H \to \gamma\gamma$ decay, the diphoton signature can be used to explore the presence of additional Higgs-like particles with different masses decaying in photon pairs [12–15]. The intriguing excess observed by ATLAS and CMS in this channel in 2015 [5, 6] encourages a pursuit of these searches with high priority.

Solving the SM problems: Dark Matter and SuperSymmetry

One of the main questions of particle physics at present concerns the constituents, and their interactions, *Dark Matter* of the so-called *dark matter* (DM). From cosmological and astrophysical observations, this kind of matter appears to be about five times more abundant than ordinary matter in the universe, and interacts only extremely weakly with ordinary matter particles and with light [16]. The SM does not contain a viable DM candidate, and thus needs to be extended to theories with additional elementary particles and interactions. One of the most studied and theoretically best-motivated candidates for physics beyond *SUSY* the SM is SuperSymmetry (SUSY). In most SUSY scenarios sparticles are produced in pairs and, once created, can not decay to final states comprising only SM particles, due to the conservation of a *LSP as DM candidate* quantum number called $R-$parity. They thus decay through cascades involving other sparticles until the lightest SUSY particle (LSP) is produced, which is stable and electrically neutral, and therefore provides a natural dark matter candidate [17]. In the data collected during the LHC Run 1 ATLAS found no indication of SUSY particle production. This translated into lower limits of about 1.4 TeV for the gluinos and the squarks (0.6 TeV for the stop), and 0.3–0.7 TeV for the gauginos [18]. If SUSY is realized in nature and is not subject to a significant amount of fine tuning, its lightest particles cannot have masses significantly higher than these limits and should be produced in the 13 TeV pp collisions. Moreover, for masses in the 1–2 TeV range, the SUSY production cross sections at $\sqrt{s} = 13$ TeV increase significantly (typically by factors 30–40) compared to the ones at 7 and 8 TeV [19, 20], while SM backgrounds only increase by a factor 2–4, thus increasing largely the sensitivity of these searches. *non-resonant di-photons* The large Run 2 dataset will allow us to probe the different SUSY scenarios, in particular with searches for excesses in the production of two non-resonant photons [21].

The Higgs boson as portal to New Physics discovery at the LHC Run 2

The increased center of mass energy $\sqrt{s} = 13$ TeV of the LHC Run 2 will dramatically increase the *$H(125)+X$* discovery potential of new heavy particles. In this respect, the study of the production of the $H(125)$ boson at $\sqrt{s} = 13$ TeV in association with other objects (jets, leptons, missing transverse energy) *additional Higgs states* represents an excellent opportunity of searching for NP at the LHC. In particular, in many models introduced to explain some of the intriguing properties of the SM, the $H(125)$ boson is the lowest-mass Higgs boson and is predicted to be produced in association with new heavy particles, or to appear *$H \to \gamma\gamma$* as part of their decay chain (see for instance Refs. [9, 22]). By exploiting the $H \to \gamma\gamma$ decay channel, which has been the leading channel for the Higgs boson discovery and for the measurement of its *associated production* properties in the ATLAS experiment, it will therefore be possible to cleanly isolate the Higgs signal in events with additional objects, and to explore the possibility of its resonant or non-resonant production associated with new particles (see for instance Refs. [14, 22, 23]) and to probe specific decay modes *rare and exotic decays* (e.g. Flavor-Changing-Neutral-Currents in the Higgs sector [24–39]). Topologies with a single photon in the final state will instead probe rare or exotic decays of the Higgs boson [40–45].

Goals of the project, scientific challenges, innovative solutions

The goals of the projects are:

1. **To search for physics beyond the SM**, where new particles would decay to final states including photons.
2. **To measure the production of the Higgs boson in association with jets, leptons and missing transverse energy, by exploiting its decay in photon pairs**; to establish the possible presence of physics beyond the SM in such event topologies where the $H(125)$ boson would be part of a resonant or non-resonant decay; and **to determine the possible existence of exotic decays of the Higgs boson**.
3. **To improve the measurement of the properties of the $H(125)$ boson using $\gamma\gamma$ decays**, and constrain the potential existence of NP by searching for any deviation from the SM predictions.

synergies between analyses common selections and final states

Each of the goals will be reached by exploiting the synergies between different analyses, that have in common the basic event selection and the use of the same objects in the final states. More details on how and when each goal will be pursued are given in the Section describing the project Work Packages (page 9) and schedule (page 24).

association of precision measures and NP searches

The project associates analyses searching for physics beyond the SM, with the precision measurements of the properties of an already established particle. These two domains – searches for NP, precision measurements – are traditionally developed within high-energy-physics collaborations by separate communities, motivated by the different needs of precision and understanding of the objects in the final state. In this respect this project proposes an innovative approach, where the same effort needed to measure with the ultimate precision the properties of the $H(125)$ boson (e.g. the Higgs boson mass with the $\gamma\gamma$ decays, strongly depending on the precise understanding of the photon energy scale calibration) will at the same time benefit to searches for NP phenomena with a similar final state (e.g. new diphoton resonances, or the $H(125)$ particle in more complex decay chains). For this reason, we propose to group analogous activities from the two domains, in order to gain from the common work needed to understand events with similar final states.

common performance work

Such an approach is certainly promising in terms of efficiency and results, but also faces the challenge of effectively coordinating several analyses with potentially different timescales. In addition, the success of the project depends on the parallel commitment to the understanding of those parts of the ATLAS detector and software that are fundamental to the reconstruction, selection and calibration of photons (e.g. the ATLAS electromagnetic calorimeter, the ATLAS e/γ reconstruction software, the identification and calibration of photons in ATLAS). Crucial to the success of the project is therefore the definition of intermediate performance goals, which will provide increasing level of precision in the understanding of the final states, each adapted to a different analysis.

coordination timescales

performance goals

State of the art, contributions provided by the consortium

leading role in $H \to \gamma\gamma$ search and discovery

In July 2012 the ATLAS Collaboration has announced the discovery of a new particle with properties compatible with those of a Higgs boson [1]. The $H \to \gamma\gamma$ decay played a fundamental role in the discovery, and the analysis of this channel was led by the members of the consortium, whose commitment to the search of the $H \to \gamma\gamma$ decays dates from the beginning of the ATLAS Collaboration [46–54, to which most members of the consortium contributed].

couplings

cross sections mass

Many efforts have been put in understanding the properties of the newly discovered particle. The $\gamma\gamma$ decay channel has been successfully used to measure its couplings [55, with contributions by NB, SL], its production differential cross section [56, with contributions by NB, SL], its mass [57, with contributions by MK, SL, NB, IW, MD] and its spin properties [58, with contributions by SL, JDV].

rare and exotic decays

At the same time, a program to search for rare and exotic decays of the $H(125)$ particle was put in place, and the first limits for some of these channels where produced [59, 60, with contributions by GM, SM, DF, JDV]. The same photons that proved crucial to the $H(125)$ boson discovery were also used to directly search for additional diphoton resonances with Run 1 data [61, with contributions by JL, NB, MD, RL] and with the first Run 2 data, in which we recently isolated an intriguing excess at 750 GeV [5, with a crucial leading role played by the full consortium]. Final states with photons were also exploited to search for new resonances in the $Z\gamma$ final state [62, with contributions by GM,SM] and for signs of BSM physics potentially involving SUSY or DM candidate in Run 1 [63, 64] and Run 2 [65, with contributions by BL, ALS].

additional resonances

coordination roles Higgs groups

In parallel to their direct contributions to the searches for NP and to the current understanding of the nature of the $H(125)$ boson, several members of the consortium (SL, NB, MK, LF, MD) have been or are currently coordinating the ATLAS Higgs activities both on the $H \to \gamma\gamma$ channel (Higgs subgroup conveners, managing around 100 physicists), and on all SM and BSM Higgs channels (Higgs conveners, managing around 500 persons). One member of the consortium (MD) coordinates the ATLAS working group searching for new resonances decaying in photon pairs. The current ATLAS Physics Coordinator is one member of this consortium (MK).

None of these results would have been possible without a coherent involvement in the program aiming to precisely measure the direct production of diphotons and photon+jet backgrounds at the LHC [66–70, with contributions by SL, GM, LR, MD, RL]; in the effort to reconstruct, trigger on, calibrate and identify photons in ATLAS [71–73, with contributions by MD, GM, SL, BL, JO, LR, DF, IW, KG]; in the maintenance, operation and calibration of the ATLAS Liquid Argon (LAr) calorimeter [74, 75, with contributions by NB, MD, IW, DF, BL].

SMDP

LAr

e/γ performance

Two members (GM, MD) were conveners of the SM Direct Photon subgroup (managing about 50 people), while other members coordinated working groups in ATLAS related to detector or object performance relevant to physics involving photons: DF and IW were LAr project leaders from 1994 to 2001 and from 2008 to 2013; MD was the convener of the ATLAS e/γ performance working group from 2012 to 2014; three members (NB, GM, MD) are or have been conveners of the ATLAS e/γ Photon Identification working group.

As demonstrated above, the consortium members have played a fundamental role in the discovery of the $H(125)$ boson and in the measurement of its properties and rare decays, and consolidated the leading position of these French groups in the ATLAS $H \to \gamma\gamma$ and photon-related physics activities, and their strong involvement in the ATLAS LAr electromagnetic calorimeter, the main detector used to reconstruct and measure photons.

workshops

Two members of the consortium (SL, RL) are or have been coordinating the Higgs activities in the *Groupement De Recherche (GDR) Terascale*, aiming at bringing together theorists and experimentalists in France and other collaborating countries. Three members of the consortium (MD, RL, NB) are or have been part of the local organizing committee of the *Les Houches Workshop*. Three members of the consortium (GM, MD, BL) are the organizers of the *Workshop on Photon Physics and Simulation at Hadron Colliders* that took place in Paris in 2012 and 2015.

interaction with theorists

All the consortium members have strong connections with the community of phenomenologists and theoreticians in and outside France. Each of the structures hosting the three partner laboratories also hosts a theory laboratory: this proximity facilitates a continuous synergy between the experimentalists and the local theoreticians working on subjects of relevance for the project. The consortium has in particular strong ties with members of the *Laboratoire de Physique Théorique et Hautes Énergies* (LPTHE) working on Higgs and BSM physics (M. Cacciari, P. Slavich, K. Benakli, M. Goodsell, M. Zaro); with members of the *Laboratoire de Physique Théorique d'Orsay* (LPT) working on Higgs physics and Effective Field Theory approach to BSM phenomena modeling (A. Djouadi, A. Falkowski,

Y. Mambrini) and on photon physics at hadron colliders (M. Fontannaz); and with members of the *Laboratoire d'Annecy-le-Vieux de Physique Théorique* (LAPTh) working on Higgs, BSM and Dark Matter physics (G. Belanger, F. Boudjema), and on photon physics at hadron colliders (J.-P. Guillet, E. Pilon). For what concerns in particular the potential connections between the Higgs sector and Dark Matter, the consortium has already initiated several fruitful interactions, in particular with theorists of the *Institut Lagrange de Paris* (of whose Scientific Council BL is a member), and with members of the theory laboratories of Annecy and Grenoble, pursuing a synergy between astro-particle physics and cosmology. The consortium members have also established fruitful collaborations with foreign phenomenologists working on NNLO calculation of photon production at hadron colliders (F. Febres-Cordero, L. Cieri).

The consortium has a coherent composition of skills and extensive competences associated to the proposed ANR project, and a proven level of excellence in all fields (detector, performance, physics analysis, interactions with theorists) required for producing high-quality and innovative results in particle physics.

Positioning of the project

défi de tous les savoirs

This fundamental research project in particle physics naturally enters the *défi de tous les savoirs* ANR category. Its program targets the most important questions left open after the discovery of a Higgs boson in 2012: the fundamental nature of this particle, and the existence of physics beyond the SM.

projet collaboratif

The collaborative project (*projet collaboratif*) is the preferred instrument in the present reality of high energy physics, where the size of experimental collaborations has grown to thousands of scientists, and the only way to make an impact is to build a critical mass of expertise and common goals. The project aims to foster collaboration and synergies between the three partners, by leveraging their complementary expertise and mutualising common tasks and activities.

leading position of French groups

The consortium behind this ANR project encompasses the members of three French groups with a history of collaboration inside ATLAS, and aims to reinforce the French presence in the international panorama of particle physics, after the fundamental role played in the discovery of the Higgs boson. The choice of using the Higgs diphoton decays in association to additional objects as portal to the discovery of new physics is motivated both by the cleanness of the signal, the already leading position of the French groups in the ATLAS $H \to \gamma\gamma$ activities, and the involvement of the French ATLAS community in the ATLAS LAr electromagnetic calorimeter used to reconstruct and measure photons. While representing an original project, this ANR project is the natural evolution of these activities.

ANR projects

formative mission

This situation was made possible by a coherent effort among the consortium members since the beginning of the ATLAS collaboration, and in particular thanks to the funding of two ANR projects on this channel: HIGGSTIME from 2006 to 2009 and HIGGSNET from 2010 to 2014. The program has been a crucial funding tool to raise the French ATLAS groups to their current leading position in a very competitive environment. These previous ANR projects mentioned above allowed the funding of seven post-doctoral positions and one Ph.D. student, who made cutting-edge contributions to the discovery and measurements in the $H \to \gamma\gamma$ channel. Three of these researchers have been subsequently hired by the CNRS, while the remaining ones continued their careers with other high-profile post-doctoral positions. In its very nature, the project aims to pursue this formative mission for young scientists at the beginning of their careers.

return to society

Research in the area of fundamental interactions and fields represents the purest human endeavor to understand the most intimate laws that regulate our Universe, and is thus of great interest for society as a whole, since it helps to redefine our common vision of the world in its fundamental building blocks. The extreme interest demonstrated by the public audience to the recent Higgs boson discovery proves that this research fulfills a fundamental need in the national research panorama.

Scientific program

Overview

Collaborative Axes

The scientific program is structured along four main *Collaborative Axes* (CA), each covering a specific area of work related to the analysis of ATLAS data collected at the LHC Run 2. The three main goals of the project described on page 6 are addressed by the four CA with the following partition:

- Goal 1 $\rightarrow$ CA1 + CA2 (NP with diphoton and mono-photon signatures, rare Higgs decays)
- Goal 2 $\rightarrow$ CA3 (NP with $H \rightarrow \gamma\gamma + X$ signatures)
- Goal 3 $\rightarrow$ CA4 (NP constraints with precision measurements of $H \rightarrow \gamma\gamma$ properties)

The partners of the consortium share their activities among different CA over the 4-years duration of the project, taking advantage of the different time-lines encompassed by the various analyses.

Transverse Tasks

In addition, three specific areas are identified which are crucial to the success of the project, and that are transverse to the various CA. These areas of work are called *Transverse Tasks* (TT). Each TT will primarily be under the responsibility of one of the laboratory partners oy the project, with some contributions from other members of the consortium, reflecting the local expertise.

Work packages: collaborative axes on data analysis

[CA1] Search for New Physics with $\gamma\gamma$ final states

Detailed work program

[CA1.a] Search for high-mass $\gamma\gamma$ resonances

MSSM 2HDM

NMSSM

scalar pseudo-scalar

diphoton resonances

A common feature of NP models involves extended Higgs boson sectors: this occurs for instance in the Minimal Supersymmetric extension of the SM (MSSM, [76–78]), and more generally in 2HDM models which include a second Higgs doublet in addition to the one present in the SM. These models typically include additional neutral scalar or pseudo-scalar states. An example is the case of 2HDM near the alignment limit, where electro-weak symmetry breaking is driven almost entirely by one of the Higgs doublets. In this case one of the neutral scalars has properties very similar to that of the SM Higgs boson, in good agreement with LHC Run 1 measurements; the other neutral states have correspondingly suppressed decays to vector bosons, leading to new narrow states with masses larger than $H(125)$ boson and sizable branching ratios to $\gamma\gamma$ [12–14]. Another example is the NMSSM, where extra states associated with the NMSSM singlet field can have large $\gamma\gamma$ branching ratios [15]. These states can be either scalar or pseudo-scalar, and have masses typically below that of $H(125)$ boson. Diphoton resonances can also occur in sectors not directly related to the $H(125)$ boson: for instance the graviton state of Randall-Sundrum models [79] could be accessible, with a mass at the TeV scale.

diphoton resonances

Searches for new diphoton resonances with $\sqrt{s} = 8$ TeV data [61] and the $\sqrt{s} = 13$ TeV data collected by ATLAS in 2015 [5] were performed by the members of the consortium. The latter search, successfully extending the Run 1 approach to a mass range reaching 2 TeV and exploiting about 3.2 fb^{-1} of data, has recently isolated an intriguing excess corresponding to a possible new resonance mass $m_X \sim 750$ GeV, with a local significance of 3.9 σ in the analysis targeting a spin-0 object, for a resonance natural width of about 45 GeV. The data collected at $\sqrt{s} = 13$ TeV during the 2016 run will allow us to establish the origin of the excess. Should it be confirmed as a genuine signal of BSM physics, the full Run 2 dataset will be crucial to measure the properties of the new object, following the program already deployed in the past for the $H(125)$ (coupling properties, spin, mass, differential cross sections - see also CA4).

photon energy calibration

The sensitivity of the search for new diphoton resonances is closely linked to the width of the $\gamma\gamma$ invariant mass peak: excellent control of the photon energy calibration is therefore a critical ingredient, both to accurately measure its mass and to estimate its natural width, and will be addressed by the TT2 tasks discussed on page 20. If similar performance as for the 8 TeV analysis is achieved, improvements in sensitivity of a factor 4-10 are expected for 100 fb^{-1} of data at 13 TeV, relative the 8 TeV result, for resonances in the mass range of few 100 GeV.

heavier state decay

The new states may be produced as part of the decay of a heavier state, as particularly in the case of states lighter than the $H(125)$ boson [15]. The event may then contain additional objects such as jets, photons, leptons or missing energy, which can be used to decrease the background levels and obtain better sensitivity. Such techniques will have a strong commonality with the tasks of CA3.

[CA1.b] Search for low-mass $\gamma\gamma$ resonances

$e \to \gamma$ background

When searching for $\gamma\gamma$ resonances with masses below that of the $H(125)$ boson, the background from dilepton production where electrons and positrons are misidentified as photons is significant, particularly near the Z boson peak [61]. A successful extension of the search discussed in CA1.a to the low-mass range will therefore be dependent on good control of photon identification: low rates of misidentification of electrons as photons will be particularly important, as well as their precise measurement with data. Such items will be addressed by work done in the context of the TT3 (page 22).

A connected effort will be devoted to the control of the performance of a low-threshold diphoton trigger, and to develop a strategy to describe the properties of the non-resonant diphoton background around the $m_{\gamma\gamma}$ turn-on introduced by the trigger requirements.

[CA1.c] Non-resonant $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$

GMSB SUSY

The reconstruction of the final state with two non-resonant photons accompanied by missing transverse energy at the LHC is a portal to the exploration of gauge-mediated SuperSymmetry-breaking (GMSB) SUSY models. In such models the gravitino $\tilde{G}$ has a mass lower than one GeV and is the LSP, while the mass of the other SUSY particles exceeds 100 GeV. The search proposed here is sensitive to the scenario in which the next-to-lightest SUSY particle is a bino-like neutralino $\tilde{\chi}_1^0$, i.e. the SUSY partner of the SM $U(1)$ gauge boson, and thus decays predominantly to $\gamma\tilde{G}$. Since two neutralinos are produced in each event from the decay chains of the two initial SUSY particles produced in the initial pp collision, the final state contains two photons and missing transverse energy arising from the undetected gravitinos.

non-resonant $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$

To keep this search as inclusive as possible, only requirements on the photons and on the missing transverse energy or the total energy flow in the event will be applied. The selection criteria will be optimized on simulated samples of signals corresponding to the different production scenarios and masses of the SUSY particles. An optimization of the photon identification and isolation criteria in the kinematic regime of interest, characterised by higher transverse momenta compared to the photons from $H \to \gamma\gamma$ decays, will be addressed in the context of the TT3. The main backgrounds will be studied with data-driven techniques by developing dedicated control samples.

γ identification isolation

A similar study has been performed with all the 8 TeV pp collisions collected by ATLAS during the LHC Run1 [21], yielding a 95% CL lower limit of 1290 GeV (590 GeV) on the value of the gluino (wino) mass, for any value of the neutralino mass above 50 GeV but less than that of the gluino (wino) mass. At the LHC Run2, given the large increase in the signal production cross section, a few signal events over an almost null background are expected for $m(\tilde{g}) \sim 1500$ GeV with the 2015 data now being analyzed, while more data will be required to explore phase-space regions corresponding to higher sparticle masses.

Many of the tools and techniques used for this study will be shared with those of the CA1.b task.

Coordinator & partners

[CA1] will be coordinated by LAPP (MD). Partners are:
[CA1.a] LAPP (NB, RL, SR, MD, JL, KG, IW, AV), LAL (ME), LPNHE (LR, AT, PL, SM)
[CA1.b] LAPP (MD, NB, IW, KG, AV), LPNHE (LR, SL, IN);
[CA1.c] LPNHE (GM, SM).

CA1 Deliverables

- Optimization of the current high-mass $\gamma\gamma$ resonance search introducing detector-based (barrel-endcap) and production-mode-based categories (jets, photons, leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$), to increase sensitivity to the possible signal at 750 GeV, and to introduce the measurement of possible production mode and spin properties. This will closely parallel the similar efforts deployed for the $H(125)$ boson in the context of CA4.
- Implementation of the $\gamma\gamma$ resonance low-mass search in the new ATLAS analysis software framework.
- Measurement and parameterization of $e \to \gamma$ fake rate (see also TT3).
- Non-resonant $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ search: optimisation of the non-resonant selection criteria for the different SUSY production modes (strong or electroweak), data-driven estimation of the main backgrounds ($Z\gamma\gamma$, $W\gamma\gamma$, $\gamma\gamma$+ jets, $e \to \gamma$ background), statistical analysis to estimate the significance of the signal or set limits on the production cross section and on the sparticle masses.
- Interaction with the theorist community to extend the interpretation of the search results to specific theory models.

[CA2] Higgs rare and exotic decays, exotic mono-photon signatures

Detailed work program

[CA2.a] $H \to Z\gamma$

$H \to Z\gamma$

In the SM the $H(125)$ boson decays to a Z boson and a photon via loop diagrams similar to those of the $H \to \gamma\gamma$ process. Both the $H \to \gamma\gamma$ and $H \to Z\gamma$ decays are thus particularly sensitive to new physics beyond the SM, as BSM particles may give rise to additional loop-induced amplitudes that would change the value of the production cross section with respect to the SM expectation. Modifications of the $H \to Z\gamma$ coupling with respect to the SM prediction are for instance expected in models with additional colorless charged scalars, leptons or vector bosons coupled to the Higgs boson and exchanged in the $H \to Z\gamma$ loop [40–42]. Alternative scenarios, in which the coupling to $Z\gamma$ of the $H(125)$ boson are modified with respect to the SM, include models in which H is a neutral scalar of a different origin [43, 44] or a composite state [45]. Any new particle giving rise to a loop-induced $pp \to \gamma\gamma$ amplitude contributes also to the $pp \to Z\gamma$ one, while the opposite is not true. For instance, scenarios with a new Z' boson which can mix with the SM Z boson would affect the latter but not the former. A determination of both the $H \to \gamma\gamma$ and $H \to Z\gamma$ decay rates can thus help to determine whether the $H(125)$ boson is the SM one, or to provide information on the quantum numbers of the new particles exchanged in the loops or on the compositeness scale.

loop-induced amplitudes

In Run 1 ATLAS searched the $Z\gamma$ decays [59] of Higgs bosons with masses between 120 and 150 GeV. For a mass of 125 GeV, the $H \to \gamma\gamma$ and $H \to Z\gamma$ branching ratios are of the same order of magnitude. However, to cleanly reconstruct the Z boson and have a decent signal-to-background ratio, only the final states $Z \to ee$ and $Z \to \mu\mu$ were selected, with a branching ratio of only 6.7%, thus reducing significantly the final cross section. No significant excess was found, leading to an observed upper limit on the production cross section of 11 times the SM prediction for $m_H = 125$ GeV. The largest excess over the background was found for $m_H = 142$ GeV, with a significance of 1.6σ. In Run 2, the increased center-of-mass energy provides an increase by a factor two of the signal $pp \to H \to Z\gamma$

cross section and similar for the main background from non-resonant $Z\gamma$ production. Performing an analysis similar to that from Run 1 on the full Run 2 data, about 100 fb^{-1} at $\sqrt{s} = 13$ TeV, will allow us to reduce the limit on the $pp \to H \to Z\gamma$ cross section to about 3 times the SM, starting to exclude part of the phase space of the models that predict larger enhancements of this decay mode. The 1.6σ bump seen in Run1 at 142 GeV, if due to a real particle, could be established at the 3σ level.

low-E_{T} γ identification

In order to further improve the sensitivity, our efforts will initially focus on the optimization of the photon reconstruction and selection performance (calibration, identification and isolation) in the low-E_{T} regime typical of these decays [TT3]. We will then exploit the 10-times larger dataset by further dividing it in event categories with improved S/B, to be optimized on simulated signal and background events by exploiting the different kinematic properties of signal and background. This may lead to 20-30% improvements in the sensitivity.

high-mass $Z\gamma$ resonances

Additionally, if the excess observed in the diphoton spectrum at 750 GeV is confirmed as a genuine signal, in many models one would expect the new object to also decay in $Z\gamma$. We will thus extend the $Z\gamma$ search to higher-masses. To increase the acceptance, in particular at very high masses in which the Z boson is produced with large transverse momentum, we will also consider the selection of hadronic Z decays (with a branching ratio $\sim 70\%$), exploiting the "jet substructure" techniques developed by ATLAS for the reconstruction of hadronically decaying boosted resonances. This analysis will crucially complement the work of CA1.a. We already performed an initial study with the $\sqrt{s} = 13$ TeV 2015 dataset [62], which we plan to improve by extending the mass interval being searched for, using event categories to improve the sensitivity of the search, and further optimising the reconstruction and selection criteria to enhance the purity of the selected sample.

[CA2.b] Search for Flavor-Changing-Neutral-Current in $t \to cH/H \to \gamma\gamma$ decays

FCNC

Flavor-Changing-Neutral-Current (FCNC) processes involving the Higgs boson are forbidden in the SM at tree level, and very much suppressed at higher orders. In some BSM models the suppression can be relaxed, and loop diagrams mediated by new bosons may contribute, yielding effective couplings λ_{tqH} orders of magnitude larger than those of the SM. Examples of such extensions are the 2HDM models of type I and of type II, like the MSSM [24–30]. In the 2HDM without explicit flavor conservation [31–39], the tcH and tuH couplings are present at tree level.

2HDM MSSM

$t \to cH/H \to \gamma\gamma$

The best limit for the $t \to qH$ branching ratio from a single channel was obtained at the LHC Run 1 by ATLAS [60] by exploiting the decay mode $H \to \gamma\gamma$, with an observed (expected) limit of 0.79% (0.51%). In this ATLAS Run 1 analysis, events were first required to fulfill the criteria used for the inclusive $H \to \gamma\gamma$ selection. Additional requirements were applied in order to select events compatible with a $t\bar{t}$ intermediate state, with one of the top quarks decaying to a Higgs boson and an up-type quark, while the other one decays to Wb, and the W decays either hadronically or leptonically. Soon after the diphoton result, other decay channels of the Higgs boson ($b\bar{b}$, $\tau\tau$,WW^*, ZZ^*) from the same data sample were analyzed by other groups in ATLAS, and a combination was performed [80]. The $b\bar{b}$ channel showed a slightly better limit than the diphoton one, while being however limited by systematic uncertainties. One therefore expects a stronger improvement for the diphoton channel with an increased data sample.

γ identification and isolation in presence of jets

For Run 2 we plan a similar analysis strategy, starting with the same criteria used by the other analyses belonging to the CA4, in order to take advantage of all common tools developed within the project. For the hadronic final state the photon identification and isolation efficiency as a function of the jet multiplicity will need to be specifically measured [TT3].

By going from 8 to 13 TeV center-of-mass energy, an increase of the $t\bar{t}$ cross-section of almost a factor 3.3 is expected, while most backgrounds increase somewhat less rapidly. With the full integrated luminosity foreseen for Run 2, about 100 fb^{-1}, an increase by a factor 16 in the signal sample is expected: assuming the same performance of the ATLAS trigger and reconstruction as in Run 1, a gain in sensitivity of about 4 is expected. This would bring the expected limit on $B(t \to qH)$, using the diphoton decay mode only, to around 0.15%, in the range predicted by the model of Ref. [31]. The combination with other Higgs boson final states, similarly to what done in Run 1, is also planned.

[CA2.c] Search for Higgs boson decays to "dark" photons

Despite strong evidence for the existence of dark matter at the cosmological level, it has not been possible up to now to establish the nature of its constituents. While the LSP of SUSY models with R-parity conservation is among the favorite candidates, several other possibilities have been considered: *dark sector* among them, one interesting possibility is a rich dark sector, communicating with the SM scalar sector via weakly interacting, heavy messengers [81]. If the dark sector features an unbroken $U(1)$ symmetry, *dark photon* to which corresponds a dark photon γ_D, kinetic mixing with ordinary photons can lead to final sates *$H \to \gamma\gamma_D$* initiated by virtual loops in which a Higgs boson decays either to $\gamma_D\gamma_D$ or to $\gamma\gamma_D$. The latter mode can be detected at the LHC by its signature of a high E_{T} photon associated to missing transverse energy [82].

$\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ trigger One of the main challenges raised by this search is the trigger. Preliminary studies have indicated that a combined trigger of one photon and $E_{\mathrm{T}}^{\mathrm{miss}}$ could have a sufficient background rejection and a reasonable acceptance, provided a tight photon identification selection is required, with an E_{T} threshold at 45 GeV or above. During the 2015 13 TeV run a $\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ trigger with a threshold at 40 GeV (45 GeV) was exercised during the initial low-luminosity run. The trigger efficiency proved to be satisfactory, but the rate remained too high when the instantaneous luminosity was higher than $5 \cdot 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Additional handles to address the rate issue, to be tested in 2016, include photon isolation and a jet veto, in view of limiting the analysis to the most promising final state with one photon and no jets with transverse momentum larger than 50 GeV.

The existing ATLAS studies [83] at 8 TeV and preliminary studies done at 13 TeV indicate that the dominant background is multi-jet production, where one jet is mis-identified as a photon while significant $E_{\mathrm{T}}^{\mathrm{miss}}$ results from tails in $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction. At the reconstruction level, optimizing the performance of the $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction for the relevant final state is the other important priority. *$e \to \gamma$ fake rate* Another important background source arises from inclusive $W \to e\nu$ production, in which the electron is wrongly reconstructed as a photon, requiring a data-driven measurement of the $e \to \gamma$ fake rate.

In this search the main discriminating variable is the transverse mass m_T built from the properties of the high E_{T} photon and the event $E_{\mathrm{T}}^{\mathrm{miss}}$, or the photon E_{T}. The m_T variable will be used similarly to $m_{\gamma\gamma}$ for the inclusive $H \to \gamma\gamma$ search, namely estimating the background under the signal by a side-band fit, but facing in this case a significantly worse mass resolution. The direct use of the photon E_{T} will also be evaluated. Part of the effort will be devoted to optimizing the fitting procedure and evaluating the associated uncertainties.

Coordinator & partners

[CA2] will be coordinated by LAL (JDV). Partners are:
[CA2.a] LPNHE (GM, SM);
[CA2.b] LAL (JDV, DF, MK);
[CA2.c] LAL (JDV, DF, MK).

CA2 Deliverables

- $H \to Z\gamma$ analysis: optimisation of the selection criteria and event categorisation in the low-mass and high-mass range (leptonic final state); statistical extraction of the results; combination with the hadronic Z boson decays.
- $t \to cH/H \to \gamma\gamma$ analysis: implementation of the analysis software in the new ATLAS analysis framework; optimisation of the selection; estimation of the main backgrounds and extraction of the signal yield; combination with other Higgs boson decay channels.

- $H \to \gamma\gamma_D$ analysis: implementation of the analysis software in the new ATLAS analysis framework; optimisation of the selection; implementation of the fit to the data and statistical extraction of the results.
- Specific performance work related to photon identification at low E_T and photon isolation in presence of jets (see TT3), and on E_T^{miss} reconstruction (see TT1).

[CA3] $H \to \gamma\gamma$ in association with jets or missing transverse energy

Detailed work program

[CA3.a] $\gamma\gamma$ + jets

$H \to \gamma\gamma$ + jets *VBF* The $H \to \gamma\gamma$ + jets signature provides a window into a broad range of physics processes involving a Higgs boson. The presence of forward jets gives sensitivity to the vector-boson fusion (VBF) production process, which provides an interesting probe of Higgs boson properties thanks to its high signal-to-background ratio and sensitivity to Higgs boson couplings to vector bosons. The $\gamma\gamma$ + jets final *VH* state is also relevant for Higgs boson production in association with a vector boson (VH), in which the vector boson decays hadronically [55]. As for VBF, this provides sensitivity to Higgs boson couplings to vector bosons, as well as a window into potential new physics producing VH final states.

The gluon-fusion production process can also produce $\gamma\gamma$+jets topologies, leading to a background contributions to the processes mentioned above. In the LHC Run 1 analyses, this background was significant (20-40% of the selected events) and associated with large uncertainties due to the poor theoretical descriptions of gluon-fusion-produced Higgs + jets process. Reducing these uncertainties is an important requirement for Run 2. This will benefit from measurements of jet multiplicity and kinematics in the data, as well as ongoing theory improvements.

bH *$b\bar{b}H$* A particularly important channel is the case where the jet(s) originate from b-quarks. In the SM, production of a Higgs boson associated with a $b\bar{b}$ pair is a rare process, but whose yield is larger than that of $t\bar{t}H$ production. It provides a window onto the Higgs boson coupling to b-quarks, complemen- *$t\bar{t}H$* tary to the $H \to b\bar{b}$ decay. As for $t\bar{t}H$, the clean signature in the $H \to \gamma\gamma$ decay mode should compensate for the small event yield and provide a measurement competitive with other decay modes.

The bH and $b\bar{b}H$ production modes are also sensitive probes of new physics, and their rates could be significantly enhanced for instance in some classes of SUSY models [84] as well as Type-II 2HDM [8].

$HH \to \gamma\gamma b\bar{b}$ Finally, $Hb\bar{b}$ is the main background to the measurement of the $HH \to \gamma\gamma b\bar{b}$, currently the most sensitive probe of the Higgs boson self-coupling at LHC. The modeling of the background was one of the leading uncertainties in the ATLAS Run 1 analysis of this process [85].

The $H \to \gamma\gamma$ decay allows a clean extraction of the jet multiplicity and kinematic information using the side-band subtraction method. The $H \to \gamma\gamma$ mode is with $H \to 4$ leptons the only decay mode where such studies are currently feasible, with both modes yielding similar uncertainties in LHC Run 1 [56, 86]. The much larger statistics available in Run 2 will lead to significant constraints on the theoretical calculations of the Higgs boson production cross sections.

The work in this channel will therefore target both NP discovery and measurement of SM yields and kinematics. The main task will be to identify signal regions and kinematic variables providing the best sensitivity for these goals. The performance of the side-band subtraction method is directly linked to the size of the $H \to \gamma\gamma$ peak. Improvements to the photon energy calibration [TT2] therefore have a direct impact on results, and are an important work area. Improvements in pileup suppression will also have a critical impact [TT3].

[CA3.b] $\gamma\gamma$ + E_T^{miss}

new long lived particles A direct coupling of the $H(125)$ with new long lived particles could provide a very interesting final state at LHC Run 2 to unveil the microscopic nature of DM for which only indirect hints of its existence through gravitational effects at large scales exist. The discovery of any type of such particles would be a major step in our knowledge of the true nature of our Universe. Such heavy stable particles are forbidden from decaying to SM particles, and could thus escape the ATLAS detector, contributing a large missing transverse energy signal. The search of the production of long lived particles in association with a $H(125)$ decaying to photons is then a very appealing channel, since the selection of $H(125)$ + $E_{\mathrm{T}}^{\mathrm{miss}}$ candidates provides both an excellent rejection of SM backgrounds and a clear signature of NP related to the DM problem. One of the very attractive properties of this channel is that it allows a completely data-driven analysis, by extrapolating the expected backgrounds in the signal region from the observed event yield in the side bands of the invariant diphoton mass distribution in data. This property was already a key property in the $H(125)$ discovery at LHC Run 1.

$H \to \gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$

The sensitivity of this channel to new physics is completely driven by detector performance, and provides a strong physics case for pushing forward the way the ATLAS collaboration understands its detector. From a calorimetric point of view, several major domains of improvement will be pushed by this analysis: in particular the improvement of the resolution on the time stamp put on each energy deposit in the ATLAS electromagnetic calorimeter, and the improvement of the $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction, mostly connected with the TT1 effort.

$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction

A first version of the analysis with the 2015 ATLAS data has been performed [65]. No excess was found and the results were interpreted in the context of two specific theoretical models. The next step of the analysis will be devoted to implement in this analysis the improved photon calibration, and to study how much the new timing reconstruction in LAr calorimeter cells will allow a reduction of pile-up effects and an improvement of the $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution. Given the large number of theoretical models predicting such signature, the analysis will also aim at a model-independent measurement of the fiducial cross section in a well defined part of the phase space, that may be compared to any such prediction. With an integrated luminosity of 30-100 fb^{-1}, this analysis would be able to either detect a signal in Higgs Portal models, or to reject those models.

Coordinator & partners

[CA3] will be coordinated by LAPP (NB). Partners are:
[CA3.a] LAPP (NB, MD), LAL (ME, MK);
[CA3.b] LPNHE (BL, ALS).

CA3 Deliverables

- $\gamma\gamma$ + jets search: implementation of H+jets "simplified" cross-section measurement with $\gamma\gamma$ decay (see CA4.b); study of optimal b-tagging algorithm and working point to isolate bH and $b\bar{b}H$ topologies; development of Multi-Variate discriminants to increase sensitivity to $t\bar{t}H/H \to \gamma\gamma$ and $HH \to \gamma\gamma b\bar{b}$ signals.
- $\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ search: improvement of the photon energy and timing resolution (see task TT1) to improve the diphoton mass resolution and the $E_{\mathrm{T}}^{\mathrm{miss}}$ performance, for better signal-vs-background separation; study of more variables (in addition to the diphoton mass and $E_{\mathrm{T}}^{\mathrm{miss}}$) for further background suppression; measurement of model-independent fiducial cross-sections for comparison to any theoretical model.

[CA4] Precision measurement of Higgs properties with the $\gamma\gamma$ decay

Detailed work program

[CA4.a] Mass of the Higgs boson with the $\gamma\gamma$ decay

Higgs boson mass

The $H \to \gamma\gamma$ channel is one of the two Higgs boson decays, with $H \to ZZ^* \to 4l$, that allows the precise measurement of the Higgs boson mass, since the photon energy and directions can be reconstructed *categories* · *γ identification and isolation* · *systematic uncertainty* · *γ energy scale and resolution* · *simulation*

with an excellent precision. In Run 1, ATLAS was thus able to measure the Higgs boson mass in this channel with a statistical precision of 430 MeV and a systematic precision of 270 MeV. While eventually the $H(125)$ mass will be best measured using $H \to ZZ^* \to 4l$, all measurements will be combined (as was done in Run 1 between ATLAS and CMS) to obtain the most accurate result and should therefore be as precise as achievable. Keeping the $H \to \gamma\gamma$ analysis as in Run 1, one expects the statistical uncertainty to decrease to 150 MeV by 2018. This uncertainty can be further reduced by better exploiting the different resolutions in different regions of the detector, and by increasing the signal-over-background ratio by improving the background rejection through the optimization of the photon identification and isolation requirements [TT3]. The systematic uncertainty will thus need to be improved by more than a factor two: to achieve this, one needs to improve the knowledge of the photon energy scale and resolution. The dominant uncertainty on the energy scale currently comes from the imperfect description of electrons and photons response by the ATLAS simulation [87]. Members of the consortium will work on mitigating this effect when propagating the calibration to the data [TT2].

[CA4.b] $H \to \gamma\gamma$ couplings and cross sections

MVA discriminants · *NP in signal strength deviations* · *model-independent cross sections* · *unfolding* · *correlations*

Once the mass of the Higgs boson is known, all its decay branching fractions in the SM are known. The production cross-sections are also known with a few percent uncertainties for a given center of mass energy. Therefore, one can compare the observed signal yields with the SM predictions in order to test them. One of the most powerful ways to perform such a comparison consists in dividing the dataset in categories where each Higgs boson production mode is enhanced with specific selections (e.g. those associated to the presence of jets in the event). This enhancement can be further increased by combining the selection variables into multi-variate (MVA) discriminants. One then assumes that the signal events will populate each category according to the SM predictions to measure the signal strength (the ratio of the observed signal yield over the SM predicted one) of each production mode. A measured signal strength significantly departing from unity would be a sign of NP effect. This kind of analysis, though powerful, has some model dependence; in order to overcome this drawback, one can perform more model-independent fiducial and differential cross-section measurements, unfolded from detector effects [56]. The ATLAS Run 1 cross-section measurements were performed using a simpler cut-based analysis in order to ease the unfolding of the detector effects. The unfolding procedure will become more complex with MVAs, and we plan to devote some effort to overcome this complication. The consortium will at the same time investigate the possibility of exploiting linear correlations between the selection variables, which could yield similar performance than MVAs, while making the unfolding procedure easier. These correlations can in principle be evaluated in data from the diphoton invariant mass side-bands.

κ-framework · *EFT approach* · *simplified cross-section*

These different signal strength and cross-section measurements will then be interpreted in a given theoretical framework, in order to search for any deviation from the SM prediction. During the LHC Run 1, the signal strength measurements were interpreted using the κ-framework: assuming a single CP-even Higgs boson, couplings scale factors κ_i are introduced in the production cross-sections and decay widths [7, Section 10.2]. This framework allows the discovery of new physics effects through overall rate deviations from the SM expectations. The κ-framework is nevertheless not fully satisfactory: it is in fact based on LO predictions, and it cannot account for shape variations in the distributions of the $H(125)$ boson kinematic variables or other Higgs boson properties potentially induced by NP. As an alternative, we plan to implement an Effective Field Theory (EFT) approach that takes into account all possible leading deviations from NP effectively described by dimension-six operators and associated with large scales. The EFT approach has several advantages: it allows the combination of Higgs-boson measurements with non-Higgs-boson ones, it is valid beyond LO, and it can incorporate a CP-odd Higgs boson mixing with the CP-even one. In order to reach this goal, the differential Higgs boson production cross-sections of relevant variables, as well as their correlations, will be measured. The simplified cross-section framework, that has been suggested for the LHC Run 2 Higgs measurements [88], follows similar principles and will also be part of the investigations.

[CA4.c] Width of the Higgs boson with the $\gamma\gamma$ interference

Interference effects between the $pp \to H \to \gamma\gamma$ and the non resonant $pp \to \gamma\gamma$ production affect the $H \to \gamma\gamma$ lineshape [89]: the phenomenon has been studied in details for the $pp \to \gamma\gamma$ gg- and qg-initiated diagrams, respectively computed at NLO and LO in QCD [90–92]. This interference has two parts, leading to two distinct effects. The first one is related to the imaginary part of the interference [93], which reduces the total Standard Model Higgs boson production cross section by about 2%. Because the effect is degenerate with the Higgs coupling, it is only measurable using constraints on the production rates from other channels. The second effect is induced by the real part of the interference, which is asymmetric with respect to the Higgs boson mass, and thus does not change the total cross section. However, when convoluted with the experimental resolution, it causes a negative shift of the diphoton invariant mass peak. This shift was initially evaluated by theorists to be smaller than 100 MeV [90], and has recently estimated by ATLAS, and in particular by members of the consortium, obtaining a value of 35 MeV [94], smaller than the current ATLAS uncertainty on the measured Higgs mass in the $\gamma\gamma$ channel. The sensitivity to this effect will increase using the data that ATLAS will collect in Run 2, in particular thanks to the larger integrated luminosity, and to planned improvements of the photon energy calibration (see TT1, page 18, and TT2, page 20), that could potentially lead to a reduction of about one third of the $H \to \gamma\gamma$ mass uncertainty. The same analysis aiming to measure the $H(125)$ mass will therefore be used to constrain its width.

interference real part

mass peak negative shift

[CA4.d] Higgs CP

Within the SM, the Higgs sector is composed of a single state, whose quantum numbers are uniquely determined: the $H(125)$ is predicted to be a neutral, CP-even, spin zero particle, with $J^{\mathrm{PC}} = 0^{++}$. Furthermore, alternative spin-parity hypotheses such as $J^{\mathrm{P}} = 0^-, 1^{\pm}, 2^+$ are already strongly disfavored by studies of Run 1 data performed both by the ATLAS and CMS experiments [58, 95]. In the context of an extended Higgs sector containing additional Higgs bosons (like in 2HDM models), the $H(125)$ could be interpreted as a mixture of CP-even and CP-odd states. As a consequence, it should exhibit effective couplings to both fermions and bosons that would deviate from the couplings of the SM Higgs.

mixture of CP-even and CP-odd states coupling deviations

Constraints on CP-dependent effective Higgs couplings can be extracted from measurements of differential cross-sections of the $H(125)$ production, in particular as a function of the angular distributions of the Higgs decay products. For example, clean CP-sensitive observables can be derived from the kinematics of the four-lepton final state in the $H \to ZZ^{(*)}$ channel. In contrast, for $H \to \gamma\gamma$ the kinematic information provided by the two photons from the Higgs decay is, by itself, not sufficient to characterize the CP properties of the Higgs. While this limitation seems to disfavor the potential of the diphoton channel for CP studies, it can be circumvented by exploiting the additional kinematic information provided by leptons or jets produced in association with the Higgs. For instance, the Higgs production by VBF can be cleanly identified by requiring two hard jets with a large pseudorapidity gap; for such $H + jj$ events, the azimuthal angle difference $\Delta\varphi_{\mathrm{jj}}$ between the two jets from VBF is a CP-sensitive observable, and its distribution can be used to disentangle the SM (CP-even) coupling from anomalous CP-even and CP-odd contributions originating from BSM bosonic couplings [96]. Angular correlations among jets produced in gluon-fusion events can also be used to extract CP-sensitive observables [97]; it has for example been noticed that such observables can be constructed for events with both two or three jets produced [98]. While such signals from gluon fusion may appear to be not as clean as in the VBF case, recent developments indicate that the treatment of these angular correlations at NLO allows the disentanglement of potential anomalous CP-even and BSM CP-odd contributions from the SM fermionic couplings, with reduced theoretical uncertainties [99].

VBF

angular correlation

A comprehensive EFT study of the Higgs sector requires inputs that can only be accessed through the diphoton channel. The topology of $H \to \gamma\gamma$ events produced in association with jets, arising either from the VBF or gluon-fusion production modes, is sensitive to either bosonic or fermionic couplings, respectively. For both kind of couplings, the EFT analysis requires the potential anomalous CP-even and CP-odd contributions to be separated from the SM prediction. Various challenges lie ahead of such an analysis program. A proper treatment of backgrounds depends on a careful characterization of angular correlations in QCD production of photons and jets; for this, recent theoretical developments based on novel NLO amplitude calculation techniques [100], together with data-driven validations on mass side-bands, benefiting from the excellent reconstruction photon performance of the ATLAS electromagnetic calorimetry, are key elements to be exploited.

Coordinator & partners

[CA4] will be coordinated by LPNHE (SL). Partners are:
[CA4.a] LAPP (NB, MD, KG, TG, IW);
[CA4.b] LPNHE (SL, AT), LAL (LF, CG, MK), LAPP (NB, MD, KG, TG, IW);
[CA4.c] LAL (LF, CG);
[CA4.d] LPNHE (JO, PL).

CA4 Deliverables

- Implementation of the $H \to \gamma\gamma$ mass, coupling, cross-section, width and CP measurement in the new ATLAS analysis software framework;
- $H \to \gamma\gamma$ mass measurement: optimisation of the detector-related event categories and implementation of the per-event expected resolution in the final measurement
- $H \to \gamma\gamma$ couplings: optimisation of the production-mode-related event categories; implementation of MVA discriminants for better separation of the production modes; measurements of simplified differential cross-sections; interpretation of the results in the contexts of κ framework and EFT;
- Higgs width: implement the latest theoretical calculations in the ATLAS simulation framework. Identify other kinematic variables that are sensitive to interference effects. Collaborate with theorists to improve the description of the interference effects on various control samples ($\gamma\gamma$ events at high-diphoton p_T; $H \to ZZ^* \to 4l$ decays; $pp \to H + 2jets$, $H \to \gamma\gamma$. Data-driven study of the angular distributions in $\gamma\gamma$ events to extract the fraction of events from $gg \to \gamma\gamma$, so far the highest systematic uncertainty on the mass shift and thus on the measured width.
- Higgs CP: data-driven study of the angular distributions and correlations of background events and definition of the optimal variables for the separation of the different CP hypotheses.
- Specific performance work related to photon identification, energy calibration and resolution optimization (see TT1, TT2 and TT3);
- Interaction with the theorist community to implement the EFT approach to constrain NP with Higgs property measurements;

Work packages: transverse tasks

[TT1] Improved calibration of the ATLAS Liquid Argon electromagnetic calorimeter

EM calorimeter intercalibration

Fundamental to the discovery of the Higgs boson in its decays in photon pairs, and to all physics involving photons in the final state, was the excellent control of the performance of the ATLAS LAr electromagnetic calorimeter, and in particular of the intercalibration of its 180.000 readout channels [74]. The energies measured in the LAr EM cells are combined into those of the electromagnetic clusters, from which the photon candidates are reconstructed in ATLAS, and are used to compute shower moments used to discriminate genuine prompt photons from photons stemming from the decay of neutral hadrons in jets. The experience developed in Run 1 has shown that, despite the already-excellent achieved performance [73], there is room for improvements in the LAr cell calibration, in

LAr cell calibration

particular by addressing the relative calibration of the electronics serving the cells in different LAr longitudinal layers, and by controlling to better precision the effect of cross-talk.

cross-talk

Detailed work program

[TT1.a] Improvement of electronic inter-calibration of LAr longitudinal layers

electronic calibration

cell resonant frequency

Studies performed during the LHC Run 1 [101] have shown that the electronic calibration of the cells in the first longitudinal layer of the ATLAS LAr EM calorimeter can be improved, by properly re-optimizing the search for the cell resonance frequency used to predict the amplitude of the pulse response corresponding to the ionization current induced by the EM showers [102]. Such improved calibration could reduce the local non uniformity of the relative response of the LAr longitudinal layers, which have been effectively measured and corrected in Run 1 using physics probes [73]. We plan to implement the corrections described in Ref. [101] as an alternative electronic calibration for the ATLAS LAr cells, and to measure the effective improvement by studying the energy resolution of electrons coming from $Z \to ee$ decays observed at $\sqrt{s} = 13$ TeV.

[TT1.b] Improvement of the description and correction for the cross-talk between LAr cells

cross-talk modeling

cluster time-stamp

cross-talk corrections

The different inter-calibration between longitudinal layers observed in data and MC in Run 1, and currently corrected with energy-independent factors for the first and second LAr layer only [73], exhibits a mild energy dependence possibly associated with an incorrect description of the cross-talk between LAr cells in the ATLAS simulation. Such an effect will need to be addressed to improve the calibration of high energy photons. In addition, these cross-talk effects forbid to build a cluster time-stamp measurement from individual cells time-stamps, since they spoil a precise timing measurement in all subleading-energy cells inside an electromagnetic cluster [74]. This prevents the use of the individual cell timing properties to fight against pile-up, that would conversely represent an important handle to improve the $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction. A part of the project will be devoted to quantify and to improve the modeling of the LAr cross-talk effects, aiming to correct them in data, and to improve the cell energy and timing measurements. Since the beginning of the LHC Run 2 data taking, the implementation of the software in order to extract the signal cross-talk shapes between each pair of LAr cells from calibration data is ongoing: this has required the development of specific signal processing techniques beyond the ones already being used in the direct signal calibration procedure. The next steps is to compute specific cross-talk corrections for the energies of cells inside electron and photon clusters, and develop a cross-talk correction alternative to that currently used by the LAr reconstruction, targeting the simultaneous calculation of the corrected cell energy and time. The completion of this development is expected for the end of the year 2016.

Coordinator & partners

[TT1] will be coordinated by LAPP (IW). Partners are:
[TT1.a] LAPP (IW, MD, KG);
[TT1.b] LPNHE (BL, ALS).

TT1 Deliverables

- Implementation of the cell calibration improvements described in Ref. [101] in the ATLAS LAr automatic calibration software;
- Study of the improvement associated to new LAr electronic calibration using $Z \to ee$ data (energy resolution);
- Complete mapping of LAr short- and long-range cross-talk using calibration data;
- Evaluation of a global cross-talk correction aiming at energy and timing improvement;

- Implementation of the improvement associated to new LAr cross-talk correction using $Z \to ee$ data (timing resolution).

[TT2] Improved calibration of the photon response

e/γ calibration

The electron and photon calibration was obtained in ATLAS [73] using the ~ 25 fb^{-1} of LHC proton-proton collision data taken during Run 1. The reconstruction of electron and photon energies is optimized using multivariate algorithms. The response of the calorimeter layers is equalized in data and simulation, and the longitudinal profile of the electromagnetic showers is exploited to estimate the passive material in front of the calorimeter and re-optimise the detector simulation.

For electrons from Z boson decays, the achieved calibration is typically accurate to 0.05%, while a precision of about 0.2% is obtained for photons coming from Higgs boson decays. This uncertainty is dominated by those regions of the detector where the large amount of material upstream of the calorimeter, and the associated uncertainties, limit the accuracy of the multivariate calibration algorithm [73]. The energy resolution is determined with a relative uncertainty of less than 10% for electrons and photons with transverse momentum up to $E_T = 60$ GeV: this uncertainty represents today the dominant source of experimental uncertainty on the $H \to \gamma\gamma$ signal strength [55].

The uncertainty on the Higgs boson mass measured by ATLAS is currently comparable to the statistical uncertainty, but during Run 2 this factor will reduce dramatically thanks to the larger expected dataset and the increased center-of-mass energy improving the signal-over-background ratio. Serious effort therefore needs to be devoted to improving the calibration of the photon response in ATLAS. Similarly, the current uncertainty on the $H \to \gamma\gamma$ signal strength is smaller than the associated theory uncertainty: on the other hand, with the advent of the N3LO gluon-fusion computation [103] the theory uncertainty will decrease, and the program has to be put in place to decrease the experimental uncertainty.

All analyses targeted by the program will profit from this improved calibration, which the consortium is planning to commit to in a program touching in particular three areas described below.

Detailed work program

[TT2.a] In-situ measurement of LAr layer inter-calibration and upstream material constraint

LAr layer intercalibration · *third EM layer* · *low gain* · *high energy γ*

The current photon energy scale uncertainty in ATLAS is typically 0.2% to 0.3% for $|\eta| < 1.37$ and $|\eta| > 1.82$; for $1.52 < |\eta| < 1.82$, the uncertainty is 0.9% and 0.4% for unconverted and converted photons, respectively [73]. At high energies, these uncertainties are dominated by the knowledge of the relative calibration of the LAr EM calorimeter layer response. Furthermore, the uncertainty model discussed in Ref. [73] is expected to be valid only up to $E_T \sim 500$ GeV: at these energies, the contribution of the third calorimeter layer to the energy measurement is in fact enhanced, and a significant fraction of electrons and photons are recorded in the electronics low gain. Neither of these aspects have been properly addressed using the LHC Run 1 data, and will be relevant for the measurement foreseen by this project, especially when involving high-energy photons.

We plan to measure the relative response of the second and third LAr layers in data using muons, electrons and unconverted photons, in order to disentangle effects associated to mis-modeling of the upstream material from effects associated to the electronic calibration. Corrections to the LAr layer inter-calibration in data are being studied using the first data collected at $\sqrt{s} = 13$ TeV. Based on Run 1 experience, an integrated luminosity of about 5-10 fb^{-1} will be enough to provide the first corrections. The full dataset collected in 2016, expected to be about 30 fb^{-1}, will allow to better evaluate these corrective factors, and at the same time to constrain the upstream material, by exploiting the ratio of the energies in the first and second layer of the calorimeter, to a precision ranging from 5% to 20 % X_0 depending on the pseudorapidity.

[TT2.b] Improvement of photon response: Multi-Variate calibration using shower shapes

The current calibration of electrons and photons in ATLAS includes a percent-level correction in specific pseudorapidity regions, supposedly associated with a different response of clusters having cells readout in different electronics gains [73]. Since the publication of Ref. [73], studies have shown that the main part of this difference is likely not to be due to a miscalibration of the LAr electronic readout gain, but is instead associated with an imperfect training of the Multi-Variate calibration for a specific class of electromagnetic showers induced by electrons and photons in a specific region of the calorimeter.

MV calibration training

The current approach to the supposedly "gain–dependent" correction presently accounts for the largest uncertainty on the energy calibration of photons impinging the detector in the region at $|\eta| \sim 1.6$, following the conservative approach adopted in Ref. [73]. In order to properly address this effect, we plan to develop a specific Multi-Variate calibration for electrons and photons, including the information of lateral cluster momenta (shower shapes) capable to discriminate the offending clusters. This new Multi-Variate calibration will be initially optimized on simulated samples of $Z \to ee$ events, then tested on 13 TeV $Z \to ee$ data to validate the improvement. This last step will include the proper mapping of the used cluster moments from data to MC simulation, since the lateral development of the EM shower in ATLAS is poorly described by the simulation (see for instance Ref. [71]).

MV calibration including shower moments

shower moment data/MC mapping

[TT2.c] In-situ measurement of electron and photon energy scale correction using $Z \to ee$ and $Z \to \ell\ell\gamma$ events

After all corrections, electrons from $Z \to ee$ events are used to fix the absolute energy scale of electrons and photons [73]. This is currently done assuming a perfect symmetry in azimuthal angle ϕ, with a given granularity in pseudorapidity η, and assuming a perfect linearity of the calibration procedure.

correction to absolute energy scale

ϕ modulation

Preliminary studies with the ATLAS Run 1 data show that an improvement in the energy resolution might be obtained using a finer η binning. This will be assessed with the increased statistics collected during Run 2, as well as the potential of introducing a ϕ-dependent correction.

η binning

The increased statistics will also allow the use of photons from $Z \to \ell\ell\gamma$ events to measure in situ the photon energy scale, instead of simply using them as a cross-check of the electron-based procedure as done during Run 1.

γ energy scale with $Z \to \ell\ell\gamma$

Coordinator & partners

[TT2] will be coordinated by LAL (LF). Partners are:
[TT2.a] LAPP (IW, KG, MD, NB);
[TT2.b] LAPP (IW, KG, MD, NB), LPNHE (BL, ASL);
[TT2.c] LAL (LF, CG), LPNHE (JO, PL).

TT2 Deliverables

- Measurement of data/MC difference in the EM layer energy scale and their ratios, by using electron, unconverted photons and muons;
- Measurement of the residual difference in the upstream material budget in data and MC, by using electron, unconverted photons and muons;
- Development of an improved Multi-Variate calibration of the photon energy response, including shower shapes to address the presence of pathological clusters in specific detector regions;
- Testing and deployment of the improved Multi-Variate calibration using $Z \to ee$ events in simulation and data, extrapolation of uncertainties to photons and to high-energy objects;
- Computation of *in-situ* energy scale corrections using $Z \to ee$ events;
- Validation of *in-situ* energy scale corrections for photons using $Z \to \ell\ell\gamma$ events;

[TT3] Photon selection and fake rejection

All the physics processes that we propose to study in the context of this project are characterized by final states containing prompt photons, i.e. photons not originating from neutral hadron decays. The identification of prompt photons in hadronic collisions is particularly challenging, since the overwhelming majority of reconstructed photons originate from neutral hadron decays or from radiative decays of other particles in processes with significantly larger cross sections. In the ATLAS experiment prompt photons are separated from background photons by means of selections on discriminating variables describing the properties of associated electromagnetic showers, and by requiring them to be isolated from other particles in the event. For both aspects, it is important to pursue two kinds of activities: an optimization of the algorithms and the selection criteria used to separate signal from background; and the measurement, on data control samples, of their performance, in order to reduce systematic uncertainties on the measured cross sections or signal strengths.

Detailed work program

[TT3.a] Photon identification: optimization and data-driven efficiency measurements.

Photon identification in ATLAS is based on a set of discriminating variables characterizing the lateral and longitudinal shower development in the electromagnetic calorimeter and the shower leakage fraction in the hadronic calorimeter. Prompt photons typically produce narrower energy deposits in the electromagnetic calorimeter and have smaller leakage to the hadronic one compared to background photons from jets, due to the presence of additional hadrons near the photon candidate in the latter case. In addition, background candidates from isolated $\pi^0 \to \gamma\gamma$ decays – unlike prompt photons – are often characterized by two separate local energy maxima in the finely-segmented strips of the first layer of the LAr electromagnetic calorimeter, due to the presence of two nearby photons. While an estimate of the efficiency of the photon identification criteria can be obtained from MC simulation, such estimate is subject to large, $\mathcal{O}(10\%)$, systematic uncertainties [66]. Ultimately, for high-precision measurements, a determination of the photon identification efficiency with an uncertainty of $\mathcal{O}(1\%)$ or less is needed, and can only be achieved through the use of data control samples.

optimization of γ identification

The activities of the consortium on photon identification will thus develop over two main areas. The first one encompasses the optimization of the photon identification criteria, to select prompt photons with a high efficiency and a high rejection of background from jets. The performance will be first optimized and estimated on simulated samples of photons and jets. Sophisticated multivariate analysis tools will be exploited to achieve best performances taking into account the correlations among the different variables. In addition to a simple cut-based approach, alternative non-linear techniques will also be investigated for better performance. In addition to a baseline selection, optimized for photons in the kinematic regime typical of $\gamma\gamma$ decays of a 125-GeV Higgs boson, alternative selections optimized for larger rejection at higher or lower photon transverse momenta, targeting photons from high-mass resonances or from low-mass resonances and $Z\gamma$ decays, will be developed. The possibility to include additional discriminating variables to those used by the current identification algorithm will also be studied.

non-linear techniques

dedicated selections for low- and high-E_T γ

data-driven γ identification efficiencies

The second area focuses on the measurements of the photon reconstruction and identification efficiencies with data-driven techniques, in order to minimize the corresponding systematic uncertainties on the physics measurements described in the previous sections. A fit to the distribution of the ratio between the energies deposited in the first and second layer of the electromagnetic calorimeter in photon-enriched samples, following the optimization performed in TT2.a, will be exploited to measure the photon conversion rate. The photon identification efficiency will be measured, inclusively and as a function of the jet multiplicity, from control samples selected from a pure sample of radiative Z boson decays, as well as extrapolated from electrons from Drell-Yan events after mapping the electron shower shape distributions to those of photons.

$e \to \gamma$ fake rate

Finally, data control samples of $Z \to ee$ decays reconstructed as $Z \to e\gamma$ will be used to measure the electron-to-photon fake rate, an important ingredient for a precise estimate of electron backgrounds in several analyses of this project (see for instance the CA2.b and CA3.c items).

[TT3.b] Optimization of photon isolation

The isolation energy is a powerful tool to distinguish direct photons from non-direct ones stemming from the decay of neutral hadrons in jets. It is estimated by collecting the energy distribution deposited in a cone around the photon candidate: for direct photons, there is no energy deposited in this cone apart from that associated to low-energy objects coming from the underlying event, multiple interactions and pile-up collisions. For non-direct photon candidates, there is some additional energy coming from the accompanying objects in the jet.

The isolation energy can be computed using different inputs: calorimeter cells or clusters, tracks, or an optimally-combined calorimetric and tracking information, performed via a particle-flow algorithm.

isolation energy corrections

Regardless of the approach, several corrections need to be applied: the core energy of the photon cluster is subtracted; a correction is applied on the residual core energy leaking into the isolation cone; the pile-up and underlying-event energy are corrected for. Building on the lessons learned during Run 1, we plan to further improve the calculation of the photon isolation energy in ATLAS for Run 2, as well as the associated corrections, in order to improve its discriminating power and to reduce the associated systematic uncertainties. The consortium will work on specific directions, addressing the known weak points in the isolation energy reconstruction.

topological cluster core subtraction

The current technique relies on MC simulation: an alternative core subtraction consists of removing the full topological cluster associated with the photon candidate in data, potentially improving the isolation energy resolution, reducing the data/MC disagreement especially at high energy. This alternative subtraction can on the other hand reduce the rejection power of isolation: while developing this alternative procedure, efforts will also be devoted to mitigating this side effect.

alternative jet-area computations

The current pile-up correction is based on a median estimation of the pile-up noise in each event, using the energy density of all jets reconstructed in the event. The use of alternative jet-area computations show promising improvements, and will be studied and implemented. The particle-flow algorithm, optimally combining the calorimetric and tracking information by removing the charged hadron contribution to the

particle-flow isolation

calorimetric isolation, can dramatically improve the isolation resolution, and will be implemented as an alternative computation of the isolation energy, to be commissioned in parallel to more traditional computations.

Control samples of photons from radiative Z boson decays and of electrons from Drell-Yan events will be used to measure the performance of the new algorithm with the Run 2 data.

Coordinator & partners

[TT3] will be coordinated by LPNHE (SL). Partners are:
[TT3.a] LPNHE (GM, SM);
[TT3.b] LPNHE (SL, AT), LAL (JDV).

TT3 Deliverables

- Optimization of photon identification at low, medium and high E_{T} in a large pile-up environment;
- Data-driven measurement of photon identification efficiencies and of electron-to-photon fake rates;
- Improvement of core energy subtraction to the isolation energy using topological clusters;
- Implementation and validation of alternative jet-area computations to correct pile-up in photon isolation energy;
- Implementation and validation of particle-flow algorithms to compute photon isolation energy;
- Data-driven measurement of photon isolation efficiencies.

Project schedule

48 months
2016-2020

Funding for this project is requested for a period of 48 months, ideally starting in Autumn 2016 and ending in Autumn 2020.

During the first year of the LHC Run 2, in 2015, ATLAS recorded 3.2 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV. At the time of writing (April 2016) the accelerator is restarting, expecting to provide first pp collisions by the end of April and 30 fb^{-1} by the end of 2016. The increased beam energy, with respect to the LHC Run 1 has lead to an cross-section increase by a factor two or larger for many of the signals being searched for, and to even larger factors (> 10) for more exotic signals. Over the period covered by this project, the LHC should provide to ATLAS an integrated luminosity of at least 100 fb^{-1}, corresponding to more than four times that collected during Run 1, allowing all searches and precision measurements discussed in this project to reach sensitivities significantly better than in Run 1.

Transverse Tasks schedule

The expected project time-line evolution is shown in Figure 1, illustrated in parallel for each Transverse Task and Collaborative Axis item. Work on the TT items related to the ATLAS LAr EM calorimeter calibration and to the photon performance will have the initial priority, and will be pursued mainly between the second half of 2016 and the first half of 2017. While full completion of these items can be expected by the first half of 2018, for some of those several iterations might be required to reach the ultimate precision. This is especially true for the TT associated with the precise calibration of the photon energy response, the data-driven measurement of photon identification efficiencies, and the refined isolation computation, that will extend to the entirety of 2018.

Collaborative Axes schedule

Most analysis activities described in the CA items will benefit from the large statistics at 13 TeV to be collected in 2016, but are expected to reach their full potential, and thus their most active period, only with the second part of the LHC Run 2 data taking (2017-2018). An exception is represented to the study of the diphoton excess at 750 GeV for which the 2016 dataset will already be enough to establish the origin of the excess.

Justification for requested means

total person-power
hire requests

17 permanent researchers take part to the project, adding up to about 382 person·month over the 48-months duration of the project. 7 Ph.D. students complement this initial person-power, adding up to 120 person·months over the relevant thesis periods. The consortium requests the funding for **three 2-year postdoctoral contracts, representing 72 person·months**, that are essential to the success of the project. Considering the three requested post-doctoral positions, the total ANR project person-power will amount to 574 person·months. The project "precariousness ratio" (*taux de précarité*) is 16%.

taux de précarité

hiring schedule

The first postdoctoral researcher will be based at LAL in 2016-2018, and would mostly work on tasks associated with TT2, and analyses belonging to the CA3 and the CA4 axes. The second postdoctoral researcher will be based at LAPP in 2017-2019, and would mostly work on tasks associated with TT1, and analyses belonging to the CA1 and the CA2 axes. The third postdoctoral researcher will be based at LPNHE in 2018-2020, and would mostly work on tasks associated with TT3, and analyses belonging to the CA1 and the CA4 axes.

budget

The funds requested to finance the project amount to **482928 €**. Table 2 details the lines composing the budget. The estimated cost for the three postdoctoral contract is 374604 €, based on a researcher CDD contract for a physicist with 2 to 6 years of post-doctoral experience (on average 62434 €/year, with small local variation between the 3 laboratories, following the *Circulaire d'emploi des personnels contractuels au CNRS – évolutions des règles de rémunération*). In addition, travel money is requested to fund 12 missions to CERN per year per hired post-doc; the cost of each trip is estimated at 594 € if coming from LAL or LPNHE (train: 180 €; 3 days stay at CERN: 414 €), or 435 € if coming from LAPP (train: 21 €; 3 days stay at CERN: 414 €). We also request funds to guarantee to each hired

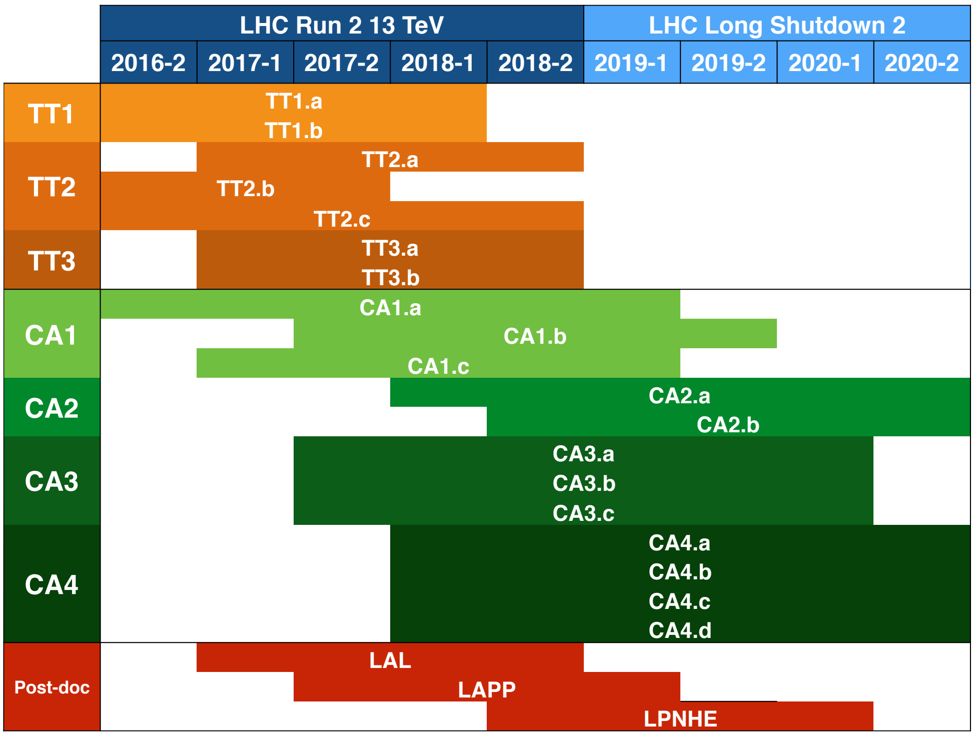

Figure 1: Project time-line, and project work periods for the post-doctoral hires.

post-doc the participation to one international conference over the 2-year contract period, and to fund a similar participation to one additional member of the consortium per laboratory every two years. The average cost of attendance to an international conference is estimated at 2100 €. The total request for missions amounts to 64152 €, corresponding to 13% of the total budget. Finally, 8400 €are requested to acquire a personal computer for each hire (2800 € each, covering either an high-end laptop – e.g. Apple Macbook – or a standard laptop and a desktop external display and docking station).

Impact of the project

The **PhotonPortal** project presents a comprehensive and coherent approach to the search for New Physics at the LHC Run 2, including direct searches using final states with photons, decay chains

Table 2: Projet budget details

Category	Budget line	Unit cost	Quantity	Total	Notes
Salary	Postdoctoral contract (average)	62434 €	6	374604 €	3 2-year postdoctoral contracts
Missions	CERN from Paris area	594 €	48	28512 €	12 travels per Postdoc per year
Missions	CERN from Annecy	435 €	24	10440 €	12 travels per Postdoc per year
Missions	Conference	2100 €	6	12600 €	1 conference per Postdoc per year
Missions	Conference	2100 €	6	12600 €	1 conference per lab every 2 years
Tools	Computers	2800 €	3	8400 €	1 laptop per Postdoc
Total				447156 €	
Administration	CNRS administrative fee	4%		17887 €	
Administration	CNRS infrastructure fee	4%		17887 €	
Total + Fees				482928 €	

involving the $H(125)$ boson, rare and exotics Higgs decays, and indirect searches exploiting the precise measurements of the $H(125)$ boson properties using the $\gamma\gamma$ decay. The project addresses with a global approach the open questions at the frontier of understanding of particle interactions after the discovery of the $H(125)$ boson at the LHC Run 1.

expected output *potential discoveries* *precision measurements*

Given its structure and goals, and the demonstrated expertise of the consortium members, the **PhotonPortal** project guarantees a large scientific production documenting the analysis results, including but not limited to potential breakthroughs in case of signals of BSM physics. The recent observation of a modest but intriguing excess of diphoton events at a mass of about 750 GeV, to which the consortium members have provided crucial contributions and essential leadership in ATLAS, represents the tip of a potential iceberg of discoveries targeted by the project over the concerned period. The measurements of the Higgs boson properties, performed by many members of the consortium with the LHC Run 1 data and recently finalized and published, testimony at the same time of the rich potential of precision measurements in the Higgs sector using the $H \to \gamma\gamma$ decays.

project timing and relevance *scientific production* *post-doc career opportunity*

The project timing is directly linked to the LHC Run 2 schedule, that will provide the bulk of the $\sqrt{s} = 13$ TeV pp dataset between 2016 and 2018. The 48-month period covered by the project will allow the exploitation of both the first few tens of fb^{-1} of data collected by ATLAS at $\sqrt{s} = 13$ TeV in 2016, essential to extend the sensitivity of the direct search for NP at LHC, and the full Run 2 dataset available on a longer timescale, fundamental for all precise measurements. The timing overlap of the different working areas over the full project period will guarantee a steady production of scientific publications, that will constitute an unprecedented career opportunity for the post-doctoral hires.

interactions and collaborations

Those aspects of the analyses associated to the interpretation of the results obtained in the Collaborative Axis work packages, relies on the already-strong collaborations with the international theorist community, and plans to foster even more the interaction between the high-energy physics experimental and theoretical communities.

French leading role in HEP

The internal coherence of the project, deliberately covering all aspects crucial to the various analyses (detector operation; physics object reconstruction, identification and calibration; direct NP searches and precision measurements in the Higgs sector), is designed to reinforce the leading role of the French laboratories on the international scene in high-energy physics.

educational and training vocation

The consortium composition, and the balance between experienced researchers, post-doctoral hires, and a solid base of Ph.D. students, testify to the vocation of the **PhotonPortal** project towards the education and training of new generations of scientists.

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