Attachment 2b to the "Wniosek o wszczęcie postępowania habilitacyjnego"
(Application for initiation of habilitation proceeding)
(file: `PZannex2bEngAutoref.pdf`)

Autoreferat
Presentation of research achievements

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Warszawa, Korzeń, July-August 2013

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1 Personal data

surname and name: Piotr Zalewski

2 Education

in reverse chronological order

1994: Ph.D. in Physics, Sołtan Institute for Nuclear Studies
Thesis title: *Study of the beauty baryons using lepton-proton correlations in the DELPHI detector*
Supervisor: prof. dr hab. Jan Królikowski
Reviewers: prof. dr hab. Jan Nassalski
prof. dr hab. Krzysztof Rybicki

1986: M.Sc. in basic problems of technology, specializing in technical physics, Department of Applied Physics and Applied Mathematics of Warsaw University of Technology
Thesis title: *Study of space-time characteristics of proton emission process in $\pi^- + Xe$ interactions at 3.5 GeV/c*
Supervisor: dr Wiktor Peryt

3 Scientific biography

3.1 Towards Ph.D. and short after

After obtaining M.Sc. degree I started to work for Warsaw DELPHI Group. At that time the HPC (High density Projection Chamber), an electromagnetic calorimeter for the DELPHI detector was built in Warsaw. Triggering scintillation counters were this part of the calorimeter that was designed and made entirely in Warsaw. For this project I contributed the most. In process of the design, I was responsible, among other things, for examining the quantum effectiveness of photomultipliers and development of methods for processing fiber connections, ensuring the desired quality of light transmission.

I had to stop this work due to the mandatory one-year military service (1987/1988).

In October 1988, I was employed at Soltan Institute of Nuclear Studies as a physicists. In 1989, during a three-month stay at CERN, I participated in the assembly and commissioning of the HPC calorimeter electronics. I also took part in supervising of the calorimeter's operation in the first period of the LEP running. The most important result of the DELPHI experiment during this period was determination of the number of light neutrinos generations by precise determination of Z resonance parameters [1, 2][1]

[1] I am a co-author of all publications of the DELPHI experiment, starting from [1] and of all

In the period from May 1990 to September 1992 I was employed by LAL (Laboratoire de l'Accélérateur Linéaire) Orsay, France. The aim of this scientific visit was to collect materials for doctoral thesis on b quark physics. I took on the task of improving electron identification in jets. I developed independent identification algorithm that has proven to be the most optimal and has been used for the official selection of hadronic Z events (collected in 1991) enriched in semileptonic heavy quark decays. This selection was the basis of all DELPHI publications from this period in which an identification of electrons in hadronic jets was used. In the most direct way I was involved in the measurement of the partial width of the Z0 into b anti-b final states using their semileptonic decays [4]. Subsequently developed (DELPHI) algorithm of electron and photon identification was based on the idea that I had proposed (i.e. an optimal use of a longitudinal segmentation of the HPC readout in the direction of developments of electromagnetic cascades).

During the remaining part of my stay in France I was working on identification of charged hadrons using RICH (Ring Imaging CHerenkov counter). The first physical results obtained with RICH, which was presented by the DELPHI collaboration at the Conference HEP'92 in Geneva, was an outcome of this study (reviewed publication of a continuation of this research came later [5]).

I continued these studies after returning to Poland. I started to focus on visibility of a signal coming from the beauty baryons, using correlation between protons (identified both by the RICH, and by measurement of the specific ionization in the main tracking detector – TPC) and muons. This analysis formed the basis of my dissertation, in which the first observation of beauty baryons in the proton channel (not through Λ^0) was reported [6].

After obtaining the Ph.D. degree I was employed as an assistant professor at Soltan Institute for Nuclear Studies (1995).

My involvement in the physics of b quarks allowed me to suggest a doctoral thesis topic associated with a measurement of b quark decay into s quark and gluon. I was acting as a tutor during this doctorate [7][2].

Until the end of data taking by the DELPHI experiment I was involved in the control of operation of sub-detectors: RICH (1991-1992) and HPC (1993-2000), and in overall quality control of the collected data. I took an active part in the work of DELPHI subgroup involved in the b quark physics until the end of the LEP 1 phase (collisions at the Z peak). Analyses done by this subgroup resulted in dozens of publications.

3.2 Searching for a new particles

With the CERN collider entering the LEP 2 phase (1996-2000), in which gradually increased center of mass energy eventually exceeded 200 GeV (by successively adding

publication of the CMS experiment, starting from [3]. Full list of my publications according to JCR database (Web of Knowledge), is in the Attachment 3b (file: `PZannex3bEngPub.pdf`).

[2]More detailed information on doctorates, in which I served as a tutor, can be found (in Polish) in the Attachment 4 (file: `PZannex4info.pdf`).

superconducting accelerating cavities), an interest in a search for new particles has increased. On the other hand, a continuation of a research in the field of b quark physics at the research frontier required an involvement in B factories (experiments Belle or BaBar), or in a longer term, in experiments at the LEP successor the LHC. Therefore I decided then to join the Warsaw CMS Group, which worked on the project of electronic for muon trigger subsystem based on the RPCs (Resistive Plate Chambers).

My main motivation was a possibility to take part in a direct search for effects beyond the Standard Model (BSM) at the highest energy that should become available. But at the same time the LEP BSM potential remained to be exploited to the full extent. At about the same time I took three research topics. The first was to exploit LEP 1 and LEP 2 data to set ultimate limits on Brout-Englert-Higgs (BEH) sector of BSM models. The second was optimization of the CMS muon system from the point of view of search for new effects. The third, connected with the second, was about searching for hypothetical long-lived massive charged particles using CMS muon system (a theme that was also extended to a search for massive neutral long-lived particles). At the same time I gave up deep involvement in b quark physics.

These three topics are described in the monograph presented for the habilitation, and are addressed in the next part (§ 4) of the present *autoreferat*.

It is worth noting that these studies were carried out by small research groups which I have organized and leaded. Since 1996 I had been leading a sub-team of the Warsaw DELPHI Group involved in the exploration of the so-called extended Higgs (BEH) models. This activity was gradually transformed into the search for the Higgs boson with the CMS experiment, and coordination of its various aspects given to those who either have obtained a doctoral degree under my direct tutoring or received it working within leaded by me sub-team of Warsaw CMS Group dealing with various aspects of a search for Beyond Standard Model (BSM) physics. I have been a head of that (Warsaw CMS) sub-team since 1996, but, beginning in 2007, I focused on the coordination of a search for massive long-lived particles that is, on the theme of which I was a forerunner in the whole CMS research team. Currently, dozens of people from several institutions are involved in this activity.

The above-mentioned study groups were formed with students attracted by topics I have been interested in. Under my supervision, as part of this activity, six M.Sc. theses and four Ph.D. theses were prepared (next three Ph.D. theses are at different level of advancement). In addition, within coordinated by me sub-team of the Warsaw CMS Group, next three doctorates, with subjects related to other aspects of the BSM, were defended.

All this work was carried out in cooperation with relevant subgroups of DELPHI and CMS experiments and were associated with the participation in subsequent grants[3] and special research programs providing funding for the participation of Polish research

[3] List of grants in which I participated is given (in Polish) in the Attachment 4 (file: `PZannex4info.pdf`).

teams in these experiments. I was also a participant in a series of phenomenological grants aimed at, among other things, study of extended BEH sector.

In 2009-2012 I was a coordinator of a bilateral cooperation between the Warsaw CMS group and the analogous group at Laboratoire Leprince-Ringuet (LLR, Palaiseau, France) in the framework of Polish-French cooperation COPIN. Joint research focused on the search for synergies among muon and electron channels, identification of long-lived particles by delay measurement in the electromagnetic calorimeter and a search for Higgs bosons in the channels with leptons τ. This cooperation resulted in two postdoctoral fellowships (accomplished by members of Warsaw CMS group) at the LLR – one of the leading CMS laboratories as far as Higgs bosons search is concerned (and to preparation of one Ph.D. thesis). These two persons coordinate BEH studies at Warsaw CMS Group at present.

In 2011 I have got three-year NCN[4] grant number N N202 167440 entitled: *Search for supersymmetry with the CMS detector at the LHC using the signature of long-lived charged massive particles.* Under this grant, about ten member research group perform the following tasks.

1. Search for long-lived massive charged particles – CMS data analysis.
2. Cascade decays in models with stau NLSP with particular emphasis on lepton decays - development of methods and CMS data analysis.
3. The design and implementation of custom time-correlation in the CMS muon trigger system and a feasibility study of the triggering on muons coming from decays of HSCPs stopped in the rocks surrounding the CMS detector.
4. Elaboration of a set of benchmark points of the parameter space of considered theoretical models in compliance with the available constraints and taking into account phenomenological differences.
5. Development of a feedback between the experiment and the theory for models with stau NLSP based on Bayesian statistical inference.

Tasks 2, 3 and 4, as far as the acquisition and analysis of the data collected by CMS in the first period of the LHC running with the highest energy and high luminosity (2011/2012), were in essential part accomplished (see § 4.4 and § 4.3 of the present *autoreferat*). We are still working on aspects of these tasks associated with the planned restart of the LHC in the year 2015. Tasks 2 and 5, consisting primarily in a reinterpretation of the CMS analyses dealing with massive long-lived charged particles and other searches for BSM physics (especially searches in leptonic channels) are in a final phase of completion.

Additional information regarding the details of my educational achievements, scientific cooperation at national and international level, activities in the subject of popularizing of science are presented[5] (in Polish) in the Attachment 4 (file: `PZannex4info.pdf`).

[4] NCN – *Narodowe Centrum Nauki* – National Science Centre.

[5] In accordance with Polish regulation: *ROZPORZĄDZENIE MINISTRA NAUKI I SZKOLNICTWA WYŻSZEGO (z dnia 22 września 2011 r.) w sprawie szczegółowego trybu i warunków przeprowadzania czynności w przewodach doktorskich, w postępowaniu habilitacyjnym oraz w postępowaniu o nadanie tytułu profesora (Dz.U. nr 204 poz. 1200 § 12.2.4).*

4 Presentation of the scientific achievement

As the scientific achievement[6] I present a monograph entitled:

Selected aspects of a search for a new particles in the DELPHI experiment at the LEP and in the CMS experiment at the LHC,

released (in Polish) by the National Centre for Nuclear Research, Świerk 2013,
ISBN 978-83-934358-9-0, of which I am the sole author.

4.1 Introduction

Presented monograph describes two aspects of a search for new particles. A search for particles of the Brout-Englert-Higgs (BEH) sector and a search for massive long-lived particles predicted, among others, by several supersymmetric scenarios.

In the first Chapter of the monograph the last fifteen years of a search for the Higgs boson is described (a shortened version is in the § 4.2 of the present *autoreferat*). Starting from the determination of the lower limit on the mass of the Higgs boson of the Standard Model, using the data collected at the LEP 2 (the limit have been valid for over a decade), going through exploration of extended BEH models using all data taken at the LEP, up to the discovery of the new particle at the LHC. I have been involved in these researches as a member of the DELPHI experiment at the LEP and the CMS experiment at the LHC. A decisive contribution I had in the DELPHI analysis of extended BEH models. The sub-team of Warsaw DELPHI Group, which was leaded by me, has done multi-channel analysis [8, 9] almost entirely (§ 4.2.2 of the present *autoreferat*).

The second Chapter of the monograph presents (almost exclusively) my direct contribution to the development of the RPC based subsystem of the muon trigger of the CMS detector (§ 4.3.2 and § 4.3.4 of the present *autoreferat*) and a method (developed by me, with a support from the sub-team – of the Warsaw CMS Group – under my leadership) of a recognition of massive long-lived charged particles by measuring their delay in the Drift Tubes of the CMS muon spectrometer (§ 4.3.3 of the present *autoreferat*).

The third Chapter of the monograph describes a development of an interest of the CMS in BSM scenarios predicting existence of massive long-lived charged or neutral particles (a shortened version is in the § 4.4 of the present *autoreferat*). The generic scenario of such kind is supersymmetry with gravitino being the lightest supersymmetric particle (LSP). I pioneered this subject in the CMS experiment [10, 11] (§ 4.4.1 of the present *autoreferat*) and I continue to contribute to the research [12, 13] with my sub-team of the Warsaw CMS Group (§ 4.4.3 of the present *autoreferat*). At present we are

[6] In accordance with Polish regulation: *Art 16. ust. 2 Ustawy z dnia 14 marca 2003 roku „O stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki” (Dz.U. nr 65, poz. 595 z późniejszymi zmianami).*

supported in part by my NCN grant N N202 167440. The Chapter ends with a description of the results recently published by the CMS Collaboration.

In the fourth Chapter of the monograph a broader perspective of a search for new particles after the first period of operation of the LHC is presented very briefly (there is no separate description of this Chapter in the present *autoreferat*). After graphical and tabular presentation of a majority of the results obtained by the ATLAS and the CMS collaborations three characteristic, in my opinion, analyses of the CMS experiment are described in more detail. The chapter concludes with a review of the literature, emphasizing the importance of the discovery of the Higgs boson with a mass of about $125\,\mathrm{GeV}/c^2$ for the search for new particles and accent desire to explain the nature of dark matter as the main motivation of such searches. I have contributed to the activities described in this Chapter by participation in the work of two major analysis-sub-groups of the CMS experiment: *SUSY* and *Exotica*. I have presented the results obtained in this field results on behalf of the CMS experiment alone (or on behalf of both CMS and ATLAS experiments) on regular basis and I have created a possibility to do so for members of my team. Searching for long-lived massive particles, the main theme of our commitment, lays at the intersection of the regions of interest of these two large analysis groups (*SUSY* and *Exotica*). The scenarios we are dealing with come mainly from the supersymmetry, whereas the topologies we look at were classified as an exotica (both by CMS and ATLAS experiments). An additional phenomenological analysis, which we do as a part of my grant, consisting of reinterpretation of search results in scenarios where gravitino acts as LSP will be an original contribution to the subject.

Monograph ends with a summary. Brief summaries are also given at end of each chapter.

Due to the statutory requirement to provide the *autoreferat* in two languages and the fact that presented monograph is published only in Polish, the *autoreferat* is not limited to an emphasis of my contribution, but it contains a shortened version of the monograph, reviewing the subject I have been working on.

4.2 Search for the Higgs bosons at the LEP and the LHC

In the July 2012 research teams of the ATLAS and the CMS experiments at at the Large Hadron Collider (LHC), announced [14, 15] the discovery of a new particle in the process of searching for the Higgs boson from the Standard Model.

The idea, derived from the condensed matter physics, to use in particle physics a spontaneous symmetry breaking in an added scalar field sector, now officially called the Brout-Englert-Higgs sector or Brout-Englert-Higgs-Guralnik-Haagen-Kibble sector, appeared in the theoretical works in 1964 [16–19] inspired by earlier theoretical accomplishments [20–23]. It was developed further by two authors [24, 25], and then used to propose electroweak symmetry spontaneously broken by BEH mechanism [26, 27] (with reference to [28]). Renormalizibility of such theory was demonstrated soon after, [29, 30].

The main prediction of that theory was an existence of a massive bosons carrying weak force, including one neutral, responsible for so called neutral currents, allowing for e.g. interaction of neutrinos with matter without changing the neutrino into charged lepton. The discovery of such process in bubble chamber Gargamelle [31] (CERN) resulted in an adoption of this concept, which has been called the Standard Model (SM).
A spectacular success of the SM was the discovery, in the early eighties of the last century, of intermediate bosons W^+, W^- and Z with masses consistent with the predictions of the model. The discovery [32–35] was made at CERN using specially developed operating mode Sp$\bar{p}$S of the SPS accelerator.

At this point, the key missing object became an elementary Higgs boson with a mass being a free parameter of the Standard Model.

4.2.1 The final result of searching for the Higgs boson of the Standard Model at the LEP collider

Large hope was associated with the last year of running of the LEP collider as far as a search for the Higgs boson was concerned. During winter shutdown 1999/2000 all available superconducting cavities were installed allowing to raise the center of mass energy of the colliding electrons and positrons up to 209 GeV.

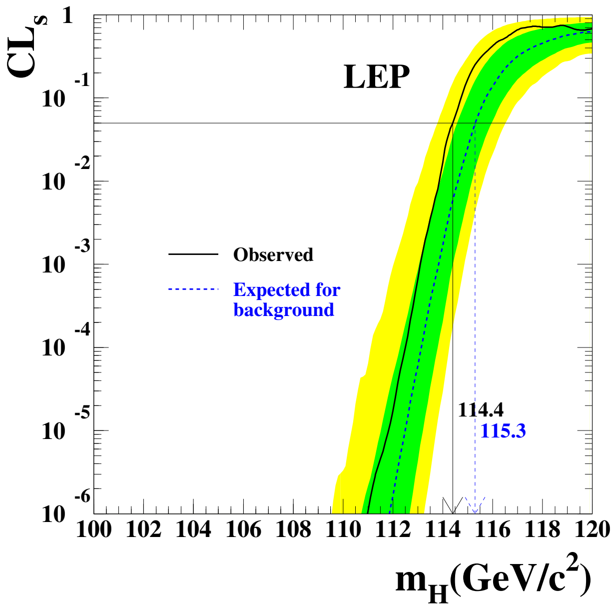
The data collected before 2000 allowed only to exclude the existence of the Higgs boson of the Standard Model of a mass less than 107.9 GeV/c^2 at 95% confidence level [36]. Finally, both preliminary results presented by ALEPH, DELPHI, L3 and OPAL collaborations [37–40] as well as the elaborated versions of these analyses [41–44] indicated a possible signal at $m_{\rm H} = 115\,{\rm GeV}/c^2$ (at statistical significance of $3\,\sigma$) only in the case of ALEPH, but without any indication in the case of DELPHI (number of events after final selection slightly lower than expectation form background alone) and without clear indication in the L3 and OPAL cases (number of events after final selection not significantly higher than expectation form background alone).

Even before the start of data collection in 2000 it was obvious that hints as to possible existence of the standard Higgs boson at the kinematic limit of the LEP 2 collider (Higgs boson mass around 115 GeV/c^2) should be searched through combined analysis of the data collected by all four LEP collaborations. The appropriate contribution were prepared by each collaboration, allowing for a final combined analysis [45]. For this purpose, the input data were categorized. The main distinguishing features were the experiment, the energy of the e^+e^- interaction and the final topology.

Since the hypothesis of an observation of a signal due to Higgs boson of the Standard Model in the LEP 2 data was not confirmed, a limit on a mass of the particle, resulting from the combined statistical analysis of available information was set. To determine the constraints it was decided to use the rate ${\rm CL_s} = {\rm CL_{s+b}}/{\rm CL_b}$, which can be seen as a way to determine conservative constraints [46]. This approach prevents an establishment of a limit when the experiment did not have sufficient sensitivity, or a downward fluctuation of the background just occurred, or background was overestimated. The

Figure 1: The CL_s value in function of the assumed mass of the standard Higgs boson mass for combined analysis of four LEP collaborations.

The dashed blue line shows the expected CL_s value (the median), the green strip contains 34% of the results of artificial experiments on each side of the dashed blue line (the yellow belt, respectively, 47.5 %) and the black line shows the observed CL_s value. The arrows illustrate how the expected and the observed lower limits on the mass of the Higgs boson were set. [45].



sensitivity of the experiment can be assessed by specifying the expected value of the limit in the absence of a signal. As an estimate of the expected value the median of results of many artificial experiments (so called toy-simulations) was used. Combined result is illustrated in the Figure 1, where dashed blue curve mark the expected value of the CL_s (the median), green strip contains 34% of the results of artificial experiments on each side of the blue line and the black line shows the observed value of the CL_s. The value of the limit corresponds to the mass for which $CL_s = 0.05$. Finally, the 95% confidence level lower limit on the mass of the Higgs boson of the Standard Model was set at $114.4\,\mathrm{GeV}/c^2$.

4.2.2 Search for the Higgs bosons beyond the Standard Model using LEP 1 and LEP 2 data

BEH sector built in the Standard Model and consisting of the single doublet of complex scalar fields, is the simplest possible version. Long before the LEP collider operation it was clear, that there is no physical justify for the exclusion of more complex scenarios, both from a theoretical and from an experimental point of view [47].

A need for a systematic verification of all possible final state topologies predicted by a wide class of models extending the simplest BEH sector of the Standard Model was present in the background of the main interest of the LEP community involved in the search for a material manifestation of the mechanism of electroweak symmetry violation, namely: the search for standard Higgs boson and Higgs bosons predicted by the MSSM (Minimal Supersymmetric Standard Model) the minimal supersymmetric extension of the SM.

The most interesting aspect of this approach was the ability to discover Higgs bosons with masses below the masses excluded in the framework of the Standard Model or within MSSM. The theme was undertaken by me in 1996, in collaboration with theoreticians from the University of Warsaw. Master students [48–50], gradually became involved in the analysis, and two of them continued this theme in their doctoral studies [51, 52][7], thus forming a study group (of the Warsaw DELPHI Group) acting for a few years under my leadership. In addition to presentation given at meetings of DELPHI working group engaged in the search for the Higgs boson the results of these analyzes were presented either by me [53–55][8] or by other members of my team at international conferences and were used to be submitted as DELPHI contributions to bi-annual conferences EPS HEP [8, 56, 57]. The last of these notes, prepared almost exclusively by my team (like the previous ones), became DELPHI publication [9], and was one of the contributions to the final combination of LEP results related to searches for the Higgs bosons [58] as well as to the last DELPHI publication on that topic [59]. In total the publication [9] alone has more than 50 citations (according to the database `inspirehep.net`).

The simplest extension of the BEH sector of the Standard Model is the Two Higgs Double Model (2HDM). The way of coupling of fermions to these doublets distinguishes several versions of this model. In [8, 9] 2HDM type II was considered, in which down quarks and leptons couple to one doublet, whereas up quarks to the other one. Variant of this model, with imposed by the supersymmetry additional constraints, is integrated in the MSSM. The choice of general 2HDM (II) model was supported by work [60] showing its compliance with the precise measurements even in a presence of light neutral scalar or pseudoscalar Higgs particles.

In each (preserving combined parity CP) 2HDM model there are two CP-even neutral bosons h and H, CP-odd neutral Higgs A and a pair of electrically charged bosons H^+ and H^-. CP conserving version of the 2HDM (II) has six free parameters, for which one can take four bosons masses, the ratio of the vacuum expectations values $\tan\beta = v_2/v_1$ (where v_2 is the vacuum expectation for doublet that couples to down quarks and charged leptons, whereas v_1 is the vacuum expectation of doublet that couples to up quarks) and the mixing angle α of neutral CP-even scalars h and H.

Production of neutral scalars form 2HDM (II) model at LEP was possible in three ways (assuming that H is too massive to be produced)

- Bjorken process $e^+e^- \to \mathrm{Z}^{(*)} \to \mathrm{Z}^{(*)}\mathrm{h}$,
- pair production $e^+e^- \to \mathrm{Z}^{(*)} \to \mathrm{Ah}$,
- Yukawa process $e^+e^- \to \mathrm{Z}^{(*)} \to \mathrm{hf\bar{f}}$ and $e^+e^- \to \mathrm{Z}^{(*)} \to \mathrm{Af\bar{f}}$.

The cross section of the first two processes are proportional to, respectively, $\sin^2(\beta-\alpha)$ and $\cos^2(\beta-\alpha)$. A lack of observation of the Bjorken process, which had been used to

[7] The work [52] was composed of two parts. One about search for the Higgs bosons in extended models using the DELPHI data and one about a feasibility study of a possibility of a determination of the quantum numbers of the Higgs boson using the CMS detector.

[8] Invited talk [55] summarized the results obtained by all four research teams working at the LEP.

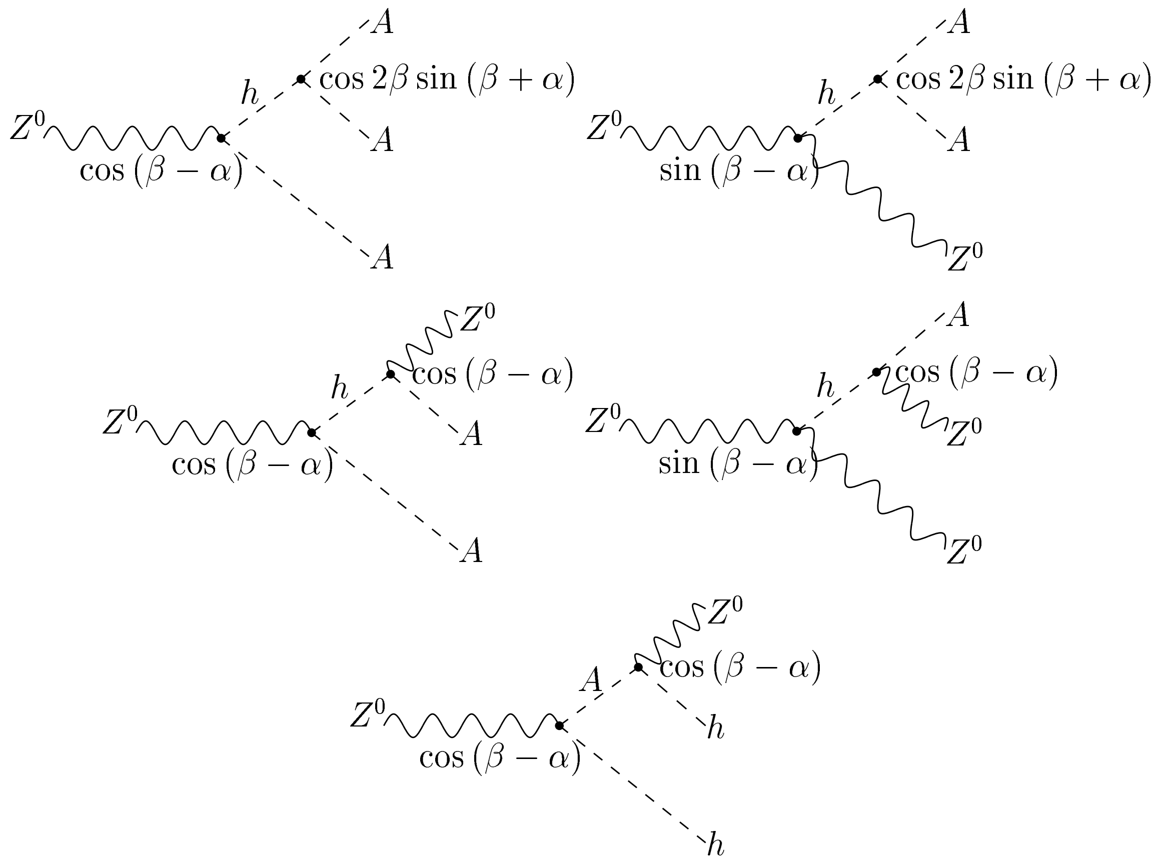


Figure 2: Diagrams of cascade decays of Higgs bosons.
On the top with the decay h→AA, in the middle with the decay h→ZA, at the bottom with the decay A→Zh.

set limits on the mass of the standard Higgs boson Higgs, constraints the value of $\sin^2(\beta - \alpha)$ in the 2HDM (II) model, but does not lead to a strict mass limits. Mixing of CP-even neutral states may lead to almost complete elimination of the Bjorken process (very small expected cross-section). A compilation of experimental results [60] shows that only if $\sin^2(\beta - \alpha) < 0.01$, then an arbitrary light Higgs boson h is not excluded. As far as Yukawa process is concerned, it had no practical significance for the Standard Model Higgs boson, whereas in the 2HDM (II) model its cross section can be significantly increased.

Additionally, depending on the mass hierarchy, there are five possible additional production and decay channels.

1. If $m_{\mathrm{h}} > 2 \cdot m_{\mathrm{A}}$ than the following channels are open:
   (a) $e^+e^- \to Z^{0*} \to$ Ah→AAA and
   (b) $e^+e^- \to Z^{0*} \to$ Zh→ZAA
2. If $m_{\mathrm{h}} > m_{\mathrm{Z}} + m_{\mathrm{A}}$ than the following channels are open:
   (a) $e^+e^- \to Z^{0*} \to$ Ah→AZA and
   (b) $e^+e^- \to Z^{0*} \to$ Zh→ZZA

3. If $m_{\mathrm{A}} > m_{\mathrm{Z}} + m_{\mathrm{h}}$ than the following channel is open:

   (a) $\mathrm{e^+e^-} \rightarrow Z^{0*} \rightarrow \mathrm{hA} \rightarrow \mathrm{hZh}$

These processes are shown schematically in the Figure 2. It is noteworthy that, if they are open, they may (depending on the value of the parameters α and β) become dominant.

The analysis [8, 9] was limited to the dominant (for $\tan\beta > 1$) decays of lighter Higgs boson to pairs $\mathrm{b\bar{b}}$ and $\tau^+\tau^-$ as well as to hadronic decays of Z boson.

Although optimization of the selection of the study was carried out using the 2HDM (II) model, the results were given in a way maximally independent from the specific model implementation. It is worth noting that the extension of the BEH sector beyond two scalar doublets does not increase the number of final states. Therefore, in an absence of a statistically significant signal above the Standard Model prediction, the following approach was chosen. Limits were set on products of appropriate cross section and branching ratio (so called: signal modifiers) in function of the assumed mass of the Higgs boson.

The results can be divided into three groups: limits on Yukawa production, limits on Bjorken production and limits on pairs production. All taking into account direct decays of Higgs particles into fermions (b quarks or tau leptons) as well as cascade decay of heavier Higgs boson to the pair of lighter bosons. Detailed results have been published in the form of tables giving excluded values of signal modifiers for each final states topology considered and for each combination of mass of Higgs bosons h and A ([8, 9] Appendix B). These results are discussed further in the monograph.

It can be noted that the analysis [8, 9] was original in several aspects. For the first time the results of searching for Higgs bosons via Yukawa process were published by DELPHI collaboration. Also for the first time, an attempt was made to find a signal in topologies with cascade decays of the Higgs bosons. For this purpose, a special method has been developed to distinguish events with many b quark initiated jets (up to six) from multi-jet background. The last element, on the one hand original, but on the other hand just becoming standard in the literature using LEP data for BEH sector exploration, was to use as model independent approach as possible. Such approach allows efficient use of the analysis to constraint any theoretical model.

The above discussed work was complemented by four analyses done and published in the same time (2003/2004). Because in none of them any statistically significant signal was found these five publications contain a set of the most model independent and the most stringent constraints on BEH sector based on the data taken by DELPHI. These four were (discussed in the monograph) publications concerning the following topics.

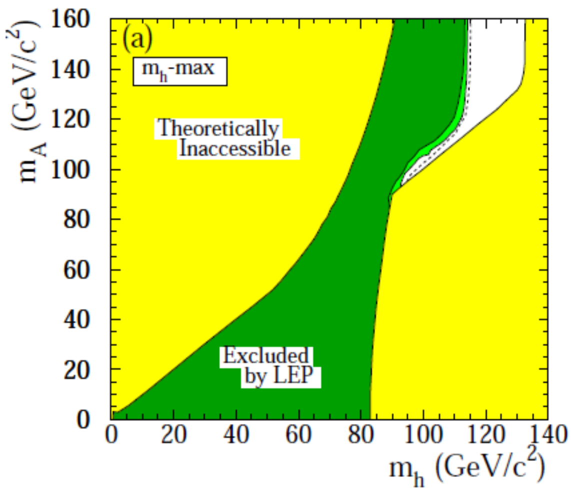
- Flavor independent search in hadronic channels [61].

- Search in photonic channels [62].

Figure 3: Exclusions at confidence levels 95% (light green) and 99.7% (dark green) for benchmark point m_h-max (and mass $m_t = 174.3\,\mathrm{GeV}/c^2$) in the projection ($m_h$,$m_A$) [58].

Dashed line shows the expected exclusion at 95% CL.

Yellow area is excluded from the theoretical point of view.



- Search for charged Higgs bosons [63].
- Search for invisible decays of neutral Higgs boson [64].

The final analysis of the DELPHI collaboration interpreting the search for Higgs bosons within the supersymmetric model was released in early 2008 [59]. In this work, an interpretation of 45 previously published studies on various production and decay channel including seven channel from the publication [8, 9] was done.

Earlier work on this topic, based on results of all four LEP collaborations, was published [58] (also with a use of [8, 9]).

Sector BEH implemented in the MSSM is a variant 2HDM (II) model with additional constraints from supersymmetry. These restrictions make it possible to describe the sector (assuming no CP violations) using only two parameters (apart form the parameters related to the breaking of the supersymmetry), for which (at the electroweak scale) one can take mass of one of the five Higgs bosons (there is four masses to choose from because both charged Higgs bosons have the same mass), and $\tan\beta$.

One of the benchmark points in the MSSM scenario is called m_h-max. As the name suggests, the mass of the lightest CP-even Higgs boson h is there forced to be maximal. Constraints for this benchmark point resulting from the combined analysis of all four LEP collaborations [58], are shown in the Figure 3. It could be concluded that mass of the h boson should be in a narrow range of 115-130 GeV/c^2 (if the mass of A boson is not less than 120 GeV/c^2) that is exactly where the Higgs boson have been found by the ATLAS and the CMS collaborations.

4.2.3 The discovery of a new particle during the search for the Higgs boson predicted by the Standard Model

The discovery of this particle was announced at the same time by both research teams of universal LHC detectors ATLAS [65] and CMS [66] in July 2012 [14, 15]. The search for the Higgs boson, verification of its nature, and searches of phenomena extending the BEH sector of the Standard Model, make highly developed research program. ATLAS and CMS have published since the beginning of 2012, that is, from the end of the collection of the data at $\sqrt{s} = 7\,\text{TeV}$ in 2011, dozens of papers on this subject.

Presented in the monograph discussion of the resent achievements in this topic is based mainly on a preliminary results [67–86] obtained with about 25/fb of the data collected by both the ATLAS and the CMS experiments in 2011 and 2012, at proton-proton collision energy of $\sqrt{s} = 7$ and $8\,\text{TeV}$. These preliminary results were prepared for the conferences *Rencontres de Moriond 2013* (subsequent works - released in May 2013 or later - are not taken into account).

Background level at hadron colliders is much higher than at electron-positron collider LEP. However, the cross sections for the production of the Higgs boson are so high, that the search can be carried out mainly in the channels with a sufficiently high expected signal-to-background ratio.

The main Higgs boson production process at the LHC is (in the Standard Model) the gluon fusion [87]. Important, although an order of magnitude smaller contributions come from the Vector Boson Fusion (VBF) [88] and the associated production with W or Z bosons [89]. Another channel with sizable contribution is Higgs boson production with a pair of top-antitop [90, 91].

Higgs boson decay channel that are essential in the search for the particles at the LHC just above the mass limit set by the LEP is the gamma-gamma channel [74, 79] despite the relatively small branching ratio [92] and a channel with even smaller branching ratio (at low Higgs boson mass), but with even better mass resolution and expected signal to background ratio, namely the decay $H \to ZZ^* \to 4\ell$, to two pairs of light charged leptons (electrons or muons), through intermediate decay into two Z bosons [75, 80]. The key experimental features for successful analysis of this channel are effective trigger, also for leptons with moderate transverse momentum, very good reconstruction of charged tracks, very good identification of leptons, including the skillful application of the criteria of lepton isolation (an illustration of the CMS analysis [80] is shown in the Figure 4).

In addition to these two channels, allowing not only for a discovery of the Higgs boson, but also quite accurate mass measurement, the signal has been found in topologies with Higgs boson decays into W^+W^- [71, 81], $\tau^+\tau^-$ [82] and $\mathrm{b\bar{b}}$ [93] pairs, for which a precise measurement of the mass is not feasible.

The discovery has been confirmed (but at much lower level of statistical significance), by the CDF and the D0 collaborations [94, 95], which had ended data taking in 2011 after decommissioning of the Tevatron. However, when it comes to proving that newly discovered particle couples to b quarks, the result of the CDF collaboration [96] is, so far, the best ($2.7\,\sigma$), whereas that of the D0 collaboration [97] is comparable to the outcome of the LHC.

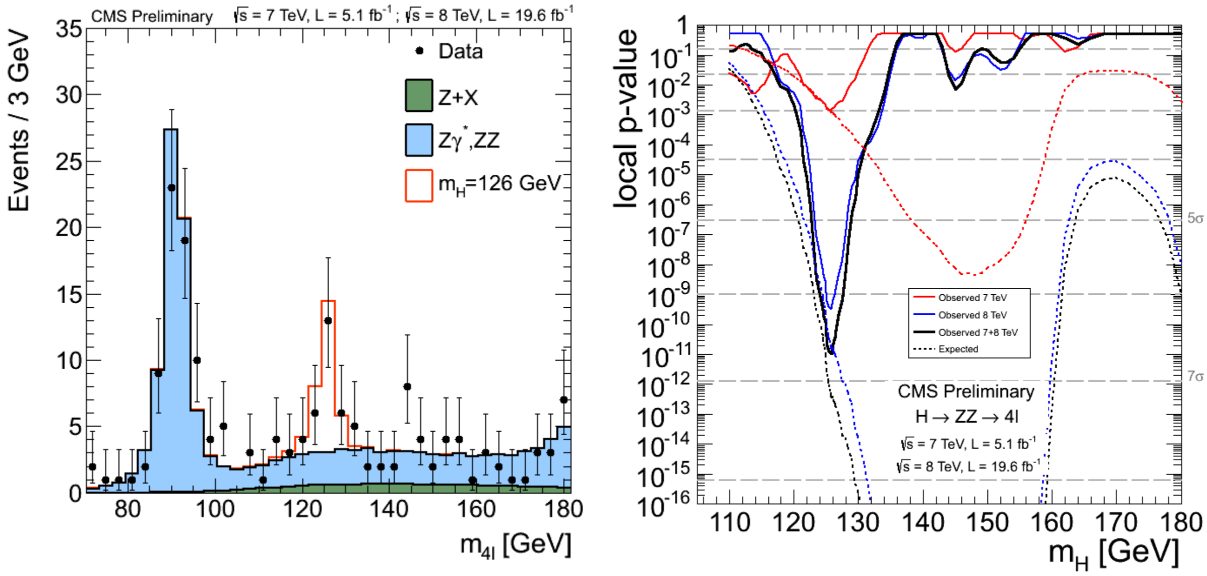


Figure 4: Illustration of the analysis $H \to ZZ^* \to 4\ell$ of the CMS collaboration [80]. The left-hand side shows the mass distribution of the two pairs of light leptons (black dots), together with the expected level of background (blue/green histogram) and the expected signal for the Higgs boson mass 126 GeV/c^2 (red histogram). The right-hand side shows the value of the test probability (p-value), in function of the tested mass. Red lines correspond to the data from 2011, blue lines to 2012, and black lines shows the results of a combined analysis. Solid lines shows observed p-value distribution (probability of fluctuation of the background in an absence of a signal), whereas dashed lines shows magnitude of the expected minimum of the p-value distribution for a given mass.

4.2.4 Study of the properties of the new particle

This study has been carried out by both research teams ATLAS [68, 73] and CMS [82] in five decay channels, respectively, into ZZ*($\to 4\ell$), $\gamma\gamma$, W$^+$W$^-$, $\tau^+\tau^-$ and b$\bar{\text{b}}$.

The first two channels allow for the accurate determination of the mass of the new particle. The average value $m_{\text{H}} = 125.5 \pm 0.2$ (stat)$^{+0.5}_{-0.6}$ (syst) GeV/c^2 have been determined by the ATLAS collaboration, whereas the CMS collaboration have been reported $m_{\text{H}} = 125.7 \pm 0.3$ (stat) $\pm\, 0.3$ (syst) GeV/c^2.

Signal strength modifiers $\mu = \sigma/\sigma_{SM}$ (with respect to the Standard Model predictions σ_{SM}) have been determined in each channel, for the mass taken from the combined analysis of each experiment. The results are shown graphically in the Figure 5. They agree, within their uncertainties, with the predictions of the Standard Model.

The combined signal strength modifiers, for the average masses have been determined to be equal to 1.30 ± 0.13 (stat) $\pm\, 0.14$ (syst) by ATLAS and 0.80 ± 0.14 by CMS.

Another highly important issue that requires experimental clarification is spin and parity J^P of the newly discovered particle[9]. If it is the Higgs boson it should be a scalar $J^P = 0^+$. The mere fact of coupling to two photons generally exclude a vector particle

[9] It is worth recalling that the first CMS feasibility study concerning possibility of a measurement of the Higgs boson quantum numbers were done in the dissertation [52] in which I was acting as the tutor. An essence of the results were published in the CMS Physics Technical Design Report [98].

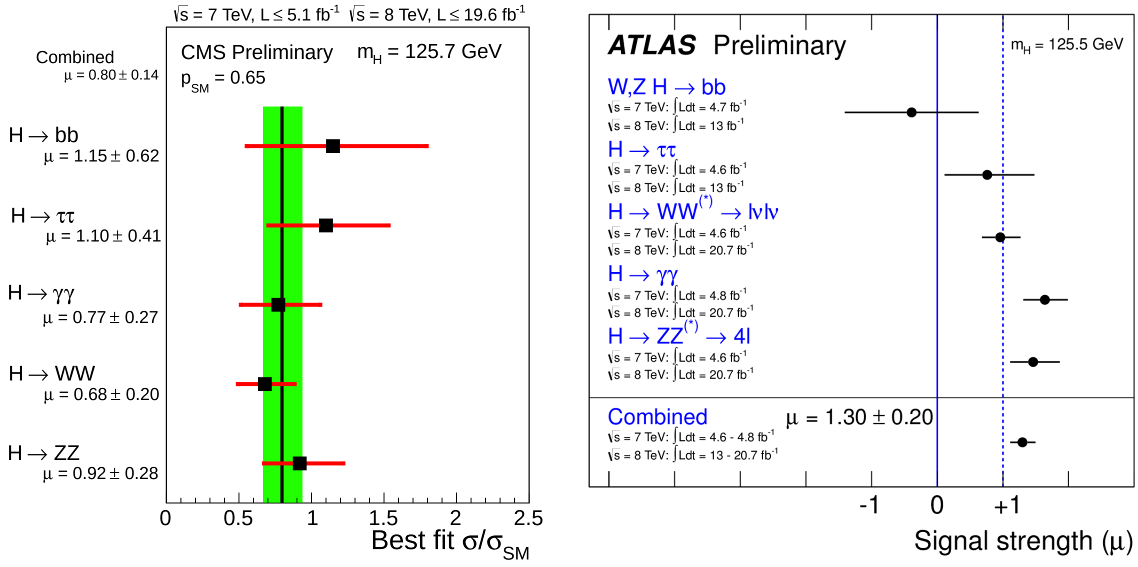


Figure 5: Comparison of the results of measurement of signal strength modifier $\mu = \sigma/\sigma_{SM}$, for different channels of an observation of the Higgs boson, on the basis of preliminary results of the CMS [82] and the ATLAS [68, 73] collaborations.

The strength modifier values(corresponding to the average mass determined by each experiment) are shown (as a squares or points with an error bars) for all five channels and for the combined result (on the left panel the combined result is shown as a black vertical line on a green strip).

(with spin $J = 1$). Determination of a spin and a parity of X particle reduces in comparison to the angular distributions of its decay products with the distributions expected for particles with a certain spin and parity J^P. The decay channel which is the best suited for that purpose is $X \to \mathrm{ZZ}^* \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$, where ℓ_1 i ℓ_2 are light leptons, preferably different (to limit combinatorial background, related to incorrect lepton pairing). The distinction can be improved by using the channels $X \to \mathrm{WW}^* \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}$ and $X \to \gamma\gamma$.

In the Figure 6 (on its left-hand side) an illustration of a distinction between $J^P = 0^+$ (orange) and $J^P = 2^+$ (blue) is shown. Colored distributions are posterior probability density for stochastic variable being minus doubled natural logarithm of profiled maximum likelihood ratios $L_{2^+_\mathrm{m}(\mathrm{gg})}/L_{0^+}$ corresponding to two hypotheses to be distinguished (the letter "m" before "(gg)" means that what is considered is the minimal tensor couplings to gluon pair). These distribution have been obtained with simulated data corresponding to the integrated luminosity of the real CMS experiment and analyzed by the same analysis chain using channels ZZ* and WW*. The red arrow shows the CMS result [82] (the measured value of the stochastic variable). The observed significance level at which one can reject the hypothesis $J^P = 2^+_\mathrm{m}(\mathrm{gg})$ corresponds to the part of the blue distributions to the right of the red arrow and is equal to $\mathrm{CL_s} = 6 \cdot 10^{-3}$ (whereas $2 \cdot 10^{-3}$ have been expected). On the right-hand side of the same Figure (6), a dependence of the level of significance of such exclusion, obtained by the ATLAS collaboration [67] is shown in function of the fraction of the $f_{q\bar{q}}$ of production of particles X by quark-antiquark annihilation. The result is based on an analysis of all

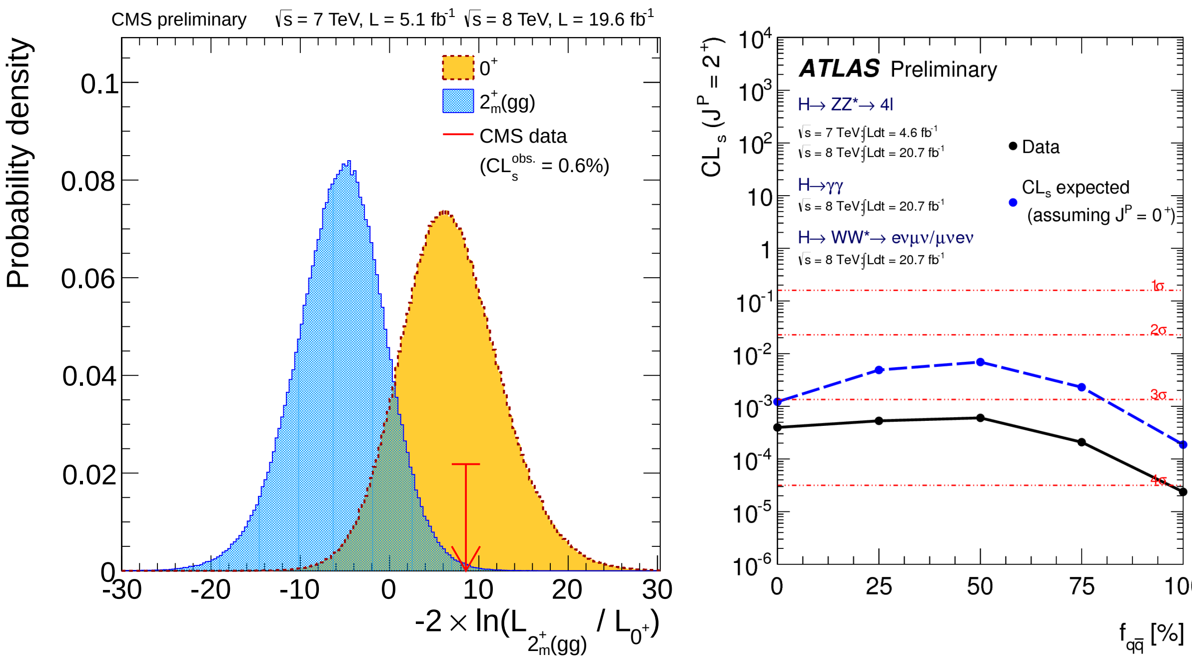


Figure 6: Determination of spin and parity of the new particle.

On left-hand side probability densities for $J^P = 0^+$ (orange) and $J^P = 2^+$ (blue) for the ratio of likelihoods of both hypotheses (simulation). The red arrow indicates the CMS result [82].

On the right-hand side a value of confidence level is shown, at which it is possible to reject the hypothesis $J^P = 2^+$ on the basis of the ATLAS analysis [67].

A more detailed description and interpretation is in the text.

three channels, in which newly discovered particle decay into vector bosons. The tensor $2^+(gg)$, taken into account by CMS, corresponds to $f_{q\bar{q}} = 0$, whereas $f_{q\bar{q}} = 100\%$ corresponds to coupling $2^+(q\bar{q})$. With the black line the observed $\mathrm{CL_s}$ is shown in the Figure whereas the blue line correspond to the expectation. As one can see the observed significance exceeds the level of $3\,\sigma$, for all values of $f_{q\bar{q}}$.

In conclusion, although statistical significance of the results is still limited, there is no reason to reject the $J^P = 0^+$ hypothesis, in accordance with an assignment of the quantum numbers expected for the Higgs boson to the newly discovered particle.

4.2.5 Summary of the Higgs boson searches

Since the fourth of July 2012 it is known about the positive result of the search the Higgs boson predicted by the Standard Model. The search has been performed by the ATLAS and the CMS collaborations at the LHC collider. This result was confirmed by an analysis of the data collected by the CDF and D0 experiments, which operated at the Tevatron. The mass of newly discovered particle have been measured using the full experimental material collected by the ATLAS and CMS experiments in 2011 (2012), at the energy in the center of mass of the colliding protons of $\sqrt{s} = 7\,\mathrm{TeV}$ $(8\,\mathrm{TeV})$.

The current value of its mass is fixed at $m_{\rm H} = 125.5 \pm 0.2$ (stat)$^{+0.5}_{-0.6}$ (syst) GeV/c^2 by the ATLAS collaboration and at $m_{\rm H} = 125.7 \pm 0.3$ (stat) $\pm$ 0.3 (syst) GeV/c^2 by the CMS collaboration. Its properties agree with these expected for the Higgs boson of the Standard Model within the uncertainty of the measurements performed so far.

Observation of the new particle at the same time match with a hypothesis of a discovery of the one of the Higgs bosons expected in many extensions of the Standard Model (with more complicated BEH sector) that predict an existence of a neutral scalar particle with properties very similar to the standard Higgs boson. In particular, it may be the lightest neutral Higgs boson predicted by supersymmetry or a scalar of two-doublet extensions of the Standard Model (see e.g. [99]).

It is worth remembering that within some extensions of the Standard Model (e.g. 2HDM), the existence of scalars form the BEH sector lighter than the newly discovered particle is not excluded. Constraints on such extensions come mainly from the publications of the LEP experiments. Improving these constraints using data taken or to be taken at the LHC will be very difficult or even impossible, because of the high level of background which prevents selection with sufficient efficiency and selectivity often already at the trigger level.

Therefore, the results of the analyzes of BEH sector performed on the basis of the data collected at the LEP, continue to be - to a large extent - to date.

4.3 A use of the CMS muon system for a search for new particles

The primary publication describing the CMS detector operating at the LHC is [66]. The detector is built around a superconducting coil producing homogeneous magnetic field magnetic field of 3.8 T, and almost 2 T in the iron return yoke. The beam pipe is the ax of the symmetry of the detector, which consists of five iron wheels forming the barrel and six iron disks forming two endcaps. The middle wheel is supporting the superconducting coil, in which both calorimeters and tracker are inserted. Endcap part of the calorimeters are attached to the internal disks. Muon system consists of four layers of gas detectors mounted in all five wheels and attached to the disks. It consists of three subsystems. Drift Tubes (DT) in the barrel, Cathode Strip Chambers (CSC) in the endcaps and Resistive Plate Chambers (RPC) both in the barrel and in the endcaps. The detector contains additional calorimeters and covers up to $|\eta| < 6.6$.

Since the beginning of the CMS project the Warsaw CMS Group gathering scientists from the Department of Physics of the University of Warsaw, National Centre for Nuclear Research (formerly the Soltan Institute for Nuclear Studies) and Warsaw University of Technology. We have undertaken the task of design, construction, commissioning, and maintenance of the electronics of the RPC based muon trigger system. It is called Pattern Comparator Trigger (PAC Trigger or PACT), because its principle of operation is to compare the actual RPC hits configuration to the previously prepared patterns.

The reason for my participation in this project have been the desire to contribute to the search for new particles using the muon system of the CMS detector in the most optimal and original way.

4.3.1 PAC Trigger subsystem based on the RPC

The chambers used in the CMS RPC have double gas gap and single readout strip layer placed between the two gaps. Strip width have been chosen in way to provide approximately $12 \cdot 12 \cdot 8 = 1152$ strips in each layer of the RPC. In the barrel there is six layers of the RPC, because in the two innermost muon stations they are on both sides of the DT chambers, whereas in the other two muon stations, they are only in front of the DT chambers. This allows for triggering on muons with small transverse momenta using only the first four RPCs (present in the first two muon stations).

The RPC system working through the first period of data collection have been limited to $|\eta| < 1.6$ and the fourth layer of the RPCs in the endcaps have not been build, mainly due financial limitations.

RPC chambers measure only ϕ coordinate. Therefore strip in the barrel are parallel to the beam axis and are radial in the endcaps. A single cell is divided into two or three groups of strips in the direction of η (z). Because of that the strip length do not exceed 125 cm which gives jitter due to signal propagation along the strip smaller then 3 ns. In total, the system contains 165000 strips. It is divided into 33 η towers. In each tower there is 144 ϕ segments defined by a group of 8 strips in the reference RPC layer. The signals from the front end electronics are transmitted to the trigger electronics by 1732 optical links and feed 396 PACT chips, grouped by (at most) four in a single trigger board. There is 108 trigger boards in 12 crates. The system triggers if among the hits assigned to a single bunch crossing, at least one of the previously prepared patterns is found. Every 25 nanoseconds the system forwards to the higher level trigger up to eight muon candidates (up to four from the barrel). To each pattern the value of the transverse momentum and the sign is assigned. Apart of that information the candidate bears a quality which value depends on the number of hits found to agree with the pattern.

In order to increase the efficiency of the trigger (sacrificing transverse momentum resolution) a sequences of hits, in which some of the hits present in the pattern are missing, are also accepted. The minimal number of hits in such sequence is three. It means that in the barrel even sequences with tree out of six hits in the corresponding pattern are accepted. The rate of the PACT was maintained approximately constant. As an instantaneous luminosity of the LHC increased appropriate thresholds p_{T}^{cut} were applied. To make this possible, the system must have sufficiently steep (selective) turn-on curves.

Performance of the PAC Trigger is discussed (among others) in [100–102].

My involvement in the PAC Trigger was particularly important at the beginning of my collaboration with the Warsaw CMS Group as evidenced by a series of notes of the CMS experiment [103–111], which constitute a contribution to the publication [3] or further development of it (see § 4.3.2 of the present *autoreferat*). Currently I am focused on the use of the PACT to trigger on massive long-lived charged particles (see § 4.3.4 of the present *autoreferat*).

4.3.2 GhostBuster – replicating PACT signals removal

One problem with the original specification of the PACT system was a high rate of double-muon trigger due to multiplication of signals caused by single muons [112]. Such artificial signals of this type are often called ghost A special algorithm aimed at its elimination has been developed by me and presented as GhostBuster [113]. This ironic name is still used (in full or as a shortcut GB, which occurs for example on PACT trigger boards).

The mechanism of the ghosts creations in the PACT system depends on whether the reproduction occurs in the direction of ϕ or η. In the first case ghost are due to the same hit sequences in the second they result from the way in which so called logical η towers are constructed: signal from one chamber are sent to more than one such tower.

A detailed description of the problem, its solution and simulation test of the GhostBuster algorithm, could be found in the public note [103] and, independently, in the Chapter 13 of the Technical Specification of the CMS Trigger System (Project TriDAS, vol 1) [3]. It is also discussed in some detail in the presented monograph. Here, only the main idea and the most important result will be recalled.

Both types of ghosts (ϕ and η) are caused primarily by using incomplete patterns.

The final result of proposed by me solution is shown in the Figure 7. Both parts of the Figure shows a comparison of genuine double-muon rate of the PAC Trigger (on the left shown by red triangles on the right by blue line) with a double-muon rate due to ghosts, in function of the double-muon threshold p_{T}^{cut}. On the left-hand side blue circles show the situation before the use of the GhostBuster, whereas, on the right-hand side the black circles shows the effect of the application of this algorithm [103]. Both drawings are the result of the full simulation of the CMS detector using CMSIM package.

One can see that for small transverse momenta, relevant for planned CMS program of $\mathrm{b\bar{b}}$ physics [114], false double-muon rate decreases by a factor of about 20, whereas, for larger transverse momenta a factor of about 10 of the rate reduction is observed and the ghost rate becomes much smaller than the genuine double muon PAC Trigger rate.

The final version of the electronic PAC Trigger system was built based on FPGA programmable integrated circuit. A single PAC comparator chip hosts not only many comparator channels but also corresponding part of the ϕ GhostBuster.

The rest of the functionality of the GhostBuster (η ghost-busting) has been integrated with the sorter chain [109]. The GhostBuster algorithm is an integral part of the system currently used [66].

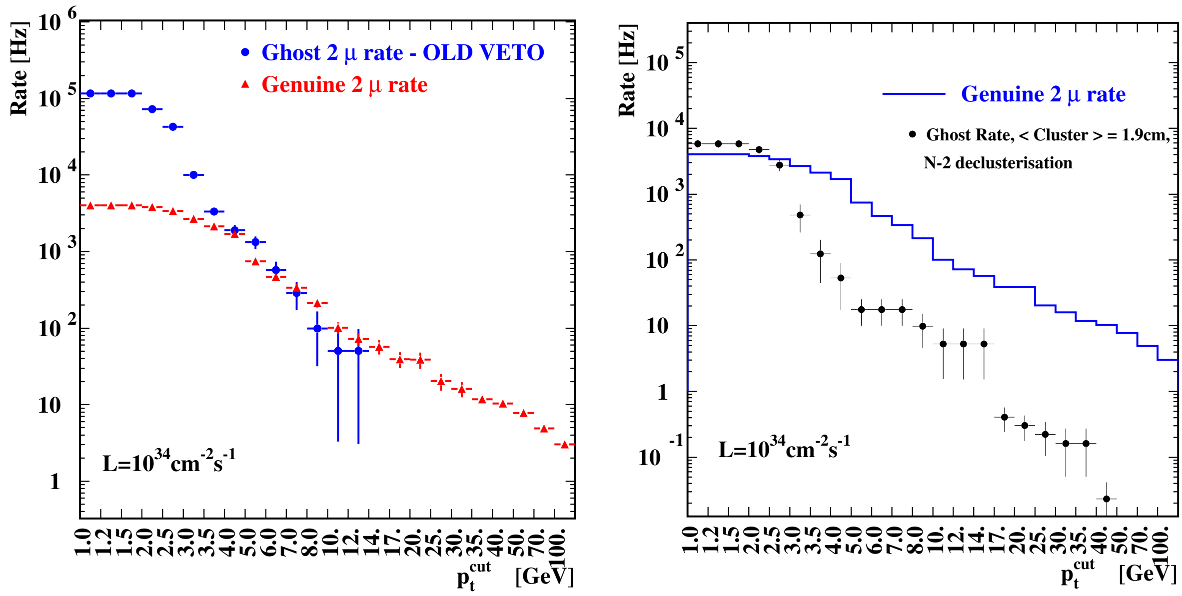


Figure 7: Double-muon PAC Trigger rate in function of the p_{T}^{cut} threshold (lower of transverse momenta assigned to two muon candidates) for genuine pairs of muons and for single muons registered as doubles due to signal multiplication (due to presence of ghosts).

On the left-hand side the situation before a use of the algorithm GhostBuster is shown: distribution for genuine muon pairs is shown by red triangles, the distribution for pairs where one of the candidates is the ghost is shown by blue dots.

On the right-hand side the situation after the use of the algorithm GhostBuster is shown [103]: the distribution of single muons, accepted as double-muons (due to ghosts), is shown by the black points, whereas distribution for genuine muon pairs (same as shown in red on the left), is drawn in blue.

It should be noted that the ranges of the vertical axes are different. The results were obtained using CMSIM – the full simulation of the CMS detector.

It should be emphasized that the GhostBuster algorithm is indispensable for a correct operation of a double-muon trigger of the CMS. It this sens it contributes to the spectacular achievements of the CMS experiment, such as the discovery and a study of the properties of the new particle via its four-lepton decay channel [15, 82], or observation of the decay $\mathrm{B}_s^0 \to \mu^+\mu^-$ [115] which have been searched for decades.

4.3.3 Time of flight measurement using Drift Tubes

This section presents the very idea of measuring the time of using Drift Tubes, in which the muon spectrometer of the CMS detector is equipped. Motivation and en evolution of a commitment of the Warsaw CMS Group to a search for massive long-lived particles using this method (among others), are summarized in the later part of the present *autoreferat* (§ 4.4). A more detailed description can be found in the presented monograph.

The possibility of measuring the time of flight had not been taken into account at the design stage of the CMS detector [114]. It turned out, however, that such a measurement is not only feasible [116], but it can be used to search for massive long-lived charged particles [10].

A muon spectrometer must fulfill two functions. Enable effective trigger of the data acquisition system and as precisely as possible measure the transverse momenta of muon candidates. For the latter function it need a precise measurement of the coordinates of tracks passing through the sensitive parts of the spectrometer. It has been estimated that a precision of about 100 microns would be optimal. A use of a drift tubes have been found as a cost-effective way to fulfill such requirement in the barrel part of the CMS. The drift tubes used have rectangular cross-section $10\,\mathrm{mm}\times 40\,\mathrm{mm}$ and a length of the order of two and a half meters (tubes that measure azimuth angle ϕ are placed parallel to the beam pipe and all have a length corresponding to CMS wheel width, the length of the tubes measuring z coordinate – along the axis of symmetry of the CMS – depend on the distance R from that axis). Tubes are assembled into, so called super-layers consisting of four layers of tubes staggered like bricks in a wall (i.e., as shown in both parts of the Figure 8). In each of the four muon station (and in each of the five wheels of the CMS barrel) there is a structure consisting of two super-layers measuring ϕ coordinate and in the three innermost stations also one super-layer measuring z coordinate.

In the middle of each tube an anode wire is placed. Readout electronics measures the time of arrival of an ionization signal (caused by a charged particle passing through the tube) at the anode wire. Drift velocity is of the order of $50\,\mu\mathrm{m/ns}$, which, at the time resolution of the order of 2 ns, gives the expected accuracy of determination of the position of about $100\,\mu\mathrm{m}$ along longer side of the tube cross-section. But this implies that the maximum drift time of the order of 400 ns. Because of that, the system, to work effectively, must write the information from (at least) the last 16 bunch crossings whenever the data is to be saved. Incidental benefit is almost no difference in the effectiveness of registration of particles coming on time (when particles produced in proton-proton interaction and moving almost with the speed of light are expected) and those coming out of time. And because system measures the position by measuring the time, it is well suited for measuring delayed particles and assuming that we are dealing with a massive long-lived charged particle, its velocity $1/\beta = v/c$. In turn, with simultaneous measurement of the momentum and the velocity, the mass of the particle can be determined.

The idea of measuring the inverse velocity $1/\beta$ is illustrated in the Figure 8 where a passage through one DT super-layer of an on time particle (on the left-hand side) and a delayed particle (on the right-hand side) are shown schematically. In the first case reconstructed hits (rec-hits) are aligned on the track (blue arrow), whereas, in the second case they are moved away from the wire by a distance corresponding to the delay of the particles arranging themselves in a sinusoid. Determination of the offset δ_x, or by how much rec-hits must by shifted towards wires to be aligned, is equivalent to measuring the delay of the particle δ_t, and on the assumption that the observed particle is delayed due velocity significantly lower than the speed of light $\beta < 1$, to the estimation of this velocity [10, 11, 117].

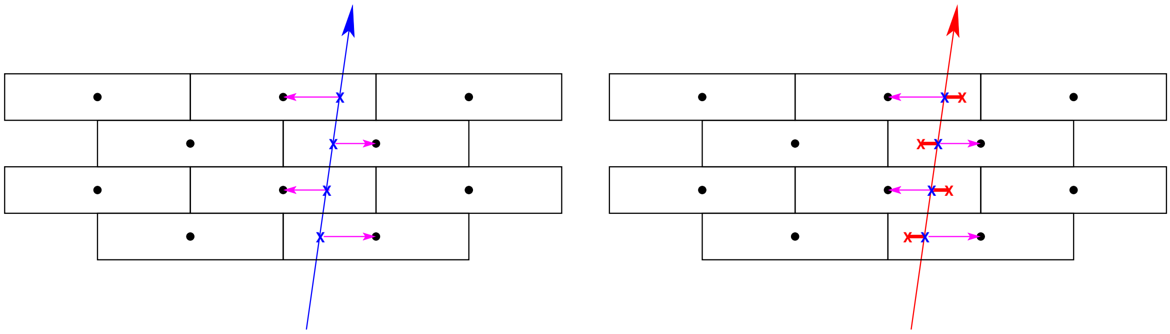


Figure 8: Sketch of a flight of a muon (blue arrow) and of a delayed particle (red arrow) by one DT super-layer [116]. On the left-hand side the reconstructed hits (blue crosses) are arranged along the muon track (blue arrow), coming on time. On the right-hand side the reconstructed hits (red crosses), are moved away from the anode wires (black circles) and do not align on red arrow. The offsets are caused by the delay of the particle.

$$\frac{\delta_x}{v_{\text{drift}}} = \delta_t = t_{(\beta<1)} - t_{(\beta=1)} = \frac{L}{c}\left(\frac{1}{\beta} - 1\right), \tag{1}$$

and hence

$$\frac{1}{\beta} = 1 + \frac{\delta_x}{L}\frac{c}{v_{\text{drift}}}, \tag{2}$$

where L is the flight distance and v_{drift} is the drift velocity.

If delayed track is due to long-lived charged massive particle, created in proton-proton interaction, then the delay should increase linearly with the distance traveled, and a contribution to the measurement of $1/\beta$ from a single hit is as follows.

$$\left(\frac{1}{\beta}\right)_{ij} = 1 + \frac{c}{v_{\text{drift}}}\frac{(\delta_x)_{ij}}{L_{ij}}, \tag{3}$$

where L_{ij} is the length of flight of the particle from the interaction point of impact to the rec-hit ij (calculated taking into account the curvature of the track).

Whereas the estimate of the inverse of the speed, taking into account all rec-hits associated with the particle track, in all N stations (projections) is given by the following formula [11].

$$\left\langle\frac{1}{\beta}\right\rangle = \frac{\sum_{j=1}^{N}\frac{n_j-2}{n_j}\cdot\sum_{i=1}^{n_j}\left(\frac{1}{\beta}\right)_{ij}\omega_{ij}^2}{\sum_{j=1}^{N}\frac{n_j-2}{n_j}\sum_{i=1}^{n_j}\omega_{ij}^2}, \tag{4}$$

where n_j is the number of rec-hits in the projection $j \in \{1,\ldots,N\}$ and the weight $\omega_{ij} = 1$ or (as it has been clarified in [117]) is equal to the flight distance $\omega_{ij} = L_{ij}$. The change was linked with an observation that the delay increases linearly with the flight length, whereas the precision of its determination does not. It should also be clarified that the factors $\frac{n_j-2}{n_j}$ correspond to the ratio of the number of degrees of freedom of the path element estimate in a given station (projection) to the number of rec-hits. Two degrees of freedom are subtracted, because at each station two parameters of path element are determined. The standard deviation of the estimate of the $1/\beta$ reads:

$$\sigma_{\langle\beta^{-1}\rangle} = \sqrt{\frac{\sum_{j=1}^{N} \frac{n_j-2}{n_j} \cdot \sum_{i=1}^{n_j} \left\{ \left(\frac{1}{\beta}\right)_{ij} - \left\langle \frac{1}{\beta} \right\rangle \right\}^2 \omega_{ij}^2}{\sum_{j=1}^{N} \frac{n_j-2}{n_j} \sum_{i=1}^{n_j} \omega_{ij}^2}} \quad (5)$$

The presented method was used in all publications in which a search for massive long-lived charged particles using CMS muon system were described [13, 118].

4.3.4 PAC comparator version sensitive to delayed particles

The LHC collider and all its detectors, have been designed to operate with a gap of 25 ns, between successive collisions of proton beams. So far, however, for optimum operating mode has been recognized a double gap mode one. This have made possible to modify the algorithms of the PAC Trigger based on signals registered by the RPC chambers to allowing for triggering on particles registered in the next bunch crossing.

Schematic diagram of the modification is shown in the Figure 9.

Selected subsequent layers of the detector, more and more distant from the point of impact, are shown one above the other, whereas from left to right, subsequent intervals timed by nominal bunch crossings (BX) are represented.

The situation at the interaction point is indicated by a series of squares. In every second square there is a string "BPTX bit" meaning that every second nominal BX there is an actual collision of proton bunches detected by BPTX (Beam Pick-up and Timing for Experiments) detectors located (on both sides) at a distance of 175 meters from the CMS detector with 50 ns time resolution. This information is transmitted to the High Level Trigger (HLT).

The next layer of the detector placed on the diagram, is the tracker. Then two layers of RPC are shown the first and the last. Each of these layers is represented by two horizontal lines. Lower correspond to the information recorded by the system (*hit in the RPC layer*), and the upper information fed to the comparator PAC (*bit in the PAC*).

Throughout the figure, the red lightning bolt symbols indicate a rec-hit due to charged particle passing through a given layer of the detector, within a time window synchronized to register particles originating from the proton-proton interaction and moving at the speed of light. The green ovals indicate that the information (assigned to a given bunch crossing) will be recorded by the data acquisition system (DAQ) when at final stage of the trigger (HLT), a decision to accept the even will be taken. Such decision is symbolized by the yellow arrow running through the entire column corresponding to a particular bunch crossing. Finally the blue squares represent the information fed to the PAC comparator, whereas the blue arrows level one PAC Trigger accept (L1). As can be seen each RPC red-hit (red lightning) produces blue square (bit) in for two BX the actual and the preceding. This is the modification of the algorithm that allows for a detection of delayed particles. The PAC comparator checks coincidence

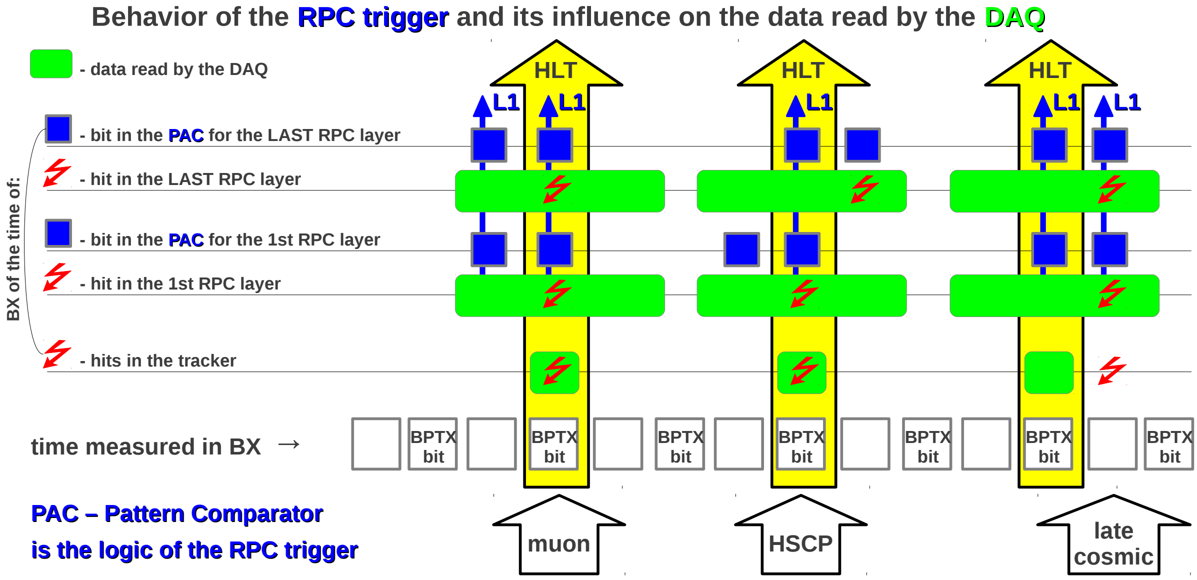


Figure 9: Sketch of an operation of the version of the PAC Tagger sensitive to delayed particles [12], activated in May 2011, and used in the analyzes [13, 118].

Description in the text (§ 4.3.4 of the present *autoreferat*).

of bits in each successive BX, and abut finding it informs the next stage of the trigger (HLT) issuing the L1 accept signal (blue vertical arrow).

The figure shows the situation for the three particles: ordinary muon coming from the proton-proton interaction; hypothetical massive charged particle produced by such interaction, for which the delay with respect to the muon increases, due to the velocity significantly lower than the speed of light (HSCP – Heavy Stable Charged Particle); and cosmic muon moving outwards (late cosmic) and passing near the center of the detector at about 25 ns after a crossing of proton bunches.

One can see that the muon from the proton-proton interaction and late cosmic muon can both leave the same sequence of hits. L1 signal is issued by the comparator in two consecutive time windows. If the L1 signal is not in a coincidence with BPTX bit it is ignored by HLT. But, if it is in the coincidence, a HLT accept is issued and the whole detector is readout. The information which is saved is green highlighted in the diagram (the ovals that intersect with the yellow wide arrow are registered). For the muon the whole information is correctly readout (all red lightning are on the green background), whereas for the late cosmic the information from the tracker will be missing (the corresponding red lighting is not on the green background).

The situation for the massive particle is different. The delay increases for it with the distance from the interaction point. The registration of the particle moves to the next time window somewhere in the muon system. In the Figure the situation is shown in which only one L1 signal is issued, but at the right time, allowing to save the information from the tracker. It should be noted that if a delay grew more rapidly, so that all the reconstructed in the muon system hits would fall in the next window (similarly to what is shown for the "late cosmic" on the very right of the Figure) the tracker hits could still be registered. (if the delay in the tracker will not exceed 12.5 ns).

The operation of the described modification of the PAC comparator can be summarized as follows. By doubling the signals in the comparator and advancing them by one time window (technically, these operations are performed in the comparator through an appropriate modification of embedded software – firmware) and using the information from the beam monitors (BPTX), muons produce HLT trigger as before the modification, whereas the massive charged particles cause HLT trigger, even if they are late (relative to the muon of the same momentum). This delay should not exceed 37.5 ns. Massive particles can be distinguished, from the late cosmic background, by requesting (at the final level of the trigger system - HLT) a presence of associated track in the tracker. The price of this modification is reduced by 25 ns the amount of time available to develop the L1 trigger by the PAC comparator.

This modification was introduced in May 2011 and has increased the registration efficiency for particularly slow massive particles, which was used in the analyses [13, 118].

After currently ongoing long shutdown (two years) of the LHC, the collider should restart not only with increased energy (13 TeV, or even nominal 14 TeV) but also with the nominal distance between the proton bunches. This will make necessary to withdraw from the described PAC Trigger modification.

The Warsaw CMS Group (under one of the tasks of my NCN grant) is engaged in the development and implementation of a trigger sensitive to delayed massive particles, appropriate to the nominal operating mode of the LHC with an interval of 25 ns between proton bunches. The idea is to extend the spatial correlation performed by PAC on the space-time correlation Suitable embedded software (firmware) modification has already been prepared. We working on an elaboration of appropriate patterns. In order to increase the delay of the particles to which the modified comparator will be able to assign the appropriate time window it is considered to shift the time window of the first two layers of the RPC system, in a way that signals due to muons will not transfer to the precedence window, whereas delayed particles will continue to be recorded in the time window corresponding to the correct bunch crossing. Without such shift only particles delayed by no more than 12.5 ns at first muon station would be accepted. Whereas, after such displacement, the acceptance could increase to about 18 ns. For $|\eta| = 0.5$, without any modification, acceptance begins to fall down for particles of $\beta < 0.75$. After the firmware modification, but without delaying the time window the acceptance start to fall down for $\beta < 0.6$, whereas, after an appropriate shift of the time window, the acceptance should fall down only after $\beta < 0.5$. It is worth remembering that the identification of massive charged particles is the more reliable, the lower is its velocity β (provided they will be recorded).

4.3.5 Summary of the author participation in the development of the CMS muon system

My main contribution was an involvement in the design of the PAC Trigger operating on the signals recorded be the RPC chambers. I have proposed an effective solution to the ghost problem that prevented correct operation of the double-muon trigger.

This solution named GhostBuster is indispensable part of the PAC Trigger. I have participated in the elaboration of the mode of operation of the PAC Trigger sensitive to delayed particles and I am responsible of a design of such version appropriate to the 25 ns gap between proton bunches mode of an operation of the LHC.

Another achievement has been a development of the method of measuring the inverse of the velocity of massive long-lived charged particles by measuring delays in the drift chambers installed in the barrel of the CMS detector. The method have been invented by me and implemented by members of the team led by me in successive versions of the CMS software. It is being used and constantly improved.

4.4 Search for massive long-lived particles in the CMS experiment

The main objective of the research programs of the ATLAS and the CMS collaborations, which use two universal detectors at the Large Hadron Collider, is to explore physics at electroweak symmetry breaking scale [98, 119–124]. The discovery of the new particle during a search for the Higgs boson in the framework of the Standard Model (§ 4.2.3 of the present *autoreferat*) is a milestone on this road. But this is not the end, rather a guidepost with a message we are supposed to start to decipher.

In the opinion of most researchers in particle physics, the Standard Model is only a low energy approximation of some deeper theory. The two most frequent complaints against SM, raised as a reason to search for its extensions in subsequent accelerators, is a lack of an explanation of the small mass of the Higgs boson, of the order of the intermediate bosons mass, whereas radiative corrections are of the order of the Planck mass (the hierarchy problem [125]) as well as missing candidate for dark matter particle. There are more weaknesses of the Standard Model but they are rarely being addressed by proposed extensions.

The hierarchy problem is a bit of an aesthetic-philosophical nature. The discovery of the new particle looking as the Higgs boson from the Standard Model bring this problem into focus, but as one can see, Nature has resolved it somehow. We just want to know how. One possible answer is some version of the anthropic principle [126, 127].

As for the dark matter is concerned the body of evidence of its reality on the one hand, and its difference from ordinary baryonic matter (or known types of neutrinos) on the other hand is impressive [128–133]. However, there is no convincing evidence that it consists of undiscovered yet particles. It is, however, a viable solution. We only known that such particles must be neutral and couples to matter (at most) weakly. It is also known that it should not be too light (relativistic) because so called hot dark matter does not agree well with a cosmological observations [131–133].

A supersymmetry [134–136]. is one of the most promising theories beyond the Standard Model. It is, undoubtedly, the most elaborated and tested theory, among these that could be not realized in Nature.

The simplest version of a supersymmetry, containing no prior assumptions as to the relationship between the parameters, is called the Minimal Supersymmetric Standard Model (MSSM) [137]. It has more than hundred free parameters, including the parameters present in the Standard Model. Supersymmetry foresees a partner for each particle of the Standard Model. The partners of bosons are fermions, and partners of fermions are bosons (scalars, two for each fermion, except neutrinos, if we assume that there are only left-chiral neutrinos). Supersymmetry is the only possible extension of the Lorentz symmetry. An invention of a supersymmetry could be compared to an invention of an antimatter [138]. Supersymmetry brings a hope to include gravity into framework describing other interactions, although implementation of such inclusion (the string theory, the M-theory [139]) is far from being understood.

If supersymmetry were exact symmetry of nature, a super-partners of the same masses as the corresponding SM particles should be observed. In such case the radiative corrections to the Higgs bosons mass (there is five Higgs boson predicted by the MSSM, because its BEH sector is the same as in the 2HDM (II) model) exactly cancel out, solving the hierarchy problem. However, we do not observe such particles and so supersymmetry must be broken. A large number of free MSSM parameters is related to an admission of all possible supersymmetry violations terms. After supersymmetry breaking, super-partners become more massive than corresponding SM particles. Expectation that some of these massive super-partners are in the reach of current accelerator experiments is related to the hope that supersymmetry could, at least partially, solve the hierarchy problem and explain eventual deviations of precise measurements from SM prediction.

There is another argument in favor of low-energy supersymmetry. It turns out that, if such symmetry exist than the running coupling constants of three interactions of the Standard Model have the same value at the GUT scale, while in the SM alone, each two intersect at a different scale [140]. Such unification of interactions is highly awaited. However, the current precision does not allow to ensure that appropriate (for such unification) super-partner masses guarantee a discovery at the LHC, or falsification of the idea.

In considering the phenomenology of supersymmetric models usually conservation of, so called, R-parity is assumed, which, by assigning positive parity to SM particles and negative to super-partners, eliminates the problem of too fast proton decay. At the same time R-parity prohibits single super-partner production and decay to SM particles alone. the particles MS (this is what solves the problem of too fast proton decay). Thus, at the end of the decay chain of pair-produced supersymmetric particles, there are two the Lightest Supersymmetric Particles (LSP). The LSP is an excellent candidate dark matter particle. Very often as such LSP the $\widetilde{\chi}_1^0$ (which is the lightest of the partners of intermediate bosons and neutral Higgs particles) is taken. But there are other possibilities, among which the most interesting is gravitino the partner of graviton. This is the scenario we are working on in Warsaw CMS Group.

4.4.1 The initial period of a development of a search for massive long-lived particles in the CMS

The main motivation to take a topic of massive long-lived particles by the Warsaw CMS Group, was a possibility to share involvement into search for beyond Standard Model (BSM) effects with contribution to the muon system of the CMS experiment. The first idea was to examine the possibility of using the muon spectrometer to measure the time of flight, in order to identify massive long-lived charged particles. It was the first feasibility study of that kind at the LHC. As a theoretical motivation the Gauge Mediated Supersymmetry Breaking (GMSB) model have been chosen. Possible signatures are determined by type of the Next to Lightest Supersymmetric Particle (NLSP). Only six parameters describe the spectrum of supersymmetric particles in this model. [141–143]. The typical NLSP particles in this model are the lightest neutralino $\widetilde{\chi}^0_1$ or lighter tau lepton partner $\widetilde{\tau}_1$. In both cases, they decay into the corresponding partner of the Standard Model and gravitino that acts as the LSP. The lifetime of the NLSP is related to the gravitino mass (both depend on the same parameter(s) describing supersymmetry breaking). Possible scenarios are an almost instantaneous decay, a decay during flight through a detector of a typical size or after leaving it.

The search for new particles in the models with neutralino or slepton NLSP require a use of a detector in a way, which goes beyond the basic requirements imposed at the stage of its design [114]. Exactly this aspect of the subject have been considered to be the most interesting. We have decided to check if the muon system of the CMS detector is capable of identifying massive long-lived charged particles and whether it can be used to detect a late decay of massive uncharged particle to photon and unobservable particle. This analysis was presented [116] at the first conference *From Planck scale to electroweak scale* in Kazimierz (Poland, 1998), and then developed and described in [10] as a contribution of the CMS experiment to the conference EPS-HEP in Tampere (Finland, 1999). Summary of the work of the ATLAS and the CMS experiments on this topic I presented [144] at the conference Higgs & Supersymmetry, which took place in 2001 in Orsay, France. These initial studies are described in more detail in the presented monograph.

The next stage of the involvement of the Warsaw CMS Group in a preparation for a search for long-lived particles began with the completion of the transition form CMS detector simulation package CMSIM based on FORTRAN 77 and GEANT 3 [145] to the object-oriented package OSCAR-ORCA written in C++ and based on GEANT 4 [146, 147]. The transitional period lasted for few years, holding the possibility of a full simulation of the detector response, which was necessary for a reliable assessment of the possibilities of using CMS to search for signatures, exceeding the scope of the design. From Again, the GMSB model was used as the phenomenological base of an analysis, namely we considered two lines obtained by allowing a range of the parameter Λ values (which fixes the scale of masses of supersymmetric particles in the GMSB model) for points SPS 8 and SPS 7 proposed [148] as benchmarks for the GMSB model, for the first period of the LHC operation.

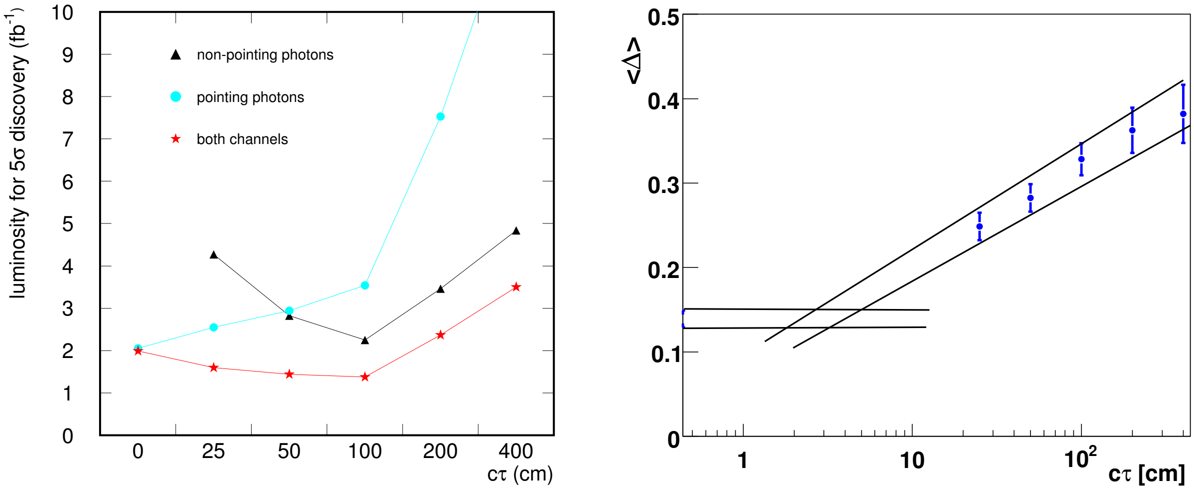


Figure 10: Illustration of a feasibility study of a search for neutralino (GMSB SPS 8 Λ=140 TeV) decaying into photon and gravitino in the CMS detector [11, 150].

On the left-hand side an integrated luminosity needed to claim discovery (at $5\,\sigma$ level) in function of the neutralino decay length $c\tau$ is shown. A result of a use of the non-pointing photon selection is shown by black triangles. The prompt photon selection performance is shown by cyan circles. The combined sensitivity of these two separate selections is shown by red stars.

On the right-hand side is shown the relationship between the average asymmetry $\langle\Delta\rangle$ and the decay length $c\tau$ of the neutralino length of neutralino is shown. The horizontal lines demonstrate the range of $\langle\Delta\rangle$ for the background.

A conclusion of the previous feasibility studies [10] was observation that for a search for neutralino decaying in flight to photon and gravitino one could relay on electromagnetic calorimeter (ECAL) alone. In the meantime, the sensitivity of a measurement of the direction of photon using ECAL was examined [149].

In our analysis [11] en estimate of the degree of photon non-pointing to the interaction point have been optimized from a point of view of detection of photons originating from a neutralino decay.

The main discriminating variable suggested by us was asymmetry Δ of the widths along principal axes of a deposit of energy recorded in a cluster of ECAL crystals.

The Main results of the study performed with full simulation of the expected background and the assessment of the significance of systematic effects are (qualitatively) presented in the Figure 10.

On the left-hand side it is shown the relationship between integrated luminosity (recorded by CMS) required to claim discovery at $5\,\sigma$ level and the neutralino decay length $c\tau$ (for neutralino mass 192 GeV/c^2 and the total supersymmetry cross section of 450 fb – model: GMSB SPS 8 Λ=140 TeV). A performance of two final selections are presented. The black triangles show the non-pointing photon selection, whereas the cyan circles the selection of photons which pass preselection criteria but do not pass the non-pointing photon selection. Using the red stars the combined result of these two separate selection is shown. As one can see the non-pointing signature outperforms the other method for $c\tau > 50$ cm (from the $c\tau = 25$ cm the horizontal axis is log-scale).

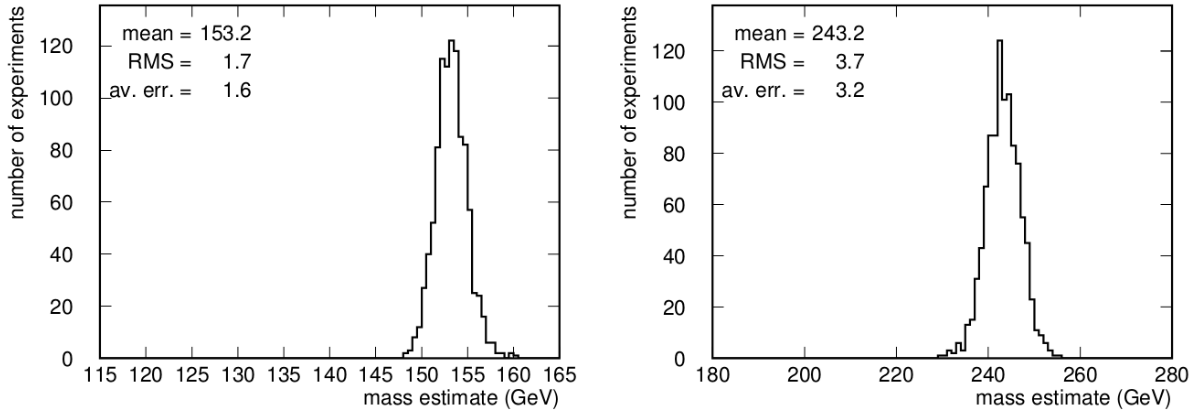


Figure 11: Distributions of the stau mass estimate obtained in a series of 1000 artificial experiments corresponding to integrated luminosity of 0.5/fb for stau mass of 152 GeV/c^2 (on the left) and 4/fb for 243 GeV/c^2 (on the right) [11].

On the right-hand side of the same figure (Fig. 10) withe a use of the blue circle with error bars an approximate linear dependence of the average asymmetry $\langle\Delta\rangle$ (for the non-pointing selection) on the logarithm of the neutralino decay length $c\tau$ (the horizontal scale is logarithmic) is shown. Horizontal lines shows the range of $\langle\Delta\rangle$ for the background. The intersection of the trend with these lines at about $c\tau = 3$ cm signify, that the neutralino decay length can be determined, with the method described in the note [11], starting at few centimeters.

In the second part of the analysis [11] we have verified a possibility of detection of long-lived sleptons. For the full simulation we have taken GMSB model with stau NLSP. Two pints form the SPS 7 line have been selected by choosing the scale parameter $\Lambda = 50(80)$ TeV. The corresponding stau mass have been $m_{\widetilde{\tau}} = 152(243)$ GeV/c^2. The choice have been dictated by limits set at colliders: LEP [151–154], HERA [155] as well as these set and predicted at Tevatron [156]. It have been assumed that stau are stable from the detector point of view. For both points cascade decays of heavier supersymmetric particles have dominated.

The events have been selected by requiring muon trigger and a presence of a pair of muons with high transverse momenta (staus are also identified as muons) and characterized by large effective transverse mass of the whole event M_{eff}. In addition the stau candidate had to be well reconstructed both in the tracker and in the muon system. The analysis have been restricted to the candidates registered by the central part of the muon spectrometer equipped with the drift tubes DT. For these candidates the $1/\beta$ have been determined (using the method described in the § 4.3.3 of the present *autoreferat*).

An important part of the work have been a determination of an accuracy with which one can determine the stau mass. For this purpose a set thousand artificial experiments have been performed by drawing number of signal and background events corresponding to the reference luminosity (for both sets of parameters of the model under consideration). Using each set of events a maximum likelihood fit have been performed determining the signal fraction in several momentum bins, the stau mass and the resolution of $1/\beta$

measurement. The results are shown in the Figure 11. On left-hand side the histogram of mass estimates is shown for generated mass 152 GeV/c^2 (and integrated luminosity 0.5/fb), whereas on the right-hand side for 243 GeV/c^2 (and 4/fb). In the Figure the average value and the RMS are given as well as an average of the mass estimate uncertainty (av.err.). The uncertainty is reported by fitting program MINUIT [157]. As one can see, the RMS of the distributions corresponds to the average accuracy estimated by MINUIT for both histograms (dispersion significantly lower than the average accuracy would indicate an insufficient total number of events used to create sets by drawing). Finally, it have been found that the mass would be determined (in GeV/c^2 units) to be $152.3 \pm 1.6\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst})$ and $243.2 \pm 3.2\,(\mathrm{stat}) \pm 1.4\,(\mathrm{syst})$, respectively.

The results of the analysis [11] were shown at SUSY07 conference [150] on behalf of the CMS experiment, along with a discussion of the corresponding analyses (only for the neutralino NLSP case) on behalf of the ATLAS experiment.

This commitment to a search for massive long-lived particles (under my leadership) resulted also in one master thesis [158] and two doctorates [159, 160].

4.4.2 New methods of searching for HSCP particles in the CMS

As realistic start date of the LHC was approaching, the theme of search for massive long-lived charged particles called HSCPs (Heavy quasi-Stable Charged Particles) in the studies of the CMS (or by many theoreticians, ChaMPs – Charged Massive Particles) was becoming more and more popular, both in terms of a development models predicting an existence of different types of such particles and in terms of a development of methods of their detection at the LHC.

The most important aspect of the search for HSCP particles in the CMS was to use specific ionization measurement in the tracker to identify them. The tracker of the CMS detector is made entirely of silicon sensors. It consists of an inner part with pixel readout (three layers) and outside part with micro-strip readout (up to dozen of layers depending on pseudo-rapidity η).

Passage of a charged particle through a single plate, as a result of ionization (and applied to the plate voltage), generates a signal in the nearest micro-strips (or pixels). A measurement of the magnitude of this signal (charge) allows to estimate particle track position with an accuracy significantly better than the distance between active sensor elements. It also allows for evaluation of the specific ionization $\mathrm{d}E/\mathrm{d}x$, the energy loss per unit length of the track in the silicon. This quantity is described by well known Bethe-Bloch formula [161], however, due to fluctuations that could be described by Landau distribution (which can not be treated as a probability density function due to the diverging integral), correct determination of $\mathrm{d}E/\mathrm{d}x$, through a number of individual measurements (signals in multiple sensors), requires to apply a systematic procedure equivalent to truncation of the largest individual measurements (or assigning to the greatest values an appropriate low weight). It turns out that a reliable result is obtained by the estimator:

$$I_{\mathrm{h}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{1}{c_i^2}}, \tag{6}$$

where N is the total number of track measurements in the individual sensors and c_i is the charge per unit path length of the i-th measurement.

This estimator allows to determine the particle mass m if its momentum p is known. For $\frac{p}{mc} = \beta\gamma$ in the range from about 0.2 to 2, $\mathrm{d}E/\mathrm{d}x$ varies as the inverse square of the velocity, which allows to estimate the mass using an approximate formula:

$$I_{\mathrm{h}} = K\frac{m^2}{p^2} + C, \tag{7}$$

where the empirical parameters $K = (2.559 \pm 0.001)\,\mathrm{MeV cm^{-1}}\,c^2$ and $C = (2.772 \pm 0.001)\,\mathrm{MeV cm^{-1}}$ were determined from data using a sample of low-momentum protons [162]. This approximate formula (7) reproduces the Bethe-Bloch formula with an accuracy of better than 1% in the range $0.4 < \beta < 0.9$ [161].

When searching for the first signs of HSCP production more important than mass determination is signal – background discrimination. For this purpose a modified version of the Smirnov–Cramer–von Mises [163, 164] discriminant was used for estimating the degree of compatibility of the observed charge measurements with those expected for particles close to the minimum of ionization:

$$I_{\mathrm{as}} = \frac{3}{J} \times \left\{\frac{1}{12J} + \sum_{i=1}^{J}\left[P_i \times \left(P_i - \frac{2i-1}{2J}\right)^2\right]\right\}, \tag{8}$$

where J is the number of track measurements in the silicon micro-strip sensors (pixel sensors are not used here), P_i is the probability for a particle close to the minimum of ionization to produce a charge smaller or equal to that of the i–th measurement for the observed path length in the detector, and the sum is over the track measurements ordered in terms of increasing P_i, whose distribution is determined experimentally.

In this way, two independent methods able to distinguishing HSCP (passing through the whole detector) from muons become available: the measurement of the specific ionization in the tracker and the measurement of the delay in the muon system (the time of flight (TOF) method).

Another important component of a preparation to a search for HSCP particles were efforts to include additional information from other subdetectors. A natural extension of the CMS detector capabilities was to take into account information from the rest of the muon system. How the PACT subsystem (based on signals from the RPC chambers) was used has already been discussed (§ 4.3.4 of the present *autoreferat*), whereas, the Cathode Strip Chambers (CSC) working as a precise muon detectors (with trigger capabilities) in the endcaps (up to pseudo-rapidity $|\eta| = 2.4$) were used to increase a geometric acceptance of the time of flight method.

A single CSC is an elongated wedge shaped chamber with shorter base facing the beam axis. Twelve or twenty four such chambers are assembled to form a single disk. In total there are four discs in each of the two CMS endcaps. A single chamber is made up of six layers. Each layer has a gas gap, radially arranged strips (cathodes - hence the name CSC) for measuring the coordinate of ϕ and anode wires (arranged transversely to the strips) which are also readout. The presence of a signal above the background on a single wire anode is checked with an effective rate of 12.5 ns, while time of an arrival of a signal received by a single cathode strip is determined on a basis of a four out of eight readings made every 50 ns (for this time estimate four successive readings starting at the one before that with the highest value are used). A typical muon track (or track of HSCP we are searching for) passes through four chamber, it means 24 CSC layers and 48 measurements of the time of flight or the delay t_i with respect to high momentum muon produced at proton-proton interaction. The value of the inverse velocity $1/\beta$ is determined as a weighted average of the individual measurements $1/\beta_i$

$$1/\beta_i = 1 + \frac{t_i \cdot \mathrm{c}}{L_i}, \tag{9}$$

where L_i is the distance from the point of interaction. The measurements differing by more than three standard deviations from the mean value are rejected. When calculating the average, the squares of ratios of the distance L_i and the precision of the measurement $(\sigma_t)_i$ are taken as weights.

4.4.3 Results of a search for HSCP particles in the CMS [13]

One of the first publications of the CMS experiment, in which a complete set of proton-proton data collected in 2012 at the energy 8 TEV (and data collected at the energy 7 TeV in 2011) is taken into account is analysis about a search for long-lived massive charged particles (HSCP) [12, 13]. Five different methods of searching for such particles (with lifetimes allowing to leave the detector before a decay) were merged into one publication. The methods used were previously described in several CMS publications, based on the subsets of currently (2013) available set of data [118, 165, 166].

Similar analyses have been published [167–171] by the competitive research team ATLAS and by teams operating at the Tevatron [172–175], and before that at the colliders LEP and HERA [151–155].

Discussed analysis is carried out in a way as independent as possible form a particular form of models predicting an existence of HSCP particles [176–178] and, thus, constraints an entire spectrum of such models. The most important distinction between different version of HSCP is its way of interacting with matter. Such particle may be neutral or charged under the strong interaction. In the first case it is called lepton-like, and in the second: hadron-like. Constraints were also found for lepton-like HSCP with electric charges different from the elementary charge [179–183].

The exemplary strongly interacting HSCP under consideration is the scalar quark stop [177] (supersymmetric partner of top quark, which may have sufficiently long lifetime in a case of very small mass difference with respect to neutralino LSP) or gluino (supersymmetric partner of gluon acting as the NLSP for example, in Split-SUSY models, in which the masses of scalar partners of fermions form Standard Model are very large) [184, 185]. It is expected that a strongly interaction HSCP hadronize immediately after the formation of the so-called R-hadron [186], which can be electrically charged or neutral. Ingredients of R-hadron interact strongly with matter, which leads to increased energy losses and possible charge exchange reactions (sign flip).

In this study two different models of the interaction of R-hadrons with the matter are used. According to the first, referred to as the cloud model [187, 188] non-interacting HSCP particle is surrounded by a cloud of colored partons. According to the second referred to as the charge-suppressed model [189] interaction with matter causes electrical neutralization of R-hadron after passing through sufficiently thick layer of matter.
In such case R-hadrons would be neutral during the flight through the muon system (after passing through calorimeters).

As the exemplary lepton-like HSCP $\tilde{\tau}$, scalar (supersymmetric) partner of the tau lepton is taken, but not only the cascade production of $\tilde{\tau}_1$ was considered, but also direct production of stau—antistau pairs. This approach allows to obtain almost model independent constraints.

The last benchmark model considered is a modified Drell–Yan production of lepton-like HSCP fermions that couple to photon and Z only via $U(1)$ coupling [190] and have fractional charges of $|Q| = 1e/3$ and $|Q| = 2e/3$ or a charges that are multiples of the elementary charge, up to $|Q| = 8\,e$

Taking into account the previous exclusion, searched particles have a mass of at least several hundred GeV/c^2. So massive particles are, to a large extent, produced at velocities significantly smaller the speed of light, and then they are significantly delayed with respect to muons and, if its charge is not fractional they have higher specific ionization $\mathrm{d}E/\mathrm{d}x$. For no very slow particles with fractional charges specific ionization may be, in turn, smaller than for conventional particles.

Given just evoked peculiarities of expected $\mathrm{d}E/\mathrm{d}x$ for different HSCP types as well as previously discussed various possibilities of R-hadrons hadronization, the following five analysis paths are used.

1) **tracker+TOF** → this analysis is the most optimal to search for single-charged lepton-like HSCP. It uses the three independent variables to distinguish HSCP particles from the background. The expected high value of the delay (due to longer time of flight – TOF) measured by the muon system, high value of $\mathrm{d}E/\mathrm{d}x$ measured by the tracker and large transverse momentum measured jointly by the muon system and the tracker.

2) **tracker-only** → analysis is dedicated to R-hadrons that arrive at the muon system as neutral. The measurements of $\mathrm{d}E/\mathrm{d}x$ and transverse momentum by tracer are used for this path.

3) **muon-only** → this analysis is conceived for R-hadrons produced as neutral. It Is complementary to the previous one. The tracker is only used to reject muon

candidates that are seen them and to reduce the background originating from cosmic muons. Tracks seen by the muon system alone with high value of the delay and large transverse momentum are selected.

4) **fractionally charged** → as the name suggests is used to search for HSCP particles of fractional charges. It is based on the search for tracks with smaller than the standard value of $\mathrm{d}E/\mathrm{d}x$. Apart from that it is very similar to the "tracker-only" path. The second variable used for the final selection is large transverse momentum (which is overestimated for fractional charge particles).

5) **multiply charged** → this last analysis path selects candidates for multiple charge HSCP particles. This is the only one in which transverse momentum measurement is not used (because it could be underestimated by large extent). It is based on the expected very high value specific ionization $\mathrm{d}E/\mathrm{d}x$. In addition, the delay measured by the muon system is used.

In all five analysis paths at least two independent variables discriminating the signal from the background are used.

In all five paths, except "muon-only", a measurement of the specific ionization $\mathrm{d}E/\mathrm{d}x$ is utilized We use discriminator I_{as} (equation 8 on page 33), except for the "fractionally charged" analysis in which a complementary discriminator I'_{as} is used, where (in the formula 8) the probabilities $P'_i = 1 - P_i$ replace probabilities P_i, because the searched for particles are expected to have lower specific ionization than those of the background.

Besides, in the first two analysis paths, the $\mathrm{d}E/\mathrm{d}x$ estimator using I_{h} (eq. 6) is used to estimate the mass of the candidate (eq. 7) and it is required that that mass is larger than an appropriately chosen threshold value (see Tab. 1).

In all analyses except "multiply charged" transverse momentum measurement is used.

In the analyzes: "tracker + TOF", "muon-only" and "multiply charged" an estimate of the inverse velocity $1/\beta$ based on the measured in the muon system delays δ_t with respect to muons (practically) moving at the speed of light.

A very important aspect of the present analysis is evaluation of the background level directly from the data. The independence of final selection variables is used for that purpose.

In any of the analysis paths no statistically significant excess of events over the expected background have been found. The largest excess (shown in Table 1) corresponds to 1.3 standard deviations. Thus began to set the upper limit on the cross section at the 95% confidence level using $\mathrm{CL_s}$ approach [191, 192] where so called *p-values* are computed with a hybrid Bayesian-frequentist technique [193] that uses a log-normal model for the nuisance parameters. These parameters are (i) integrated luminosity known with a relative accuracy of 2.2% (4.4%) for data collected at $\sqrt{s} = 7\,(8)$ TeV, (ii) the efficiency of the selection, and (iii) background estimate. The uncertainty in the theoretical cross section (which is needed to determine the lower limit on the mass from the upper limit on the observed cross section) is not considered as a nuisance parameter.

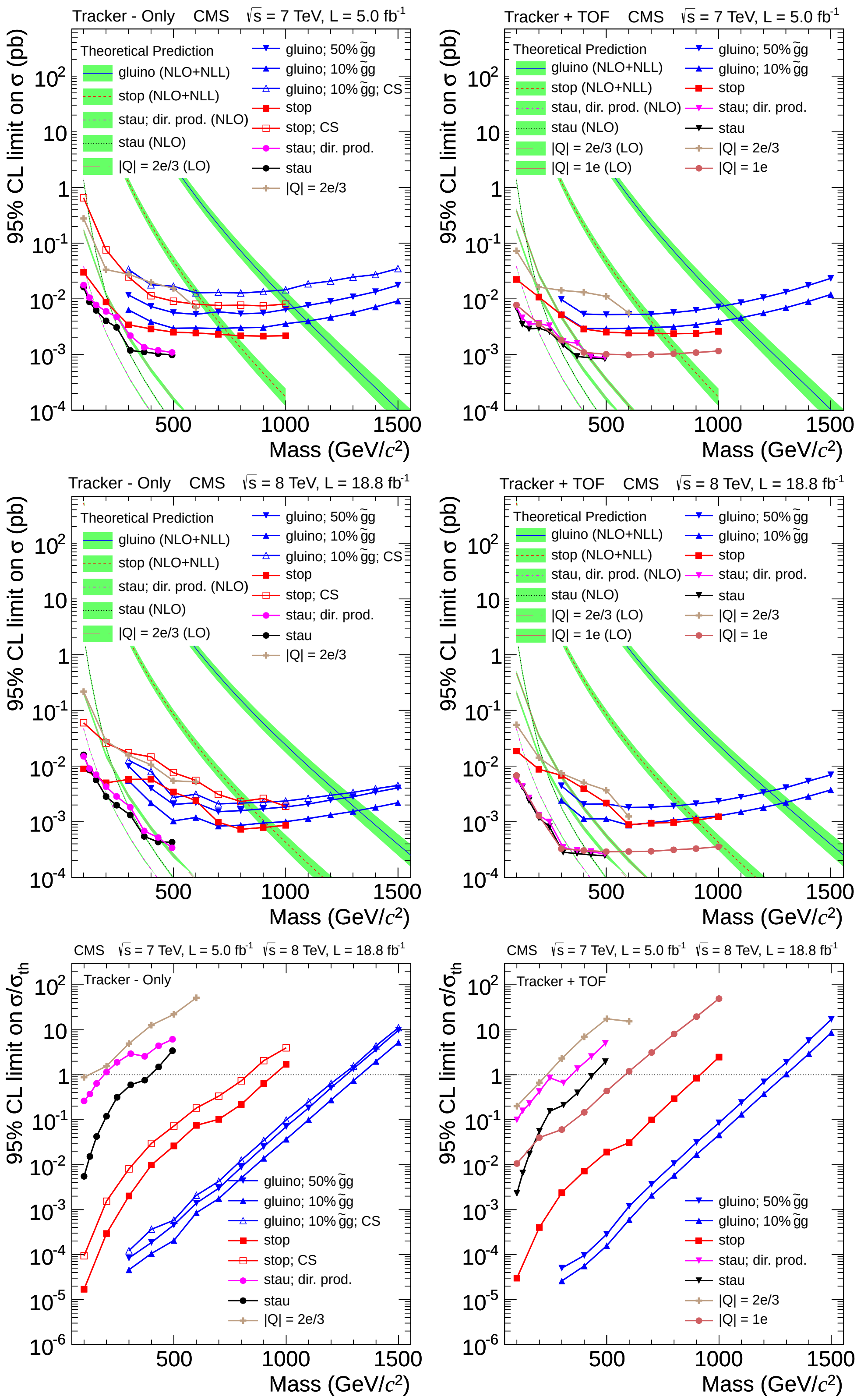


Figure 12: The top (middle) row corresponds to the analysis of data collected in 2011 (2012) at $\sqrt{s} = 7(8)$ TeV and shows the upper limit on the cross section at 95% confidence level for different models (see legend), for the analysis path "tracker-only" in the left column and the analysis path "tracker + TOF" in the right column, as a function of the mass of the searched particle. The bottom row shows the upper limit (obtained by a combination of both sets of data) of the ratio of the excluded cross section to its theoretical value, also as a function of the mass of the searched particle. [13].

Table 1: Observed and expected (in an absence of a signal) number of events after the final selection (threshold values are given in the table), for all five analysis paths. Background uncertainty estimates includes statistical and systematic contributions. The discriminator I'_{as} is used only in the “fractionally charged” path ($|Q| < 1e$), in other paths (except ”muon-only” where $\mathrm{d}E/\mathrm{d}x$ measurement is not utilized at all) the I_{as} discriminator is used [13].

analysis path	final selection criteria of the signal region				events number $\sqrt{s} = 7\,\mathrm{TeV}$		events number $\sqrt{s} = 8\,\mathrm{TeV}$	
	p_{T} [GeV/c]	$I_{\mathrm{as}}^{(\prime)}$	$1/\beta$	mass(I_{h}) [GeV/c^2]	expected	obs.	expected	obs.
tracker+TOF	> 70	> 0.125	> 1.225	> 0	8.5 ± 1.7	7	44 ± 9	42
				> 100	1.0 ± 0.2	3	5.6 ± 1.1	7
				> 200	0.11 ± 0.02	1	0.56 ± 0.11	0
				> 300	0.020 ± 0.004	0	0.090 ± 0.02	0
tracker-only	> 70	> 0.400	–	> 0	7.1 ± 1.5	8	33 ± 7	41
				> 100	6.0 ± 1.3	7	26 ± 5	29
				> 200	0.65 ± 0.14	0	3.1 ± 0.6	3
				> 300	0.11 ± 0.02	0	0.55 ± 0.11	1
				> 400	0.030 ± 0.006	0	0.15 ± 0.03	0
muon-only	> 230	–	> 1.400	–	–	–	6 ± 3	3
$\|Q\| < 1e$	> 125	> 0.275	–	–	0.12 ± 0.07	0	1.0 ± 0.2	0
$\|Q\| > 1e$	–	> 0.500	> 1.200	–	0.15 ± 0.04	0	0.52 ± 0.11	1

In the Figure 12, in the upper two rows, presented are upper limits on the cross section as a function of the mass of searched particles: gluino pairs (blue triangles and lines); stop-antistop (red squares and lines); direct production of stau-antistau pairs (magenta signs and lines); cascade production of staus in the considered GMSB model (black signs and lines); and particles with only $U(1)$ coupling and charges $|Q| = 2e/3$ (beige crosses and lines) and $|Q| = 1e$ (terracotta circles and lines – only in the right column). The left column represents the analysis path “tracker-only”, whereas, the right column the analysis path “tracker + TOF”. The top (middle) row shows constraints obtained using 2011 (2012) data.

Open blue and red symbols (only in the left column) correspond the “charge-suppressed” hadronization model of R-hadrons [189], where R-hadrons became neutral after passing sufficiently thick material layer.

The bottom row shows the upper limit (obtained by a combination of both sets of data) of the ratio of the excluded cross section to its theoretical value, also as a function of the mass of the searched particle.

Upper limits on the cross section obtained for the R-hadron are slightly more restrictive for the analysis path “tracker-only”. They are of the order of 1 fb, and weakly dependent on the mass of searched particles.

Upper limits on the cross section obtained for lepton-like particles of elementary charge practically do not depend on the model or the kind of particle or its mass (for masses above 300 GeV/c and analysis path “tracker + TOF”) and are not worse than 0.4 fb.

In the Figure 13, a comparison of lower mass limits obtained in the present analysis (red filled circles) with previously published studies is shown.

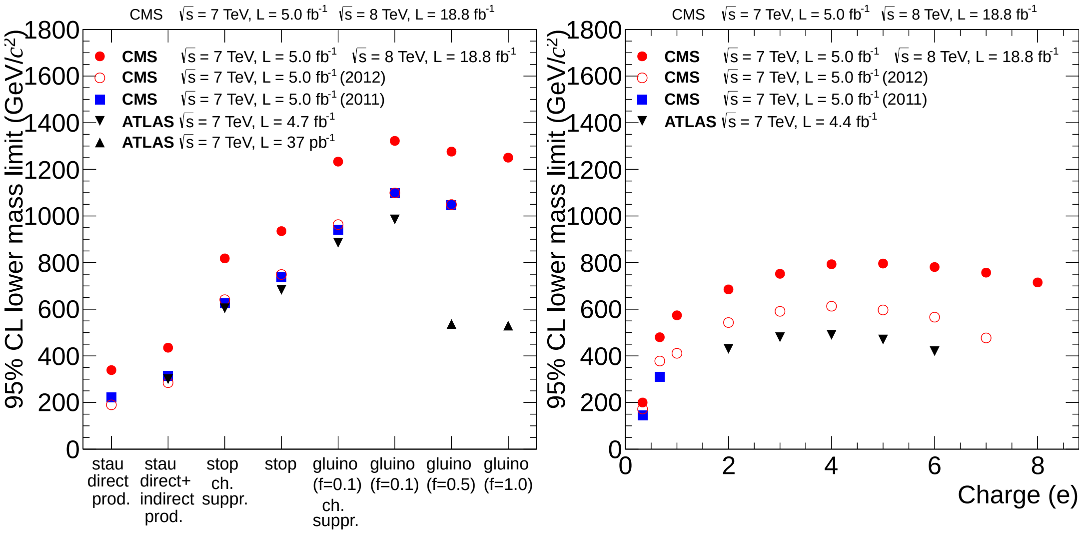


Figure 13: Lower mass limit at 95% confidence level for various models. On the left panel model types are given on the x-axis. The right panel shows the exclusion for Drell-Yan particles with charges given on the x-axis. Red filled circles correspond to the present analysis [13]. The data sets used in the previously published CMS and ATLAS analyses [118, 165–171] are given in the legends.

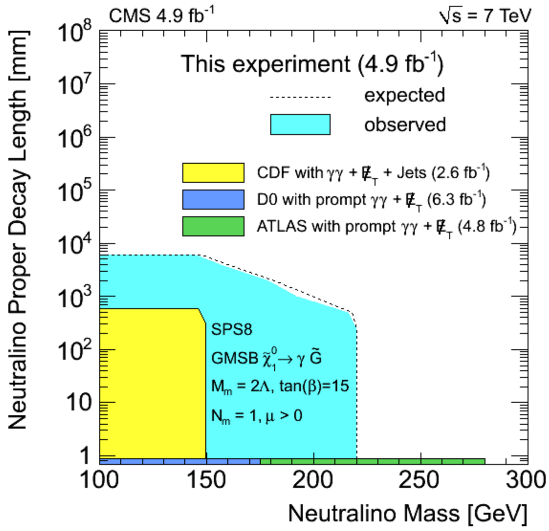
Comparison with the results of the ATLAS experiment is possible only for the data collected at the energy $\sqrt{s} = 7\,\text{TeV}$ (in 2011), since the results of the data collected in 2012 have not yet been published by this experiment (May 2013). The results of two analyses of the CMS experiment of the data collected in 2011 are shown. Red open circles correspond to the present analysis of this data, and the blue squares to previously published analysis [118]. The present results are slightly worse for stau HSCP than the results of the last year analysis [118]. The reason for that is the withdrawal from fine tuned optimization of the selection in favor of its standardization to facilitate a use of present analysis for models that were not taken as reference (benchmark) points in the present analysis.

The constraints set by the presented analysis are the most stringent when it comes to massive long-lived charged particles (HSCP) leaving detector before the decay.

4.4.4 Selected searches for long-lived particles in the CMS

Search for neutralino decaying into photon and gravitino inside the CMS detector were performed in several ways. Prompt decay was examined in a preliminary analysis [194] while in publication [195] converting photons were used. Finally, in the analysis [196], the shape of the deposit in the electromagnetic calorimeter (ECAL) and an estimate of the delay measured by ECAL were used. An aggregate limit determined in this last analysis is shown in the Figure 14 with the cyan area, whereas, the boundary of the expected exclusion with black dotted line. Limits set by other experiments are shown in various colors. Obtained constraints cover $c\tau \in (1\,\text{mm}, 600\,\text{mm})$ and neutralino mass form 100 to 240GeV/c^2.

Figure 14: Constraints on the plane (mass,$c\tau$), for neutralino from GMSB model (SPS 8), decaying into photon and gravitino, obtained in the analysis [196] of the CMS experiment.



A complementing to the search for massive long-lived charged particles (HSCP) flying through the detector without decay, is a search HSCP stopping and decaying in the CMS detector [197]. The stopping efficiency depends on the interaction of the particles with matter. Since it is expected that R-hadrons lose their energy faster than other HSCP particles and as the cross sections for producing R-hadrons are greater than the production of other HSCP, the analysis was limited to a search for R-hadrons. R-hadrons that stop in the detector are these with the lowest kinetic energies.

The expected signal is an energy deposit appearing in the calorimeter at a time when there was no beam crossing in the detector. The most important types of background are muons from the beam halo (a result of the interaction of a halo of the proton beam with matter around the accelerator), cosmic muons (in both cases, the muon induced electromagnetic cascade are the source of background) and instrumental background. Muons from the halo was removed, by vetoing events in which any signal was detected in the muon system. Instrumental background was carefully removed and evaluated by appropriate procedures. For evaluation of background originating from cosmic muons the data at a lower instantaneous luminosity were used. Since no signal were found over the expected background, the limits on the cross section and the mass of searched particles in function of their lifetime were set. Obtained restrictions are shown in the left panel of the Figure15. Continuous red curve corresponds to gluino exclusion, and the dotted blue to stop exclusion. one can see that the range constant effectiveness of the exclusion covers the lifetimes from a few microseconds to dozens of minutes (nine orders of magnitude).

On the right panel of the Figure 15 a mutual complementarity of this method and the search for flying through the detector R-hadrons is shown. Black histogram shows a velocity distribution of R-hadrons containing gluino with mass 600 GeV$/c^2$ (scale on the vertical axis is arbitrary). The blue histogram shows the fraction of R-hadron accepted by selection stopped in the detector HSCP, whereas, the green histogram a fraction accepted by the selection of HSCP flying through the detector without stopping and without decay.

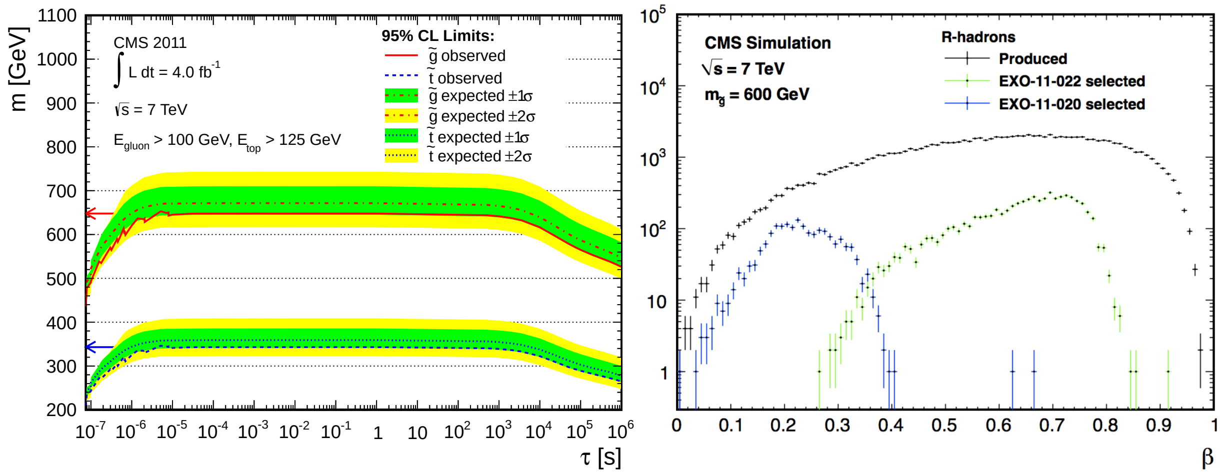


Figure 15: Illustration of the search for R-hadrons, stopping in the CMS detector [197].

On the left-hand side a lower limits on the gluino mass (red lines) and the stop mass (blue lines), in function of a lifetime of these particles are shown.

On the right-hand side an illustration of the synergy between CMS analyses (both made using the data from 2011): "stopping HSCP" [197] (blue points) and "flying through HSCP" [118] (green points). The black points shows the shape of the velocity distribution of simulated (600 GeV/c^2) gluino, whereas, the colored points shows the same distribution after corresponding final selections.

4.4.5 Summary of the author contribution to long-lived particle searches

The first study concerning a feasibility of a search for charged or neutral NLSP decaying to gravitino and corresponding SM partner using CMS detector was done under my leadership before the year 2000 [10]. This work has been never published in a peer-reviewed journal, but its results were shown for several years at the conferences by other members of the CMS collaboration. The work was also cited (e.g. in the monograph [177]).

The next step was to conduct a full analysis of the visibility of models with $\tilde{\chi}_1^0$ NLSP or $\tilde{\tau}$ NLSP [11]. This work was published, according to the rules endorsed by the CMS collaboration, as *CMS Analysis Note*. The analysis, in order to obtain this status, had to go through very restrictive procedure of its approval. It was presented by me at the SUSY07 conference [150].

As a realistic launch date of the LHC was approaching both the number of models predicting massive long-lived particles as well as ways of searching for them, were grow quickly I decided to focus the work of leaded by me sub-team (of the Warsaw CMS Group) on scenarios with massive long-lived charged particles (HSCP). Models with neutralino NLSP become the domain of teams involved in construction of the CMS electromagnetic calorimeter ECAL. But my team has played an important rôle in the development of method of measuring the time of flight of photons by the calorimeter ECAL via direct cooperation with the *Laboratoire Leprince Ringuet* (Palaiseau, France) under Polish-French cooperation *COPIN*, which was coordinated by me in the years 2009-2012 (in this respect, and from the Polish side).

Leaded by my team is, above all, involved in the search for massive long-lived charged particles (HSCP)[10] under the NCN grant number N N202 167 440, for which I am responsible.

The results have been presented on regular basis at international conferences by me [198, 199] and other participant of the grant I am responsible for.

4.5 Summary

Presented monograph describes some aspects of the search for new particles in experiments at LEP and LHC. Selected were those to which the author contributed in significant way. Namely, the search for the Higgs boson predicted, in particular, by extensions of the Standard Model and a search for massive long-lived particles.

In the first Chapter of the monograph (§ 4.2 of the present *autoreferat*) presented the last several years of searching for new BEH particle sector. From the history of the undiscovered Higgs boson in the LEP 2, passing by the use of the data collected by experiments at LEP for a search for Higgs bosons in the, so called, extended models, to the discovery of a new particle with a mass of about $125\,\mathrm{GeV}/c^2$ by the ATLAS and the CMS experiments at the LHC and finding of an indication of existence of such particle in the data taken by the CDF and the D0 experiments operating at the Tevatron (until its decommissioning in 2011). The author had a part in this quest as an active participant of the DELPHI experiment at the LEP and the CMS experiment at the LHC, with a particularly significant contribution in a search for Higgs bosons within the extended models using data collected by the DELPHI experiment.

The second and the third Chapters of the monograph describe issues related to the search for massive long-lived particles with the CMS detector. In the second chapter (§ 4.3 of the present *autoreferat*) author's contribution the PACT muon trigger system of the CMS detector is presented and invented by the author method of measuring the inverse velocity of massive long-lived charged particles by measuring the delay in the Drift Tubes of the CMS detector. The third chapter (§ 4.4 of the present *autoreferat*) discusses the evolution of interest of the CMS research team in scenarios with massive long-lived particles. The author was a pioneer of to this subject in the CMS and have been contributing to it significantly. The Chapter ends with a summary of results obtained in this field.

The last Chapter of the monograph shows a wider view of the discussed subject. A majority of results obtained by the ATLAS and the CMS experiments during a search for BSM phenomena is presented in a tabular way. Then a sample of characteristic, in author's opinion, analyses of the CMS experiment are discussed in more detail. In the second part of this Chapter, on the basis of selected phenomenological publications (not co-authored by the author of the monograph) it is argued, that one of the most important questions, that can be answered by an analyse of data to be collected by experiments at the LHC, is the nature of the dark matter. At the same time, if the dark

[10] The most recent analysis is published as [13]

matter consists in substantial part of weakly interacting massive particles (WIMPs) the LHC may be supplemented or even surpassed by the next generation of experiments aimed at direct or indirect detection of such particles. These experiments are to become operational in the next few years. However, if the dark matter consists of super-weakly interacting massive particles (SWIMPs), like gravitino, only the LHC has a chance to make a discovery by observing massive (possibly long-lived) particles decaying to the dark matter particles (inside or outside detectors). Unfortunately, there is no any guarantee. Searched particles can be unexisting or be too massive to be produced. In the Chapter the importance of the discovery of the Higgs boson with a mass of about $125\,\mathrm{GeV}/c^2$ in restricting a freedom of choice of parameters to models extending the Standard Model is also underlined. The contribution of the author to the subject covered in the last chapter is, above all, a frequent presentation of results on behalf of the CMS experiment at international conferences [198–204] and developing methods for interpreting the results within models in which the that dark consist of SWIMP particles under his NCN grant N N202 167440.

The results in the monograph are as of May 2013, they reflects the situation after the *Moriond 2013* conferences, without taking into account analyzes prepared for the summer conference in 2013.

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