SCREAM: Sampling Calorimetry with REsistive Anode Micromegas

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Abstract

The goal of the project is to develop an imaging gaseous calorimeter for jet spectroscopy at a future linear collider and a the high luminosity large hadron collider (LHC). The intrinsically fast and high dynamic range response of the Micromegas detector makes it an excellent candidate to meet the challenges posed by the environment at both colliders. Given its high rate capability, excellent ageing property and calibration stability, a Micromegas based calorimeter is likely to outperform current prototypes optimised for the reconstruction of jets by the Particle Flow method. The proposed calorimeter is a 1.5 m deep sandwich of 50 dense material plates and thin Micromegas chambers of $50 \times 50\,\mathrm{cm}^2$ transversal size. With dedicated front-end electronics, this prototype will measure the energy of electrons and hadrons up to 100 GeV. It will provide crucial inputs to the design of calorimeter systems optimised for Higgs boson study at current and future particle physics experiments.

Contents

1 Scientific and technological goals

1.1 Higgs boson study in e^+e^- and pp collisions

The detailed study of the electroweak symmetry breaking mecanism and of the properties of the Higgs boson are some of the physics goals motivating the construction of a linear electron positron collider (ILC or CLIC). This physics case is now enhanced with the discovery by the ATLAS and CMS experiments at LHC of a new particle compatible with the Standard Model (SM) Higgs boson. At a 500 GeV linear collider, the production cross-section of a SM Higgs boson is only two orders of magnitude smaller than that of the background (light quark pair production and beamstrahlung). Therefore no trigger is necessary and all physics events are recorded. This makes this machine a powerful tool to measure the couplings of the Higgs boson to fermions, vector bosons and to itself with unprecedented precision. The production cross-section, however, is small. At $\mathcal{L} = 5 \times 10^{34}$ /cm^2/s, one Higgs per hour will be produced and all final states (mostly hadronic) should be measured. This calls for excellent jet energy resolution and a new approach to calorimetry called the Particle Flow Approach (PFA). Its merits are evaluated by the CALICE collaboration by means of simulation, detector R&D and testbeams.

In pp collisions at LHC, triggering is the key to dig out rare signals among overwelhming backgrounds and one focuses on easy-to-identify signatures (*e.g.* leptons, photons). The production of a Higgs boson by vector boson fusion (so-called VBF) yields a clear signature and is the second dominant channel for Higgs production ($\sim 20\,\%$ of $\sigma_{\rm tot}$). The two vector bosons are radiated off valence quarks that fragment into two jets emitted in the forward and backward directions (VBF quarks peak at $\eta = \pm 3$). This signature proves particularly useful to reject QCD backgrounds caracterised by jets at central rapidities. The ability to tag VBF-Higgs events relies on the performance of the forward calorimetry. During the 2014–2017 LHC run, the increase of the luminosity (and consequently of pile-up) will push the forward calorimeter performance to its limit. The CMS collaboration has thus established a roadmap for upgrading the forward calorimeters. Different options are considered among which a Particle Flow calorimeter. The final decision will be motivated in a Technical Design Report by the end of 2016 and a new forward calorimeter system should be installed in CMS during the 2017 shutdown.

1.2 Micromegas for particle flow calorimetry

Advances in the fabrication techniques of large size Micromegas triggered a few years ago a strong interest in using this detector for sampling calorimetry. Indeed Micromegas fulfills some basics desirable features for measuring the energy of particles by total absorption. Firstly, its ouput is strickly proportional to the energy deposited in the gas medium up to the breakdown limit (*i.e.* $\sim 10^4$ times the energy deposited by a minimum ionising particle). In addition, a signal uniformity better than a few percent is guaranted over areas of several m^2. Besides linearity and spatial uniformity, the rate capability of Micromegas surpasses by far the performance of traditional gaseous detectors. With a careful detector design, proton fluxes up to 10^9 mm^2/s can be sustained before saturation effects from the ionic space charge become significant. Micromegas has initially been studied for calorimetry at a future linear collider where the radiation environment is benign. Its unique rate capability, however, opens the way to applications in much more severe environments such as in the forward regions of CMS ($3 \leq |\eta| \leq 5$).

The Micromegas calorimeter described in this proposal is intended for the reconstruction of jets by a Particle Flow algorithm. The latter aims at reconstructing all particles in an event by combining the information from all sub-detectors (precise tracker and highly granular calorimeters). It is largely recognized as the most promising solution to achieve excellent di-jet mass resolution and therefore drives the design of calorimeter and tracking systems at future linear colliders. The CMS detector is not optimised for Particle Flow but this method improves its performance to jets, taus and $E_{\mathrm{T}}^{\mathrm{miss}}$ up to $|\eta| \sim 2.5$. From 2018 and beyond, an upgrade of the forward regions is foreseen with possibly a Particle Flow calorimeter.

Large size Micromegas chambers ($1 \times 1\,\mathrm{m}^2$) have been studied in the context of calorimetry at a linear collider by the LAPP detector R&D group. Recently, the CMS forward upgrade working group identified this technology as strongly relevant to the foreseen upgrade. The construction of a Micromegas calorimeter prototype could therefore benefit to both LC and LHC communities. This proposal is meant to build it. Main design constraints and technological goals are summarised in the next two sections. Emphasis is put on the improvements with respect to existing Particle Flow calorimeter prototypes.

1.3 Goals at a linear collider

Calorimeter design at a linear collider is driven by the need for high granularity. Technical requirements are well identified: self-triggered front-end electronics embedded inside the active layers to allow for high lateral and longitudinal segmentation. In addition, ASICs should be powered synchronously to the accelerator clock so heat dissipation is minimal and no active cooling is required. Four $1 \times 1\,\mathrm{m}^2$ Micromegas prototypes with 2-bit (or semi-digital) electronics have been constructed at LAPP and inserted inside the CALICE SDHCAL steel absorber structure. Testbeam results demonstrate that these technical requirements are fulfilled. More interestingly, they indicate that the hadron response of a 50 layers digital calorimeter becomes highly non-linear above 30 GeV. Non-linearities arise from the finite size of the readout cells ($1 \times 1\,\mathrm{cm}^2$) and the counting (or digital) approach. They are manageable in an ILC-like steel calorimeter using information from additional thresholds but are expected to become prohibitively large when measuring showers of high energy density (tungsten absorbers with smaller x_0 and R_{M}, electrons, photons) or of high energy (≥ 100 GeV). In such problematic cases, a full analogue readout is the only way to restore linearity and improve resolution.

1.4 Goals at a high luminosity LHC

At the luminosity foreseen in 2018 and beyond, the expected particle flux in the forward calorimeters of CMS is $\sim 10^6/\mathrm{s}/\mathrm{cm}^2$. In order to disentangle complex physics events from large backgrounds, high segmentation, precise timestamping and fast triggering capability of the calorimeters will be mandatory. In these respects, a Particle Flow calorimeter is appealing. Still, requirements for the sampling detectors are stringent. Stable performance in a high radiation environment should be guaranted for several years of operation, limiting the choice to radiation hard detectors with excellent aging properties. A Particle Flow calorimeter offers potentially very high triggering capability. Information based on the fine longitudinal segmentation can be exploited to tag specific event topologies. Still, this is very challenging as information from selected layers should be processed at the front-end level extremely fast.

2 Relevance and strategical features

2.1 Proposed prototype

The LAPP linear collider detector group benefited twice from ANR funds through the DHCAL and SPLAM projects. The DHCAL funds were invested in the construction of four $1 \times 1\,\mathrm{m}^2$ Micromegas prototypes. Segmented into $1 \times 1\,\mathrm{cm}^2$ cells, they fulfill most of the technical requirements for a linear collider. Monte Carlo simulation were also conducted to assess the performance of a Micromegas hadron calorimeter. In the framework of the SPLAM project, resistive protections against gas discharges were successfully implemented on prototypes of intermediate size ($16 \times 16\,\mathrm{cm}^2$). Part of the results obtained with the large chambers have already been published in reference journals and additional papers will be submitted by the end of 2013.

The next step of the project is naturally the construction of a calorimeter with resistive Micromegas chambers. In order to contain hadronic cascades, this instrument should mainly be deep. Indeed, 95 % of the energy of a 100 GeV hadron shower is on average contained inside a cylinder of $1.5\,\lambda_{\mathrm{int}}$ radius and $8\ \lambda_{\mathrm{int}}$ height. With steel aborbers ($\lambda_{\mathrm{int}} = 16.7\,\mathrm{cm}$), this translates into a diameter and height of 50 cm and 134 cm respectively. With a fine sampling frequency of $0.15\,\lambda_{\mathrm{int}}/$ layer, the required number of layers is 55. Thanks to the longitudinal segmentation, only hadrons showering early in the calorimeters can be studied and 50 layers should be sufficient to study hadron showers up to $\sim 100\,\mathrm{GeV}$. At higher energies, leakage at the rear of the calorimeter will impact on the energy resolution. The proposed calorimeter is a 1.5 m deep sandwich of 50 dense material plates and thin Micromegas detectors of $\sim 50 \times 50\,\mathrm{cm}^2$ transversal size.

2.2 Expected performance

Expected performance of a Micromegas calorimeter relies on a Monte Carlo model that was tuned to reproduced the available testbeam data (response to muons, electrons and pions). With a simple energy reconstruction method, the expected energy resolution for electrons (in an Ar/W ECAL) and hadrons (in an Ar/Fe HCAL) in the case of a perfect analogue readout are: $30\,\% / \sqrt{E}$ and $85\,\% / \sqrt{E}$ over an energy range of 5–70 GeV. These figures are upper limits on what can be achieved as more sophisticated algorithms reduce fluctuations. For instance, tagging cells with signals above a given high threshold as electromagnetic deposits, the hadronic resolution already improves to $55\,\% / \sqrt{E}$ after applying proper weights. This is competitive with the measured performance of existing CALICE hadronic calorimeters: $45\,\% / \sqrt{E}$ (scintillator/steel with SiPM and analogue readout) and $75\,\% / \sqrt{E}$ (RPC/steel with 2-bit readout). Eventually, these numbers should be compared to what is necessary for Particle Flow to work: $20\,\% / \sqrt{E}$ and $60\,\% / \sqrt{E}$ for electrons and hadrons. Therefore, the single particle resolution of a Micromegas calorimeter should be good enough for the targeted application. The main advantage of Micromegas rather lies in the calibration simplicity (compared to a scintillator with SiPM readout), the absence of ionic space charge in the gas (compared to RPCs) and its unique capability to cope with very high particle flux.

2.3 Cost

The compact transversal size of the proposed prototype will keep the costs low. Moreover, the R&D necessary to build a 50 layer Micromegas calorimeter prototype is basically complete. The manufacturing technique of the mesh is well in hand and the current PCB design is easily scalable to the desired size ($48 \times 48\,\mathrm{cm}^2$). The acquisition system (readout boards and FPGA firmware, software) have been developed and proved reliable during several testbeams of the RPC-SDHCAL prototype ($\sim 1/2$ million channels) in 2012. More than half of the cost of the project will be devoted to the addition of an ADC to each channel of the existing MICROROC chip and to the production of 1800 units of this new chip. This modification should be light considering that MICROROC has been horoughly characterised (on testboard and on detector) and that the ADC circuit already functions in different chips. The new chip will have the same packaging and pinout as MICROROC and thus will be readily compatible with the current PCB design. Test material and procedures can also be re-used. For these reasons, the cost of a fully equipped prototype should be of the order of 265 k€. This is relatively cheap regarding the physics potential of this instrument.

2.4 Timescale

The timescale of the project is short (two years). It accounts for prototyping of single units, construction of 50 units and detailed characterisation of the calorimeter prototype at CERN testbeam and irradiation facilities. Single unit prototyping (enlargment of PCB size, resistive film optimisation) is expected to start late 2014 on individual ressources of the consortium partners. The construction phase would begin in spring 2015 if ANR funds are granted and once the new ASICs are produced and tested. A first testbeam could be conducted by the end of 2015 with possibly a reduced number of layers. The year 2016 would be dedicated to a complete test program to assess all relevant performance. This timescale is short but realistic thanks to the limited R&D required. It allows to provide crucial inputs to the CMS Technical Design Report (for the phase 2 ugrade) expected by the end of 2016. The fate of a future linear collider could be decided in the next coming years. Meanwhile, the opportunity to bring the Micromegas calorimeter project to maturity and to promote it above concurrent projects should not be missed.

3 Consortium description

The consortium consists of six partners from France, Greece, the United State of America and Israel. The partners are listed below and their respective contribution summarised hereafter.

- CNRS/IN2P3/Laboratoire d'Annecy-le-Vieux de physique des particules, Annecy-le-Vieux, France: M. Chefdeville (coordinator), Y. Karyotakis, I. Koletsou;

- CNRS/IN2P3/Omega, Palaiseau, France: C. de la Taille, N. Seguin-Moreau
- CEA/Institut de recherche sur les lois fondamentales de l'Univers, Gif sur Yvette, France: D. Attié, M. Besançon, Sergey Ganjour, M. Titov;
- NCSR/Institute for Nuclear and Particle Physics, Demokritos, Greece: G. Anagnostou, G. Daskalakis, T. Geralis;
- University of Minnesota, School of Physics and Astronomy, Minneapolis, United State of America: R. Rusack;
- Weizmann Institute of Science, Department of Physics and Astrophysics, Rehovot, Israel: S. Bressler.

CNRS/IN2P3/LAPP Will be in charge of designing and producing 50 ASIC and readout boards and of the assembly of the 50 Micromegas chambers.

CNRS/IN2P3/Omega Will be in charge of designing, producing and testing the front-end ASIC, 1800 units will be needed to fully equip the calorimeter.

CEA/IRFU Will be in charge of the manufacturing of the resistive layer and Micromegas mesh onto the 50 ASIC boards and of the subsequent quality checks.

NCRS/INPP Will be in charge of the optimisation of the resistive layer for full discharge protection and operation at high efficiency up to very high rates.

UMN/SPA Will be in charge of the testbeam infrastructures at CERN in the CMS beam line and of the optimisation of the gas mixture for HL-LHC conditions.

WIS/DPA Will be in charge of providing 10 THGEM-based active layers for the tail catcher of the Micromegas calorimeter prototype.