# Imaging of Vector Boson Scattering and Fusion with Radiation Hard and High Granularity Calorimeters in CMS

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After the historical discovery of a Higgs boson at the Large Hadron Collider (LHC) in 2012, studies of vector boson scattering and vector boson fusion have received increased attention within the experimental and the theoretical particle physics communities. These processes are characterized by a quark scattering with another quark via a space-like exchange of electroweak gauge bosons: W, Z, or photons. If a single Higgs is produced the process is referred to as vector boson fusion (VBF) while the emission of two electroweak bosons is classified as a vector boson scattering (VBS) process.

The exploration of the vector boson scattering and fusion offers promising avenues to investigate the mechanism of electroweak symmetry breaking and to search for new phenomena. In the absence of a Higgs boson, the vector boson scattering cross section increases as the center of mass energy increases resulting in violation of unitarity. A precision measurement of its cross section will therefore test whether or not the discovered Higgs boson is the particle stabilizing the unitarity and will probe for phenomena like delayed unitarity which possibly hide new physics at scales unreachable by direct searches. VBS also tests the $SU(2)_L \times U(1)_Y$ gauge symmetry governing the vector boson self-couplings and thus enables a quest for the existence of anomalous quartic gauge couplings.

If new physics is realized at lower energy scales, new particles can be produced directly at the LHC. Several theories for physics beyond the standard model, including supersymmetry, low scale seesaw scenarios with heavy neutrinos, dark matter models predict the production of new states via vector boson fusion. The VBS and VBF processes share a peculiar experimental characteristic: the production of two final-state quarks reconstructed as narrow jets in the forward regions of the detector. Enabling the LHC experiments to efficiently detect the forward jets and to discriminate VBS and VBF signals from the background will advance our knowledge of the standard model and push the boundaries in the search for new phenomena.

The PI proposes to develop precision measurements and searches for new physics using the VBS and VBF processes, and study the extension of the CMS detector to increase the acceptance for these processes in the High Luminosity LHC era (HL-LHC, 2026-2038). The analyses will be carried out in the proton-proton collision data collected by the CMS experiment during the LHC Run2 (2015-2018, 160/fb) and Run3 (2021-2023, ~150/fb expected). These analyses will set the foundations for the program at the HL-LHC during which the machine is expected to deliver 3000/fb.

**Precision measurements of the Vector Boson Scattering Cross Sections and Searches for Supersymmetry**

This program focuses on two complementary approaches to search for new phenomena: precision measurements of the vector boson scattering cross sections and direct searches for the production of supersymmetric particles via VBF production. The PI plans to support one research assistant dedicated to the VBS precision measurements and a second one invested in searches for SUSY. Both research assistants will establish the analyses using the data collected during Run2 and further optimize it during Run3.

VBS measurements are currently carried out by the ATLAS [1,2,3,4,5] and CMS [6,7,8] collaborations in the clean final states with two or three leptons from the decay of two same-charge W bosons and W/Z bosons. An extension of the analysis to include the fully hadronic decays of the gauge bosons will open up unexplored regions of phase and parameter space. This novel analysis presents exciting challenges, both on the theory side and on the experimental one. Several standard model processes and most noticeably the so-called pileup (additional proton-proton interactions occurring in the bunch crossing of the VBS process) represent a significant source of background. Jet identification techniques exploiting the use of jet substructure information are therefore essential tools to achieve optimal signal to background discrimination. This program includes the development of advanced techniques for jet tagging that will enable the CMS experiment to efficiently identify high momentum W and Z bosons decaying into jets and to efficiently discriminate a quark-jet from the primary interaction against a quark- or gluon-jet from pileup.

The search for the direct production of supersymmetric particles focuses on the search for higgsinos produced via VBF. Arguments based on naturalness and unification motivate the higgsinos to be the lightest SUSY particles with a mass close to the Higgs boson mass. Despite being relatively light, higgsinos may be hiding in the data collected so far because their very low momentum daughter particles are reconstructed with low efficiency. Several searches have been initiated by the CMS [9] and ATLAS [10] collaborations that just recently surpassed the sensitivity reached by the LEP experiments. Extending the search to the VBF production will provide enhanced sensitivity thanks to the forward jets uniquely characterizing the signal. The program will support a search for the pair production of higgsinos produced via VBF in final states with and without leptons, benefitting from the development of the jet tagging algorithms carried out in the context of the VBS precision measurements.

**Design of radiation hard silicon sensors and design of a highly granular calorimeter for the forward region in CMS**

This program includes two distinct yet related components: the design of radiation hard silicon sensors and the design of a highly granular calorimeter to instrument the forward region (3<|eta|<5) of the CMS detector. The PI plans to supervise the research assistants listed above in these research areas as well.

The CMS Collaboration plans to upgrade the end cap calorimeter (1.5<|eta|<3.0) with an innovative silicon-sensor-based High Granularity Calorimeter (HGCal) in preparation for the HL-LHC. The new calorimeter will significantly improve the forward jet tagging capability of CMS thanks to its high granularity and timing measurement. The large number of channels (6M) of 0.5-1$cm^2$ in size will provide a unique imaging capability of showers for the particle flow reconstruction algorithms.

The novel technology of the HGCal detector could be also exploited to upgrade the Hadronic Forward (HF) detector of CMS that covers the 3<|eta|<5 range. Currently the spatial and energy resolutions of the HF detector are not sufficient to support the tagging of jets from VBS/VBF processes. The distribution of these jets peaks in the 3<|eta|<4 range. This presents a strong motivation for augmenting the current HF detector by installing new HGCal like layers of silicon detector in front of it. This would not only improve the spatial and energy resolution in the forward region but also introduce the capability of providing a timing measurement of the jets and therefore help their association to the correct interaction vertex despite the lack of tracking information. The radiation tolerance of the current HGCal sensors would allow a coverage up to |eta| of 4, but a successful improvement of the radiation hardness could enable the coverage even further.

The PI is proposing to work on the development of a silicon sensor design that would withstand higher radiation levels. Prototype sensors would be irradiated at the Irradiation Test Area and tested at the Test Beam Facility of Fermilab. The PI played a key role in the design of the current HGCal sensors and established their testing procedures and the proposed work would be a natural continuation of his efforts. Radiation hard silicon calorimeters are also important for the development of the field in preparation for the next generation of future colliders where radiation levels are expected to be two orders of magnitude higher.

Currently, the PI with the help of a team of engineers and a research assistant at Fermilab plays a leading role in the mechanical and cooling design of the HGCal detector and setting up the assembly site at the Silicon Detectors Facility of Fermilab. The PI proposes to continue to work with his team to prepare the design for the extension of the HF detector with the HGCal like active layers. The research assistants working on the VBS/VBF measurements and searches will contribute to the optimization of the layout from the physics performance point of view. The physics case for the new detector as well as the design will be documented in a technical proposal and serve as a motivation for an up-scope of the HL-LHC CMS Upgrade project. The feasibility of this up-scope is strong due to the large overlap with the currently approved HGCal subproject, reusing most of its design elements. The total core cost of the proposed HF upgrade is estimated to be in the $5-7M range and it is not part of this proposal.

**Principal investigator's recent collaborators and advisors:**

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