DETAILED RESEARCH EXPERIENCE

I have worked on many different but related projects throughout my research career. In the CMS collaboration, the group/team which provides the objects such as, electrons, muons, jets, hadronic taus etc is called a Physics Object Group (POG) and the group coordinating the analyses is called a Physics Analysis Group (PAG). The POG and PAG are lead by usually two physicists who are expert in the subject, called conveners. I have worked with many different physics objects and physics analysis groups. Here is the summary of my research experience:

Physics Analysis

Search for Dark Matter candidate I proposed an interesting search for the dark matter produced in association with Higgs boson (mono-Higgs) and lead all the publications including mono-H$\rightarrow$ bb final state. I am **principle analyst and coordinator** for dark matter in mono-Higgs ($\rightarrow$ bb) final state. **[2015-Now]**. I have developed the analysis framework starting from MINIAOD including analysis strategy, statistical analysis, and interpretation of results for the mono-Higgs ($\rightarrow$ bb) final state when the Higgs boson is Lorentz boosted and decays in into a pair of b-jets close to each other. I have continuously worked towards bringing new ideas and improving the analysis using new techniques which has resulted in the present shape of the analysis.

- I have performed the first statistical combination of mono-Higgs analyses result in $\rightarrow$ bb and $\rightarrow \gamma\gamma$ decay channels using 2.3 fb^{-1} of pp collision data. **JHEP 10 (2017) 180**.
- I have developed novel techniques to reconstruct and tag the Lorentz boosted Higgs boson ($\rightarrow$ bb) and performed the analysis with $\approx$15x more data collected at CMS. **Eur. Phys. J. C 79 (2019) 280**, **JHEP 11 (2018) 172**.
- I later performed the first statistical combination of mono-Higgs analyses in five decay channels, namely, bb, $\gamma\gamma$, $\tau\tau$, ZZ, WW. **JHEP 03 (2020) 025**. This was very complex analysis due to analysis performed by different teams and many correlated nuisances to deal with.
- Given the huge amount of data to anlyze and new analysis softwares and techniques are available. I have recently developed the analysis framework using NANOAOD framework which will be new norm in near future. The analysis is now performed in fully parallel and columnar manner using new tools like awkward1 arrays, uproot4, and more general python tools like pandas and matplotlib for cleaning and visualisation.
- The fore mentioned developments are now being used to perform the full Run 2 version of the analysis of mono-Higgs. In order to add interpretation which predicts low and medium Lorentz boost for the Higgs boson a new category is being worked out, where Higgs boson can be reconstructed two jets. I have already demonstrated that resolved category captures the lost signal w.r.t analysis with merged boosted Higgs boson alone. Performed the statistical combination of low and high Lorentz boosted Higgs boson categories to gain sensitivity for the full CMS Run-2 analysis. (In progress).
- The resolved category added to the mono-Higgs can be tweaked to search the dark matter produced in association with non-resonant pair of bottom quarks. I have developed the analysis strategy and tools for the same. The analysis is advance stage and planed for Moriond 2021 or soon after. (In progress).

Search for Heavy Resonances Another related area of interest is to search for new heavy resonances which are signature of physics beyond the SM. I consider the final states when a heavy resonance decays into a pair of Higgs bosons (HH) or a Higgs boson in association with a aweak vector boson (VH).

- Developed the strategy for the signal event (HH$\rightarrow$4b) selection and optimised it for better signal significance. **Phys. Lett. B 781 (2018) 244**
- Member of the team optimising the signal (VH$\rightarrow ll, \nu\nu + bb$) selection and performing the cross-check as a parallel analysis. **Phys. Lett. B 768 (2017) 137**

Search for Higgs boson The research work accomplished during my PhD was the search for the Higgs boson in ZZ $\rightarrow 2l2\tau$ final states. The analysis itself consisted of 8 decay modes. The huge background and many decay modes made it one of the most complex analyses.

- Performed the feasibility study and developed the trigger strategy.
- Developed independent tools for event selection, optimisation and statistical analysis.
- The improvements made in the hadronic tau reconstruction directly used in the analysis to improve the significance.
- The analysis was published multiple time independently and as a part of H $\rightarrow$ ZZ$\rightarrow$ 4l analysis. **JHEP 03 (2012) 081**, **EPJC 73 (2013) 2469**,
- Results were later also used to measure the production cross-section of SM diboson process. **JHEP 01 (2013) 063**.

Physics Objects

Jet and p_T^{miss} The group's aim is to understand the fundamental physics objects jets and p_T^{miss}. These are key part in most from the searches hunting for dark matter, graviton, SUSY searches etc. I have been studying the high p_T^{miss} tails, which is generally the signature for signal, via multiple methods for a significant fraction of my research career.

- **Detector defects:** The presence of dead electronics channels in the Electromagnetic calorimeter (ECAL) and Hadron calorimeter (HCAL) can lead to high fake p_T^{miss}. The study carried out to produce the map of these detector holes and an algorithm was developed with the detector performance group to recover the energy deposited in this region. The new algorithm was implemented and validated using data collected in 2015.
- p_T^{miss} **Scanning:** Another source of high fake p_T^{miss} in data is due to detector electronics defects or unknown features in the reconstruction algorithms. These effects are usually overlaid in the newly collected data and be can easily be seen in p_T^{miss} tails. In the study performed two measures were taken. First, the events with high and exceptionally high values of p_T^{miss} were checked manually and to trace the actual problem. Second, a new data stream (Hotline) was used to check the tails and look for possible issues. Hotline data stream saves events with very high energy objects and ready for analysis within couple of hours of data taking. Finally, the filters were developed and performance was checked regularly in data. These filters are now recommended for collaboration wide usage and useful in rejecting huge filters are further tuned after better understanding of data collected p_T^{miss} tails.
- **Jet and p_T^{miss} Data Quality Monitoring:** Software expert for the JET-p_T^{miss} DQM and validation from 2016-2018. The software was updated and upgraded from time to time and more functionalities were added to spot problems related to detector, reconstruction and for debugging.
- **AUXJMEDQM:** I developed a new tool (AUXJMEDQM) to see the time evolution of observables. The newly developed tool uses the existing information which are produced to monitor the data quality and check the time evolution of a given variable for the full dataset in a short duration. The tool is mainly a quick but robust outlier detector. The changes in the detector configuration is spotted effortlessly. It is welcomed and now part of the monitoring producere to see the time evolution distributions from time to time.

The studies performed in the Jet p_T^{miss} group were part of the **JINST 14 (2019) P07004**

Tau Tau POG is charged with the understanding hadronic decays of taus, reconstruct and isolate them. They are key part of many searches, including H$\rightarrow \tau\tau$, SUSY and SM measurements. My contribution to Tau POG has been multi-fold.

- Measured the tau energy scale and its uncertainty using the tau-like gluon jets.
- I setup the first version of Tau ID Validation software to keep track of performance with changes and time.
- Devised the technique to make tau decay mode reconstruction to be pile up independent.
- Optimised the selection for three prong tau decay modes which lead to increase in signal efficiency by 10% keeping the mis-identification rate at same level.
- The reconstruction of high p_T hadronic tau was improved by optimising the selection which resulted in 40-50% increase in the efficiency above 200 GeV while keeping low mis-identification rate.
- The rate of mis-identification from electron to hadronic tau was measured to be 2-5% depending on the selection criteria used. The measurement was done using Tag and Probe method.

The studies performed in the Tau group were part of the journal published paper **JINST 11 (2016) P01019** and also recommendation for collaboration wide usage.

Detector

ECAL During my post-doctoral research period at FSU I am a member of the ECAL operations team and perform a variety of studies for ECAL Trigger group. I am an expert and experienced CMS ECAL shifter with role of DGL/Detector On Call [DGL/DoC]. One of the main project is to measure the size of L1-trigger pre-firing using ECAL Trigger primitives, measure relative size of different sources and then find methods to monitor and control it in the Run 3. A number of studies have been performed in order to understand the cause and measure them. The first study includes the analysis of full readout raw data from ECAL electronics to measure the total size of pre-firing in 2017 and 2018 data, i.e. with before and after this issue was solved by resetting the online detector timing. This serves as an benchmark and all the factorized components of pre-firing should sum up to this measurement.

The initial hypothesis about the cause of pre-firing is, it is occurring due to two sources, (i) in the front end electronic chip (FENIX) and the effect is supposed to be present in the emulator and supposedly can be simulated if needed, (ii) in the trigger concentration card (TCC) where the out of phase-ness of data and TCC clock lead to shift in the time by 1 bunch crossing (BX) and lead to the pre-firing and not present in the emulator.

To measure the relative size of these two effects three additional studies are performed:

1. A study was performed using data collected in 2018 where phase between data and electronics is changed. This gives an insight on the size of pre-firing probability as a function of the time shift we might observe in future.
2. To compliment this, special data was collected to measure the effect of TCC alone, where the phase of data and TCC clock is changed manually and data is recorded and then alignment is checked. The rate of mis-alignment roughly the pre-firing probability due to the TCC alone.
3. At last the simulation setup was developed to understand the effect coming from the FENIX. As this effect is already present in the emulator and hence a shift in the timing at this stage and re-emulating the digis can provide the missing piece of information we need to understand the issue better.

Therefore, the set of four studies mentioned above gives a full picture about the ECAL Trigger pre-firing. The results are being finalised and in discussion with Level 1 trigger group to understand how study can be used in Run 3 to control the pre-firing rate. The findings and proposal for Run 3 will eventually be summarised in a detector note.

HCAL I have actively contributed to the back-end electronics testing of Forward Hadron Calorimeter upgrade project. I set up a testing lab at SINP with help of Prof. Manoj Sharan. I was the first one to test initial prototypes of micro HCAL Trigger and Readout (μ HTR) and its various components at SINP. The power mezzanines and auxiliary power mezzanines were stress tested for long hours to ensure its quality. The task was accomplished using APIs developed in C++, with help of engineers from University of Minnesota. I have also perfomed the high speed links testing and characterisation of the optical splitters and Pluggable Parallel-Fiber-Optic Modules (PPODs). The backend electronics components were later installed and used for data collection during Run 2. The work is summarised in the form of an internal detector note CMS DN-2014/009.

HGCAL I have participated in the development of the future generation calorimeter which will replace the present ECAL and HCAL in the forward direction.

- **Standalone simulation:** A standalone GEANT4 setup to simulate the proposed Particle Flow Calorimeter was develped (later named HGCAL). The initial prototype considered sampling calorimeter with gas as an active material. The measurement of resolution, linearity and Moliere radius for ECAL and HCAL were performed to optimise the geometry. The thickness of absorber layer, active material gas type and its operating pressure were main parameters used for the optimisation of the geometry. The initial studies concluded that gas based calorimeter could not met the required for the resolution and hence Silicon was proposed and used as an active material.
- **Validation software:** Developed the software for the validation of SimHits, Digis and RecHits for HGCAL. The software packages were developed within the CMS software suite which is still being used by the collaboration to validate the new version of simulation, digitisation and reconstruction codes.
- **Test beam:** I have actively participation in data analysis of HGCAL test beam. One electronics module was tested in November 2016 test-beam with electron beam to exploit the timing capabilities of the Silicon (Si) sensors. The timing resolution of Si cells w.r.t timing reference detector was measured for each cell and then later combined with linear energy weights to achieve better performance. The study concluded that the time resolution of the Si cells can be used to separate the hard interaction and the pile up vertices in the HL-LHC phase when the average expected pileup would be 200. The results were part of the publication **JINST 13 (2018) 10, P10023**