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Elementary Particle Interactions with CMS at LHC

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The High Energy Particle Physics group of the University of Tennessee (UTK) participates in the search for new particles and forces in proton-proton collisions at the LHC. In 2006, the group joined the Compact Muon Solenoid (CMS) experiment at the LHC, CERN, Geneva, Switzerland. Over the last three years the group contributed to several tasks essential to the physics program and took on leadership positions:

- Search for new generations of particles predicted by beyond standard model scenarios and exotic hadrons predicted by quantum chromodynamics based models;
- Determination of rate of multiple particle production due to multiple parton interactions during a single proton-proton collision which impacts the determination of absolute production rate or cross section of any particle;
- Improved measurement of luminosity for each bunch crossing with a new detector. Luminosity is needed for all searches to establish the amount of misidentified signal from well-known reactions and to turn observed signal yields into cross sections;
- New technologies for highly pixelated charged particle detectors to be used at a high-luminosity LHC.

Search for New States

The main goal of the CMS experiment is to find new particles and forces between them beyond the standard model of particle physics. While there are several theories guiding searches the strategy is to explore the full phase space accessible with proton-proton collisions at center-of-mass (CM) energy of 7 TeV, 8 TeV, and since 2015 at 13 TeV with high beam intensities making best use of the detection capabilities of CMS. To this avail the UTK group is searching for new signals in the 4-muon final state with the 2-muon invariant mass range below the Z^0 resonance Models based on supersymmetric extensions of the standard model predict the existence of a pseudo-scalar Higgs at low mass. In the static quark model based on quantum chromodynamics ordinary mesons and baryons are formed from quark-antiquark pairs and three quarks, respectively, and both types are abundantly observed. Other so-called exotic combinations between quarks and gluons such as glueballs (constituent gluons) and hybrids (constituent quark-anti-quark-gluon) or 4-quark states, potentially acting like di-meson states, are allowed as well, but none have been unambiguously identified . The problem is that they are difficult to distinguish from ordinary states based on their mass or decay pattern, and do possess quantum numbers like ordinary states. The forming of 4-quark states has recently gained attention with the discoveries of B-factories supported by the LHCb experiment. The LHC particularly allows access to not-yet discovered states with constituent charm and beauty quarks, expected at substantially higher masses and with typical decays via charmonia and bottomonia. The CMS and ATLAS detectors are well suited to search for such resonant states at central rapidity. CMS measures J/psi pair transverse momenta and invariant masses not accessible with the LHCb experiment and uses event filters for fast selection of final states with J/psi and Upsilons. The J/psi pair analysis required establishing the reconstruction of muons near the detector acceptance limit that has been accomplished with the measurement of the cross section for prompt J/psi pair production conducted by our graduate student.

One of the reactions benchmarking the detector is the Higgs boson decay into 4 muons via two Z^0 resonances. The CMS detector is well suited for the detection and measurement of muons where we extended their momentum range to as low as 2 GeV/c. Particularly, we focused on states decaying via J/psi and Upsilon (Y) mesons that might exhibit resonant states, and they occur in a mass range where indeed states with constituent charm and/or beauty quarks are expected. Our group has performed a measurement of the cross section of J/psi-pair production that provided important information to theoreticians to create models of particle production in proton-proton collisions. This year we are publishing the Y(1s) pair final state measurement.

Such models are necessary to distinguish the non-resonant contribution to the final states from new signals. The underlying dynamics at parton level applies to all energies and searches, and our measurement emphasized the underestimate of double-parton scattering (DPS) contribution by prior models. It led to a new round of model developments that now include contributions from double parton scattering and higher order calculations of single-parton scattering. Particularly, the relatively large DPS contribution was unexpected and implies that a new particle dependent on its mass can be produced twice in a single proton-proton (or proton-anti-proton) collision. Furthermore, the J/psi-pair and Y-pair measurements together with the recent J/psi Y measurement of the D0 experiment seem to support a trend that DPS reactions involving jets deviate systematically from quarkonia pair measurements. It seems to imply that the gluons occupy a smaller region in the proton than qq-bar, qg parton states that contribute to jet-related production channels. Furthermore, our measurement demonstrated the need to include intermediate color-octet states of J/psi (Upsilon). The measurement of the J/psi (Upsilon) pair and Y J/psi cross sections at 13TeV CM energy challenge the correct energy dependence in the recently published models. The UTK group implemented and tested the fast online event filters to ensure that these final states are acquired with significant statistics. Data are reconstructed and the results are moving towards publication. To extract those results with least dependence on models we developed a novel strategy that has now become a standard for similar measurements. In this approach a signal probability for each event is obtained from a maximum likelihood fit to four event variables. Corrections for detector acceptance and efficiencies are applied on event-by-event basis using detector simulations based only on the measured kinematic quantities, rather than predicted quantities.

Apart from the J/psi pair final state exclusively addressed by the UTK group, new hadronic states binding 4 quarks are expected e.g. just below the Y-pair threshold. Hence, states are searched for in the Y(1S) plus 2-muon final state with the 2-muon invariant mass below the Y(1S) resonance, including Y J/psi and Y – light mesons. The UTK group provided an independent analysis of this final state. Particular emphasize was put on different muon selection strategies and sideband distributions to probe the non-resonant distribution under a potential signal. In case of the UTK analysis of J/psi pairs and the Y Y* analysis performed by the analysis group based in FNAL the strategy is to establish the reconstruction and selection on 7 TeV and 8TeV data and with a frozen strategy predict the outcome at 13TeV without inspecting the declared signal region (blind analysis). The cross-check also increased confidence in the best muon selection and reconstruction strategy across different searches.

One of the primary goals of the CMS experiment is to look for new physics signatures indicative of theories of quantum gravity. As no evidence of any such theoretical predictions has been observed, there are a variety of potential models one can consider as a basis for such a search. The common thread in the majority of these models is the existence of some number of extra dimensions beyond the 3 + 1 of space-time. The relative weakness of gravity is explained by allowing it to propagate through these additional dimensions, reducing the gravitational flux substantially. Consequently, the fundamental Planck scale, the energy scale at which gravity becomes comparable in strength to the electroweak and strong nuclear interactions, decreases as well. If the fundamental Planck scale is within reach of the collision energy of the LHC, then the decay products of quantum gravitational interactions may become observable in the CMS detector.

Most existing searches for quantum gravity effects on CMS have been largely model-dependent. An alternative idea is that once one crosses the fundamental Planck scale, all standard model processes should slowly but steadily be overtaken by the production of microscopic black holes. Therefore, it is also possible to perform a quantum gravity search by looking for a deficit of some kind in kinematic distributions beyond some energy threshold. The process with the highest overall cross-section as observed by CMS is inclusive production of particle jets. These are collinear streams of particles. The attenuation of jet production beyond some energy or momentum threshold is called “jet extinction”. The search was performed by our postdoc on 2011 and 2012 CMS data published with CMS Collaboration, “Search for jet extinction in the inclusive jet-pt spectrum from proton-proton collisions at sqrt(s) = 8 TeV”, Phys. Rev. D 90 (2014) 032005. CMS reconstruction algorithms use the excellent tracking resolution on charged particles in association with the energy deposited in the calorimeters to associate a direction and momentum with these jets. The statistical power of the jet sample may then be leveraged for searches for new physics. Certain standard candle particles, such as the W and Z bosons or the top quark, may decay into two or more jets. If the decay of these particles is sufficiently boosted in the laboratory frame, these jets may be merged into a single wide jet by the basic CMS reconstruction. In the last few years, new "substructure" techniques have been developed to resolve multiple subjets from a single jet topology with a high efficiency. These boosted jets may be evidence of new physics such as excited gauge states (Z'), Dark matter, or leptoquarks. As an expert on jet ID and jet substructure on CMS, our postdoc has reviewed and provided feedback on many exotic particle searches based on jets and this year for all of those results that aim for the ICHEP conference.

Beam Radiation and Luminosity Measurements

Any particle search at the LHC depends on the detailed knowledge of the luminosity, and continued efficient proton-proton collisions require monitoring of the beam conditions and warnings and alarms in case of adverse beam scenarios all the time. The rate of particle production in proton-proton collisions is the product of the cross section for the process and the luminosity. The latter is a measure for the accelerator that a proton-proton collisions results in a particle reaction such as the Higgs-boson production and it depends on the details of the particle beams (beam currents or number of protons per colliding bunch, number of colliding bunches and frequency of collisions, and cross sectional area of beam overlap). The luminosity is used to predict the amount of fake signals (backgrounds) that need to be subtracted in a particular process to isolate signal and to turn observed signals into cross sections that can then be compared to model predictions. In case of the Higgs boson, the knowledge of the luminosity determines the precision with which the Higgs production can be compared to the standard model prediction. A significant discrepancy between measurement and standard model is indication for new physics. In general, precise cross section measurements allow distinction between models describing any new phenomena. Since beam conditions change from fill-to-fill and during a fill of the LHC it is important to record the luminosity continuously. The LHC typically uses more than 1,000 filled bunches that collide at minimum every 25ns (or 50ns). The amount of protons varies between filled bunches, and there are empty bunches, and the conditions at which they collide vary within a bunch. The pixel luminosity telescope (PLT) has been added as upgrade in early 2016 to measure the bunch-by-bunch relative luminosity at the CMS collision point on a time scale of a few seconds and a stable high-precision measurement of the integrated luminosity over the entire lifetime of the CMS experiment - the goal is with an uncertainty to better than 2%. An important aspect is that the PLT allows a distinction between particles originating from the collision point from particles that are produced elsewhere (beam background) introducing a non-linear dependence on the luminosity. This is difficult to measure with single-plane instruments or calorimeters. The PLT consists of several three-layers of silicon pixel detectors, the same as used in the CMS pixel detector but in addition with a fast hit counter per plane that is used to define a bunch-by-bunch triple-coincidence trigger. On each side of the CMS detector at a radius of about 5cm at a distance of 1.8 m from the central collision point 8 telescopes are arranged cylindrically around the beam pipe. The goal is to make the PLT the primary luminometer of CMS and improve its precision with continued systematic studies of fully reconstructed particle tracks that are samples at a lower rate. The PLT is part of several instruments that measure the relative luminosity. The measurements are coordinated and compared to analyses of exclusive final states such as the production of Z0 resonances and the luminosity reported by LHC and other experiments at LHC. Furthermore, calibrations are obtained with Van de Meer (VdM) scans. The goal is to progressively improve the knowledge of the luminosity. For data taking, the goal is to unify the interface and procedures between different instruments and increase robustness of operations with automation and monitoring, and maintain a critical pool of experts.

The US-CMS is the dominant contributor to the PLT. The main collaborating institutes are Princeton, Rutgers, Tennessee, Wisconsin, and Vanderbilt. Furthermore, the PLT and instruments to monitor beam radiation that the UTK group in the past helped to build and commission are coordinated by a sub-detector group of the CMS collaboration called BRIL. The PI, Stefan Spanier,has taken on the project management within US-CMS, and leading roles in the overall BRIL collaboration.

Detector Technology R&D

The PLT detector is placed closest to the beam pipe and has to cope with the more intense radiation over the next years. Close monitoring of its performance is mandatory. It might just be sufficient to continue and only replace damaged detectors. At the same time we continue to investigate radiation harder materials and readout configurations. As the PLT is a much smaller system compared to the pixel detector it is well suited to benchmark new technologies if proven radiation hard in the laboratory and beam tests. For phase II detector upgrade the present technology is expected to be inadequate for pixel detectors. At the same time improvements in the manufacturing of CVD diamonds could overcome some of the radiation induced effects. Other materials such as sapphire are also considered. The single-crystalline diamonds initially used for the PLT after neutron irradiation showed a dependence on the rate due to trapping of secondary charges (polarization effect). Better materials from different vendors are being tested in collaboration with RD42. We perform the research for upgrade sensor material and readout electrodes with the group of Professor Lukosi at UTK Nuclear Engineering and Professor Lloyd Davis at the Space Institute of the University with strong involvement of our undergraduate students. A promising venue is to introduce vertical (3D) electrodes in diamond detectors that allow charge collection over much shorter distances (much faster) potentially increasing the signal height and, if still present, overcoming the aforementioned adverse effects introduced by radiation. Two venues are explored: introducing carbon-like (conductive) diamond with a high-power fast laser or/and etching columns to be refilled with conductive material. The shorter and higher signals are well suited for the advocated digital readout. For application as pixel luminosity telescope either as an independent detector or integrated in a newly designed pixel detector the readout chip will have to include a fast-trigger mode. The goal is to follow developments of the pixel detector and provide solutions and help define requirements. Results of our measurements of adverse effects of neutron irradiation on charge collection in single-crystalline diamond detectors and the progress in the creation of 3D electrodes in diamond have been presented in conferences and journal publications.

The activity in detector operations and new technology research resulted in presentations at internal reviews and international conferences (IEEE conference, international pixel workshop, APS) and resulted in publications (Nucl. Instrum and Methods, European Journal for Instrumentation, IEEE Transactions).

Summary

The UTK group has made and continues to make significant contributions to detector operations for beam radiation and luminosity measurements, data analysis, and technology R&D over the period of this grant. The members supported other analyses groups as members and leaders of analysis review committees and ensured the data quality during online data taking. Furthermore, the members took leading roles in the detector operations. Our analyses by themselves are important feedback to theoretical development of models for particle production in proton-proton collisions at LHC.

Our graduate students and postdoctoral researchers have obtained employment in industry or academia. Our research involved several undergraduate students that were able to make significant contributions to the LHC project, e.g. by designing and building electronics for the beam radiation monitoring, by programming monitoring software, and by taking part in diamond detector tests at test beams at CERN and Fermilab, and in the laboratory at the University, giving them a unique learning experience and educating them in conducting fundamental research. Computing is an essential part of our research: we were able to establish a high-performance computing center for research at the University adopting the same concepts for shared resources (GRID computing) that are used at LHC. This increased the potential of other DOE funded research at the University campus. We contribute to the Particle Data group that maintains the table of Particle Properties by writing summaries and reviewing publications. We reach out to the local community by giving presentations to local organizations and lectures in local colleges.

Publications

As a result of the commissioning of the PLT, the arrival of new data at 13 TeV CM energy, and measurements in the laboratory of neutron-irradiated detectors there are several publications in preparation and submitted for publication with the involvement of the group at UT. In 2015 all our graduate students obtained author ship with the CMS collaboration.

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Personnel

Personnel	*Position*	*Support*
Stefan Spanier	Professor, PI	Summer salary (2 months)
Keith Rose	Postdoctoral Researcher	100%
Grant Riley	Graduate Student	100%
Krishna Thapa	Graduate Student	50%
Joseph Heideman	Graduate Student	100%
Gerald Ragghianti	Computer Technician	0%
Daniel Garza	Undergraduate Student	0%
Alexander Krohn	Undergraduate Student	0%

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