Final Report
Grant DE-FG02-96ER41005
Particle Physics Research Program

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TASK A: High Energy Collider Physics

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1 Project Objectives

P. Karchin

The primary objective is to support the operation, upgrade and data analysis of the Compact Muon Solenoid (CMS) experiment at the European Center for Nuclear Research (CERN). The operational and upgrade effort is centered on the endcap muon detector sub-system. The data analysis project is a search for quark and gluon substructure as manifest in the cross section for high mass oppositely charged di-lepton pairs. A second objective is the completion of data analysis from the Collider Detector at Fermilab (CDF) experiment on precision measurement of the oscillation between neutral D mesons and their anti-particles.

The proposed work on CMS is a continuation and expansion of a successful on-going program of research, started in 2007, when Karchin and collaborators from Wayne State proposed to join CMS, with major operational contribution to the cathode strip chamber (CSC) system of the end-cap muon system. Since that time, Karchin and Mattson with Ph.D. students Sowjanya Gollapinni and Chamath Kottachchi have contributed to CSC operational shifts at Point 5, and detector performance group (DPG) studies using CSC data at the cluster and track segment level. Ph.D. students Gollapinni, and Pramod Lamichhane have been regular contributors to central shifts for data quality management and computing. (For details about shifts see “Professional Activities and Honors” in “Appendix 6: Other Attachment.”) We propose continuing work on the CSC sub-system to include detector operations at Point 5, DPG studies, and central operations shifts.

A new project is the construction and installation of 128 additional CSC chambers which will comprise the outer radius ring (ring 2) of the end-cap muon detector stations located furthest from the interaction point (ME+42 and ME-42). The WSU group will manage the manufacture and testing of front-end and digital output cables and contribute to the installation at point 5 during long shutdown 1 (LS1), scheduled for 2013 and 2014. Karchin, with research engineer Alfredo Gutierrez and student C. Kottachchi are overseeing production of the required cables, using commercial vendors. Karchin and Gutierrez collaborate on the GEM (GEMS for CMS) project based at CERN, to develop large area, high-rate gas electron multiplier (GEM) chambers suitable for the end-cap muon system. Such chambers may significantly improve the muon trigger capability for future high luminosity operation of the LHC. Karchin has contributed to planning sessions and Gutierrez has contributed to the installation and operation of prototype chambers in an extracted beam at CERN.

We propose to continue the promising data analysis project on the search for contact interactions in the di-lepton channel. Preliminary results, presented later in this proposal, show excellent sensitivity in the di-muon channel. We plan to use the full data set up to LS1 to obtain the best possible sensitivity, and we propose to expand the analysis to the di-electron channel.

The proposed work on CMS would be carried out by Karchin, a new post-doc to be based 50% at CERN, engineer Gutierrez, and students Gollapinni, Lamichhane, and Kottachchi. Mattson, in his proposed program as P.I., will collaborate on the contact interaction analysis.

Caroline Milstene, an adjunct professor, has established an independent research program in CMS, and proposes continued work on hadron calorimeter operation and upgrade, tracker simulation studies, and

physics analysis. (See the section of Appendix 6 on “Additional Activities of Caroline Milstene, Adjunct Professor.”)

Analysis of the full CDF data set is proposed for precision studies of $D^0 - \bar{D}^0$ mixing in the $K\pi$ channel. This work would be carried out by Karchin and Mattson, who, together with former Ph.D. student Nagesh Kulkarni, conducted the analysis which led to the publication showing strong evidence (3.8σ) for mixing, based on an integrated luminosity of about 1.5 /pb. With the final CDF data set based on about 10 /pb, we expect to be able to achieve the first single-measurement 5σ “observation” of mixing, to make precise measurements of the mixing parameters, and to search with improved sensitivity for CP-violation in the mixing process, which, if observed, would be an unambiguous signal for new physics. This year, Kulkarni has been working on this project on a voluntary basis, and we recently received supplemental funding to support him as a post-doc for six-months, to work on this project.

R. Harr

Harr proposed three major analysis objectives for the 2009 to 2012 grant: search for a low mass Higgs boson in the associated production mode $Z^0 H$, where the vector boson is observed in the decay $Z^0 \rightarrow \ell^+ \ell^-$ and the Higgs in $H \rightarrow b\bar{b}$ using at least 3 fb^{-1} of CDF data; continue to exploit the CDF data to search for rare charm decays, specifically $D^0 \rightarrow \mu^+ \mu^-$; and study the mechanism for electroweak symmetry breaking with CMS data, in particular, searching for the Higgs boson. To accomplish these Harr received 3-years of summer salary, 1.5 years of funding for a graduate student, 1.5 years of funding for a CMS-based postdoc, travel money, and money for miscellaneous research expenses. These monies were supplemented with CMS operations money for the postdoc salary and travel to CERN, and URA money for the graduate student. Additional manpower was obtained with the use of undergraduates, supported through a Wayne State REU grant, or with internal funding.

The first two objectives were fulfilled, resulting in two papers published in 2010: a limit on the branching fraction of $D^0 \rightarrow \mu^+ \mu^-$ in Physical Review D [23]; and a result on the search for the Higgs boson produced in association with a Z^0 boson using 5.2 fb^{-1} of integrated luminosity [26]. The third objective is still ongoing, but much progress was made over the summer of 2011 thanks to two REU students. The students’ work initiated the collaboration of Wayne State with a group centered at the Fermilab LPC that is working on Higgs boson search and electroweak physics with the lepton, neutrino, and two jet final state. The direction Harr has chosen is to measure the trilinear gauge couplings, with the goal of constraining or observing effects beyond the standard model.

Service work in support of CDF and CMS operations was carried out as well. Harr served three one-week shift leader shifts at CDF, and two one-week CSC shifts at CMS. C. Clarke served a twelve-week ace round at CDF. A. Sakharov has served four one-week CSC shifts at CMS and spent a year handling the weekly data certification task for CSC.

Harr’s proposed objectives for the period of this grant include the measurement of trilinear gauge couplings with CMS data, the search for exclusive W decays in CDF and CMS data, and the search for rare charm decays in CDF data. The group must also carry out service work for CMS, and as CDF winds down, Harr will be investigating other secondary projects to become involved with. These and additional activities being pursued by Harr’s group are described in detail in the following sections. The support requested to undertake this work is 3-years of summer salary for Harr, 3 years of graduate student salary and tuition to support alternately one of two Ph.D. students, 3 years of salary plus COLA for a postdoc stationed at CERN, travel support for the students, postdoc, and Harr, and funds for miscellaneous research expenses.

Harr is exploring other projects to begin as CDF winds down. Possible projects include CMS upgrades, part-time involvement with another experiment (something small scale), or detector R&D. Working on a CMS upgrade project is attractive since it would give students an obvious project for CMS service work.

M. Mattson

Mattson was working for the Wayne State group, with Karchin as PI, since 2002. For this grant proposal, Mattson is applying as a new P.I. The first objective is to support work for operations and upgrade of the Tracker (silicon) for the Compact Muon Solenoid (CMS) experiment at the European Center for Nuclear Research (CERN). The second objective is data analysis for contact interactions in the di-lepton channel using data collected by CMS. The third objective is data analysis to continue working on precision measurement of the oscillation between neutral D mesons and their anti-particles, using data collected by the Collider Detector at Fermilab (CDF) experiment. Both analysis projects are in collaboration with groups headed by P. Karchin, and were described by him previously.

For the past two years, Mattson has been involved with operations for the CDF experiment, which will finish at the end of September 2011. CDF management was looking for experienced experimenters, who in the past have worked well with the operations group to keep the detector running. Mattson was actively recruited for projects involving overall operations and the silicon detector.

In 2008, Mattson was active at both CERN and Fermilab, contributing to operations for the cathode strip chamber (CSC) system at CMS. The proposed work for 2011 onwards is with the Tracker system. Talks are in progress with the CMS Tracker management about two possible projects where Mattson could contribute. The first project is silicon detector upgrades, which are necessary to handle expected increases in the luminosity of the LHC over the next few years. New silicon sensors will be needed to handle expected radiation damage and high data rates. Ph.D. student Pramod Lamichhane is already working on this project with the Fermilab group (headed by Leonard Spiegel). Mattson would join this group. (See the letter of support from Dr. Spiegel in Appendix 6.) This project is currently short-handed for experienced physicists. The second project is working on an alignment algorithm project that was started some years ago. The original plan was for CMS to use two independent alignments, but the second algorithm has languished due to only enough support to operate one alignment project. Tracker management wants to revive this second alignment project. Mattson would be responsible for resurrecting this project, making improvements, operating it on new data, and verifying the current alignment being used.

The CMS analysis proposal is to join the project on the search for contact interactions in the di-lepton channel. The work will include using the full data set, using the analysis method being developed this fall for the di-muon channel. This analysis will eventually be expand to the di-electron channel.

The CDF analysis for $D^0 - \bar{D}^0$ mixing in the $K\pi$ channel is a continuation of work done by Mattson, Karchin, and Nagesh Kulkarni, a former Ph.D. student. The analysis which led to the publication showing strong evidence (3.8 sigma) for mixing, based on an integrated luminosity of about 1.5 /pb. With the final CDF data set based on about 10 /pb, we expect to make precise measurements of the mixing parameters, and to be able to achieve the first single-measurement 5-sigma “observation” of mixing. After that result is completed, the analysis will continue with a search for CP-violation in the charm mixing process, which, if observed, would be an unambiguous signal for new physics.

Mattson currently lives near Fermilab. All proposed projects could be done at Fermilab, with only the occasional trip to conferences or to meet with CMS colleagues directly.

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2 History of the Task A Research Group

Our group has its roots at Yale University where Karchin started as assistant professor in 1986 working on fixed-target charm experiments at Fermilab (E691 and E769). These experiments pioneered the use of silicon microstrip detectors and established many basic properties of charm production and decay. In

1990 Harr joined as post-doc with Karchin in a test project at the CERN $S\bar{p}\bar{p}S$ collider (P238) which established the use silicon microstrip detectors to measure secondary vertices in a forward geometry, close to the beam axis. This technique is now used with great efficacy in the LHCb experiment at CERN. We had hoped to exploit this technique for beauty physics at the SSC, but after the SSC termination, we joined the HERA-B experiment at DESY, with similar goals.

Our group moved to Wayne State in 1995 under an initiative to establish a program of research in high energy particle physics in the Department of Physics and Astronomy. In the period 1994-2001, we played a major role in the HERA-B experiment at DESY. We managed the construction and operation of the muon detector and we designed, built and operated the front-end readout electronics for the muon system. We were active in the physics analysis for the production cross sections for beauty and J/ψ particles, and for the search for the rare decay of the D^0 into a muon pair.

We joined the CDF experiment at Fermilab in 2001 and Wayne State gained institutional membership in 2002. Our group has played major roles in operations and physics analysis - recent work is described in this proposal. In early 2008, Wayne State formally joined the CMS Collaboration at the LHC and its Endcap Muon Collaboration. This work is described in detail in this proposal.

3 CMS Experiment at the LHC

3.1 Operations

Central Shifts

Students and Post-doc

Central shift crews monitor and control the overall operation of the CMS detector. Some types of central shifts can be taken at the Fermilab remote operations center (ROC). These include on-line data quality monitoring (DQM) and computing (CSP) operations. S. Gollapinni and P. Lamichhane have participated in these shifts; individual contributions are listed in the section on Professional Activities in Appendix 6. Central shifts, both at Fermilab and at CERN are proposed until long shutdown 1.

CSC Operational Shifts

Students and Post-doc

The “Detector On-Call” (DOC) expert is responsible for 24-7 operation of the CSC system during a one-week period. Graduate student C. Kottachchi took a two-week training session at CERN in October 2010 and served two DOC shifts in 2011. Continued participation by the WSU group is proposed until the start of LS1.

Maintenance of CMS Cathode Strip Chamber Software

R. Harr, A. Sakharov

The Wayne State group is responsible for maintaining a key piece of code for the operation of the cathode strip chamber (CSC) system, the UNPACKER. We inherited responsibility for this code from the Rice University group when we joined CMS. As the name implies, this code unpacks the data from the CSC front end electronics into a standard format for all subsequent processing (validation, alignment, tracking and reconstruction). This code runs online and is necessary for the operation of the high level trigger. This aspect connects us to the operational aspect of the CSC system, and has led us to a number of projects directly with or related to the UNPACKER code during the past year.

Stabilization of the trigger throw system (TTS) of CMS required the reduction of data flow and access to additional variables encoded in the CSC raw data payload. To reduce the data flow, zero suppression of anode data has been implemented. Sakharov revised the UNPACKER software to handle zero suppressed data.

During the 2010 run, a lot of effort was expended on synchronizing the CSC detectors. Sakharov implemented code to propagate specific timing information from the raw data to the software objects for the reconstructed hits. This was done without introducing new variables into the data format, a procedure that requires additional tests due to the possibility of breaking other code. This additional timing information was used to substantially improve the segment timing distribution.

During detector checkout with cosmic rays, before first beam in 2008, it was noted that some segments are reconstructed at large distances from the hits used in the segment. Sakharov and Harr studied the problem and found that an instability in the inversion of a covariance matrix can occur [4]. The problem affects the reconstruction of perfectly good, high momentum, normal incidence muons that just happen to have the wrong combination of hit errors. A fix would recover good muon segments at the rate of several percent. Sakharov has devised a scheme to ameliorate the problem, with an accompanying improvement in the distribution of track χ^2 . The new segment reconstruction code has been deployed since the first collisions at $\sqrt{s} = 7$ TeV.

CSC Offline Data Quality Monitoring

C. Clarke, R. Harr, A. Sakharov, K. Siehl

Data quality monitoring (DQM) of the CSC data is an important service to the CMS experiment. There are two stages to DQM: fast response online monitoring, and more detailed offline monitoring. The final certification of the data taken in every run is made by CMS physics validation team (PVT) on the basis of the quality of offline data reconstruction. The decision of PVT relies on the feedback from subsystem experts given every week within a weekly data certification round. A weekly round includes all collision runs taken during the previous 7 days. Shortly after the start of data taking in 2010, the CSC detector physics group created a group of experts to do data certification for CSCs and give feedback to PVT requests. Harr and Sakharov are part of the CSC data certification team for offline DQM and each has taken several of the weekly certification rounds. Sakharov serves as the expert for the PVT feedback as well as the expert for feedback to online DQM shift. The service of Sakharov includes the daily control of the online DQM shifter notes and preparation of the weekly reports on the data certification for the PVT.

In the beginning of October 2010, CSC switched from subdetector shifts to local CSC DQM shifts. Sakharov was one of the first to take this new kind of CSC shift. CSC DPG and CSCops use the expertise and feedback of Sakharov to refine the CSC DQM shift instructions. Under the request of CSC DPG and CSCops Sakharov has developed specially dedicated CSC DQM shift layouts which has been deployed into the CMS offline graphical user interface. The WSU group service for the further development of CSC offline DQM is still ongoing.

End-Cap Muon System Upgrade

P. Karchin, A. Gutierrez, Post-doc, and Students

The CMS muon system is based on an instrumented return yoke for the solenoidal magnet. The overall geometry of the system is shown in Figure 1. A central barrel section has four detector stations (superlayers), each station with drift tube and resistive plate chambers. Identical endcap detectors each have four stations, the innermost three stations containing both cathode strip chambers (CSC) and resistive

plate chambers and a fourth, outermost station containing only CSCs.

The CSCs are organized into “rings” of trapezoidal shaped, 6-layer chambers with strips along the radial direction and wires perpendicular to the strips. There are 468 such trapezoidal chambers in each endcap. The signals from wires and strips are used to form a trigger and the signals are digitized for accepted triggers.

In the present configuration, the outer radius rings of the CSC stations located furthest from the interaction point (ME+42 and ME-42) are not instrumented. However, with the ever-increasing luminosity of the LHC, the trigger rate could be significantly reduced (for a given p_T threshold) by instrumenting these chambers. A new project is the construction and installation of 128 additional CSC chambers for these two rings. The WSU group is managing the manufacture and testing of front-end and digital output cables and will contribute to the installation at point 5 during long shutdown 1 (LS1), scheduled for 2013 and 2014. Karchin, with research engineer Alfredo Gutierrez and student C. Kotachchi wrote the specification document for the required cables, managed the bid process, and now supervise the production at an industrial company.

To meet the goal of robust, efficient muon detection, CMS employs dual independent detector systems. In the end-cap region, these systems are the cathode strip chambers (CSC) and resistive plate chambers (RPC). The CSC system has acceptance in the region $0.8 < |\eta| < 2.4$, whereas the RPC system covers only $|\eta| < 1.6$. To preserve the dual system concept and to allow operation at the highest planned LHC luminosities, a group lead by Dr. Archana Sharma of CERN has proposed a system based on micro-pattern gas detectors (MPGD) to provide coverage in the region $1.6 < \eta < 2.4$. The detectors are constructed with three-layers of gas electron multiplier (GEM) foils immersed in a simple gas mixture of argon and carbon dioxide.

Test-beam studies using 1 meter length prototype chambers, as shown in Figure 2, were conducted in October, 2010, and summer, 2011. WSU research engineer Alfredo Gutierrez was at CERN for the two-week period of the 2010 test and for a two-week period for the summer 2011 tests. He made well-recognized contributions to the intense efforts to install and operate the prototype chambers, and to make quick modifications when needed. Karchin contributes to the GEM project planning and gave a talk on the subject at the recent TIPP conference [2]. The GEM muon detector is under consideration for the CMS Upgrade [1]. Furthermore, the GEM development is of general interest as a new technique for large-area, high-rate charged particle position measurement.

Figure 1: Longitudinal cross-section of the CMS detector showing the Muon Barrel (MB) and Muon Endcap (ME) detectors.

Figure 2: Prototype triple-GEM muon detector system tested in a secondary beam at CERN in October, 2010. The detector modules, located downstream of beam-defining scintillation counters, are trapezoidal in shape with 1 meter vertical dimension.

Tracker Operations

M. Mattson, P. Lamichhane

The CMS Tracker consists entirely of silicon detectors. The pixel detector is closest to the beam pipe, with cylindrical layers from 4-11 cm and disks at either end, containing 65 million pixels. Outside of that is the strip detector, with ten layers of silicon reaching out to a radius of 130 cm.

Before data taking started, CMS developed two independent alignment packages for the tracker, which was intended to allow important cross checks between the two versions. Although the code exists for the second package, it has not been maintained for some time due to lack of resources. Mattson will take over this project, which will require reviving the code to use current software releases. After that, improvements will be needed for the algorithm. The long term goal is to run it on new data and produce a new alignment, which can be compared to the currently used algorithm. This project can be performed at Fermilab, and the overall estimate is 6 people-months of work.

Rad-Hard Silicon Sensor Development

M. Mattson, P. Lamichhane

CERN is planning to increase the LHC luminosity to $10^{34} \text{ cm}^{-2}\text{sec}^{-1}$ for Phase 1, within a few years. Results of Phase 1 will lead to decisions on how to achieve Phase 2, which will increase luminosity to 10^{35} . The radiation at these luminosities will require new silicon detector designs. The pixel detector will need to be upgraded for Phase 1, and both pixel and strip detectors will need upgrades for Phase 2.

P. Lamichhane, in collaboration with Fermilab (Dr. Lenny Spiegel is principal collaborator), has already worked on testing a new type of silicon pixel sensor, manufactured by Hamamatsu (HPK), which has a crystal structure expected to have increased radiation tolerance. Mattson and Lamichhane, in collaboration with Fermilab, will work on testing new silicon strip detectors from Hamamatsu. Many prototypes were made, with varying strip pitches and design. They were tested at Fermilab this past summer. Measurements of sensor properties from bench and beam tests were reported by Lamichhane at the recent TIPP conference [3]. The prototypes have now been exposed to a large radiation dose, and will be tested again this fall. The goal is to identify a baseline sensor technology for the CMS Phase 2 upgrade, exploring sensor types (ex. p-on-n or n-on-p), thickness, and different hadronic irradiation scenarios.

EMU Institution Board

P. Karchin was elected chair of the Institution Board of the CMS End-cap Muon (EMU) Collaboration in September, 2009, and re-elected in July of this year. The chair organizes and chairs the programs for EMU collaboration meetings which are held during parallel sessions at the thrice-yearly CMS weeks. At the EMU meetings, activities are reviewed and future plans are discussed. The past four meetings have included physics presentations by graduate students who have been active in EMU sub-system work, and whose physics analyses utilize the muon system. This builds an EMU “community” and gives a “vertical” perspective on the use of the EMU system from trigger to analysis. The EMU collaboration is chartered in the US-CMS constitution, and the chair represents the EMU collaboration in CMS advisory boards.

3.2 Physics Analysis

Search for Quark/Lepton Substructure in the Di-lepton Channel

S. Gollapinni, P. Karchin, C. Kottachchi, P. Lamichhane, M. Mattson, C. Milstene

In the standard model, quarks and leptons are point particles. However, they could have substructure at a smaller distance (larger momentum transfer) scale than has yet been probed. In a classical analogy, if finite diameter particles collide with impact parameter less than their diameter, the particles make “contact” and their scattering cross section deviates from that determined by a “non-contact” force at a distance. For classical Rutherford scattering, the contact interaction is due to the strong nuclear force and the force at a distance is the Coulomb force between the alpha particle and the target nucleus.

A universal theoretical framework describing contact interactions in high energy particle collisions was developed in a seminal paper by E. Eichten, K. Lane and M. Peskin [5] in 1983 followed by a detailed exposition for hadron colliders by E. Eichten, I. Hinchliffe, K. Lane et al. [6] in 1984. In these papers, the authors present forms for the Lagrangian densities for various scattering processes including di-lepton and di-jet production in p-p collisions. We have chosen to search first for a contact interaction in the di-muon channel, which is particularly promising because of the unambiguous signature in the detector of two muons with large invariant mass.

The scattering amplitude for $pp \rightarrow \mu^+ \mu^- X$ can be written as

$$a = a_{Z/\gamma} + a_{CI}$$

where $a_{Z/\gamma}$ is due to the standard model sub-process $q\bar{q} \rightarrow \gamma^*/Z^* \rightarrow \mu^+ \mu^-$ (Drell-Yan production) and a_{CI} is due to the contact interaction. The differential cross-section can be written as,

$$\frac{d\sigma}{dm} = \frac{d\sigma}{dm}(DY) + \eta \frac{I}{\Lambda^2} + \frac{C}{\Lambda^4}$$

where m is the di-muon invariant mass, $\frac{d\sigma}{dm}(DY)$ is the standard model (Drell-Yan) cross-section, I is the interference term between the DY and contact amplitudes, $\eta = +1(-1)$ for completely constructive (destructive) interference, Λ is the energy scale of the contact interaction, and C is a pure contact term.

In the context of the CI model, we studied the total cross-section for di-muon production in the kinematic range accessible by the CMS detector. We utilized a generator-level simulation by Pythia, which has an implementation for a contact amplitude with left-handed quark and lepton currents, referred to as the “left-left” model. The total cross sections as a function of Λ for the cases of completely constructive and destructive interference are shown in 3. The standard model limit is approached as $\Lambda \rightarrow \infty$. Note that at small values of Λ , the cross-section far exceeds the SM value. With increasing Λ , the cross-section falls monotonically to the SM value for constructive interference. For destructive interference, the cross section falls below the SM value, reaches a minimum at about 6 TeV, then rises asymptotically to the SM value.

In Figure 4 we show a comparison of observed event yields versus dimuon invariant mass and yields expected from the combination of SM, left-left model contact interactions and background processes for a data set corresponding to an integrated luminosity of 789/pb at collision energy of 7 TeV. The expected yields include a full detector simulation. Two values of Λ are chosen for illustration, each considered with fully constructive or destructive interference between the DY and CI amplitudes. The predicted cross-sections fall monotonically with increasing mass, for masses above the Z -peak. Deviations from the standard model cross section would appear as an enhancement (“tail”) with increasing mass. The enhancement is reduced for increasing values of Λ . The data are visually (and quantitatively) consistent with the standard model prediction.

Given that the data are consistent with the SM (χ^2 probability of 0.59), we can compute expected and observed lower limits on Λ . A binned likelihood function is constructed for simulated SM or real data using a predicted event yield based on simulated left-left model contact interactions for a particular value of Λ . A lower limit on Λ is derived from the integral of likelihood from Λ to infinity, as shown in Figure 5 for simulated and real data. The 95% values of the integral correspond to Λ values of 9.7 TeV (data) and 10.0 TeV (simulation) for constructive interference; the values are 7.9 TeV (data) and 8.0 TeV (simulation) for

Figure 3: Pythia simulation of the combination of standard model and left-left model contact interactions producing a dimuon pair. Total cross sections as a function of contact energy scale parameter Λ are shown for the cases of completely constructive and destructive interference. The center of mass energy is 7 TeV and each muon must satisfy the conditions $|\eta| < 2.4$ and $p_T > 30$ GeV/c. The curves are quadratic fits to the cross section values. The standard model cross section is approached in the limit $\Lambda \rightarrow \infty$.

Figure 4: Observed event yields versus dimuon invariant mass and yields expected from the combination of SM, contact interactions and background processes for a data set corresponding to an integrated luminosity of 789 /pb at collision energy of 7 TeV.

Figure 5: Integral of likelihood from Λ to infinity, for simulated and real data for destructive interference (a) and constructive interference (b).

destructive interference. These limits can be compared to the current best limits of 4.9 TeV (constructive) and 4.5 TeV (destructive) from ATLAS [8] based on 40 /pb. Our CMS analysis is now extended to a data set corresponding to 2.3 /fb and a publication is planned in 2012 using the full 2011 data set of about 5 /fb.

This analysis is carried out by the Wayne State group in collaboration with Dr. Lenny Spiegel of Fermilab. Our WSU/Fermilab analysis group meets weekly and we participate in meetings of the CMS sub-group on non-resonant exotica and the CMS exotica group. Analysis of contact interactions will be a major activity of the WSU group during the period of this proposal. Using a rapidly increasing data set, we will test a variety of models, and explore inclusion of the di-electron channel. This work will be the basis for the Ph.D. dissertations of Gollapinni, Kottachchi, and Lamichhane.

Investigations of Electroweak Symmetry Breaking

R. Harr, A. Sakharov, K. Siehl, K. Krylova (undergraduate), K. McGee (undergraduate)

The standard model based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ is an enormously successful theory, with stunningly well confirmed predictions stemming from electroweak symmetry breaking (EWSB). Yet, the mechanism behind EWSB remains unknown. While many possibilities have been proposed, the original $SU(3)_C \times SU(2)_L \times U(1)_Y$ model assumed the Higgs mechanism for EWSB, and this has remained the standard choice [9]. This choice predicts the existence of a Higgs boson, all of whose properties are known except its mass. One of the primary objectives of the LHC is the elucidation of the mechanism of EWSB, for instance, by discovering a Higgs boson.

Harr is involved in the search for a low mass Higgs boson at CDF. With the CMS experiment Harr's group has taken the lead in making a first measurement of the trilinear gauge couplings in diboson events with a leptonic W decay and a hadronic W or Z decay, referred to as the $\ell\nu jj$ final state. This work is being carried out with the $\ell\nu jj$ group anchored at the Fermilab LHC Physics Center (LPC) using the same final state to search for the Higgs boson.

The work began in the summer of 2011 with the projects of two REU students, Krylova of SUNY Buffalo and McGee of Johns Hopkins, aided by Dr. Kalanand Mishra of Fermilab. McGee investigated requirements to separate WW and WZ to $\ell\nu jj$ events from the primary backgrounds of W + jets, Z + jets, $t\bar{t}$, single top, and QCD events. These investigations required a combination of MC and data. Krylova investigated methods to simulate anomalous trilinear gauge couplings, and quantities sensitive to anomalous couplings. The Monte Carlo code to simulate anomalous couplings is still in an evolving state. She was able to setup and run a version of the MCFM code, producing parton level output that can be used to weight PYTHIA or HERWIG events to mimic the effects of anomalous couplings.

Previous measurements of trilinear gauge couplings in hadronic collisions have been carried out in either the $W\gamma$, $Z\gamma$, or fully leptonic $WW \rightarrow \ell\nu\ell\nu$ events. Attempting this measurement in the semileptonic

Figure 6: For scenarios with anomalous couplings, the ratio to the standard model of the distribution of transverse momentum of the highest momentum jet is plotted. The coupling κ , has the value unity in the SM, and is varied by amounts of ± 0.05 , ± 0.15 , and ± 0.25 .

diboson events is challenging, but the higher event yields and more detailed information available make it attractive to try (see Fig. 6). The REU students have laid the groundwork for a first measurement with 2011 data.

K. Siehl has taken this on as his thesis project. We hope to keep the undergraduates involved for as long as they are willing, and with Sakharov and collaborators from the LPC, we are aiming to complete the first measurement in 2012. With additional data in 2012 we will refine the measurement, and work to reach higher diboson q^2 , with a result coming in late 2013. He should complete his thesis in 2014. If the Higgs boson is discovered, the measurements at high mass will test the SM for anomalies due to new physics. If the Higgs boson is ruled out, the measurements can play an important role in testing the behavior of the trilinear gauge couplings in the energy range where new physics is expected to show up in order to cancel standard model amplitudes that would otherwise challenge unitarity. In either scenario we see this measurement as an interesting test for new physics.

Exclusive W Decays

C. Clarke, R. Harr, A. Sakharov

The mass of the W boson receives corrections from known and unknown particles. The dominant contribution from known particles comes from $t\bar{b}$ loops. Additional SM contributions arise from Higgs bosons, such that precise measurements of W boson and the t -quark masses can be used to predict the Higgs boson mass.

Measurements of the W boson mass at hadron machines are traditionally carried out using leptonic W decays and fitting the transverse mass M_T distribution. Using this technique, CDF and D0 have achieved about $40 \text{ MeV}/c^2$ uncertainty on the W mass [11], and they are working towards measurements with about $25 \text{ MeV}/c^2$ resolution. These measurements achieve their impressive results owing to a significant amount of work in understanding and controlling systematic effects.

An alternative technique is to use fully reconstructed, hadronic W decays. The natural width of the W resonance is $2 \text{ GeV}/c^2$. The uncertainty on an individual, fully reconstructed W decay will be a small fraction of the width, so the achievable statistical uncertainty on the W mass is roughly $\sigma_m = (2 \text{ GeV}/c^2)/\sqrt{N}$ where N is the number of reconstructed W decays. We believe the systematic uncertainty will be negligibly small in comparison, but this remains to be verified. Just 400 fully reconstructed W decays are needed to reach $100 \text{ MeV}/c^2$ uncertainty, and 10,000 decays to reach $20 \text{ MeV}/c^2$ uncertainty.

on the W mass. Additionally we can directly observe the W line shape and measure the width with comparable accuracy.

The first goal is to reconstruct an exclusive W decay. Appropriate decay modes are necessary. They must be readily triggered and preferably have a final state consisting of all charged tracks. The most obvious decay that fits these requirements is $W^+ \rightarrow J/\psi D_s^+$, shown in Fig. 7, where the decay $J/\psi \rightarrow \ell^+ \ell^-$ provides the necessary trigger signature. A literature search turned up no estimates for this branching fraction. Estimates exist for radiative modes of the form $W \rightarrow P\gamma$ where P is a pseudoscalar meson [12]. Petrov has estimated the branching fraction of $W^+ \rightarrow J/\psi D_s^+$ to be about 2×10^{-5} [13], considerably higher than the as-yet-unseen $P\gamma$ modes. A recent preprint [14] estimates the inclusive $W \rightarrow J/\psi X$ branching fraction to be about 10^{-4} , consistent with Petrov's estimate. Using 100 nb for the W production cross section, 6% for the $J/\psi \rightarrow \mu^+ \mu^-$ branching fraction, and 10% for the fraction of D_s decays that can be reconstructed, we estimate 12 reconstructed W decays per inverse femtobarn, or about 60 in the 2011 data and 2 to 3 times as many in the expected 2012 data.

Figure 7: Feynman graph for the decay $W^+ \rightarrow J/\psi D_s^+$.

We expect the primary background to come from $b\bar{b}$ events, where one B hadron decays to a J/ψ and the other to a D_s . About 0.1% of events contain a pair of B hadrons, about 1% of B hadrons decay to J/ψ , and about 25% of B hadrons decay to a D_s meson, yielding about 2×10^{-6} of events that will contain a J/ψ and D_s . This would form the main combinatoric background. The total rate is about 2 orders of magnitude greater than the expected rate of $W \rightarrow J/\psi D_s$ events, but with an exponentially falling mass distribution. Some combinatorial background is expected, but in the vicinity of the W resonance, the combinatorial background should be comparable to the signal. Measuring the combinatorial background in a wide mass window around the W resonance will allow us to reliably predict the amount under the resonance. Further suppression may be possible by requiring the J/ψ to come from the primary vertex and imposing isolation criteria around the J/ψ and D_s .

Observing the decay, or setting a limit on the branching fraction, will allow us to make sensible projections for mass measurement prospects. Harr with postdoc Alexandre Sakharov, and graduate student Christopher Clarke are performing a search for this decay with the 2011 CMS data. An analysis note should be ready in early 2012, with a paper to follow. The number of W bosons in the full CDF data set is comparable to the 2011 CMS data, so we are performing a parallel search with CDF data, discussed in Sec. 4.5.

While this project was originally motivated to measure the W boson mass, it represents a new technique that could have other uses yet to be explored. For example, we could apply this to flavor-changing neutral-current decays of the W and Z bosons, or measure $|V_{cd}/V_{cs}|$ from the ratio of $W^+ \rightarrow J/\psi D^+$ relative to $W^+ \rightarrow J/\psi D_s^+$ decays. Exploration of the possibilities has just begun. Observation of the first fully reconstructed W boson decay is a prerequisite.

4 CDF Experiment at Fermilab

4.1 CDF Detector Operation

R. Harr, P. Karchin, M. Mattson

The WSU group played a major role in operating the CDF experiment. From April 2010 - January 2011, Mattson served as Operations Manager, responsible for the 24-7 operation of the experiment during a

one-week period, with two off-weeks between each on-week. Mattson also served as leader of the “on-call” team responsible for 24/7 trouble-shooting of the calorimeter front-end electronics. Harr and Karchin have served as “scientific coordinators”, leading the control room shift crew for 7 day periods.

From January 2011 - October 2011, Mattson served as one of two Sub-Project Leaders for CDF Silicon Operations. The Silicon detector is vital for analyses that require hadronic tracking and B-tagging. The Silicon group was responsible for keeping the detector operating at high efficiency, diagnosing problems, and making repairs, with the SPLs making the decisions. The detector was originally designed to be used up to 5/fb of integrated luminosity. By the end of Run II, the Tevatron delivered over 12/fb. Despite operating well past its designed lifetime and declining support resources, the silicon detector continued operating well up to the end of data taking.

Mattson’s service for CDF Operations was made possible by special funding from a DOE supplement, a Fermilab sub-contract, and a Fellowship from the Fermilab Universities Research Association.

4.2 Heavy Flavor Group Convener

R. Harr

The heavy flavor or B physics group of CDF has amassed an impressive set of physics results including the measurement of J/ψ and b -hadron production cross sections (516 citations) [15], the measurement of B_s^0 mixing (394 citations) [16], and the measurement of the mass of the $X(3872)$ state (371 citations) [17]. And with the full dataset, there are a number of important analysis left to finish, and a large number of potential analysis that can be done. Therefore, Harr was thrilled when offered the opportunity to serve as one of the heavy flavor conveners beginning in January 2011. In the 10 months since, the group has produced 12 publications, with 4 more papers submitted for publication, about 10 drafts in preparation, and about 10 more analyses in progress. The publications include the first observation of the Ξ_b^0 baryon [18], the first measurement of the lifetime in the $B_s^0 \rightarrow J/\psi f_0(980)$ decay mode [19], and the first two-sided limit for the branching fraction of $B_s^0 \rightarrow \mu^+ \mu^-$ [20]. This is proving to be a very active period for CDF heavy flavor physics.

Physics group conveners track active analyses and manpower in their group, ensure that the tools and data for analysis are available, ensure that special computing resources can be allocated for high priority items, oversee the approval of analyses and see that they move to publication, request godparents (reviewers) for writing papers, assemble abstracts and requests for conference talks, review talks, and oversee the promotion of the results. The responsibilities of the conveners have increased with the thinning of the CDF collaboration.

The nominal two-year term for Harr would run from January 2011 to December 2012. With the termination of Tevatron operations, we expect the physics output to slow, and it is possible that Harr would continue beyond December 2012, depending on the interest of someone to assume the task. Therefore, this work could continue beyond the first year of the proposal. For 2011, Harr requested additional travel money from DOE, and a teaching buyout from Fermilab. Assuming the physics output slows, the teaching buyout wouldn’t be necessary in 2012, but additional travel funds will still be needed.

4.3 Rare Charm Decays

R. Harr, E. Nagelkirk (undergraduate)

Flavor-changing neutral current (FCNC) decays are suppressed at tree level in the SM, making them potentially sensitive to the appearance of new physics (NP) effects [21]. R. Harr has pioneered the analysis of rare charm decays at CDF. Rare charm decays are sensitive to new physics couplings to up-type quarks that may not appear in rare kaon and bottom decays.

Harr has concentrated thus far on searching for the decay $D^0 \rightarrow \mu^+\mu^-$, with its rather simple signature. Harr has been a primary author of two CDF papers on searches for $D^0 \rightarrow \mu^+\mu^-$ [22, 23], the first in 2003 with W. Ashmanskas, and the second in 2010 with E. Berry, I. Furic, and Y.K. Kim. These analyses employed a method that can be easily extended to other FCNC and lepton-flavor violating modes: $D^0 \rightarrow \mu^\pm e^\mp$, $D^0 \rightarrow e^+e^-$, $D_{(s)}^+ \rightarrow h^+\mu^+\mu^-$, and $D_{(s)}^+ \rightarrow h^-\mu^+\mu^+$ where h is a kaon or pion. We used data selected with a displaced vertex trigger, and identified decays in a kinematically similar reference mode with a well known branching fraction, $D^0 \rightarrow \pi^+\pi^-$, and used this to normalize the measurement of the rare decay. In the case of $D^0 \rightarrow \mu^+\mu^-$, the rare mode is distinguished from the reference mode by the identification of the daughter tracks as muons rather than pions based on detector information. The latest result set a limit on the branching fraction of 2.1×10^{-7} at the 90% confidence level.

With Wayne State undergraduate student E. Nagelkirk, Harr has developed a third analysis utilizing a different technique aimed at maximizing the sensitivity of the CDF data. The improvements build on the knowledge acquired in the two previous analyses. The biggest change is to use dimuon triggered data rather than the displaced vertex triggered data. The displaced vertex trigger is operated only at sufficiently low luminosity, while the dimuon trigger operates at all but the very highest machine luminosities. This switch will increase the number of potential $D^0 \rightarrow \mu^+\mu^-$ events by up to an order of magnitude.

With high enough statistics, the $D^0 \rightarrow \pi^+\pi^-$ mode appears as background in the data due to pion decay or punchthrough to the muon chambers, subsequently firing the trigger. The strategy is to take advantage of this background to normalize the search, as was done in the previous searches. But this time a substantial amount of punchthrough is needed, about 10^3 events, to provide an adequate normalization signal. In the past analyses, this background could be reduced to a negligible level with tight muon identification requirements – the measurement of the normalization mode could be done prior to muon identification requirements were imposed. But now, the background is an integral part of the analysis, and the final trick is to measure the contribution of $D^0 \rightarrow \mu^+\mu^-$ on the background consisting of combinatorial dimuons and a peaking $D^0 \rightarrow \pi^+\pi^-$ signal. The $D^0 \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow \pi^+\pi^-$ signals appear as Gaussian peaks of about $\sigma = 10 \text{ MeV}/c^2$ and separated by about $10 \text{ MeV}/c^2$. The ability to separate the two signals will ultimately determine the level of sensitivity we can achieve.

At this time we have a large amount of data processed and have made a first pass at optimizing the final event selection. E. Nagelkirk has graduated and gone on to Ph.D. studies at the University of Alabama, Huntsville. Harr will find another undergraduate to assist him so that a preliminary result can be ready in 2012.

4.4 Search for the Z_b^+ States

R. Harr, M. Schott (undergraduate)

In a recent paper [24], the BELLE collaboration reports evidence for two new exotic states in the $b\bar{b}$ system, $Z_b^+(10610)$ and $Z_b^+(10650)$. They observe these states in the decay chains $\Upsilon(5S) \rightarrow Z_b^\pm \pi^\mp \rightarrow \Upsilon_{(1,2,3)} \pi^+ \pi^-$ where $\Upsilon_{(1,2,3)}$ is one of the $1S$, $2S$, or $3S$ states of the Υ . From the decay chain, one can infer that the states contain $b\bar{b}$, but being charged, they must contain additional quarks, firmly placing them in the category of exotic mesons, if confirmed.

With Wayne State REU student M. Schott, Dr. S. Behari of Johns Hopkins, and Dr. J. Lewis of Fermilab, Harr is searching for these states with CDF data. This work began as the summer research project of M. Schott. During the summer he has learned how to use the CDF data and analysis code, and produced preliminary mass plots for $\Upsilon(1S) + \pi^\pm$ and $\Upsilon(1S) + \pi^+ \pi^-$. The former represents the search for the $Z_b^\pm$ states and the latter is as a check to reconstruct $\Upsilon(2S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$, a decay not yet seen in CDF data.

M. Schott is eager to continue this work on a part time basis during the academic year. He is now in position to optimize the event selection, using the $\Upsilon(2S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$ as a benchmark. We should have

a preliminary result in 2012.

4.5 Exclusive W Boson Decays

C. Clarke, R. Harr

The motivation and basic technique of this analysis is discussed in the context of CMS in Sec. 3.2. The number of W bosons in the full CDF data set is comparable to the number in the 2011 CMS data, and we're in a position to take advantage of this to effectively double the statistics for an early analysis aimed at establishing the first fully reconstructed exclusive W decays. This work is carried about by graduate student C. Clarke along with Harr and Dr. Pasha Murat of Fermilab.

4.6 Measurement of D^0 - $\bar{D}^0$ Mixing

P. Karchin, M. Mattson, N. Kulkarni

At the beginning of Run II, in 2001, charm mixing had not been observed, but continued to be the subject of intensive search efforts dating back almost to the discovery of the charm quark in 1974. Theoretical interest was, and remains, two-fold. What is the standard model rate taking into account long-range QCD effects? What new physics could be manifest in an observable mixing rate? From the experimental viewpoint at CDF, the big question in 2001 was whether we could observe the “wrong-sign” decay chain $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^+ \pi^-$, which is sensitive to mixing, without a Cerenkov detector for particle identification. However, we developed a technique using kinematic suppression to obtain a wrong-sign signal with good signal-to-background ratio and used this to set a competitive limit for mixing using a time-integrated approach. We published this result in 2006 [29].

The field changed dramatically in March of 2007 with substantial evidence for mixing discovered by the Babar and Belle experiments. This led us to begin an expedited time-dependent analysis in the $K\pi$ channel to test Babar's result. (Belle had set only a limit in this channel.) Our efforts came to fruition quickly and we reported evidence for mixing at the 2007 Lepton Photon Conference, with subsequent publication of our result in early 2008 [30].

Now, evidence for D^0 - $\bar{D}^0$ mixing comes from two sources: lifetime differences between the decays $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow K^- \pi^+$, measured by BaBar and Belle, and time-dependence of the ratio R of $D^0 \rightarrow K^+ \pi^-$ to $D^0 \rightarrow K^- \pi^+$ measured by CDF [30] and BaBar. While the combined evidence for mixing is convincing, no single measurement has reached the 5σ criterion for “observation”. Our recent analysis effort has focused on using the largest available data set to reach the “observation” level. This goal requires not only a larger data set than used in our “evidence” paper, but also study of additional, smaller systematic effects that could affect the result at the 5σ level. The analysis technique and the new systematic studies are discussed below.

Our mixing analysis is based on the measurement of the time-dependence of the ratio R of $D^0 \rightarrow K^+ \pi^-$ to $D^0 \rightarrow K^- \pi^+$ decay rates. This ratio is theoretically well-described by a quadratic function of t/τ , where t is the proper decay time and τ is the mean D^0 lifetime.

$$R(t/\tau) = R_D + \sqrt{R_D} y' (t/\tau) + \frac{x'^2 + y'^2}{4} (t/\tau)^2, \quad (1)$$

In the equation above, R_D is the squared modulus of the ratio of DCS to CF amplitudes. The parameters x' and y' are linear combinations of “physical” parameters x and y according to the relations

$$x' = x \cos \delta + y \sin \delta \quad \text{and} \quad y' = -x \sin \delta + y \cos \delta,$$

where $x = \Delta M/\Gamma$, ΔM is the mass difference between the D^0 meson weak eigenstates, $y = \Delta\Gamma/2\Gamma$, and $\Delta\Gamma$ is the decay width difference between these eigenstates. Γ is the average decay width of the eigenstates.

The parameter δ is the strong interaction phase difference between the doubly Cabibbo-suppressed and Cabibbo-favored amplitudes. In the absence of mixing, $x' = y' = 0$ and $R(t/\tau) = R_D$.

Events are selected in real time with a trigger system developed for a broad class of heavy flavor decays. The trigger selects events with a pair of oppositely charged particles that are consistent with originating from a secondary decay vertex separated from the beamline.

In the off-line analysis, we reconstruct the “right-sign” (RS) Cabibbo-favored decay chain $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^- \pi^+$, and the “wrong-sign” (WS) decay chain $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^+ \pi^-$. The relative charges of the pions determine whether the decay chain is RS (like charge) or WS (opposite charge). The RS and WS D^* decays have the same kinematics, and differ only in decay time distributions. To reduce systematic uncertainties, we use the same set of cuts for both the RS and WS decay modes.

The ratio t/τ is determined for each D^0 candidate by $t/\tau = m_{D^0} L_{xy}/(p_T \tau)$, where $m_{D^0} = 1.8648 \text{ GeV}/c^2$ and τ of $410.1 \pm 1.5 \text{ fs}$. To study $R(t/\tau)$, we divide the data into 20 bins of t/τ ranging from 0.75 to 10.0. We choose bins of increasing size from 0.25 to 2 to reduce statistical uncertainty at larger times.

To determine the consistency of our data with the no-mixing hypothesis, we compute Bayesian contours containing the region with the highest posterior probability. The contours in the x'^2 - y' plane are shown in Fig. 8, using a data sample corresponding to an integrated luminosity of about 4 fb^{-1} . The fitted values of the mixing parameters x'^2 and y' are indicated. The no-mixing point lies on the contour corresponding to 5.3 Gaussian standard deviations

Figure 8: Bayesian probability contours in the $x'^2 - y'$ parameter space corresponding to one through six equivalent Gaussian standard deviations for a data sample corresponding to about 4 fb^{-1} . The closed circle is the best fit value for the mixing parameters. The cross indicates the no-mixing point.

While the analysis remains completely data-driven, we are now using Monte Carlo studies with full detector simulation to validate the data-driven procedures. These studies include the impact parameter distribution of D^0 s originating from B-decays, as well as reconstructed mass distributions from background channels. As examples, fully simulated backgrounds to the wrong-sign signal originating from D^0 decays are shown in the $K\pi$ mass plot of Figure 9. The simulated backgrounds are consistent with mass spectra from real data. Validation studies are underway in which simulated data are generated under the assumption of particular mixing parameters, then the same analysis procedure is applied as used for real data to extract the simulated parameters.

We have started the analysis of $R(t/\tau)$ for D^0 and $\bar{D}^0$, separately. This will provide a measurement which is sensitive to CP-violation. The experimental challenge is to take into account small differences in detector efficiency among K^+ , K^- , π^+ , and π^- species, due to differences in absorption cross sections in the detector material.

Figure 9: Full simulation of backgrounds to the wrong-sign $K\pi$ mass distribution originating from D^0 decays. The yields are normalized with respect to the number of right-sign $K\pi$ decays corresponding to the same integrated luminosity.

5 Project Time Table

Year 1	support CMS muon and tracker operations complete CMS ME4 cable construction validate tracker alignment package complete evaluation of rad-hard silicon sensors publish contact interaction result based on 2011 data publish CDF D-mixing result complete CDF analysis of exclusive W decays publish CDF rare charm decay result publish trilinear gauge coupling result based on 2011 data oversee production and publication of CDF heavy flavor results
Year 2	install CMS ME4 chambers analyze contact interaction for 2012 data implement new tracker alignment test prototype of rad-hard silicon strip modules complete CMS analysis of exclusive W decays complete work with CDF data
Year 3	support CMS muon and tracker operations test production quantities of silicon strip modules continue search/measurement of contact interactions publish trilinear gauge coupling result based on 2012 data explore W mass and width measurements explore new physics analysis projects

Task B: Theoretical Particle Physics Project Description

Principal Investigators:

Alexey A. Petrov, Professor

Gil Paz, Assistant Professor

1 Introduction and Project Objectives

The DOE Office of High Energy Physics continuing mission is defined “to understand how our universe works at its most fundamental level.” Research done by the WSU particle theory group fits this bill perfectly by formulating new approaches for theoretical, computational, and experimental research that explore the fundamental laws of physics. Cutting-edge theoretical research in particle phenomenology employs techniques of effective field theories to understand the structure of the most fundamental Lagrangian describing such basic phenomena as the origin of mass and matter. One of the most important obstacles hampering our understanding of these phenomena is the effect of strong interactions, which complicates the interpretation of experimental observables in terms of the fundamental parameters. There is a clear need to develop new and sharpen the existing theoretical tools needed for clean interpretations of experiments aimed at the understanding of those fundamental questions. In particular, the promise of investigations of heavy quark states is the systematic control of the effects of strong interactions by exploiting symmetries arising in the limit of infinite mass of the heavy quark. Thus, these analyses also probe the non-perturbative sector of Quantum Chromodynamics (QCD). The outcomes of such analyses are especially important in analyzing data from such facilities as LHC at CERN.

The *primary objective* of the research effort described in this proposal is the understanding of the structure of the fundamental Lagrangian obtained from experimental data. This objective will be accomplished by pursuing three specific goals:

- to study possible manifestation of new physics effects in the transitions of beauty and charm hadrons and to study theoretical uncertainties in those transitions due to strong interactions
- to investigate phenomenological applications of new physics models at the LHC
- to look for astrophysical implications of new physics scenarios

This proposal is to continue a vigorous research program in theoretical particle physics at Wayne State University, which involves applications of quantum field theory to the problems of particle phenomenology. This program has been supported by the DOE grant DE-FG02-96ER41005 for a number of years and is motivated by the need to uncover effects of fundamental physics probed by high energy physics experiments both directly and indirectly.

2 Personnel

Faculty: Alexey A Petrov (Professor), Gil Paz (Assistant Professor)

Post-Doctoral Research Associate: Andrew Blechman (2009-12)

Graduate Students: YG Aditya (PhD candidate, est. grad: 2013), Kris Healey (PhD candidate, est. grad: 2013)

The particle theory group at WSU has strong connections to the theoretical nuclear physics group of Prof. Sean Gavin and Prof. Abhijit Majumder. In the last five years three of the groups' graduate students obtained their PhDs: M. AlFfiky (2008, currently a lecturer at the Ain Shams University in Egypt), A. Badin (2010, currently a postdoc with Duke University), and G. Yeghiyan (2011, currently an Assistant Professor at Grand Valley State University (MI)). One student, M. Salhi, was awarded Masters degree in 2009.

Paz was hired as an Assistant Professor effective August 18, 2011. Petrov was promoted to Full Professor effective August 18, 2011.

3 Summary of recent accomplishments

In the preceding funding period WSU particle theory group obtained several important results. These results provide insight and guidance for activities conducted by experimental groups worldwide. The general thrust of research of the group involves a multitude of approaches to search for the physics beyond the standard model (SM): from precise evaluations of indirect effects of new physics (NP) in low energy data, especially from decays of heavy flavored states, and in astrophysical experiments to direct searches for NP at the LHC. This is done in anticipation of new data from the LHC experiments which, if reveals signals of physics beyond the standard model, would help to identify which model of NP matches the signature best by combining both direct and indirect signatures.

Paz and Petrov have published over 110 papers, which were cited close to 4000 times. Among the most important results are analyses of charm-anti-charm mixing, final state interactions in B-decays, heavy-quark phenomenology, extraction of $|V_{ub}|$ from inclusive B decays, non-perturbative uncertainties in rare decays, new mechanism for mediation of supersymmetry breaking, and model independent studies of the proton's charge radius.

Petrov was a recipient of the WSU Career Development Chair in 2008-09, which allowed him to buy off his teaching obligations for that academic year. As a result, Petrov spent a semester at the University of Michigan at Ann Arbor. A continuous presence of the groups' members at the Michigan Center for Theoretical Physics (MCTP) at the University of Michigan, where Paz and Petrov are Associate Members, has shaped new themes of the group's research program.

3.1 Summaries of recent research results

A. FLAVOR PHYSICS

Indirect probes of new physics in B_s and D transitions. In recent years several important experimental advances in the physics of heavy flavors were reported. In particular, many observables in B_s and D systems, such as mixing parameters, were studied. While no clear indirect sign of new physics was seen, several interesting anomalies were reported. These anomalies might go away as more data is analyzed or they might be harbingers of impending observation of new physics. In either case, correlations among several observables need to be studied.

New data, in particular on the $B_s \rightarrow \mu^+\mu^-$ branching ratio, is expected to push the level of accuracy down to the SM level. Since SM calculation of $Br(B_s \rightarrow \mu^+\mu^-)$ is “clean”, and since many NP models predict enhancement of that branching ratio, it is important to correlate it with other observables in the B_s system. Likewise, similar observables in the D^0 system are interesting and important both theoretically and experimentally.

Together with J. Hewett, E. Golowich, S. Pakvasa, and WSU grad student G. Yeghiyan, Petrov performed a study of the standard model fit to the mixing quantities ΔM_{B_s} , and $\Delta\Gamma_{B_s}/\Delta M_{B_s}$ in order to bound contributions of new physics to B_s mixing. They used this to explore the branching fraction of $B_s \rightarrow \mu^+\mu^-$ in certain models of new physics [1]. In most cases, this constrained NP amplitudes for $B_s \rightarrow \mu^+\mu^-$ to lie below the SM component. Together with J. Hewett, E. Golowich and S. Pakvasa, Petrov pointed out how, in certain models, the same combination of new physics couplings occur in the amplitudes for both D^0 - $\bar{D}^0$ mixing and the rare decays $D^0 \rightarrow \ell^+\ell^-$. If the new physics dominates and is responsible for the observed mixing, then a very simple correlation exists between the magnitudes of each, so the rates for the decay $D^0 \rightarrow \ell^+\ell^-$ are completely fixed by the mixing. Observation of $D^0 \rightarrow \ell^+\ell^-$ in excess of the standard model prediction could identify new physics contributions to D^0 - $\bar{D}^0$ mixing [2].

Earlier, Petrov and his collaborators provided the first comprehensive, up-to-date analysis of those possible new physics contributions to the mass difference ΔM_D in D^0 - $\bar{D}^0$ mixing. They considered the most general low energy effective Hamiltonian and included QCD running of effective operators, as well as explored an extensive list of possible NP models that can generate these operators. In many scenarios, they found strong constraints that surpass those from direct searches [3].

Most often signals of new physics in the mixing of K , D and B -mesons are associated with enhancement of the mass difference of neutral mass eigenstates, i.e. with the NP-enhanced $|\Delta Q| = 2$ processes. Together with E. Golowich and S. Pakvasa, Petrov performed the first general analysis of new physics contributions to the $D^0 - \bar{D}^0$ lifetime difference, $\Delta\Gamma_D$. It turns out that $\Delta\Gamma_D$ can serve as a powerful discriminator among models of new physics [4]. Together with G. Yeghiyan, Petrov further re-examined constraints from the recent observation of $\Delta\Gamma_D$ on the parameters of supersymmetric models with R-parity

violation (RPV). They also discussed the importance of the choice of weak or mass basis when placing the constraints on RPV-violating couplings from flavor mixing experiments [5]. In a single-author paper, WSU graduate student G. Yeghiyan re-examined NP contribution to the lifetime difference in $D^0 - \bar{D}^0$ mixing within the non-manifest Left-Right Symmetric Model. It was shown that the diagrams mediated by a propagator with $W_L - W_R$ mixing, which were believed to give the dominant contribution, are in fact negligible in sum of diagrams [6], contrary to what was claimed before.

Other flavor physics studies. In the past decade, one of the major challenges of particle physics has been to gain an in-depth understanding of the role of quark flavor. In this time frame, measurements and their theoretical interpretation have advanced tremendously. A much broader understanding of flavor has been achieved. Petrov recently participated in several large studies related to flavor physics. One of them summarizes the results of the current generation of experiments that is about to be completed and it confronts these results with the theoretical understanding of the field which has greatly improved in the past decade [7]. Petrov also participated in the studies of physics capabilities of SuperB factory in Italy, in particular in regards to rare B decays and charm physics [8].

Petrov took part in the study of physics potential of a possible fixed-target program based on a ~ 1 TeV proton source. The study used an example of the Tevatron fixed-target program to illustrate the high discovery potential possible in the charm and neutrino sectors [9].

Charmless inclusive B decays. Charmless inclusive B decays such as $B \rightarrow X_u l \bar{\nu}$, $B \rightarrow X_s \gamma$, and $B \rightarrow X_s l^+ l^-$, play an important role in the extraction of fundamental standard model parameters and in constraining its possible extensions. There has been a lot of progress in the recent years in our understanding these decays. In the case of $B \rightarrow X_s \gamma$ this progress has changed our view of the structure of inclusive radiative B decays.

Paz has studied the contribution of subleading jet functions to inclusive decay distributions of B mesons [10]. These are power corrections which are suppressed both Λ_{QCD}/m_b and by α_s . Together with the recent two loop calculation of the leading order hard function for $B \rightarrow X_u l \bar{\nu}$, this paper will allow for a more precise description of inclusive B decays in the end point region. This will have implications for $B \rightarrow X_s \gamma$ and the extraction of $|V_{ub}|$.

Together with M. Benzke, S. J. Lee, and M. Neubert, Paz has suggested a novel factorization formula for the $B \rightarrow X_s \gamma$ photon spectrum in the endpoint region. To all orders in $1/m_b$, the factorization formula contains besides terms with the structure $H J \otimes S$ familiar from inclusive $B \rightarrow X_u l \bar{\nu}$ decay distributions, “resolved photon” contributions of the form $H J \otimes S \otimes \bar{J}$ and $H J \otimes S \otimes \bar{J} \otimes \bar{J}$, where S and $\bar{J}$ are new soft and jet functions. These new contributions arise whenever the photon couples to light partons instead of coupling directly to the effective weak interaction, see Fig. 1. They appear first at order $1/m_b$ and are related to operators other than $Q_{7\gamma}$ in the effective weak Hamiltonian. The resulting uncertainty on the decay rate defined with a cut $E_\gamma > 1.6 \text{ GeV}$ was estimated to be approximately $\pm 5\%$ [11]. Together with M. Benzke, S. J. Lee, and M. Neubert, Paz has shown that in the standard model the leading contribution to the inclusive CP asymmetry in $B \rightarrow X_{s,d} \gamma$

Figure 1: Graphical illustration of the three terms in the QCD factorization theorem for $\bar{B} \rightarrow X_s \gamma$ decay in the endpoint region [11]. The dashed lines represent soft interactions.

decays arises from a long-distance effect in the interference of the electro-magnetic dipole amplitude with the amplitude for an up-quark penguin transition accompanied by soft gluon emission. Using model estimates for the associated hadronic uncertainty for the CP-asymmetry, they predicted a value in the range $-0.6\% < \mathcal{A}_{X_s \gamma}^{\text{SM}} < 2.8\%$. In view of current experimental data, a future precision measurement of the flavor-averaged CP asymmetry would signal the presence of new physics only if a value below -2% was found. A cleaner probe of new physics was suggested by the difference of the CP asymmetries in charged versus neutral $B \rightarrow X_s \gamma$ decays [12].

B. MODEL-BUILDING AND PHENOMENOLOGY

There are several unexplained hierarchies that pervade the standard model of particle physics. One of these is the “Flavor Hierarchy”, which raises the question of why the quark and lepton masses and the mixing angles span six orders of magnitude. In comparison, the gauge couplings are all within a factor of ten or so of each other, and even that factor of ten can be explained through the renormalization group picture. It is not at all clear how to explain the fermion masses in a similar way. Together with A. Blechman and G. Yeghiyan, Petrov reconsidered the flavor problem in scenarios with two Higgs doublets. By studying two generation toy models, they looked for flavor basis independent constraints on Yukawa couplings that will give the mass hierarchy while keeping all Yukawa couplings of the same order. They generalized those findings to the full three generation case. They found that two constraints are needed to be placed on the Yukawa couplings to generate the observed mass hierarchy, and a slight tuning of Yukawa couplings of order 10%, much less than the standard model [13]. They are now studying how these constraints can be realized, and testing how much flavor changing currents are under control for various flavor “standard candles” such as meson mixing and forbidden decays.

Some time ago, P. Langacker, L.-T. Wang, I. Yavin and Paz have suggested a new mechanism for the mediation of Supersymmetry (SUSY) breaking, called “ Z' mediation” [14, 15]. In this scenario, SUSY breaking in a hidden sector is mediated via a massive $U(1)'$ gaugino, which also couples to the visible sector. More recently, J. de Blas, P. Langacker, L.-T. Wang

and Paz have combined Z' with anomaly mediation [16, 17]. The combined scenario solves the tachyonic slepton problem of anomaly mediation and avoid significant fine tuning in Z' mediation.

C. LHC PHENOMENOLOGY

One of the most important properties of new physics particles that will be discovered at the LHC is their spin. Determination of spins of produced particles is especially important since many NP scenarios can have very similar experimental signatures. SUSY models and models with universal extra dimensions provide two clear examples of such scenarios. In principle particle spins can be measured from their production cross sections once their mass is approximately known. The method works in practice because spins are quantized and cross sections depend strongly on spins. It can be used to confirm, for example, the spin-1/2 of the top quark. Direct application of this method to supersymmetric theories will have to overcome the challenge of measuring mass at the LHC, which could require high statistics. Together with G. Kane, J. Shao, and L.-T. Wang, Petrov proposed a method [18] of measuring the spins of the colored superpartners by combining rate information for several channels and a set of kinematical variables, without directly measuring their masses. This method can be applied to the measurement of spin of other new physics particles.

D. ASTROPHYSICS: BLACK HOLES AND DARK MATTER

From the observational point of view, there are currently three classes of black hole candidates: super-massive black holes in galactic nuclei, stellar-mass black holes formed from the gravitational collapse of heavy stars and possible intermediate mass black holes. From the theoretical side, one could also expect *primordial* black holes, formed in the early Universe and with mass roughly in the range $10^{-5} - 10^{38}$ g. A discovery of primordial black holes may shed light on gravity, cosmology and particle physics.

Together with WSU postdoc C. Bambi and A. Dolgov (Ferrara), Petrov has discussed the possibility that primordial black holes with mass about $10^{16} - 10^{17}$ g make the cosmological dark matter and are also responsible for the observed and unexplained 511 keV line from the Galactic Center. They have shown that such a possibility requires some fine-tuning on the black hole mass distribution, but cannot be excluded [19]. They also studied a novel mechanism of antimatter production by primordial black holes smaller than 10^{20} g, which does not involve the Hawking effect. The basic observation is that black holes surrounded by a ionized medium acquire a net electric charge, because of the large value of the proton to electron mass ratio. If the black hole mass is smaller than 10^{20} g, the electric field at the horizon can reach the critical value of vacuum instability and the production of electron-positron pairs may be efficient [20].

Beauty and charm e^+e^- factories running at resonance thresholds have unique capabilities for studies of the production of light Dark Matter particles in the decays of $B_q(D)$ meson pairs. Together with A. Badin, Petrov provided a comprehensive study of light Dark Matter production in heavy meson decays with missing energy in the final state, such as $B_q(D^0) \rightarrow$

“missing energy” and $B_q(D^0) \rightarrow \gamma + \text{“missing energy”}$. Such transitions can be studied at flavor factories by tagging the missing-energy decays with $B_q(D^0)$ decays “on the other side” [21].

Badin, Petrov and Yeghiyan also discussed a set of constraints on light DM annihilation into photons in the effective field theory framework [22]. In addition, WSU graduate student G. Yeghiyan in a single author paper examined decays of a spin-1 bottomonium into a pair of light scalar Dark Matter particles, assuming that Dark Matter is produced due to exchange of heavy degrees of freedom. He confronted his results with the experimental data and showed that Dark Matter production in Upsilon decays may lead to constraints on parameters of the models containing a light spin-0 DM particle [23].

Invited review papers

In the last several years Petrov co-authored several topical review papers. In one review, written for *Rev. of Mod. Phys.*, Petrov and A. Ryd (Cornell) provided a comprehensive review of hadronic decays of D and D_s mesons [24]. They discussed current theoretical and experimental challenges and successes in understanding of hadronic transitions of those mesons. A brief overview of the theoretical and experimental tools were given before discussing the absolute branching fractions for D and D_s mesons. Cabibbo suppressed and rare hadronic decays were discussed and compared with theoretical predictions before summarizing current understanding of hadronic multi-body decays. This review complements earlier charm physics review written by Petrov and experimentalists M. Artuso and B. Meadows [25] for *Ann. Rev. of Nucl. and Part. Sci.* in 2008.

A number of recent breakthroughs, surprises, and continuing puzzles in heavy quarkonium physics called for a new review summarizing recent advances in the field. The task was taken on by the Quarkonium Working Group. Petrov was a Section Coordinator for the Spectroscopy chapter of this review and wrote several subchapters. This work, published in *Eur. Phys. J. C.*, systematically addressed new results in the physics of heavy quarkonia and concluded by prioritizing directions for ongoing and future efforts [26].

Editorships of conference proceedings in 2009-2011

Together with Paul Karchin, Petrov was an Editor of the Proceedings of the 2009 Meeting of the Division of Particles and Fields of the American Physical Society (DPF-2009), which was held on campus of Wayne State University on 26-31 July 2009. The proceedings, published as SLAC eConf [27], can be found at <http://www.slac.stanford.edu/econf/C090726/>.

4 Service and Outreach

Members of WSU particle theory group maintained high-visibility status in the physics community. Together with Karchin, Petrov organized and chaired 2009 Meeting of the Division of Particles and Fields of the American Physical Society (DPF-2009). DPF meeting

Name	Position	Support	Years	Position after WSU
Postdocs and lecturers				
A. Blechman	postdoc	DOE/WSU	2009-12	currently at WSU
C. Bambi	postdoc	DOE/WSU	2007-08	University of Tokyo (Japan)
F. Gabbiani	postdoc	DOE/WSU	2003-06	Industry
J. Tandean	lecturer	WSU	2004-05	University of La Verne (CA)
A. Onishchenko	postdoc	DOE/WSU	2002-04	Hamburg Univ. (Germany)
Graduate students				
M. AlFiky	Ph.D.	DOE/WSU	2001-08	Lecturer, Ain Shams U. (Egypt)
A. Badin	Ph.D.	NSF/WSU	2005-10	Postdoc at Duke U
G. Yeghiyan	Ph.D.	DOE/WSU	2005-11	Asst. Prof., Grand Valley State U.
Y.G. Aditya	Ph.D.	WSU/NSF	2007-13	currently at WSU
K. Healey	Ph.D.	WSU/DOE	2007-13	currently at WSU
M. Sun	MA/MS	WSU	2001-03	University of Michigan
M. Salhi	MA/MS	WSU	2007-09	University of Tennessee

Table 1: Former students and postdocs of WSU particle theory group

is a major national conference in particle physics occurring every other year. The conference was held on campus of Wayne State University on 26-29 July 2009 [28] with over 400 participants attending and was considered a success [29]. Petrov was also a member of the Program Committee and a Convener of the Heavy Flavor Parallel Session for the following meeting of DPF, DPF-2011 [30], held in Providence (RI) on 8-13 August 2011.

Petrov served as a convener of the heavy flavor parallel session for the Continuous Advances in QCD workshop in 2008. He is continuously serving as a convener of the "Beyond the Standard Model / Super-B factory" topical group of the International Quarkonium Working Group [31], organizing topical workshops at Nara (2008), FNAL (2010), and GSI (2011).

Petrov is an Editor for journals *Advances in High Energy Physics* (ISSN: 1687-7357) and *Central European Journal of Physics* (ISSN 1644-3608). For years he has been a referee for Phys. Rev. D., Phys. Rev. Lett., JHEP, Eur. Phys. Journ. C, J. of Phys. G, and other internationally recognized physics journals. Petrov is also a referee for the DOE and NSF grant proposals. He has been a member of the DOE site visit committee to the University of Arizona in 2009 and a REU Grant Panel Member for the NSF's Division of Physics (2010) and Division of Astronomical Sciences (2009). Since coming to WSU in 2001, Petrov supervised seven graduate students, as well as postdoctoral associates and lecturers. Please see Table 1 for their careers after leaving WSU. Petrov is a P.I. of a successful Research Experience for Undergraduates (REU) program supported by an NSF grant [32]. This program integrates Astrophysics, Theoretical and Experimental Particle and Nuclear Physics as main components. A large fraction of the students currently majoring in physics at WSU has been associated with our REU program. New WSU theory faculty, Paz and

Majumder, agreed to join REU effort in 2012. Petrov also gave supporting lectures to WSU QuarkNet students.

Paz is on the editorial board of ISRN High Energy Physics [ISSN: 2090-7419] of Hindawi Publishing (<http://www.isrn.com/journals/hep/>). Paz is a referee for the JHEP, Phys. Rev. D, Phys. Rev. Lett., Nucl. Phys. B, Phys. Lett. B, and Mod. Phys. Lett. A.

Research presentations. In 2009-11 Petrov gave several invited plenary talks: at CHARM 2009 (Lemen, Germany), at BEAUTY-2009 (Heidelberg, Germany), at the *Progress and Challenges in Flavour Physics* (Primosten, Croatia) at CKM-2010 at the University of Warwick (Coventry, UK), and at the *Lattice meets Phenomenology* Workshop at Durham University (UK) summarizing the status of the field in charm physics. In addition, he gave a talk on SUSY bound states at the International Workshop on Heavy Quarkonium at FNAL [33]. He also participated in the program *Indirect Searches for new physics at the time of LHC* at the Galileo Galilei Institute of Theoretical Physics in Florence, Italy in the Spring of 2010, as well as in the program *Flavor physics* at Aspen Center for Physics in the Summer of 2011. WSU postdoc Blechman gave a talk at the DIS-2010 conference. WSU students Badin and Yeghiyan each gave two parallel talks at DPF-2009 [34].

In the years 2009-11 Paz gave several invited talks: at a PVDIS workshop (Madison, WI), at the Vxb 2009 Workshop (SLAC, CA), at the SCET 2010 Workshop (Munich, Germany), at CKM-2010 at the University of Warwick (Coventry, UK), and at Moriond QCD 2011 (La Thuile, Italy). Paz also contributed talks to: SUSY 2009 (Boston, MA), PHENO 2010 and PHENO 2011 Symposia (Madison, WI), Panic 2011 (Cambridge, MA), DPF 2011 (Providence, RI), and DNP 2011 Meeting (East Lansing, MI). He also participated in SCET 2009 (Cambridge, MA) and SCET 2011 Workshops (Pittsburgh, PA), the program *Indirect Searches for new physics at the time of LHC* at the Galileo Galilei Institute of Theoretical Physics in Florence, Italy in 2010, and LoopFest X Conference (Evanston, IL).

In 09-11, Petrov and Paz presented research seminars at over two dozens of universities [35].

Awards. The following awards were given to the members of the particle theory group

A. A. Petrov	WSU Board of Governors Faculty Recognition Award, 2010
	WSU Richard J Barber Physics Faculty Award, 2010
	WSU Career Development Chair, 2008-09
K. Healey	WSU T. Rumble Fellowship, 2011-12
A. Badin	WSU T. Rumble Fellowship, 2009-10
G. Yeghiyan	WSU Knoller Fellowship, 2009-10

Petrov was promoted to Full Professor effective August 18, 2011.

5 Proposed Research Activities and Future Plans

The *primary objective* of the research effort described in this proposal is the understanding of the structure of the fundamental Lagrangian from experimental data. We propose a variety of projects ranging from studies of QCD in colliders and heavy-quark systems and analyses of indirect effects of new physics to LHC phenomenology and studies of Dark Matter. The obtained results will be important for the interpretation of experimental data obtained at the LHC experiments, as well as for astrophysical observatories. We shall discuss those activities in turn.

PHENOMENOLOGY OF HEAVY FLAVORS AND INDIRECT PROBES OF NEW PHYSICS

New physics signatures in B_s transitions. B_s system rapidly becomes the forefront of studying possible indirect effects of new physics. New data on $B_s \rightarrow \mu^+ \mu^-$ branching ratio from CDF, CMS and LHCb is pushing the level of accuracy down to the SM level, further restricting available parameter space of NP models. In addition, reported anomalies in the like-sign dimuon charge asymmetry from the semileptonic decays of B-mesons,

$$A_{sl}^b = \beta_d a_{sl}^d + \beta_s a_{sl}^s, \quad \text{with} \quad a_{sl}^q = \frac{|\Gamma_{12}^q|}{|M_{12}^q|} \sin \phi_q \quad (1)$$

underline the importance of studies of B_s decays and mixing. An average of recent D0 and CDF measurements of A_{sl}^b [36] implies

$$a_{sl}^s = (-12.7 \pm 5.0) \times 10^{-3}, \quad (2)$$

which, if compared to the SM prediction of $(2.06 \pm 0.57) \times 10^{-5}$ reveals a 2.5σ discrepancy. Note that individual D0 measurements have a slightly larger discrepancy. While a 2-3 σ discrepancy might well be a fluctuation, it is instructive to see what NP can cause it and how those causes correlate with other observables in B_s system.

As can be seen from Eq. (1), a_{sl}^s can differ from its SM value if new physics affects M_{12} (or ΔM_s , as $\Delta M_s = 2|M_{12}^s|$) with non-zero ϕ_q . This has been pointed out by many authors [37]. Alternatively, NP can enhance Γ_{12}^s or, correspondingly, B_s lifetime difference, $\Delta\Gamma_s$. This possibility for enhancing a_{sl}^s has been explored recently in [38]. Interestingly, possible NP enhancement of $\Delta\Gamma_s$ by $\Delta B = 1$ NP interactions has been proposed by Petrov and his collaborators before recent measurements of a_{sl}^s became available [39].

Petrov proposes a systematic study of possible $\Delta B = 1$ NP contributions to a_{sl}^s and $\Delta\Gamma_s$. A generic NP $\Delta B = 1$ Hamiltonian $\mathcal{H}_{NP}^{\Delta B=1}$ can be written as

$$\begin{aligned} \mathcal{H}_{NP}^{\Delta B=1} &= \sum_{q,q'} D_{qq'} [\bar{\mathcal{C}}_1(\mu) Q_1 + \bar{\mathcal{C}}_2(\mu) Q_2] , \\ Q_1 &= \bar{b}_i \bar{\Gamma}_1 q'_i \bar{q}_j \bar{\Gamma}_2 s_j , \quad Q_2 = \bar{b}_i \bar{\Gamma}_1 q'_j \bar{q}_j \bar{\Gamma}_2 s_i , \end{aligned} \quad (3)$$

where the spin matrices $\bar{\Gamma}_{1,2}$ can have an arbitrary Dirac structure, $D_{qq'}$ are some NP-generated coefficient functions [4], and $\bar{\mathcal{C}}_{1,2}(\mu)$ are Wilson coefficients evaluated at the energy scale μ . This gives us the following contribution of $\Delta B = 1$ NP to the lifetime difference:

$$\Delta\Gamma_s^{NP} = -\frac{8G_F\sqrt{2}}{M_{B_s}} \sum_{qq'} D_{qq'} V_{qb}^* V_{q's} (K_1 \delta_{ij} \delta_{kl} + K_2 \delta_{kj} \delta_{il}) \sum_{m=1}^5 I_j(x, x') \langle \bar{B}_s | O_m^{ijkl} | B_s \rangle, \quad (4)$$

where i, j, k, l are the color indices, $\{K_\alpha\}$ are some combinations of Wilson coefficients [39].

Besides exclusive B-decays considered in [38], the same operators of Eq. (3) would also affect both absolute lifetimes of B_q and Λ_b states, and, separately, lifetime ratios of $\tau(B_s)/\tau(B_d)$ and $\tau(\Lambda_b)/\tau(B_s)$ and other heavy baryons. SM predictions of those quantities [40] suffer from less hadronic uncertainties, while their precise measurements are already available – and will even be better with upcoming LHC data. Building on his earlier calculation of lifetimes in the SM [40], Petrov will perform a comprehensive analysis of possible new physics effects in $\Delta B = 1$ operators.

CP-violation in non-leptonic decays of charmed mesons. Charmed quark serves as an important lab for our understanding of non-perturbative QCD: in some sense its mass is “in between” being heavy and light (as compared to Λ_{QCD}), so the techniques developed for dealing with non-perturbative QCD effects in heavy or massless quark limits are not directly applicable here. In that respect, understanding non-leptonic charm decays presents a formidable problem. In light of new experimental data expected from BES-III (which recently started taking data), LHC-B, and Belle (Super-Belle) experiments, it is important to have accurate description of non-leptonic decays of charmed mesons and baryons. It might be surprising that after spectacular advancements in description of non-leptonic decays of beauty particles [41] the developments of theoretical calculations in charm were quite modest. This is quite unsettling, as, for example, it forces experimental groups to use old BSW model calculations for estimates of their experimental sensitivities. It is also important to have a reliable description of non-leptonic decays for searches of new physics in charm CP-violating asymmetries. In many models of NP these asymmetries have sources different from those probed in B-meson transitions.

Some reasons for such slow progress in understanding non-leptonic decays of charm can be understood if one considers direct, “carbon-copy” application of B-meson factorization theorem to charm transitions [42]. Up to corrections Λ_{QCD}/m_c the amplitude for D decay to two mesons M_1 and M_2 reads

$$\begin{aligned} \langle M_1(p_1) M_2(p_2) | Q_i | D(p) \rangle &= f^{D \rightarrow M_1}(p_2^2) \int_0^1 dx T_i^I(x) \Phi_{M_2}(x) \\ &+ \int_0^1 d\xi dx dy T_i^{II}(\xi, x, y) \Phi_D(\xi) \Phi_{M_1}(x) \Phi_{M_2}(y), \end{aligned} \quad (5)$$

where $f^{D \rightarrow M_1}(p_2^2)$ is a $D \rightarrow M_1$ form factor, and Φ_i are the corresponding light-cone distribution amplitudes for M_i and D . $T^{I,II}$ are hard-scattering kernels calculable in perturbation

theory, and Q_i are the effective operators governing $\Delta c = 1$ weak transitions [25]. It was found [42] that the calculations do not reproduce data on $D \rightarrow K\pi$ transitions well, unless additional model-dependent assumptions are provided, sometimes overriding the results of the calculation based on Eq. (5). Are non-perturbative corrections $\mathcal{O}(\Lambda_{\text{QCD}}/m_c)$ too big?

Petrov proposes a complete, multi-prong investigation of non-leptonic charm transitions. First, contributions of nearby light-quark resonances $R = \pi(1800), \dots$ etc. to transition amplitudes will be investigated. While formally $\mathcal{O}(1/m_c)$, they might give be the most $1/m_c$ correction to Eq. (5), as they contribute a potentially large factor $(m_D^2 - m_R^2 + i\Gamma_R m_D)^{-1}$ for $m_R \sim m_D$. The relevant technique was already developed by Petrov and his collaborators [43]. Second, as was noted years ago [44], a description of $D \rightarrow M_1 M_2$ decay in the $N_c \rightarrow \infty$ limit yields surprisingly good results. Factorization theorem of Eq. (5), along with large N_c counting rules, could provide a good description of leading $1/N_c$ -corrections to the result of [44] in the combined large m_c and large N_c -limits and can explain the old rule of “discarding $1/N_c$ corrections” in charm decays [45]. Finally, the decay amplitude of Eq. (5) acquires an imaginary part through the hard scattering kernels. Thus, investigations of perturbative and non-perturbative parts of the strong interaction phases, needed for theoretical calculations of “direct” CP-violating asymmetries, becomes possible, at least in the combined $N_c \rightarrow \infty$ and $m_c \rightarrow \infty$ limits. For example, one can assess the relative contribution of “perturbative” strong phases and non-perturbative phases due to “nearby resonances.” Also, an analysis of $SU(3)$ -breaking in decay amplitudes will be performed (for previous $N_c \rightarrow \infty$ studies see [46]).

Petrov will also perform a calculation of direct CP-violating asymmetries due to NP amplitudes in the above-described framework (for previous calculations see [47]). In particular, recent constraints on CP-violating asymmetry

$$\Delta a_{CP} = a_{CP}(KK) - a_{CP}(\pi\pi), \quad \text{with} \quad a_{CP}(f\bar{f}) = \frac{\Gamma(D^0 \rightarrow f\bar{f}) - \Gamma(\bar{D}^0 \rightarrow f\bar{f})}{\Gamma(D^0 \rightarrow f\bar{f}) + \Gamma(\bar{D}^0 \rightarrow f\bar{f})}, \quad (6)$$

which is a convenient observable at LHCb [48] due to cancelation of many systematic uncertainties. It will be calculated in both SM and in several models of NP. This CP-violating asymmetry is non-zero because of flavor $SU(3)$ breaking in D^0 decay. Current LHCb constraint is $\Delta a_{CP} = (-0.275 \pm 0.701 \pm 0.25)\%$.

Studies of $D^0 - \bar{D}^0$ mixing amplitudes in 't Hooft model. The $D^0 - \bar{D}^0$ system is unique among the neutral mesons in that it is the only one whose mixing proceeds via intermediate states with down-type quarks. The mixing is very slow in the standard model, because the third generation plays a negligible role due to the smallness of $|V_{ub}V_{cb}^*|$ and the relative smallness of m_b , so the Glashow-Iliopoulos-Maiani (GIM) cancellation is very effective. This makes the calculation of $D^0 - \bar{D}^0$ mixing amplitudes very difficult [49, 50]. In fact, in the limit $|V_{ub}V_{cb}^*| \rightarrow 0$ and flavor $SU(3)$, both mass and lifetime difference in D^0 system are exactly zero [51]! Thus, the calculation of ΔM_D and $\Delta\Gamma_D$ amounts to calculation of $SU(3)$ -breaking corrections.

An interesting question that can be posed is what order in $SU(3)$ -breaking parameter m_s one expects to see non-zero values for ΔM_D and $\Delta \Gamma_D$. Using group-theoretical arguments, it was shown in [49] that $\Delta M_D, \Delta \Gamma_D \sim \mathcal{O}(m_s^2)$. However, it was suggested [50] $\mathcal{O}(m_s)$ effects can be found (it is interesting to note that the leading-order result in $1/m_c$ expansion scales as $\mathcal{O}(m_s^4)$ [52]!). Since a complete analytic solution of QCD in $3+1$ dimensions is not available, it is difficult to prove dynamically that $\Delta M_D, \Delta \Gamma_D \sim \mathcal{O}(m_s^2)$.

It turns out that a lower-dimensional version of QCD in one space and one time dimension is exactly solvable in the limit of large number of colors, $N_c \rightarrow \infty$. It is known as the 't Hooft model and is believed to be a good testing ground for the ideas that might prove useful and important in analyzing theories in $3+1$ -dimensions. In a weak coupling regime, where its coupling constant scales as $g \sim (N_c)^{-1/2}$, as $g^2 N_c \rightarrow \text{const.}$, with $N_c \rightarrow \infty$, this model was employed to study duality violations in heavy meson decays [53].

Since group-theoretic arguments of [49] are not sensitive to the number of space dimensions, Petrov proposes to use 't Hooft model to study m_s dependence of the mixing parameters. Preliminary studies performed by Petrov indicate that such a study can be done using developed numerical techniques [54]. Dialing in several numerical values of the strange quark mass, Petrov will obtain the dependence of the mixing amplitudes on m_s with a fit.

Radiative B decays. Radiative B decays $B \rightarrow X_s \gamma$ are important probes of new physics. The precise measurement of the total branching ratio and the CP asymmetry constrains many possible models of new physics. The photon spectrum in $B \rightarrow X_s \gamma$ can be utilized for precision extraction of $|V_{ub}|$ and its moments are used for extraction of $|V_{cb}|$. To achieve these goals, a good theoretical control over non-perturbative effects is needed.

$B \rightarrow X_s \gamma$ has a complicated short distance structure that involves the full effective Hamiltonian and not just one current operator as in $B \rightarrow X_{u,c} l \bar{\nu}$. As a result, there exists a class of non-perturbative power corrections unique to radiative B decays. These so called “resolved photon contribution” probe the hadronic structure of the photon. While some of these effects were discussed in the literature, [55]–[61], they were thought to be small or under control. Furthermore, their general structure was not identified or understood.

A more systematic approach was taken in [62] and [11]. In [62] it was shown that these non-perturbative effects lead to Λ_{QCD}/m_b corrections to the total $B \rightarrow X_s \gamma$ decay rate. This was very surprising since the common lore in the field has been that power corrections to the total rate only enter at order $\Lambda_{\text{QCD}}^2/m_b^2$. The effects of these non-perturbative corrections on the total branching ratio were analyzed systematically in [11]. It was shown there that they result in the largest error (up to 5%) in the NNLO calculations of the total rate.

The resolved photon contributions have a much more dramatic effect on the CP asymmetry in $B \rightarrow X_s \gamma$. For almost 20 years [63] the CP asymmetry was assumed to be dominated by perturbative effects [64, 65, 66] and to be in the standard model around 0.5%. Comparing the theoretical prediction to the measured value, $\mathcal{A}_{X_s \gamma} = -(1.2 \pm 2.8)\%$ [67], there is room for new physics effects. There are many studies of such effects on the CP asymmetry, see for

example the references within [12]. From the experimental side, reducing the experimental error below the 1% level is one of the goals of the future B factories [68, 69]. When resolved photon effects are taken into account, it turns out that the CP asymmetry is actually *dominated* by non-perturbative effects. In the standard model the CP asymmetry can be in the range $-0.6\% < \mathcal{A}_{X_s\gamma}^{\text{SM}} < 2.8\%$ [12].

From the above discussion it is clear that resolved photon contributions can have an important impact. So far their effects were only studied for the CP averaged $B \rightarrow X_s\gamma$ rate and the CP asymmetry for $B \rightarrow X_s\gamma$. Their effects on $B \rightarrow X_s l^+ l^-$ and the photon spectrum in $B \rightarrow X_s\gamma$ are unknown.

Paz proposes a systematic study of the resolved photon effects for $B \rightarrow X_s l^+ l^-$. These would arise from contributions of operators in the weak Hamiltonian, which are different from the operators contributing to $B \rightarrow X_s\gamma$. As a result, this decay mode might be sensitive to new physics effects that do not contribute to $B \rightarrow X_s\gamma$. Recent studies of power [70] and perturbative [71] corrections to $B \rightarrow X_s l^+ l^-$ have found sizable corrections to $B \rightarrow X_s l^+ l^-$ and in particular to the zero of the forward-backward asymmetry of this decay. It is important to complete the picture and study the resolved photon contributions. The need for such a study was also emphasized in [71].

The effects of the resolved photon contributions on the photon spectrum in $B \rightarrow X_s\gamma$ are not known numerically. The same holds for the moments of the photon spectrum. Paz proposes a systematic study of these effects. The former are important for the extraction of $|V_{ub}|$ from $B \rightarrow X_u l \bar{\nu}$. The latter are important for the extraction of $|V_{cb}|$ from inclusive decays. The current approach is to perform a global fit to moments of $B \rightarrow X_c l \bar{\nu}$ and $B \rightarrow X_s\gamma$ and extract from them $|V_{cb}|$, the b quark mass m_b , and the HQET parameter λ_1 (also known as μ_π^2) [67]. There is a visible difference between the extraction of m_b from fits that includes $B \rightarrow X_s\gamma$ and fits that do not include it. Whether this is due to a systematic effect or just a statistical fluctuation is unknown. Thus, the effects of resolved photon contributions should be considered. This point was also emphasized in [72].

To try and reduce the theoretical error on $B \rightarrow X_s\gamma$ as much as possible, one would like to have a better theoretical control on the resolved photon contributions. One possible way is to use other decay modes. Similar non-local matrix elements can arise in semi-inclusive B decays [73] and in color-suppressed $B \rightarrow D\pi$ decays [74]. For the latter one can use heavy quark symmetry to relate $B \rightarrow D$ matrix elements to B meson forward matrix elements. Paz proposes a study that would see whether combining information from these decays modes can lead to a better estimate of the resolved photon contributions.

The resolved photon contribution to the $B \rightarrow X_s\gamma$ decay rate were studied in [11] at $\mathcal{O}(\alpha_s \Lambda_{\text{QCD}}/m_b)$. A concern was raised [75] that the effects due to charm penguin loops might be accidentally small at this order. It was advocated that the $\mathcal{O}(\alpha_s^2 \Lambda_{\text{QCD}}/m_b)$ corrections from charm penguin loops be studied. Paz proposes to extend the formalism of [11], and study these effects.

Semileptonic charmless B decays. Semileptonic charmless B decays allow for the extraction of $|V_{ub}|$. In order to reject background from $B \rightarrow X_c l \bar{\nu}$ decays, experimental cuts are imposed. These cuts introduce an intermediate scale, the jet scale, on top of the familiar hard and soft scales. The use of the Soft Collinear Effective Theory (SCET) allows to separate these three scales by the means of factorization theorems. The decay spectra can then be written as a product of hard perturbative functions and a convolution of perturbative jet functions and non-perturbative shape functions. Symbolically the factorization formula is

$$d\Gamma \sim H \cdot J \otimes S + \frac{1}{m_b} \sum_i h \cdot J_0 \otimes s_i + \frac{1}{m_b} \sum_k h \cdot j_k \otimes S + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{m_b^2}\right), \quad (7)$$

where only terms for which there are explicit expressions for all of their perturbative components are listed. The rest of the $1/m_b$ suppressed terms for which we do not have such explicit expressions can be found in [76] and [77].

The current extraction of $|V_{ub}|$ [67] is at what could be described as an “NLO” (in α_s and Λ_{QCD}/m_b) level. Namely, the leading power perturbative hard (H) and jet functions (J) are calculated at one loop and the subleading hard (h) and jet (J_0) functions are calculated at tree level. More recently there has been work in the field towards what can be described as an “NNLO” analysis. The leading order hard function (H) was calculated to two loop order by various groups [78]–[81]. Paz has calculated one type of power corrections, namely subleading jet functions (j_k), which are suppressed both Λ_{QCD}/m_b and by α_s [10].

In order to improve the determination of $|V_{ub}|$ to an “NNLO” level, the new calculations need to be implemented. This requires work from theory in revising the way the perturbative and the non-perturbative components are combined. In particular, one has to be careful in implementing power corrections in order to avoid double counting as was explained in [10]. Furthermore, the extraction of $|V_{ub}|$ relies on a non-perturbative input from $B \rightarrow X_s \gamma$. The current analyses do not include the resolved photon contribution to the photon spectrum, which as explained to in the previous subsection, are still not known numerically. Paz proposes to do an “NNLO” study that includes these new perturbative and non-perturbative inputs. Such a study would take us to the boundary of what is possible theoretically, and allow for a maximal use of available and future high precision experimental data.

QCD AND COLLIDER PHYSICS

An important theoretical advance in the last decade has been the development of SCET. This effective field theory is tailored to describe emission of collinear particles, which have a large energy and a small invariant mass. Although it was developed originally for flavor physics, in recent years it has been applied to problems beyond that, such as hard QCD and jet physics. Since SCET is an effective field theory, it is clear how to separate the perturbative from the non-perturbative and how to include power corrections. The following describes several projects in applying SCET to several outstanding issues in QCD.

Power Corrections. Mondejar and Pineda [82, 83] have studied the operator product expan-

sion at subleading power for deep inelastic scattering in the context of the 't Hooft model: two dimensional QCD in the large N_c limit. Being solvable, this model allows to directly compute the moments associated to the cross section at subleading power. Surprisingly, they report a breakdown of the operator product expansion beyond leading power. This result is very alarming. The use of the operator product expansion is an indispensable tool in perturbative QCD. Paz proposes to study this issue using SCET.

Resummation Beyond Leading Power. A related topic follows from Paz's work on subleading jet functions for inclusive B decays [10]. Since these functions are related to time order products of collinear fields, they appear outside of the context of flavor physics, for example in DIS at $x \rightarrow 1$. Paz proposes to study the factorization and resummation beyond leading power using the tool of SCET.

Transverse Momentum. Transverse momentum dependent parton distribution functions (TMDPDF) are generalization of the regular parton distribution function. These objects, which appear, for example, in factorization formula for Drell-Yan and Higgs production at small transverse momentum, do not seem to be well defined in QCD [84]. Factorization proofs given in the context of SCET for these processes have not been able to give a satisfactory operator definition of these objects [85, 86, 87]. Recently, Collins has proposed a new definition of TMDPDF [88, 89]. The relation of this definition to the ones presented in [85, 86, 87] is not clear [89]. Clearly this issue requires further study. Paz proposes to study TMDPDFs using SCET.

LHC PHENOMENOLOGY

Z' mediation of supersymmetry breaking. Some time ago P. Langacker, L.-T. Wang, I. Yavin and Paz have suggested a new mechanism for the mediation of Supersymmetry (SUSY) breaking, called “ Z' mediation” [14, 15]. In this scenario, SUSY breaking in a hidden sector is mediated via a massive $U(1)'$ gaugino, which also couples to the visible sector. In a more recent work, J. de Blas, P. Langacker, L.-T. Wang and Paz, have combined Z' with anomaly mediation [16, 17]. This allows to solve the tachyonic slepton problem of anomaly mediation and avoid significant fine tuning in Z' mediation.

The combined anomaly and Z' mediation scenario has interesting phenomenology that Paz proposes to study. In the combined scenario the gaugino spectrum is completely determined by the anomaly mediation. However, since additional exotic matter is introduced, the spectrum of the gauginos can be dramatically different from the MSSM. In the specific models considered in [16, 17] the gluino is only somewhat heavier than the Lightest Supersymmetric Particle (LSP), which is the wino in this case. Since stops and sbottoms are typically lighter than the first two families of squarks, the decay products of the gluino are mainly dominated by the third generation states: $b\bar{b} + \tilde{N}_0$, $t + \bar{b} + \tilde{C}^+$, and $t\bar{t} + \tilde{N}_0$. Another prominent feature of this scenario is the presence of a Z' gauge boson with $M_{Z'}$ around several TeV, unlike the pure Z' -gaugino mediation where $M_{Z'}$ is typically very heavy. Such a Z' has an excellent chance of being discovered at the LHC. Detailed measurements of its properties provide clues crucial to piecing together the complete picture of mediation of

supersymmetry breaking.

Observing CP asymmetries at the LHC. In a paper written together with P. Langacker, L.-T. Wang and I. Yavin, Paz has presented a new observable that is sensitive to CP violating phases in supersymmetric extensions of the standard model [90]. Considering a cascade decay of a heavy squark, which decays into a quark, two opposite-sign leptons, and an LSP, one can form a triple product from the momenta of the two leptons and the quark. To observe CP asymmetries, one needs both a CP even (“strong”) and a CP odd (“weak”) phase. In a Lorentz invariant notation, such a triple product will appear as Levi-Civita tensor multiplied by i . Thus, it carries a “strong phase” of $\pi/2$. The “weak phase” arises from the neutralino-slepton-lepton coupling in the Lagrangian. In [90] it was shown that in a case where the cascade decay proceeds via an on-shell neutralino and an off-shell slepton, the resulting CP asymmetries can be observed at the LHC.

Paz proposes a study that looks for similar observables in other decay channels. These may involve more particles in the cascade or the polarization vectors of some of the particles. One would also want to think about observing CP phases in other models of new physics. In [90] it was crucial that the neutralinos were Majorana fermions, in some other cases these conditions may be relaxed.

Properties, production and decays of exotic bound states of SUSY particles. Many examples of physics beyond the Standard Model contain colored objects that can potentially form bound states. One possibility is SUSY with light top squarks [91]. It is interesting to study phenomenology of those states. One reason is that these states can decay via annihilation of constituents (e.g. top squarks), which could lead to precise determinations of their masses. This is possible due to the fact that all particles in the final state can be detected [92].

Preliminary studies performed by Petrov and A. Blechman indicate that in some regions of SUSY parameter space, these states can have novel decay channels not considered previously [92]. For example, the bound states that can mix with Higgs bosons, leading to rich experimental signatures. Petrov proposes to consider radiative leptonic decay channels of those states. Those channels are interesting due to the fact that the lowest-mass bound state of stops has quantum numbers 0^{++} , which implies that its decays to a pair of fermions are helicity suppressed. Addition of the photon to the final state lifts this helicity suppression, making such decay channels as $\mu^+\mu^-\gamma$ quite attractive for the experimental studies of such exotic bound states.

Finally, Petrov collaborates with Harr on calculation of exclusive W -decays, such as $W \rightarrow J/\psi D_s$ in SCET. These processes can be used to precisely determine W mass at LHC.

DARK MATTER

Weakly-Interacting Massive Particles (WIMPs), stable neutral states, which exist in many extensions of the standard model, provide a good solution to cosmological Dark Matter problem. Correct identification of the nature of WIMP will lend support to one or another extension of the SM possibly detected at the LHC (see above). It is thus not surprising

that much of the recent efforts in both high energy and astrophysical experiments has been directed towards searches for those states. However, despite numerous experimental and theoretical efforts we are still far from understanding of DM nature and properties.

Resonant Dark Matter (DM) interactions. Compatibility of the CDMS and XENON null results [93, 94] with observation of the annual modulation by DAMA [95] and CoGeNT [96] is probably one of the most intriguing experimental puzzles that is yet to be solved in the dark matter phenomenology. Recently several possible solutions of this problem were proposed. While some of them place reasonable doubt onto DAMA results [97], others involve rather developed models of dark matter. Among proposed models are resonant DM (rDM) [98], inelastic [99], and composite [100] dark matter.

Petrov proposes to see the issue from a slightly different perspective. Since DAMA and CoGeNT experiments both detect events with very small recoil energy, a possible explanation of positive result of DAMA and CoGeNT and null results of the other experiments (such as CDMS) can be due to enhanced low-energy cross section of DM-nuclear interaction. Petrov proposes to study the possibility of the existence of the low energy DM-nucleus resonant bound state using the effective field theory formalism.

6 Summary

With new data available from LHC and astrophysical experiments, high energy physics will continue to be an exciting field for a long time. Petrov and Paz proposed a comprehensive program of investigations in theoretical particle physics that includes indirect searches for new physics, LHC phenomenology and Dark Matter studies. All of those issues address the same problem of understanding of the structure of the fundamental Lagrangian obtained from experimental data. The discussed issues are among the most intriguing ones, and Petrov and Paz’s current and past research has strongly positioned them to address them.

PROJECT TIMETABLE

Year I: **Heavy flavors:** resolved photon contribution in $B \rightarrow X_s \gamma$ (Paz); NP in lifetime differences in B_s (Petrov). **LHC pheno:** anomaly and Z' mediation phenomenology (Paz); exotic SUSY bound states (Petrov). **QCD:** Studying the breakdown of OPE in the 't Hooft model using SCET (Paz).

Year II: **Heavy flavors:** resolved photon contribution to $B \rightarrow X_s l^+ l^-$ (Paz); $D^0 - \bar{D}^0$ mixing in 't Hooft model (Petrov); CP-violation in charm decays (Petrov). **QCD:** resummation beyond leading power (Paz). **LHC pheno:** Anomaly and Z' mediation (Paz). **Astro:** sticky Dark Matter in effective field theory (Petrov)

Year III: **Heavy flavors:** $\mathcal{O}(\alpha_s^2 \Lambda_{\text{QCD}}/m_b)$ corrections from charm loops (Paz); semileptonic decays (Paz); exclusive charm decays (Petrov). **QCD:** TPDF using SCET (Paz) **LHC pheno:** CP asymmetries at the LHC (Paz); exclusive W decays in SCET (Petrov)

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(Task B)

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