"Report in the Energy and Intensity Frontiers, and Theoretical Physics at Northwestern University"

Funding Opportunity Announcement Number: DE-SC0010143

5/1/13 – 3/31/16

Institution: Northwestern University
633 Clark Street, Crown Center 2-502 Evanston, IL 60208

Administrator: Kelly Morrison
(847) 491-4800, OSR-Evanston@northwestern.edu

PI: Mayda Velasco, Full Professor of Physics and Astronomy
2145 Sheridan Road F155, Evanston, IL 60208
(847) 467–7099, m-velasco@northwestern.edu

Co-PIs: André de Gouvêa, Ian Low, Francis Petriello, Heidi Schellman, Michael Schmitt, Mayda Velasco

Programs: Energy and Intensity Frontiers and Theoretical Physics

DOE Office of Science: Division of High Energy Physics
DOE Office of Science Program Review Contact: Abid Patwa;
(301) 903-0408, Abid.Patwa@science.doe.gov

Organization: Northwestern University
Project Director: Mayda Velasco
Programs: Energy and Intesity Frontiers and Theory
PIs: André de Gouvêa, Ian Low, Francis Petriello,Heidi Schellman, Michael Schmitt, Mayda Velasco
Award Number: DE-SC0010143
Project Title: Research in the Energy and Intensity Frontiers and Theoretical Physics at Northwestern University

Executive Summary

The Northwestern (NU) Particle Physics (PP) group involved in this report is active on all the following priority areas: Energy and Intensity Frontiers. The group is lead by 2 full profs. in experimental physics (Schmitt and Velasco), 3 full profs. in theoretical physics (de Gouvêa, Low and Petriello), and Heidi Schellman who is now at Oregon State. Low and Petriello hold joint appointments with the HEP Division at Argonne National Laboratory.

The theoretical PP research focuses on different aspects of PP phenomenology. de Gouvêa dedicates a large fraction of his research efforts to understanding the origin of neutrino masses, neutrino properties and uncovering other new phenomena, and investigating connections between neutrino physics and other aspects of PP. Low works on Higgs physics as well as new theories beyond the Standard Model. Petriello pursues a research program in precision QCD and its associated collider phenomenology. The main goal of this effort is to improve the Standard Model predictions for important LHC observables in order to enable discoveries of new physics.

In recent years, the emphasis on experimental PP at NU has been in collider physics. NU expands its efforts in new directions in both the Intensity and the Cosmic Frontiers (not discussed in this report).

In the Intensity Frontier, Schmitt has started a new effort on Mu2e. He was accepted as a collaborator in April 2015 and is identified with important projects.

In the Energy Frontier, Hahn, Schmitt and Velasco continue to have a significant impact and expanded their CMS program to include R&D for the real-time L1 tracking trigger and the high granularity calorimeter needed for the high-luminosity LHC. Hahn is supported by an independent DOE Carreer Award and his work will not be discussed in this docummment. The NU analysis effort includes searches for rare and forbidden decays of the Higgs bosons, Z boson, top quark, dark matter and other physics beyond the standard model topics. Four students completed their PhD: Kubik is now contributing to the Cosmic Frontier program, Pollack to both the Intenstity and Energy Frontiers and Pozdnyakov and Odell will continue in the Energy Frontier. All our research scientists, Anastassov, Ofierzynski, Lusito, and Stoynev, have found new positions. The new post-docs are Travato from Scuola Normale de Pisa, Odell from Northwestern and Bhattacharya from Brown. Trovato is now supported by Hahn, and so is Sung, previously at MIT.

Organization: Northwestern University
PIs: Michael Schmitt, Mayda Velasco
Title: Energy Frontier Physics
Report for May 2013 – March 2016

Energy Frontier Physics and CMS

The NU group strikes a balance between key standard model physics, Higgs physics, and searches for new particles. This effort includes rare and forbidden decays of the Higgs boson, Z boson and top quark, searches for dark matter and additional Higgs bosons, in both the 8 and 13 TeV data.

Our previous involvement in the hadron calorimeter and the endcap muon system hardware, calibration and software is now rechanneled to the endcap high granularity calorimeter (HGC) development. The tracking trigger development continues both at the HLT level (Run-2) and at L1 (Phase-2).

This document is origanized as follows. We provide a brief summary of recent achievements and the list the changes in personnel.

Personnel: The CMS group at Northwestern (Table 1) is led by two full professors, Mayda Velasco and Michael Schmitt, and one assistant professor, Kristian Hahn (not included in this report).

The main changes in personnel are due to the departure of three research fellows: Anton Anastassov (now at Nokia), Radek Ofierzynski (now at Varian Medical Systems), Letizia Lusito (now at the Euro-Mediterranean Center on Climate Change - CMCC), and Stoyan Stoynev (now at Fermilab); and the graduation of four PhD students: Andy Kubik (now at the Cosmic Frontier), Brian Pollack (now at the Intenstity and Energy Frontiers), Andrey Pozdnyakov and Nate Odell (both continue in the Energy Frontier).

Some of the accomplishments in the 2013-2016 period:

1. Publication in PLB: Search for a Higgs boson decaying into a Z and a photon in pp collisions[1], Velasco editor, Pollack's thesis.
2. Publication in PRD: Detailed study of final-state radiation in decays of Z bosons produced in pp collisions[2], Schmitt editor, Kubik's thesis.
3. Publication in PRL: Search for Flavor-Changing Neutral Currents in Top-Quark Decays into a Z boson and light quark[3], Velasco editor.
4. Publication in JHEP: Measurement of the differential and double-differential Drell-Yan cross sections[4].
5. Publication in PLB: Search for Higgs Dalitz decays $H \to \gamma^*\gamma \to \ell\ell\gamma$[5], includes $H \to (J/\Psi)\gamma \to \mu\mu\gamma$, Pozdnyakov editor and thesis.
6. Made public: Search for high mass scalar boson $A \to Z\gamma \to \ell\ell\gamma$ searches (HIG-14-031)[7], Pollack editor and extension to even higher masses (HIG-16-014). Combined paper with 13 TeV data to be submitted for publication soon, Velasco co-editor[21].

Table 1: Summary of CMS Personnel as of March 2016: Mayda Velasco (MV), Michael Schmitt (MS) and Kristian Hahn (KH).

name	location	physics	detector	supervisors/comments
Faculty				
Mayda Velasco	NU	Higgs, Top	HGC	
Michael Schmitt	NU	Exotica, EWK	HGC	
Kristian Hahn	NU	EWK, Higgs, DM	Tracker, L1 Trigger Upgrade	
Post-docs				
Nate Odell	NU	Top, Higgs	HGC	MV & MS woking at CMS in $H \to b\bar{b}$
Saptaparna Bhattacharya	NU	Higgs, searches	HGC	MV & MS, Previously at Brown Univ. woking at CMS in SUSY Searches
Brian Pollack	NU	Higgs, Ana. Tech.	HGC	MV & MS (1/2 in Mu2E)
Marco Trovato	NU:CERN (3:1)	Top, Higgs, DM	HLT L1 Tracker Upgrade	MV & KH, Previously at Scuola Normale Superiore di Pisa, CDF
Kevin Sung	CERN:NU (1:3)	Higgs, EWK, DM	Tracker DAQ L1 Tracker Upgrade	KH, Previously at MIT woking at CMS in $H \to 2\ell 2\nu$
Senior Graduate Students				
Nicholas Mucia	NU	SUSY, Exotica	CSC-MUON	MS, 6th year
Graduate Students				
Thoth Gunter	NU	EWK and Random Forest	TBD	MS, 3rd year
Stanislava Sevova	NU/CERN	Exotica - DM	Tracker Upgrade	KH, 3rd year
Incoming Graduate Students				
James Bueghly	NU	Higgs	HGC	MV, at CMS since 2014
Ziheng Chen	NU	SUSY, TOP	HGC	MS & MV, at CMS since 2013
Undergraduate Students				
Yao Li	NU	—	HGC	MV, HGC testbeam
Lacey Rainbolt	NU	—	Analysis Techniques	MS

7. Made public: Search for top quark decays via Higgs-boson-mediated flavor changing $t \rightarrow Hc$ (TOP-13-017)[9], in the multi-lepton channel, Odell editor. Collaboration wide review finished, to be submitted for publication.

8. Major contribution to the global event description (GED) and reconstruction for 2015 startup (conveners Anastassov, Stoynev).

9. Major contribution to tracking usage in the high level trigger (HLT) in preparation for 2015 startup (convener Trovato).

10. CO2 Cooling test for the high granularity calorimeter design, phase 2 upgrade (Velasco, J.F. Low).

11. High granularity calorimeter DAQ development needed for the testbeam, phase 2 upgrade (Velasco, Odell and Bueghly).

12. HGC simulations testing and development – Bhattacharya.

13. Beam radiation instrumentation and luminosity (BRIL) on call experts in 2015, Pozdnyakov (previously Odell, Pollack). Gunter continues in 2016.

14. Luminosity determination, convener Stoynev, referee Velasco [11, 12] for 7 and 8 TeV and Schmitt [13, 14] for 13 TeV.

15. Velasco Selected co-convener for the Standard Model Physics (SMP) group starting Sept. 2016.

16. Snowmass 2013: Velasco convener for top quark rare decays and contributer to physics facilities; Odell contributer to top quark studies; Schmitt contributer to electroweak studies

Leadership

As described below, we play a wide range of leadership roles in CMS and the particle physics community.

Convenerships: Anton Anastassov and Stoyan Stoynev served as the co-conveners of the reconstruction group until 2014. This responsibility was especially large given the need for revamping the event data model. Marco Trovato served as CMS convener for HLT tracking triggers working group. Mayda Velasco serves as the leader of the Higgs Rare Decay Group thanks to her visionary role in the $H \rightarrow Z\gamma$ and $\gamma\gamma^*$ modes and now will be in charge of the combine paper of all the FCNH top decay searches (Multi-leptons, $b\bar{b}$ and $\gamma\gamma$). Michael Schmitt serves as a member of the Standard Model Physics Editorial Board and of the Statistics Committee. Velasco will start as Standard Model Physics Convener in Sept. 2016.

ARCs: CMS convenes an Analysis Review Committee (ARC) for every public physics document. The ARCs provide a focussed skeptical review completely independent of the physics group conveners. The "green light" for collaboration-wide review (CWR) is given by the ARC, only after all issues have been resolved by the authors. Naturally, the physics coordinator seeks knowledgeable and critical people to serve on ARCs.

The NU group has been tapped by Physics Coordination to serve on ARCs many times. In the 2013–2016 period, Schmitt has served on 2 ARCs, Stoynev on 1 ARCs, and Velasco on 10 ARCs and 5 as chairs (plus 4 for feasibility studies made for the Summer 2013 Study).

Special CMS Committees: Velasco served on a special committee to assess the readiness of the hadronic calorimeter (HCAL), two in 2014. This committee was convened in response to problems with HCAL work during the present long shutdown.

Velasco continues to be on the Selection Committee for Guest Visitors at the LPC at Fermilab.

Velasco presented a special lecture on the main Physics topics pursued at CMS during RUN-1 at the LPC at Fermilab; Schmitt presented lectures in electroweak physics in Mumbai, India.

Velasco has organized several workshop or served in their advisory committees. Example, Velasco is in the LOC for ICHEP-2016.

Special High Energy wide service: Velasco and Schmitt both served as reviewers for DOE, NSF and various journals.

Velasco is a HEPAP members since March of 2015.

CMS Physics

Higgs Boson Rare Decays (PI: Velasco)

The study of the SM Higgs boson is a major NU focus. We are developing searches in rare decay channels, we participate in meetings of the LHC Higgs Working Group, and Velasco evaluated options for future Higgs factories.

A fundamental scalar particle has been discovered and its mass is 125 GeV. Certain loop-induced decay modes are sensitive to new physics. The branching fraction $B(H \to \gamma\gamma)$ is about 0.3%, and the related channels $H \to Z\gamma$ and $H \to \gamma^*\gamma$ have similar rates. We have led the effort in these channels. In the first channel $Z \to \ell^+\ell^-$ decays are selected, ($\ell^\pm$ stands for $e^\pm$ and $\mu^\pm$), and the results were published in July 2013 [1]. Her CMS analysis group has since expanded significantly. Her NU group finished several Higgs rare decay searches and now is working on four different decay modes for Run-2:

1. $H \to Z\gamma \to \ell^+\ell^-\gamma$ with the matrix-element (ME) and multivariate analysis (MVA) methods. This analysis was possible after (PD) Pollack implemented the proper angular correlations of the $\ell^+\ell^-\gamma$ system in the physics generator. The gain in sensitivity is about 10-15% compared to the already NU-CMS published results that we produced [1] in 2013. The work was docummented by (PD) Pollack in AN-14-211 [15], and will be used in the RUN-2 13 TeV analysis.

2. $H \to \gamma^*\gamma \to \ell^+\ell^-\gamma$, the so-called *Dalitz mode* has now been expanded to include the electron channel, as the results presented in MORIOND [16] of 2014 were purely based on the dominant muon channel. The electron and muon combined results were submitted for publication, HIG-14-003[5]. The docummentation and final paper was produced by (GS) Pozdnyakov and he made all the approval presentations. The low invariant mass of the $\ell^+\ell^-$ pair poses a severe experimental challenge because the leptons emerge with a very small opening angle, causing them to fail the standard isolation criteria, at both the offline reconstruction and the trigger level. Since this decay mode is very rare, little attention was paid to this problem and we were forced to develop the requisite tools. We identified alternative triggers and modified the lepton reconstruction. It should be noticed that the ratio $\Gamma(H \to \ell\ell\gamma)/\Gamma(H \to \gamma\gamma)$ is expected to be about 0.05 for electrons and muons. One of the reasons to work on this $\ell\ell\gamma$ channel is that will give us access to CP violating phases that are not accessible with the

pure $H \to \gamma\gamma$ decay mode. For RUN-2, the main issues in the muon channel is due to the redefinition of the muon plus photon trigger and improvements have been proposed.

3. $H \to (J/\psi)\,\gamma$, the approved analysis performed by (GS) Pozdnyakov, (GS) Bueghly and Stoynev is docummented in AN-13-335 [17] and included in the HIG-14-003 paper[5]. Stoyan and Velasco in collaboration with Petriello come up with a new idea on how to have access to the Higgs to $c\bar{c}$ coupling at the LHC using this $\ell^+\ell^-\gamma$ topology, that so far has been assumed not to be possible. Their initial work on this subject, "Higgs boson decays to quarkonia and the Hccbar coupling[18], was performed with Frank Petriello and already published. Since then, additional work has been done in this subject by Stoynev and Petriello, see [19]. The $H \to (J/\psi)\gamma$ search will be significantly improved in RUN-2 thanks to special triggers developed by us.

4. $H \to \mu\mu$, will be a source of background as it contributes via final-state radiation (FSR). As described below, we are experts of FSR in Z decays and also Drell-Yan. We will also pursue this rare decay channel, which has similar level of significance as the other rare decay channels that we are pursuing and is the missing item to have the full $m_{\mu\mu}$ spectrum.

In **2016-2017** New postdoc and (GS) Bueghly will be involved in these analyses. More details below on the fitting/statistical analysis techniques been developed by Pollack in collaboration with Schmitt.

In **2018-2019** we will have enough data (100 fb^{-1}) to be sensitive to these channels. We will perform a combined analysis of the full $m_{\ell\ell}$ spectrum.

Searches for Higgs Bosons in Beyond the Standard Models Scenarios (PI: Velasco)

1. $A \to Z\gamma$, a search for high mass (200-500 GeV) scalar bosons with a narrow or a wide decay width for the $A \to Z\gamma \to \ell\ell\gamma$ decay channel was performed by (PD) Pollack [7]. The extended limit to higher masses was also perfomed by Pollack, and made public for Moriond 2016 [8]. The limits set in this analysis are more sensitive (up to 100x) than any other diboson decay channel, and about 50% more sensitive than the related ATLAS search. There is significant interest on this search, as many beyond the standard model scenarios predict a suppression of $A \to \gamma\gamma$ and an enhancement of $A \to Z\gamma$.

   Interest in this analysis increased in 2015 and 2016 due to the gamma-gamma enhancement at 750 GeV. We have now combined $A \to Z\gamma$ with the 13 TeV data [21] and will be published shortly.

   This analysis will be continued in Run-2, where the mass range of the search will be extended into the TeV range and paying special attention to the muon channel.

2. $A \to \mu\mu$, Low-mass dimuon resonance search:

   Velasco and J.F. Low are interested to search for a low-mass dimuon resonance ($A \to \mu^+\mu^-$). A feasibility study using the 8 TeV Monte Carlo samples for 20 fb^{-1} integrated luminosity shows that a 5-sigma FCNH signal significance can be achieved for a branching fraction $\mathcal{B}(t \to Ac) \times \mathcal{B}(A \to \mu^+\mu^-)) \geq 0.00066$ assuming the resonance mass $m_A = 30$ GeV. The distributions of dimuon invariant mass, binned by jet multiplicities, where the branching fraction of 0.00066 is used. The significance is the highest in the final state of $\mu^+\mu^-$ + 1 b jet + 1 additional central jet. The dominant background process there is the $t\bar{t}$ production which accounts for 90%.

This has been extended by Velasco and Odell in order to participated in the characterization of an upward fluctuation in the dimuon mass spectrum observed with the 8 TeV CMS data. Our contribution was first aimed at verifying and validating the results of our collaborators on CMS. In 2016, we have mostly been responsible for characterizing the statistical significance of the observed excess and taking into account the so-called look elsewhere effect. To achieve this we have adopted a novel technique (attributable to Eilam Gross and Ofer Vitells) that allows for efficient calculation of the probability of having observed the excess anywhere in our search range.

Searches for Forbidden Decays Involving Boson (PIs: Velasco and Schmitt)

- Search for FCNC Z Decays: Mucia and Schmitt have conducted a search for the forbidden decay $Z \to e\mu$. This is the central topic in Mucia's PhD thesis (defended June 2016). The search sensitivity is four times lower than the OPAL limit, and nearly twice as low as a prior ATLAS result.

- Composite Higgs searches: Velasco, (GS) Odell and (PD) Trovato are studying two Higgs doublet models (2HDM) with tree-level flavor-changing neutral Higgs currents (FCNH) in which $B(t \to Hc) = 1\%$ [22]. The search for $t\bar{t} \to Hc + Wb \to WWj + \ell\nu b \to \ell\nu\ell\nu j + \ell\nu b$ was performed in the tri-lepton and same-sign di-lepton topologies (31 different channels). Challenges in both the tri-lepton and same-sign channels were met until a good agreement between data and simulation in the control regions was achieved. The main discrimination is provided by the H_T, missing energy and jet multiplicities. The analysis is approved and public[9]. No excess of events over the SM background is observed and a $B(t \to Hc)$ branching fraction larger than 0.93% is excluded at the 95% confidence level. Due to the inclusion of the same sign events, the limit found in our multi-lepton analysis is better than those previously found by CMS[23], where a 1.3% exclusion at the 95% confidence level was made.

There are other FCNH searches for the case where the Higgs boson decays into two photons or $b\bar{b}$. Velasco is now officially incharge of editing the combined analysis paper (Multi-leptons plus $\gamma\gamma$ plus $b\bar{b}$) and (PD) Trovato produced the combined limit. Since other groups are involved it is hard to predict times scales, but prelimiary results already show that a 0.4% exclusion at the 95% confidence level is possible.

Standard Model Physics (PI: Schmitt)

Searches for new physics demand detailed, quantitative studies of SM processes. Accurate measurements of key cross sections and rates allow us to tune Monte Carlo models and also provide powerful constraints on the proton's parton distribution functions (PDFs). Furthermore, fundamental SM parameters such as M_W and electroweak couplings can be accurately measured at a hadron collider.

- Final State Radiation of Photons in Z decays: The first measurement of final-state radiation in Z decays was published in 2015. This landmark paper is the work of Andy Kubik (now at TAMU) and Schmitt.

- Measurement of the cross section $d\sigma/d\phi^*$: The distribution of the transverse momentum (q_T) of Z bosons is an important problem in QCD. The low q_T region depends on non-perturbative effects while the high q_T region demands higher-order corrections. The precision of cross section measurements at the LHC has reached the point where experimental resolution on q_T is a challenge. To bypass this problem, a new observable, ϕ^*, was invented that depends only on the angles of leptons emitted in Z decays; the resolution of ϕ^* is much better than the resolution on q_T. ϕ^* correlates well with q_T and theoretical predictions are available.

Mucia and Schmitt played an important role in the measurement of $d\sigma/d\phi^*$ in the dimuon channel, using the 8 TeV data. This analysis was part of Mucia's thesis. The results have been approved and a public physics analysis summary is in an advanced state. Schmitt helps with the writing of the paper.

- Measurement of the WW cross section: Schmitt and Gunter are making an innovative measurement of the fiducial WW cross section. Until recently, the measured values were somewhat in excess of the theoretical predictions, while the ZZ cross sections agreed perfectly. Speculations centered either on a problem with the jet veto (used to eliminate $t\bar{t}$ background) or new physics.

We (Gunter, Schmitt, Rainbolt) invented a radically new method using random forests to measure the cross section [24]. Gunter is conducting a real analysis with full simuation and real data, and his preliminary results were well-received by the CMS diboson group. Our plan is to demonstrate the technique with 8 TeV CMS data and then to perform a high-precision measurement with 13 TeV data. This project will be the core of Gunter's PhD thesis.

New Techniques for Finding New Physics:

Schmitt has devoted most of his research time to developing new techniques for finding new physics in the CMS data. Undergraduates Ms. Lacey Rainbolt and Mr. Raymong Chang play important roles in this, as well as Thoth Gunter and Brian Pollack.

Velasco and Odell have now joined this effort as needed by the analysis to invenstigate the observation of a 30 GeV dimuon resonance produced in association with jets.

CMS Upgrade Work for the High Luminosity LHC

The recent P5 report [40] and the updated European Strategy for Particle Physics [41] both identify the HL-LHC as the highest near/medium-term priority for the particle physics community. The HL-LHC addresses three physics drivers: Precision Higgs, Dark Matter and the "Unknown". For this program to be a success, a better endcap calorimetry will be need and the detector as a whole must have good performance at very high rates and high pile up. Which translate into having more sophisticated reconstruction and triggering algorithms, and higher granularity detectors. Our group is involved in both the endcap high granularity calorimetry and the level-1 tracking trigger.

High Granularity Calorimeter R&D (PIs: Velasco and Schmitt)

With the extension of the tracker to higher pseudo-rapidity, a high granularity calorimeter (HGC) in the endcap region is needed to take full advantage of the investment and improve the reconstruction using particle flow techniques.

The HGC has several components: First sections are a silicon-based electromagnetic calorimeter (EE) and front-hadronic calorimeter (FH). They are characterized by having: (a) Simple modules with some absorber in the EE section; (b) Modules mounted onto solid copper cassettes which include cooling infrastructure; (c) Cassettes are inserted into an absorber/structural matrix; (d) Many key services are integrated onto cassettes or in the immediate detector volume. The back section is a scintillator/brass sampling hadronic calorimeter with radiation-tolerant scintillator.

As described below, we are involved in: (1) the cassette liquid CO2 design, (2) testbeam DAQ

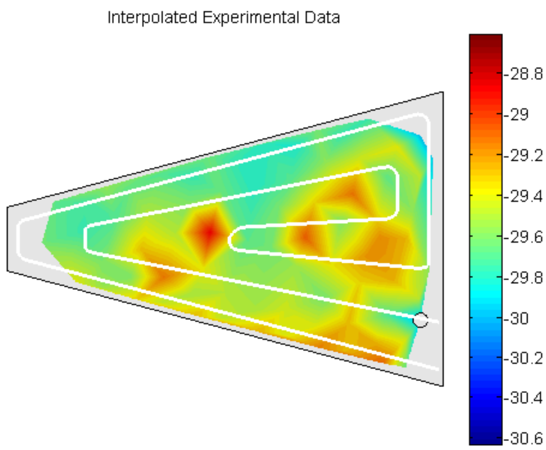

Figure 1: Interpolated temperatures of experimental data from RTD readings (°C).

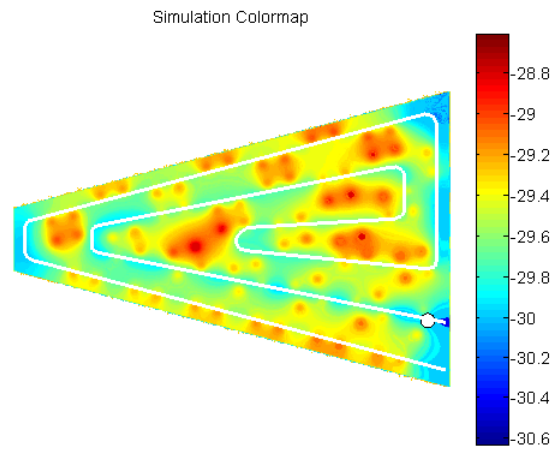

Figure 2: Colormap representing temperatures of simulated data (°C).

development and ultimately test beam data taking and analysis needed to validate not only the design, but also (3) the simulation and clustering algorithms.

CO_2 ***Cooling for High Granularity Calorimeter:*** A major goal of the CMS Phase 2 upgrades is the development of a silicon-based HGC. The HGC will be composed of a series of trapezoidal casettes. Each cassette will consist of a copper cooling plate with sensors mounted on both sides. One important task is to ensure that each cassette is held at a constant and uniform temperature of -30°C. To achieve this, a copper tube carrying flowing liquid CO_2 is embedded in the cooling plate. Velasco, Low, (GS) Bueghly, and undergraduate Andrejevic performed a temperature analysis of an HGC cassette prototype. The prototype was developed by collaborators at the University of Minnesota and Fermilab.

The CO_2-cooled cassette prototype was tested at Fermilab's Silicon Detector Facility (SiDet) with a liquid CO_2 setup. HGC electronics were simulated by small heaters, and temperature readings were taken using 77 RTDs dispersed across the plate. Discrete temperature measurements were linearly interpolated to construct a continuous map of the heat distribution across the plate. The experimental temperature distribution is shown in Figure 1. The maximum temperature spread across the plate was measured to be 1.1°C, an encouraging result for the current cassette and CO_2 tube design. Additionally, the experimental distribution was compared with a simulated temperature map, shown in Figure 2. The simulated and experimental temperature maps show good agreement, with a mean temperature difference (simulated minus experimental) of 0.032°C with standard deviation 0.17°C. The CO_2 design is not final and Velasco's group will continue to perform temperature analyses for the HGC cassettes as they are further developed.

Data Acquisition for High Granularity Calorimeter: Velasco's group is actively involved in the development of a data acquisition system for the HGC as part of the CMS Phase 2 upgrades. This work was begun in the summer of 2015 by Velasco, Low, (GS) Bueghly, and undergraduate Andrejevic, along with collaborators at the University of Minnesota. Andrejevic has since returned to Cornell for the new term, and undergraduate Li has joined the group. In 2016 the work is

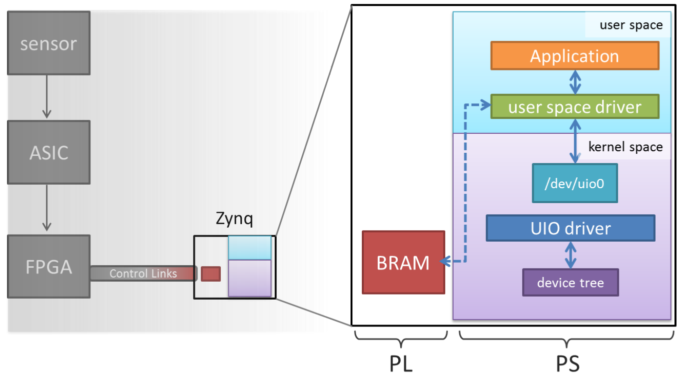

Figure 3: A visualization of key steps in the data transfer process. General data flow preceding the arrival of data to the Zynq is shown on the left. The right side provides a closer look at the interaction between the programmable logic (PL) and processing system (PS) of the Zynq in completing the transfer.

been done by Odell and Bueghly. The work is being undertaken with the aim of use with the test beam at Fermilab. The development approach hopes to refine calorimeter readout by introducing a new device to to the data acquisition architecture: the Zynq All-Programmable System-on-Chip (SoC), manufactured by Xilinx. The Zynq architecture includes both processor (PS) and FPGA (PL) components. It thus affords a number of novel features, including built-in interfacing between PS and PL devices and integration of an embedded operating system within a data acquisition framework.

The general data acquisition design is shown in Figure 3. Raw data from an HGC sensor are sent to an application-specific integrated circuit (ASIC). The data are then transferred to an Artix FPGA for initial processing before being delivered by AC-coupled control links to a board with a Zynq setup. For this board, we use the ZedBoard, manufactured by Digilent. The focus of Velasco's group is in successfully accessing the inbound data on the Zynq PL, transferring the data to the Zynq PS, developing and integrating software to produce a data readout, and moving the data readout to an external machine via the ZedBoard's built-in ethernet port. In practice, this involves temporarily storing data in a block of memory (BRAM) on the Zynq PL. An embedded Linux development kit, Petalinux, is used to place a hardware-compatible operating system on the Zynq PS. This operating system is used to access the data in the BRAM and run data readout software on the board. These components, and their placement in the data acquisition design, are shown in Figure 1. Ongoing development by the group includes creating a realistic data generator for testing our design and working to increase read and write speeds with the Zynq PS.

This DAQ develpment has required for us to work very closely with the developers of the OTSDAQ (based on the XDAQ framework used by CMS) and experts on the front end electronics. The new XDAQ is important for the testbeam taking place at Fermilab and CERN.

Simulation and Algorithm Development: Schmitt's group is contributing to the simulation of the HGC. Namely, Bhattacharya has run validation codes for the simulation and identified problems and provided assistance in solving them. More recently, she has investigated the timing capabilities of the HGC and, according to simulation, this device will measure the time of a shower with a precision better than 0.3 ns. This requires taking into account the time of propagation of the shower itself.

Schmitt and Bhattacharya intend to work with the algorithms group. Their work will shift gradually from simulation studies to algorithm development during the 2016–17 period.

Operations and Maintenance Responsibilities During Run-2

The NU group has M&O responsibilities in several areas which includes: (1) HLT: Tracking and Higgs channels (Trovato, Bueghly, Velasco); (2) Beam instrumentation, luminosity and simulation (Velasco, Schmitt, Podznyakov, Pollack, Odell, Stoynev and Gunter); (3)production of simulated events (Pollack and Bhattacharya) and (4) we are expert (and on-call experts) on several types of shifts (Pollack, Mucia, Gunter and Sung).

Conferences, Workshops, Lectures, Schools, etc.

1. "Top physics," plenary talk at Aspen 2016, by M.Velasco
2. "Heavy Higgs Searches from CMS," BF 2015, by B. Pollack
3. "Top quark measurements," CIPANP 2015, by N. Odell
4. "Search for Z decays to an electron and a muon," APS 2015, by N. Mucia
5. "Measurement of $d\sigma/d\phi^*$," APS 2015, by N. Mucia
6. "The CMS L1 Track Trigger at the HL-LHC," USLUA 2014, by M. Trovato
7. "Fermionic Decays of SM Higgs," PIC 2014, by A. Pozdnyakov
8. "Performance analysis and future applications of the upgraded fast beam counter monitor at CMS," IBIC 2014, by B. Pollack
9. "SM Higgs in boson decay modes (CMS)," SUSY 2014, by S. Stoynev
10. "Search for the standard model Higgs boson," LHCP 2014, by A. Pozdnyakov
11. Physics Lectures: CMSDAS School at the LPC (Jan. 2014), FNAL, "What have we learned at the LHC?" by M. Velasco
12. "Electroweak Physics at the LHC: Where are we now?", Invited talk, Mumbai, India January 6, 2014, by M. Schmitt
13. Public Lecture: Puerto Rico (Jan. 2014), "Why are so excited about the discovery of the Higgs Boson?", by M. Velasco
14. LPC Workshop: JetMET at High Pile-up, Preparation for LHC Run II, 27-28 January 2014 LPC, Fermilab, attended by M. Trovato
15. Poster and proceding: IBIC conference 2014 at Monterey, CA. "Performence and Upgrade of the fast beam condition monitor at CMS" by B. Pollack
16. "Vector Boson Production at CMS", Invited talk, LoopFest 2014 Brooklyn, NY June 17, 2014, by M. Schmitt

17. “Higgs boson decay to ccbar”, (invited talk), Physics at LHC and beyond, Quy-Nhon,Vietnam (10 August 17 August 2014) by Stoynev

18. Poster at LHCP-2014, New-York. On Jul. 2014. “Search for a Higgs boson decaying into $\gamma^*\gamma \rightarrow \mu\mu\gamma$ with dilepton mass below 20 GeV in pp collisions at $\sqrt{s} = 8$ TeV” by A. Pozdnyakov

19. “SM Higgs in Boson Decay Modes” (CMS, plenary talk) SUSY2014, University of Manchester, Manchester, UK (21 July 26 July 2014) by S. Stoynev

20. Physics in Collision Symposium, Bloomington, Sep. 2014 (CMS, plenary talk). “Fermionic Decays of SM Higgs” by A. Pozdnyakov, Proceedings: “Fermionic Decays of SM Higgs”, Conference Report, CMS-CR-2014-363, [arxiv:1411.1981 [hep-ex]]

21. HCPSS 2014 – Hadron Collider Physics Summer School at FNAL, August 11 - 22, 2014 attended by N. Mucia

22. Theory Meeting Experiment symposium (TMEx 2014), Warsaw on September 3-5, 2014, (Invited Plenary talk), “Dark Matter Searches at the LHC” by M. Velasco

23. “Solving the CDF dijet mass bump”, ETH Zurich Seminar, Oct. 1, 2014, by M. Trovato

24. “Rare Higgs decays as probes for Higgs couplings to first- and second-generation quarks” HXSWG BR Subgroup Meeting, CERN (8 October 2014) by S. Stoynev

25. “Rare Higgs decays as probes for Higgs couplings to first- and second-generation quarks”, HXSWG open meeting on off-shell and signal-background interference issues, CERN (24 October 2014) by S. Stoynev

26. Talk “The CMS L1 Track Trigger at the HL-LHC”, US LHC Users Association Annual Meeting, ANL, Nov. 12-14, 2014, by M. Trovato

27. “Higgs boson decaying to bosons including $Z\gamma$,” HC 2013, by M. Velasco

28. “Search for Higgs in bosonic channels,” Photon 2013, by L. Lusito

29. “Charged lepton flavor violation at CMS,” CLFV 2013, by L. Lusito

CMS References and Internal Notes

[1] CMS Collaboration, “Search for a Higgs boson decaying into a Z and a photon in pp collisions at $\sqrt{s} = 7$ and 8 TeV,” Phys. Lett. B **726**, 587 (2013) [arXiv:1307.5515 [hep-ex]].

[2] CMS Collaboration, “Study of final-state radiation in decays of Z bosons produced in pp collisions at 7 TeV,” Phys. Rev. D **91**, 092012 (2015) arXiv:1502.07940 [hep-ex].

[3] CMS Collaboration, “Search for Flavor-Changing Neutral Currents in Top-Quark Decays $t \rightarrow Zq$ in pp Collisions at $\sqrt{s} = 8$ TeV,” Phys. Rev. Lett. **112**, no. 17, 171802 (2014) arXiv:1312.4194 [hep-ex].

[4] CMS Collaboration, “Measurement of the differential and double-differential Drell-Yan cross sections in proton-proton collisions at $\sqrt{s} = 7$ TeV,” JHEP **1312**, 030 (2013), arXiv:1310.7291 [hep-ex].

[5] CMS Collaboration, "Search for a Higgs boson decaying into $\gamma^*\gamma \to \ell\ell\gamma$ with low dilepton mass in pp collisions at $\sqrt{s} = 8$ TeV," Phys.Lett. **B753**, (2016) 341-362, arXiv:1507.03031 [hep-ex].

[6] CMS Collaboration, "Search for New Physics in the V/jet + MET final state," CMS Physics Analysis Summary, CMS-PAS-EXO-12-055, (2015).
`https://cds.cern.ch/record/2036044/files/EXO-12-055-pas.pdf`

[7] CMS Collaboration, "Search for scalar resonances in the 200-500 GeV mass range decaying into a Z and a photon in pp collisions at $\sqrt{s} = 8$ TeV," CMS-PAS-HIG-14-031.

[8] CMS Collaboration,"Search for Higgs to Zγ decays in an extended mass range at 8 TeV", CMS-PAS-HIG-16-014 (2016).

[9] CMS Collaboration, "Search for top quark decays via Higgs-boson-mediated flavor changing neutral currents in pp collisions at $\sqrt{s} = 8$ TeV," CMS-PAS-TOP-13-017.

[10] CMS Collaboration, "V Tagging Observables and Correlations," CMS Physics Analysis Summary, CMS-PAS-JME-14-002, (2014).
`http://cds.cern.ch/record/1754913/files/JME-14-002-pas.pdf?version=1`

[11] CMS Collaboration, "CMS Luminosity Based on Pixel Cluster Counting - Summer 2013 Update," CMS-PAS-LUM-13-001.

[12] CMS Collaboration, "Luminosity Calibration for the 2013 Proton-Lead and Proton-Proton Data Taking," CMS-PAS-LUM-13-002.

[13] CMS Collaboration, "CMS Luminosity Measurement for the 2015 Data Taking Period ," CMS-PAS-LUM-15-001.

[14] CMS Collaboration, "CMS Luminosity Calibration for the pp Reference Run at 5.02 TeV ," CMS-PAS-LUM-16-001.

[15] Brian Pollack, Andrey Pozdnyakov, Stoyan Stoynev, and Mayda Velasco , Chia-Ming Kuo, Chiu-Ping Chang, Maxim Konyushikhin , Rong-Shyang Lu , Luisa Fernanda Chaparro, Andres Carlos Florez, "Searches for a Higgs boson decaying into a $\gamma^*\gamma$ to a dilepton plus a photon in pp collisions at a center of mass energy of 8 TeV,", CMS AN-2014/211

[16] CMS Collaboration, "Search for a Higgs boson decaying into $\gamma^*\gamma$ to $\mu^+\mu^-\gamma$ with dilepton mass below 20 GeV in pp collisions at $\sqrt{s} = 8$ TeV", CMS-PAS-HIG-14-003", (2014)

[17] Andrey Pozdnyakov, Stoyan Stoynev and Mayda Velasco, "Search for a Higgs boson decaying into J/ψ + γ in pp collisions at a center of mass energy of 8 TeV," CMS AN-2013/335

[18] G. T. Bodwin, F. Petriello, S. Stoynev and M. Velasco, "Higgs boson decays to quarkonia and the $H\bar{c}c$ coupling," Phys. Rev. D **88**, no. 5, 053003 (2013) [arXiv:1306.5770 [hep-ph]].

[19] A. L. Kagan, G. Perez, F. Petriello, Y. Soreq, S. Stoynev and J. Zupan, "Exclusive Window onto Higgs Yukawa Couplings," Phys. Rev. Lett. **114**, no. 10, 101802 (2015) [arXiv:1406.1722 [hep-ph]].

[20] Brian Pollack, Mayda Velasco, "Search for high-mass Higgs-like resonances decaying to a Z and a photon", CMS AN-2014/215

[21] CMS, "Search for high-mass resonances in Zγ to ee$\gamma/\mu\mu\gamma$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV", CMS-PAS-EXO-16-019 (2016).

[22] T. P. Cheng and M. Sher, Phys. Rev. D **35**, 3484 (1987)). "Mass Matrix Ansatz and Flavor Nonconservation in Models with Multiple Higgs Doublets," Phys. Rev. D **35**, 3484 (1987).

[23] CMS Collaboration, "Search for anomalous production of events with three or more leptons in pp collisions at $\sqrt{s} = 8$ TeV," Phys. Rev. D **90**, 032006 (2014) [arXiv:1404.5801 [hep-ex]].

[24] J. L. Rainbolt, T. Gunter and M. Schmitt, "Using Random Forests to Classify W^+W^- and $t\bar{t}$ Events," [arXiv:1410.8058].

[25] R. Boughezal, Y. Li and F. Petriello, "Disentangling radiative corrections using the high-mass Drell-Yan process at the LHC," Phys. Rev. D **89** 034030 (2014) [arXiv:1312.3972].

[26] A. Banfi, S. Redford, M. Vesterinen, P. Waller and T. R. Wyatt, "Optimisation of variables for studying dilepton transverse momentum distributions at hadron colliders," Eur. Phys. J. C **71**, 1600 (2011) [arXiv:1009.1580].

[27] D0 Collaboration, "Precise study of the Z/γ^* boson transverse momentum distribution in $p\bar{p}$ collisions using a novel technique," Phys. Rev. Lett. **106**, 122001 (2011) [arXiv:1010.0262].

[28] ATLAS Collaboration, "Measurement of angular correlations in Drell-Yan lepton pairs to probe Z/γ^* boson transverse momentum at $\sqrt{s} = 7$ TeV with the ATLAS detector," Phys. Lett. B **720**, 32 (2013) [arXiv:1211.6899]

[29] NNPDF Collaboration, "Parton distributions for the LHC Run II," arXiv:1410.8849.

[30] J. Gallicchio and M. D. Schwartz, "Seeing in Color: Jet Superstructure," *Phys. Rev. Lett.*, **105** 022001 (2010).

[31] T. Lapsien, "V + top in CMS," BOOST 2014, London, (2014).
`https://indico.cern.ch/event/302395/session/17/contribution/32/attachments/571654/787373/boost2014_10.pdf`

[32] K. Hahn, "Searches for Dark Matter with boosted topologies in CMS," BOOST 2015, Chicago, (2015).
`https://indico.cern.ch/event/382815/session/6/contribution/2/attachments/1138074/1629657/CMS-DM-hahn-boost2015.pdf`

[33] D. Abercrombie *et al.*, "Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum,"
arXiv:1507.00966

[34] K. Hahn and K. Sung, Simplified Models for Scalar Dark Matter, model files, `https://svnweb.cern.ch/cern/wsvn/LHCDMF/trunk/models/HF_S+PS/contributed_by_KristianHahn`

[35] T. du Pree *e*t al., "Search for Dark Matter produced in association with top quark pairs", CMS Internal Analysis Note, CMS AN 2015/120 `http://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2015/120`

[36] The CMS Collaboration, "Boosted Top Jet Tagging at CMS," CMS Physics Analysis Summary, CMS-PAS-JME-13-007, (2014).
`http://inspirehep.net/record/1280973/files/JME-13-007-pas.pdf?version=1`

[37] A. Hoecker *et al.*, "TMVA: Toolkit for Multivariate Data Analysis," *PoS* **ACAT** 040 (2007). arXiv:physics/0703039

[38] The CMS Collaboration, "Measurement of the Polarization of W Bosons with Large Transverse Momenta in W + jets Events at the LHC," *Phys. Rev. Lett.*, **107** 021802 (2011).

[39] The CMS Collaboration, "Measurement of the W-boson helicity in top-quark decays from ttbar production in lepton+jets events in pp collisions at $\sqrt{s} = 7$ TeV, *JHEP*, **10** 167 (2013).

[40] `http://www.usparticlephysics.org/p5/`

[41] `http://council.web.cern.ch/council/en/EuropeanStrategy/esc-e-106.pdf`

[42] R. Frazier *et al.*, "Software and firmware for controlling CMS trigger and readout hardware via gigabit Ethernet," *Physics Procedia*, **37** 18921899 (2012).

[43] `http://www.xilinx.com/support/documentation/ip_documentation/aurora_8b10b_protocol_spec_sp002.pdf`

[44] `http://www.xilinx.com/support/documentation/ip_documentation/aurora_64b66b_protocol_spec_sp011.pdf`

[45] The CDF Collaboration, "The CDF Silicon Vertex Trigger," *Nucl. Instrum. Meth.*, **A518** 532-536 (2004). arXiv:physics/0306169

[46] S. Amerio *et al.*, "The GigaFitter: Performance at CDF and Perspectives for Future Applications," *J. Phys.: Conf. Ser.* **219** 022001 (2010).

Organization: Northwestern University
PIs: André de Gouvêa, Ian Low, Frank Petriello
Title: Theoretical Physics
Report for May 2013 – March 2016

Theoretical Particle Physics, André de Gouvêa

Personnel: Jeffrey Berryman (graduate student 2013–present), André de Gouvêa (PI), Daniel Hernández (postdoc, 2013–present), Kevin Kelly (graduate student 2014–present), Jennifer Kile (postdoc, 2010–2013), Andrew Kobach (graduate student 2011–2015).

The research efforts of this research group (PI plus postdoc and graduate students) concentrate on theoretical high energy physics, more specifically on the phenomenology of the physics that lies beyond the standard model of particle physics (SM). Two concrete facts reveal there are phenomena to which the SM has no well defined answer. First, there is the very strong, albeit indirect, evidence that most of the mass of the Universe is contained in the form of 'dark matter.' Equally strong is the evidence that the dark matter is not made up of any of the fields of the SM (baryons, neutrinos). It is hence very likely that new fields, with unknown properties and interactions, unaccounted for by the SM, exist. Second, it is established, beyond reasonable doubt, that neutrinos have non-zero masses. Non-zero neutrino masses are not allowed in the textbook version of the SM, but can be accommodated in a variety of different ways if the SM is modified. Most of the research efforts of this proposal are concentrated on exploring these two known evidences of physics beyond the standard model.

One of the main goals of this research effort is to explore the new physics that has manifested itself in the leptonic sector. There are several key issues the PI, together with other members of this research group and collaborators, have addressed, some of which will be described in more detail below. They are associated with three different broad particle physics questions: (a) what is the physics responsible for neutrino masses and lepton mixing, and how can we learn more about it?; (b) what can we learn from next-generation neutrino experiments and other so-called intensity frontier experimental efforts?; and (c) how is the physics responsible for neutrino masses related to the physics of electroweak symmetry breaking and the dark matter puzzle, and what can we expect to learn, as far as neutrino physics is concerned, from the on-going collider experiments and other searches for new physics?

- During the last year, the PI, together with Jeff Berryman, Kevin Kelly, Andrew Kobach, and other collaborators, has been exploring the consequences of new physics, beyond nonzero neutrino masses, to next-generation long-baseline oscillation experiments, especially DUNE. We have payed some attention to new sources of CP-invariance violation. In [10] we explored whether DUNE can detect new neutrino mass states, and measure the new physics parameters, including new sources of CP-invariance violation. In [8] we explored whether and how well DUNE can constrain new neutrino interactions that modify neutrino propagation through matter. In [3], we explored whether DUNE can test scenarios that link the small neutrino masses to the existence of new dimensions of space. Most recently, in [1], we explored the issue of degeneracies between CP-conserving new phenomena and CP-violating versions of the standard three-neutrinos paradigm, and how these can be addressed by combing different next-generation experiments, including DUNE, Hyper-Kamiokande, and PINGU.

- In [11], the Pi and Dani Hernández proposed a new physics scenario that explains small Dirac neutrino masses and dark matter. In more detail, we postulate a new $U(1)$ chiral gauge theory under which only new chiral fermions transform. Anomaly cancellation requirements dictate the particle content of the theory and naturally lead to the existence of virtually massless fermions – the right-handed neutrinos – and stable massive fermions – the dark matter particle. There, we also explored a novel, painless mechanism for generating chiral, anomaly free, $U(1)$ gauge theories. In [2], we extended our procedure in order to generate any number of chiral, anomaly free, nonabelian gauge theories. This way, we developed a tool for generating well defined dark sectors which are very promising ideas for understanding dark matter, dark photons, and nonzero neutrino masses.

- In [9], Andrew Kobach and the PI computed the current bounds on neutral heavy leptons, also referred to as sterile neutrinos, assuming their masses range between 1 eV and 1 TeV. The bounds obtained are as model independent as possible, and take into account the act that the sterile neutrinos can have interactions with unknown new states, including the dark matter. In [21], Kobach and a experimental postdoc at Northwestern, worked on how precision tau-decay measurements can be used to constrain how much new neutrino mass states can mix with the tau neutrinos. Their bounds, and expectations for future bounds from upcoming experiments, including the Super B-Factory, are the most stringent constraints on this observable when the new neutrino mass is around 1 GeV.

- In [15], Daniel Hernández and Jeff Berryman proposed that the flavor structure of the quark sector of the Standard Model is determined by a vectorial $SU(2)$ flavor symmetry, dubbed "Flavorspin," under which quarks transform as triplets. They explore the different consequences of their idea, and find that they can explain all observed masses and mixing parameters while making predictions for yet-to-be-observed phenomena, including flavor-changing neutral current processes. This idea is being explored further and augmented to include the lepton sector and related observables.

- In [18], the PI, Kevin Kelly, and Andrew Kobach, explored the possibilities of detecting CP-invariance violating effects in short-baseline experiments, assuming the short-baseline anomalies are a consequence of the existence of a fourth neutrino mass eigenstate and a new oscillation frequency related to a mass-squared difference around 1 eV^2. We found that an experiment like NuSTORM has some sensitivity to observing these novel sources of CP-invariance violation.

- In [24], the PI, Jeff Berryman, Dani Hernández, and a visiting postdoc from Brazil explored the consequences of new neutrino propagation to the neutrino flavor-changing phenomenon. We proposed a new, "generalized-decay" propagation Hamiltonian for neutrinos that allows for novel flavor mixing parameters. Following up on our original proposal, the PI, Berryman and Hernández revisited the current model-independent bounds on neutrino the ν_1 and ν_2 lifetimes from the observations of solar neutrinos at Borexino and SNO [19]. Our results and estimates have stimulated the SNO experiment to revisit their data in order to extract novel bounds on the neutrino lifetimes (work in progress).

- In [22], Jennifer Kile, Andrew Kobach, and a collaborator considered the possibility of a gauged lepton-flavor interaction that couples at tree level the muon and tau leptons and the dark sector. In this scenario, dark matter interacts only with particles of muon and tau flavors at tree level and has loop-suppressed couplings to quarks and electrons. They find that if such a gauged flavor interaction exists at a scale $\mathcal{O}(100\text{ GeV} - 1\text{ TeV})$, it allows for a consistent phenomenological framework, compatible with the muon $g-2$, the relic density, direct detection, indirect detection, charged-lepton decays, neutrino trident production, and results from hadron and lepton colliders.

- In [27], the PI, Andrew Kobach, and a visiting graduate student from Valéncia, Spain, explored relations between nonzero neutrino masses and baryon-number violating phenomena, assuming grand unification ideas are realized in nature. In more detailed, we made use of an effective-operator approach and assumied that nature is SU(5) invariant at very short distances, and estimated the consequences of different scenarios that lead to light Majorana neutrinos for low-energy phenomena that violate baryon number minus lepton number $(B-L)$ by two (or more) units, including neutron–antineutron oscillations and $B?L$-violating nucleon decays.

- In[29], the PI, Daniel Hernández, and a collaborator revisited the issue of naturalness, discussing some implicit assumptions that underly some of the most common statements, which tend to assign physical significance to certain regularization procedures. We explored a more pragmatic definition of the hierarchy problem that does not rely on peeking beyond the murky boundaries of quantum field theory: we investigated the fine-tuning of the electroweak scale associated with thresholds from heavy particles, which is both calculable and dependent on the nature of the would-be ultraviolet completion of the Standard Model. We further discussed different manifestations of new high-energy scales that are favored by experimental hints for new physics with an eye toward making use of fine-tuning in order to determine natural regions of the new physics parameter spaces.

- In [34], Andrew Kobach, then a graduate student at Northwestern, explored how, and how well, one can measure the mass of collider-stable particles at hadron colliders. In particular he concentrated on estimating how heavy must a collider-stable particle be so that its mass can be qualitatively distinguished from zero at a hadron collider. This result has important consequences for distinguishing the production of a new collider stable particle from new neutrino-producing interactions.

- In [38], the PI, Jennifer Kile, and a collaborator, revised the standard model computation of the Higgs to gamma gamma branching ratio, concentrating on its apparent dependence on the regularization procedure and how $U(1)$ gauge invariance is guaranteed. We speculated about the meaning of the different regularization procedures and pondered whether processes like Higgs to gamma gamma can be used as a way of phrasing the gauge hierarchy problem.

- During the last several years, the PI was heavily involved with planning exercises related to the near, intermediate, and long-term future of particle physics. He was involved in the workshop related to the Intermediate Neutrino Program, [14], which aimed at understanding the neutrino physics opportunities before the middle of the next decade when DUNE is expected to start taking data. The PI was also a member of the 2014 version of P5 [25], which spelled out a concrete plan for particle physics in the USA for the next decade. The PI was heavily involved in the latest Snowmass process working as a convener for the Neutrino Working Group [30, 31]. The PI was also part of a Snowmass White Paper on the opportunities in theoretical neutrino physics [32].

- The PI is a member of the ICFA Neutrino Panel [17, 26], charged with promoting international cooperation in the development of the accelerator-based neutrino-oscillation program and promoting international collaboration in the development of a neutrino factory as a future intense source of neutrinos for particle physics experiments.

- The PI is an active member of the Particle Data Group [23], working as an encoder for SUSY searches.

- The PI is an active participant in several experimental activities and proposals. These include (i) the DUNE experiment [5, 6, 7] and its predecessor, LBNE [35, 36], where the PI has been involved with understanding the capabilities of DUNE to look for new phenomena, (ii) the new $g-2$ experimental at Fermilab [12, 16], where the PI has worked on understanding its sensitivity to new physics, (iii) the *Mu2e* experiment [20], where the PI has worked on understanding how to constrain new phenomena (iv) the NuSTORM proposal [28, 33], where the PI has worked on the sensitivity of the proposal to new neutrino states and (v) the DAEdALUS proposal [37].

- The PI was involved in several studies that led to white papers and similar publications and preprints. These include a detailed study of the physics of light sterile neutrinos [4], partially driven by the short-baseline anomalies and the intriguing evidence for keV dark matter; the study of next-generation searches for neutral heavy leptons and other phenomena [13], which will ultimately lead to the SHiP proposal at CERN; a detailed study of the physics capability of a diverse intensity frontier program at Fermilab, once referred to as Project X [39].

Group's publication and preprints (2013-2016)

[1] A. de Gouvêa and K.J. Kelly, "False Signals of CP-Invariance Violation at DUNE," arXiv:1605.09376 [hep-ph].

[2] J.M. Berryman, A. de Gouvêa, D. Hernndez and K. J. Kelly, "Imperfect Mirrors of the Standard Model," arXiv:1605.03610 [hep-ph].

[3] J.M. Berryman, A. de Gouvêa, K.J. Kelly, O.L.G. Peres and Z. Tabrizi, "Large, Extra Dimensions at the Deep Underground Neutrino Experiment," to appear in Physical Review D, arXiv:1603.00018 [hep-ph].

[4] M. Drewes *et al.*, "A White Paper on keV Sterile Neutrino Dark Matter," [arXiv:1602.04816 [hep-ph]].

[5] R. Acciarri *et al.* [DUNE Collaboration], "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) : Volume 1: The LBNF and DUNE Projects," arXiv:1601.05471 [physics.ins-det].

[6] R. Acciarri *et al.* [DUNE Collaboration], "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) : Volume 4 The DUNE Detectors at LBNF," arXiv:1601.02984 [physics.ins-det].

[7] R. Acciarri *et al.* [DUNE Collaboration], "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) : Volume 2: The Physics Program for DUNE at LBNF," arXiv:1512.06148 [physics.ins-det].

[8] A. de Gouvêa and K.J. Kelly, "Non-standard Neutrino Interactions at DUNE," Nucl. Phys. B **908**, 318 (2016) doi:10.1016/j.nuclphysb.2016.03.013 [arXiv:1511.05562 [hep-ph]].

[9] A. de Gouvêa and A. Kobach, "Global Constraints on a Heavy Neutrino," Phys. Rev. D **93**, no. 3, 033005 (2016) doi:10.1103/PhysRevD.93.033005 [arXiv:1511.00683 [hep-ph]].

[10] J. M. Berryman, A. de Gouvêa, K.J. Kelly and A. Kobach, "Sterile neutrino at the Deep Underground Neutrino Experiment," Phys. Rev. D **92**, no. 7, 073012 (2015) doi:10.1103/PhysRevD.92.073012 [arXiv:1507.03986 [hep-ph]].

[11] A. de Gouvêa and D. Hernández, "New Chiral Fermions, a New Gauge Interaction, Dirac Neutrinos, and Dark Matter," JHEP **1510**, 046 (2015) doi:10.1007/JHEP10(2015)046 [arXiv:1507.00916 [hep-ph]].

[12] I. Logashenko *et al.* [Muon g-2 Collaboration], "The Measurement of the Anomalous Magnetic Moment of the Muon at Fermilab," J. Phys. Chem. Ref. Data **44**, no. 3, 031211 (2015). doi:10.1063/1.4917553

[13] S. Alekhin *et al.*, "A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case," arXiv:1504.04855 [hep-ph].

[14] C. Adams *et al.*, "The Intermediate Neutrino Program," arXiv:1503.06637 [hep-ex].

[15] J. Berryman and D. Hernández, "Flavorspin," arXiv:1502.04140 [hep-ph].

[16] J. Grange *et al.* [Muon g-2 Collaboration], "Muon (g-2) Technical Design Report," arXiv:1501.06858 [physics.ins-det].

[17] J. Cao *et al.* [ICFA Neutrino Panel Collaboration], "On the complementarity of Hyper-K and LBNF," arXiv:1501.03918 [physics.acc-ph].

[18] A. de Gouvêa, K.J. Kelly and A. Kobach, "CP-invariance violation at short-baseline experiments in 3+1 neutrino scenarios," Phys. Rev. D **91**, no. 5, 053005 (2015) doi:10.1103/PhysRevD.91.053005 [arXiv:1412.1479 [hep-ph]].

[19] J.M. Berryman, A. de Gouvêa and D. Hernández, "Solar Neutrinos and the Decaying Neutrino Hypothesis," Phys. Rev. D **92**, no. 7, 073003 (2015) doi:10.1103/PhysRevD.92.073003 [arXiv:1411.0308 [hep-ph]].

[20] L. Bartoszek *et al.* [Mu2e Collaboration], "Mu2e Technical Design Report," arXiv:1501.05241 [physics.ins-det].

[21] A. Kobach and S. Dobbs, "Heavy Neutrinos and the Kinematics of Tau Decays," Phys. Rev. D **91**, no. 5, 053006 (2015) doi:10.1103/PhysRevD.91.053006 [arXiv:1412.4785 [hep-ph]].

[22] J. Kile, A. Kobach and A. Soni, "Lepton-Flavored Dark Matter," Phys. Lett. B **744**, 330 (2015) doi:10.1016/j.physletb.2015.04.005 [arXiv:1411.1407 [hep-ph]].

[23] K.A. Olive *et al.* [Particle Data Group Collaboration], "Review of Particle Physics," Chin. Phys. C **38**, 090001 (2014). doi:10.1088/1674-1137/38/9/090001

[24] J.M. Berryman, A. de Gouvêa, D. Hernández and R.L.N. Oliveira, "Non-Unitary Neutrino Propagation From Neutrino Decay," Phys. Lett. B **742**, 74 (2015) doi:10.1016/j.physletb.2015.01.002 [arXiv:1407.6631 [hep-ph]].

[25] S. Ritz *et al.* [HEPAP Subcommittee Collaboration], "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context,"

[26] J. Cao *et al.*, "Initial report from the ICFA Neutrino Panel," arXiv:1405.7052 [physics.acc-ph].

[27] A. de Gouvêa, J. Herrero-Garcia and A. Kobach, "Neutrino Masses, Grand Unification, and Baryon Number Violation," Phys. Rev. D **90**, no. 1, 016011 (2014) doi:10.1103/PhysRevD.90.016011 [arXiv:1404.4057 [hep-ph]].

[28] D. Adey *et al.* [nuSTORM Collaboration], "Light sterile neutrino sensitivity at the nuSTORM facility," Phys. Rev. D **89**, no. 7, 071301 (2014) doi:10.1103/PhysRevD.89.071301 [arXiv:1402.5250 [hep-ex]].

[29] A. de Gouvêa, D. Hernández and T.M.P. Tait, "Criteria for Natural Hierarchies," Phys. Rev. D **89**, no. 11, 115005 (2014) doi:10.1103/PhysRevD.89.115005 [arXiv:1402.2658 [hep-ph]].

[30] J. L. Hewett *et al.*, "Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 2: Intensity Frontier," arXiv:1401.6077 [hep-ex].

[31] A. de Gouvêa *et al.* [Intensity Frontier Neutrino Working Group Collaboration], "Working Group Report: Neutrinos," arXiv:1310.4340 [hep-ex].

[32] A. de Gouvêa, A. Friedland, P. Huber and I. Mocioiu, "Opportunities in Neutrino Theory – a Snowmass White Paper," arXiv:1309.7338 [hep-ph].

[33] D. Adey *et al.* [nuSTORM Collaboration], "nuSTORM - Neutrinos from STORed Muons: Proposal to the Fermilab PAC," arXiv:1308.6822 [physics.acc-ph].

[34] A.C. Kobach, "Measuring the Mass of Dark Matter at the LHC," Phys. Rev. D **88**, 116001 (2013) doi:10.1103/PhysRevD.88.116001 [arXiv:1308.5671 [hep-ph]].

[35] C. Adams *et al.* [LBNE Collaboration], "Scientific Opportunities with the Long-Baseline Neutrino Experiment," FERMILAB-CONF-13-300.

[36] C. Adams *et al.* [LBNE Collaboration], "The Long-Baseline Neutrino Experiment: Exploring Fundamental Symmetries of the Universe," arXiv:1307.7335 [hep-ex].

[37] C. Aberle *et al.*, "Whitepaper on the DAEdALUS Program," arXiv:1307.2949.

[38] A. de Gouvêa, J. Kile and R. Vega-Morales, "$H \to \gamma\gamma$ as a Triangle Anomaly: Possible Implications for the Hierarchy Problem," arXiv:1306.5767 [hep-ph].

[39] A.S. Kronfeld *et al.*, "Project X: Physics Opportunities," arXiv:1306.5009 [hep-ex].

Final Reports for 05/01/2013 – 03/31/2016, Ian Low

Group members during the project period (in chronological order):

- Stefania Gori (postdoc at Argonne and U. Chicago) was not supported by this grant and is now a postdoc at Perimeter Institute for Theoretical Physics.
- Boris Harutyunyan (graduate student at NU) was partially supported by this grant.
- Ahmed Ismail (postdoc at Argonne and UIC) was not supported by this grant.
- Tao Liu (postdoc at UC Santa Barbara) was not supported by this grant and is now a junior faculty in Hong Kong Science and Technology University.
- Matthew Low (graduate student at U. Chicago) was not supported by this grant.
- Nausheen Shah (postdoc at Fermilab) was not supported by this grant and is now a postdoc at U. Michigan, Ann Arbor.
- Roberto Vega-Morales (graduate student at NU) was fully supported by a Fermilab Fellowship in Theoretical Physics from August 2012 to August 2013.
- Yi Chen (HEP experimental graduate student at Caltech) was not supported by this grant. He defended in the summer of 2014 and is in the military service in Taiwan.
- Peisi Huang (postdoc at Argonne and U. Chicago) was not supported by this grant.
- Anirudh Krovi (a second year graduate student at NU) joined the group in the fall of 2014. He was supported by a University Fellowship from NU, teaching assistantships and a supplemental RA from this grant.
- Zhewei Yin (a first year graduate student at NU) joined the group in the fall of 2015. He was supported by a University Fellowship from NU and a supplemental RA from this grant.

Overview

Research efforts in this group focused on particle phenomenology in the area of beyond-Standard-Model (BSM) physics. The majority of activity evolves around possible new physics associated with the newly discovered 125 GeV Higgs boson and at the LHC. In particular, much attention was paid to possible connection and interplay with ongoing experimental analyses at the LHC, as well as with possible future high energy e^+e^- and pp colliders. Some works involved possible signals of dark matter.

Professional Activities During the Project Period

- Convener of the BSM Higgs working group (WG3) for the LHC Higgs Cross-section Working Group, 2014 - Present.

- *TASI 2016: Anticipating the Next Discoveries in Particle Physics*, Boulder, Colorado, 2016: Co-Scientific Director.
- Member of the International Advisory Committee, Higgs Couplings workshops, 2015 – Present.
- *IAS Program on the Future of High Energy Physics*, Hong Kong University of Science and Technology, Hong Kong, 2015: theory convener.
- *Flavor and Top Physics at 100 TeV Workshop*, Institute of High Energy Physics, Chinese Academy of Science, Beijing, 2015: Co-organizer.
- *After the Discovery: Hunting for a Non-Standard Higgs Sector*, Centro de Ciencias de Benasque Pedro Pascual, Spain, 2014: Co-organizer.
- *Exploring TeV Scale New Physics with LHC Data*, Program at Kavli Institute for Theoretical Physics, Santa Barbara, 2013: Scientific Adviser.
- 35 invited talks at conferences, workshops, summer schools and seminars during the project period.

Research Articles

- Precision Higgs Measurements: Constraints from New Oblique Corrections – New particles entering into self-energies of the Higgs boson would necessarily modify loop-induced couplings of the Higgs, if the new particle carries standard model gauge quantum numbers. For a 1 TeV new particle, deviations in these "Higgs oblique corrections" are generically of the order of $v^2/(1\text{TeV})^2 \sim 5\%$. We study constraints on masses and couplings of new scalars and fermions that can be derived from 5-10% deviations in the Higgs digluon and diphoton partial widths. To reduce theoretical uncertainties, we present next-to-leading order QCD corrections to the Higgs-to-digluon coupling for scalars and fermions in arbitrary representations of $SU(3)$ color group, by applying the low-energy Higgs theorems at two-loop order. As a by-product we provide a new value for NLO QCD corrections to the top squark contributions to digluon decays that differs from existing literature. We also emphasize that precise measurements of Higgs couplings to W boson and top quark are prerequisite to precise determinations of Higgs oblique corrections from new particles. This work is collaborated with S. Gori (Argonne/U.Chicago). It appeared in Ref. [1].
- Impersonating the Standard Model Higgs Boson: Alignment without Decoupling – In models with an extended Higgs sector there exists an alignment limit, in which the lightest CP-even Higgs boson mimics the Standard Model Higgs. The alignment limit is commonly associated with the decoupling limit, where all non-standard scalars are significantly heavier than the Z boson. However, alignment can occur irrespective of the mass scale of the rest of the Higgs sector. In this work we discuss the general conditions that lead to "alignment without decoupling", therefore allowing for the existence of additional non-standard Higgs bosons at the weak scale. The values of $tan\beta$ for which this happens are derived in terms of the effective Higgs quartic couplings in general two-Higgs-doublet models as well as in supersymmetric theories, including the MSSM and the NMSSM. Moreover, we study the information encoded in the variations of the SM Higgs-fermion couplings to explore regions in the $m_A?\tan\beta$ parameter space. This work is collaborated with M. Carena (Fermilab), N. Shah (U.Michigan), and C.Wagner (Argonne/U.Chicago). It appeared in Ref. [2].

- Redux on "When is the Top Quark a Parton? – If a new heavy particle phi is produced in association with the top quark in a hadron collider, the production cross section exhibits a collinear singularity of the form $\log(m_\phi/m_t)$, which can be resummed by introducing a top quark parton distribution function (PDF). We reassess the necessity of such resummation in the context of a high energy pp collider. We find that the introduction of a top PDF typically has a small effect at $\sqrt{S} \sim 100$ TeV due to three factors: 1) α_s at the scale $\mu = m_\phi$ is quite small when $\log(m_\phi/m_t)$ is large, 2) the Bjorken $x << 1$ for $m_\phi \leq 10$ TeV, and 3) the kinematic region where $\log(m_\phi/m_t) >> 1$ is suppressed by phase space. We show that the effect of a top PDF is generically smaller than that of a bottom PDF in the associated production of $b\phi$ and consider the example of $pp \to tH^+$ at next-to-leading logarithm order. This work was collaborated with S. Dawson (Brookhaven) and A. Ismail (ANL/UIC). It appeared in Ref. [3].

- New Observables for CP Violation in Higgs Decays – Current experimental data on the 125 GeV Higgs boson still allow room for large CP violation. The observables usually considered in this context are triple product asymmetries, which require an input of four visible particles after imposing momentum conservation. We point out a new class of CP violating observables in Higgs physics which require only three reconstructed momenta. They may arise if the process involves an interference of amplitudes with different intermediate particles, which provide distinct strong phases in the form of the Breit-Wigner widths, in addition to possible weak phases that arise from CP violating couplings of the Higgs in the Lagrangian. As an example, we propose a forward-backward asymmetry of the charged lepton in the three-body Higgs decay, $h \to \ell^+\ell^-\gamma$, as a probe for CP-violating Higgs couplings to $Z\gamma$ and $\gamma\gamma$ pairs. Other processes exhibiting this type of CP-violation are also discussed. This work was collaborated with Yi Chen (Caltech), Adam Falkowski (LTP Orsay) and Roberto Vega-Morales (LTP Orsay) . It appeared in Ref. [4].

- A Double Take on the Double Higgs Production – Gluon-initiated double Higgs production is the most important channel to extract the Higgs self-coupling at hadron colliders. However, new physics could enter into this channel in several distinctive ways including, but not limited to, the Higgs self-coupling, a modified top Yukawa coupling, and an anomalous Higgs-top quartic coupling. In this work we initiate a study on the interplay of these effects in the kinematic distributions of the Higgs bosons. More specifically, we divide the transverse momentum and the total invariant mass spectra into two bins and use the differential rates in each bin to constrain the magnitude of the aforementioned effects. Significantly improved results could be obtained over those using total cross section alone. However, some degeneracy remains, especially in the determination of the Higgs trilinear coupling. Therefore, an accurate measurement of the Higgs self-coupling in this channel would require precise knowledge of the magnitudes of other new physics effects. We base our analysis on a future 100 TeV proton-proton collider. This work was collaborated with Chuan-Ren Chen (National Taiwan Normal University). It appeared in Ref. [5].

- Complementarity Between Non-Standard Higgs Searches and Precision Higgs Measurements in the MSSM – Precision measurements of the Higgs boson properties at the LHC provide relevant constraints on possible weak-scale extensions of the Standard Model (SM). In the context of the Minimal Supersymmetric Standard Model (MSSM) these constraints seem to suggest that all the additional, non-SM-like Higgs bosons should be heavy, with masses larger than about 400 GeV. This article shows that such results do not hold when the theory approaches the conditions for "alignment independent of decoupling", where the lightest CP-even Higgs boson has SM-like tree-level couplings to fermions and gauge bosons, independently of the non-standard Higgs boson masses. The combination of current bounds from direct Higgs boson searches at the LHC, along with the alignment conditions, have a significant impact on the allowed MSSM parameter space yielding light additional Higgs bosons. In particular, after ensuring the correct mass for the lightest CP-even Higgs boson, we find that precision measurements and direct searches are complementary, and may soon be able to probe the region of non-SM-like Higgs boson with masses below the top quark pair mass threshold of 350 GeV and low to moderate values of $\tan\beta$. This work is collaborated with Marcela Carena (Fermilab), Howard Haber (UC Santa Cruz), Nausheen Shah (Michigan) and Carlos Wagner (Argonne/Chicago). It appeared in Ref. [6].

- Adler's Zero and Effective Lagrangians for Nonlinearly Realized Symmetry – Long ago Coleman, Callan, Wess and Zumino (CCWZ) constructed the general effective lagrangian for nonlinearly realized symmetry by finding all possible nonlinear representations of the broken group G which become linear when restricted to the unbroken group H. However, in the case of a single Nambu-Goldstone boson (NGB), which corresponds to a broken $U(1)$, the effective lagrangian can also be obtained by imposing a constant shift symmetry. In this work we generalize the shift symmetry approach to multiple NGBs and show that, when they furnish a linear representation of H that can be embedded in a symmetric coset, it is possible to derive the CCWZ lagrangian by imposing 1) the "Adler's zero condition," which requires scattering amplitudes to vanish when emitting a single soft NGB, and 2) closure of shift symmetry with the linearly realized symmetry; knowledge of the broken group G is not required at all. Using only generators of H, the NGB covariant derivative and the associated gauge field can be computed to all orders in the NGB decay constant f. This work appeared in Ref. [7].

- A Minimally Symmetric Higgs Boson – Models addressing the naturalness of a light Higgs boson typically employ symmetries, either bosonic or fermionic, to stabilize the Higgs mass. We consider a setup with the minimal amount of symmetries: four shift symmetries acting on the four components of the Higgs doublet, subject to the constraints of linearly realized $SU(2)xU(1)$ electroweak symmetry. Up to terms that explicitly violate the shift symmetries, the effective lagrangian can be derived, irrespective of the spontaneously broken group G in the ultraviolet, and is universal in all models where the Higgs arises as a pseudo-Nambu-Goldstone boson (PNGB). Very high energy scatterings of vector bosons could provide smoking gun signals of a minimally symmetric Higgs boson. This work appeared in Ref. [8].

- On-shell interference effects in Higgs final states – Top quark loops in Higgs production via gluon fusion at large invariant final state masses can induce important interference effects in searches for additional Higgs bosons as predicted in, e.g., Higgs portal scenarios and the MSSM when the heavy scalar is broad or the final state resolution is poor. Currently, the limit setting as performed by both ATLAS and CMS is based on injecting a heavy Higgs-like signal neglecting interference effects. We performed a study of such "on-shell" interference effects in $pp \to ZZ$ and find that they lead to a $\leq \mathcal{O}(30\%)$ width scheme-dependent modification of the signal strength. Including the continuum contributions to obtain e.g. the full $pp \to ZZ \to 4\ell$ final state, this modification is reduced to the 10% level in the considered intermediate mass range. This work is collaborated with Christoph Englert (Glasgow) and Michael Spannowsky (Durham). It appeared in Ref. [9].

- What's in the Loop? The Anatomy of Double Higgs Production – Determination of Higgs self-interactions through the double Higgs production from gluon fusion is a major goal of current and future collider experiments. We point out this channel could help disentangle and resolve the nature of ultraviolet contributions to Higgs couplings to two gluons. Analytic properties of the double Higgs amplitudes near kinematic threshold are used to study features resulting from scalar and fermionic loop particles mediating the interaction. Focusing on the hh invariant mass spectrum, we consider the effect from anomalous top and bottom Yukawa couplings, as well as from scalar and fermionic loop particles. In particular, the spectrum at high hh invariant mass is sensitive to the spin of the particles in the loop. This work was collaborated with S. Dawson (Brookhaven) and A. Ismail (ANL/UIC). It appeared in Ref. [10].

- Same-Sign Dilepton Excesses and Light Top Squarks – Run 1 data of the Large Hadron Collider (LHC) contain excessive events in the same-sign dilepton channel with b-jets and missing transverse energy (MET), which were observed by five separate analyses from ATLAS and CMS collaborations. We show that these events could be explained by direct production of top squarks (stops) in supersymmetry. In particular, a right-handed stop with a mass of 550 GeV decaying into 2 t quarks, 2 W bosons, and MET could fit the observed excess without being constrained by other direct search limits from Run 1. We propose kinematic cuts at 13 TeV to enhance the stop signal, and estimate that stops could be discovered with 40 inverse fb of integrated luminosity at Run 2 of the LHC, when considering only the statistical uncertainty. This work appeared in Ref. [11].

- On the Alignment Limit of the NMSSM Higgs Sector – The Next-to-Minimal Supersymmetric extension of the Standard Model (NMSSM) with a Higgs boson of mass 125 GeV can be compatible with stop masses of order of the electroweak scale, thereby reducing the degree of fine-tuning necessary to achieve electroweak symmetry breaking. Moreover, in an attractive region of the NMSSM parameter space, corresponding to the "alignment limit" in which one of the neutral Higgs fields lies approximately in the same direction in field space as the doublet Higgs vacuum expectation value, the observed Higgs boson is predicted to have Standard-Model-like properties. We derive analytical expressions for the alignment conditions and show that they point toward a more natural region of parameter space for electroweak symmetry breaking, while allowing for perturbativity of the theory up to the Planck scale. Moreover, the alignment limit in the NMSSM leads to a well defined spectrum in the Higgs and Higgsino sectors, and yields a rich and interesting Higgs boson phenomenology that can be tested at the LHC. We discuss the most promising channels for discovery and present several benchmark points for further study. This work appeared in Ref. [12].

- Same-Sign Dilepton Excesses and Vector-like Quarks – Multiple analyses from ATLAS and CMS collaborations, including searches for ttH production, supersymmetric particles and vector-like quarks, observed excesses in the same-sign dilepton channel containing b-jets and missing transverse energy in the LHC Run 1 data. In the context of little Higgs theories with T parity, we explain these excesses using vector-like T-odd quarks decaying into a top quark, a W boson and the lightest T-odd particle (LTP). For heavy vector-like quarks, decay topologies containing the LTP have not been searched for at the LHC. The bounds on the masses of the T-odd quarks can be estimated in a simplified model approach by adapting the search limits for top/bottom squarks in supersymmetry. Assuming a realistic decay branching fraction, a benchmark with a 750 GeV T-odd b-prime quark is proposed. We also comment on the possibility to fit excesses in different analyses in a common framework. This work appeared in Ref. [13].

- Double Soft Theorems and Shift Symmetry in Nonlinear Sigma Models – We show both the leading and subleading double soft theorems of the nonlinear sigma model follow from a shift symmetry enforcing Adler's zero condition in the presence of an unbroken global symmetry. They do not depend on the underlying coset G/H and are universal infrared behaviors of Nambu-Goldstone bosons. Although nonlinear sigma models contain an infinite number of interaction vertices, the double soft limit is determined entirely by a single four-point interaction, together with the existence of Adler's zeros. This work appeared in Ref. [14].

- Implications of Gauge Invariance on a Heavy Diphoton Resonance – Assuming a heavy electroweak singlet scalar, which couples to the Standard Model gauge bosons only through loop-induced couplings, $SU(2)_L x U(1)_Y$ gauge invariance imposes interesting patterns on its decays into electroweak gauge bosons, which are dictated by only two free parameters. Therefore experimental measurements on any two of the four possible electroweak channels would determine the remaining two decay channels completely. Furthermore, searches in the WW/ZZ channels probe a complimentary region of parameter space from searches in the $\gamma\gamma/Z\gamma$ channels. We derive a model-independent upper bound on the branching fraction in each decay channel, which for the diphoton channel turns out to be about 61%. Including the coupling to gluons, the upper bound on the diphoton branching fraction implies an upper bound on the mass scale of additional colored particles mediating the gluon-fusion production. Using an event rate of about 5 fb for the reported 750 GeV diphoton excess, we find the new colored particle must be lighter than O(1.7 TeV) and O(2.6 TeV) for a pure CP-even and a pure CP-odd singlet scalar, respectively. This work appeared in Ref. [15].

Related Publications and Preprints – Ian Low

[1] S. Gori and I. Low, JHEP **1309**, 151 (2013) [arXiv:1307.0496 [hep-ph]].

[2] M. Carena, I. Low, N. R. Shah and C. E. M. Wagner, arXiv:1310.2248 [hep-ph].

[3] S. Dawson, A. Ismail and I. Low, Phys. Rev. D **90**, 014005 (2014) [arXiv:1405.6211 [hep-ph]].

[4] Y. Chen, A. Falkowski, I. Low and R. Vega-Morales, arXiv:1405.6723 [hep-ph].

[5] C. R. Chen and I. Low, arXiv:1405.7040 [hep-ph].

[6] M. Carena, H. E. Haber, I. Low, N. R. Shah and C. E. M. Wagner, arXiv:1410.4969 [hep-ph].

[7] I. Low, Phys. Rev. D **91**, no. 10, 105017 (2015) doi:10.1103/PhysRevD.91.105017 [arXiv:1412.2145 [hep-th]].

[8] I. Low, Phys. Rev. D **91**, no. 11, 116005 (2015) doi:10.1103/PhysRevD.91.116005 [arXiv:1412.2146 [hep-ph]].

[9] C. Englert, I. Low and M. Spannowsky, Phys. Rev. D **91**, no. 7, 074029 (2015) doi:10.1103/PhysRevD.91.074029 [arXiv:1502.04678 [hep-ph]].

[10] S. Dawson, A. Ismail and I. Low, Phys. Rev. D **91**, no. 11, 115008 (2015) doi:10.1103/PhysRevD.91.115008 [arXiv:1504.05596 [hep-ph]].

[11] P. Huang, A. Ismail, I. Low and C. E. M. Wagner, Phys. Rev. D **92**, no. 7, 075035 (2015) doi:10.1103/PhysRevD.92.075035 [arXiv:1507.01601 [hep-ph]].

[12] M. Carena, H. E. Haber, I. Low, N. R. Shah and C. E. M. Wagner, Phys. Rev. D **93**, no. 3, 035013 (2016) doi:10.1103/PhysRevD.93.035013 [arXiv:1510.09137 [hep-ph]].

[13] C. R. Chen, H. C. Cheng and I. Low, JHEP **1603**, 098 (2016) doi:10.1007/JHEP03(2016)098 [arXiv:1511.01452 [hep-ph]].

[14] I. Low, Phys. Rev. D **93**, no. 4, 045032 (2016) doi:10.1103/PhysRevD.93.045032 [arXiv:1512.01232 [hep-th]].

[15] I. Low and J. Lykken, arXiv:1512.09089 [hep-ph].

Technical report for Petriello task

- The PI, graduate student Chris Focke, former group member Xiaohui Liu and collaborators developed the N-jettiness approach to NNLO calculations in hadronic collisions [3]. This method led to the first two complete results for jet production processes to NNLO precision at the LHC: W-boson production in association with a jet [3], and Higgs boson production in association with a jet [4]. Percent-level jet phenomenology at the LHC is for the first time possible because of these results, as is a precision comparison of the measured Higgs boson kinematics with Standard Model predictions. These calculations will play a critical role in the continued search for physics beyond the Standard Model during the LHC Run II.

- The PI and collaborators realized that rare exclusive decays of the Higgs boson to light mesons could potentially constrain the Yukawa couplings of the Higgs boson to first and second generation quarks. This was first discussed in the context of using the decay $H \to J/\psi + \gamma$ to constrain the Higgs-charm coupling [5, 6], and later extended to other decays including the ρ, ω and ϕ mesons to probe the up, down and strange Yukawa couplings [7]. These exclusive decays are the only known ways of directly constraining the up, down and strange Yukawa couplings, and one of only two ways (along with charm-tagging [8, 9]) of directly constraining the Higgs-charm coupling. These analyses are now being performed by both ATLAS and CMS.

- The PI and collaborators completed their development of the sector-improved residue subtraction approach to NNLO computations. They applied it to the calculation of Higgs production in association with a jet at the LHC, first in pure Yang-Mills theory [13] and then to the dominant gg and qg partonic channels [14]. This was the first NNLO calculation of the dominant partonic scattering channels for Higgs+jet production, the importance of which was recognized by the publication of this work as a Physical Review Letter. Higgs production in association with a jet is now the only process for which the dominant partonic channels are known through NNLO using two different subtraction techniques: both sector-improved residue subtraction and the N-jettiness subtraction technique discussed above. This serves as a highly important validation of both subtraction schemes.

- The PI and Xiaohui Liu showed how to resum large jet-veto logarithms that plague the Higgs plus jet cross section at the LHC [10, 11], decreasing the theoretical error on this process. They indirectly extended the resummation of this process into the low0p_T region of the final-state jet, producing a new covariance matrix with reduced errors for use in experimental analyses [12].

- In Ref. [16], the PI, former group member Ye Li and collaborators presented a detailed numerical study of lepton-pair production via the Drell-Yan process above the Z-peak at the LHC, using the `FEWZ` code authored and maintained by the PI. Their results consistently combined next-to-next-to-leading-order QCD corrections and next-to-leading-order electroweak effects and include the leading photon-initiated processes, using a recent extraction of the photon distribution function. They focused on the effects of electroweak corrections and of photon-photon scattering contributions and demonstrated which kinematic distributions exhibit sensitivity to these corrections. They showed that a combination of measurements allows these corrections to be disentangled and determined separately. In particular, they demonstrated that the photon PDF effects become increasingly important in high energy collisions, and they proposed specific LHC data sets that could be used immediately to constraint this quantity.

- The study of top quark pair production has become precision physics at the LHC. With cross sections and differential distributions being measured with accuracies at the percent level, similarly precise theoretical predictions are needed in order to reliably interpret data. The required theoretical accuracy is only attainable with the inclusion of NNLO QCD corrections in the calculation of inclusive and differential cross sections. In Refs. [17, 18], postdoctoral researcher Abelof and collaborators presented a fully differential NNLO calculation for top pair hadro-production in the quark-antiquark channel. Their results were obtained with the antenna subtraction method, extended to treat massive colored fermions [17], and they include distributions in the top quark rapidity and transverse momentum, as well as the invariant mass, rapidity and transverse momentum of the top-antitop system. They also computed the NNLO corrections to the forward-backward asymmetry at Tevatron, confirming a previous result that they are large and improve the agreement of the theory predictions and the experimental measurements by the D0 collaboration [20].

- Graduate student Chris Focke and former group members Ye Li and Xiaohui Liu performed a first study of Higgs-boson production in exclusive jet bins at possible future 33 and 100 TeV proton-proton colliders [1]—machines that have received renewed interest recently. They compared the cross sections that were obtained by using fixed-order perturbation theory with those that were obtained by including, as well, a resummation of large logarithms that are induced by the jet-binning in the gluon-fusion and associated production channels. The central values that were obtained by the best available fixed-order predictions differ by $10-20\%$ from those that were obtained after including resummation over the majority of phase-space regions considered. Additionally, including the resummation dramatically reduces the residual scale variation in these regions, often by a factor of two or more. They showed that in several new kinematic regimes that can be explored at these high-energy machines, the inclusion of resummation improvement is mandatory.

Related Publications and Preprints – Petriello

[1] R. Boughezal, C. Focke, Y. Li and X. Liu, Phys. Rev. D **90**, no. 5, 053001 (2014).

[2] R. Boughezal, C. Focke and X. Liu, arXiv:1501.01059 [hep-ph].

[3] R. Boughezal, C. Focke, X. Liu and F. Petriello, Phys. Rev. Lett. **115**, no. 6, 062002 (2015).

[4] R. Boughezal, C. Focke, W. Giele, X. Liu and F. Petriello, Phys. Lett. B **748**, 5 (2015).

[5] G. T. Bodwin, F. Petriello, S. Stoynev and M. Velasco, Phys. Rev. D 88, **053003** (2013).

[6] G. T. Bodwin, H. S. Chung, J. H. Ee, J. Lee and F. Petriello, Phys. Rev. D **90**, no. 11, 113010 (2014).

[7] A. L. Kagan, G. Perez, F. Petriello, Y. Soreq, S. Stoynev and J. Zupan, Phys. Rev. Lett. **114**, no. 10, 101802 (2015).

[8] C. Delaunay, T. Golling, G. Perez and Y. Soreq, Phys. Rev. D **89**, no. 3, 033014 (2014).

[9] I. Brivio, F. Goertz and G. Isidori, arXiv:1507.02916 [hep-ph].

[10] X. Liu and F. Petriello, Phys. Rev. D **87**, 014018 (2013).

[11] X. Liu and F. Petriello, Phys. Rev. D **87**, 094027 (2013).

[12] R. Boughezal, X. Liu, F. Petriello, F. J. Tackmann and J. R. Walsh, Phys. Rev. D **89**, 074044 (2014).

[13] R. Boughezal, F. Caola, K. Melnikov, F. Petriello and M. Schulze, JHEP **1306**, 072 (2013).

[14] R. Boughezal, F. Caola, K. Melnikov, F. Petriello and M. Schulze, Phys. Rev. Lett. **115**, no. 8, 082003 (2015).

[15] G. Aad *et al.* [ATLAS Collaboration], JHEP **1409**, 112 (2014).

[16] R. Boughezal, Y. Li and F. Petriello, Phys. Rev. D **89**, no. 3, 034030 (2014).

[17] G. Abelof, A. Gehrmann-De Ridder, P. Maierhofer and S. Pozzorini, JHEP **1408**, 035 (2014).

[18] G. Abelof and A. Gehrmann-De Ridder, JHEP **1412**, 076 (2014).

[19] G. Abelof, A. Gehrmann-De Ridder and I. Majer, arXiv:1506.04037 [hep-ph].

[20] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **90**, 072011 (2014).

Organization: Northwestern University
PIs: Michael Schmitt
Title: Intensity Frontier Physics
Report for May 2013 – March 2016

Mu2e

The Northwestern group was admitted by the Mu2e Collaboration as a collaborating institution in April 2015. Schmitt leads this effort, which initially was supported by university funding. (The DOE are supplying funding starting in 2016.)

The Northwestern effort is focused on two tasks: (1) provide an accurate model of the magnetic fields of the production solenoid (PS) and the detection solenoid (DS), and (2) study backgrounds coming from trapped muons and/or electrons. In the 2015 – 2016 period, Schmitt and (postdoc) Pollack concentrated on the first task, while Velasco and (student) Chen worked on the second.

The magnetic fields are central to the operation and success of the Mu2e experiment. Aside from providing the means for meausuring the momentum of electrons emerging from the capture target, they also collect and direct charged particles from the production target through the entire apparatus. The signal for muon-to-electron conversion is an essentially mono-energetic line at the end of the electron energy spectrum; the position and sharpness of that line are critical. Consequently, the magnetic field must be known accurately.

Our scheme for the magnetic field map incorporates Maxwell's equations. We define a scalar potential that satisfies Laplace's equation and expand that function in a series of Bessel's functions. Our expansion is accurate at the 10^{-5} level. The data that determine the coefficients in the expansion will come from a field-mapping system (FMS) that will be deployed before the detectors are inserted into the DS. The FMS employs high-quality Hall probes that measure the magnetic field vector at a grid of points throughout the volumes of the DS and PS. We will use these measurements to determine the coefficients by means of a χ^2 fit.

We have studied the impact of calibration, positioning, and orientation of the Hall probes. Our studies show that Hall probes calibrated at the level of 10^{-4}, placed at the level of 1 mm, and oriented at the level of 0.1 μr will be adequate.

The DS magnetic field is complicated and magnetic "pockets" could be present that trap muons and electrons. If these trapped particles wander out of these pockets during the duty cycle of the experiment, they could constitute a serious background. (The experiment is designed to have an expected background less than 0.3 events for the entire running period.) Chen and Velasco searched for and found some magnetic pockets by running the full Mu2e simulation. The results were preliminary and this work will be carried forward by Pollack and Schmitt.

Organization: Northwestern University and Oregon State
PIs: Heidi Schellman
Title: Intensity Frontier Physics
Report for May 2013 – March 2016

Intensity Frontier Physics at Northwestern
Schellman Group

July 18, 2016

Introduction

Personnel: Heidi Schellman was supported by this Northwestern DOE grant from May 1, 2013 to August 2015 when she moved to NSF funding through Oregon State University. Postdoc Leah Welty-Rieger was supported by this grant from May 1, 2013 to December 30, 2014. Postdoc Laura Fields was supported by this grant, by a Fermilab Intensity Frontier Fellowship and by Northwestern University funds until August 31, 2015. Graduate student Cheryl Patrick was supported by this grant from May 1, 2013 until her graduation in March 2016.

The emphasis in the Schellman group is on precision measurements of nucleon structure and electroweak processes. In order to obtain a precise understanding of the weak interactions, the group has studied heavy flavor physics and vector boson production at the Tevatron, neutrino scattering in the NuTeV and MINERvA neutrino scattering experiments, participated in the design of the $g-2$ experiment tracking systems and most recently design work for the DUNE experiment at Fermilab. Our long term goal is measurements of the CP violating phase δ in a long baseline neutrino oscillation experiment. In support of that program, we have concentrated on precision characterization of neutrino and anti-neutrino interaction signatures in the 0.3-10 GeV range and on design optimization for the DUNE/LBNF beamline.

Final results from the D0 and CDF experiments

After the Tevatron stopped taking data in 2011, we switched our main emphasis to the Fermilab Intensity Frontier program. However, Schellman remained on D0 as a collaborator in the electroweak physics group and head of the editorial board for W/Z+jets measurements. The V+jets work [1, 2, 3, 4, 5, 6, 7], W and Z charge asymmetry measurements, [8, 9, 10] and her previous efforts on the W mass [11, 12] led to 13 publications in 2013-2015 culminating in a review article on Tevatron electroweak physics[13].

The $g-2$ Experiment at Fermilab

PI Schellman and a Northwestern postdoc Welty-Rieger were also collaborators on the muon $g-2$ experiment, E989 which is under construction at Fermilab. We are not longer participating in $g-2$ due to the move to DUNE/LBNF.

Over the period 2012-2014, the Northwestern group made significant contributions to the early design work for a new tracker system. As the magnetic field enters directly into the extraction of a_μ extremely precise understanding of the muon beam's trajectory in the storage ring is necessary. The tracker is intended is to reduce the uncertainties due to magnetic field components parallel to the beam (pitch correction) and due to residual effects of the electric fields used for focussing (electric field correction) to 0.05 ppm. The tracking systems will also help reduce another source of uncertainty, pileup in the calorimeters, by allowing an independent measure of the number and spatial distribution of multiple interactions in calorimeter modules. Schellman and postdoc Welty-Rieger worked with Brendan Casey of Fermilab and collaborators from Liverpool and NIU on the design of straw chamber tracking modules which will be placed in front of two of the calorimeter stations.

Welty-Rieger performed detailed simulation studies of the physical layout of the tracking subsystem to understand the interplay between the physical layout and the tracker and calorimeter acceptance. A large contribution was the development of accurate physical models, including both active detectors and services such as manifolds and gas lines, of the tracking stations in the simulation code which could be modified easily in software as the design of the tracker evolved, These studies have been invaluable in assessing the effects of realistic mechanical layouts of the vacuum pipe, gas system and electronics on physics performance as we proceed to the full Technical Design Report and finalize the tracker design.

Schellman produced standalone track fitting code which was used to optimize the tracker design[14] for the Conceptual Design Report[15]. Their work on simulation and layout has led to substantial improvements in the mechanical design of the tracker[16, 17]. Welty-Rieger has continued her software work on the $g-2$ project as a part-time software consultant at Fermilab.

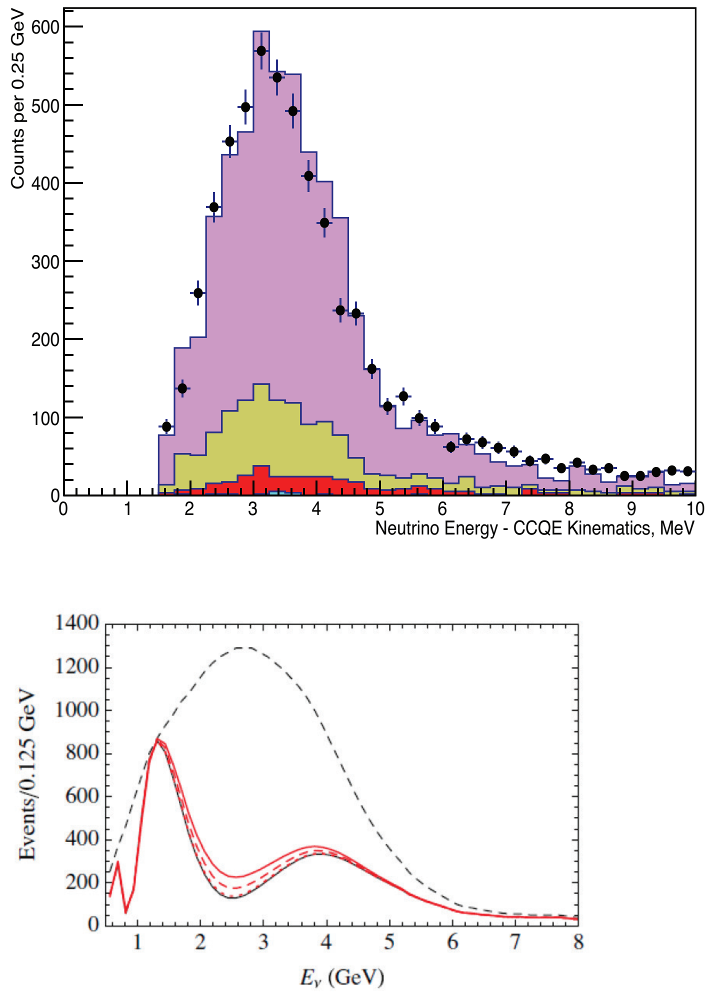

Figure 1: Reconstructed anti-neutrino energy distribution from a subset of MINERvA low energy CCQE data. The points show the MINERvA data and the histograms are (from top down) CCQE, resonance production, DIS and coherent scatters from the `GENIE`[36] anti-neutrino event simulation with $m_A = 0.99$. The design LBNF anti-neutrino spectrum[18] is shown for comparison.

MINERvA neutrino cross section experiment

The MINERvA group at Northwestern consisted of Heidi Schellman, postdoc Laura Fields and graduate student Cheryl Patrick. MINERvA is a dedicated experiment [19] to measure neutrino cross sections in the 1-20 GeV range. It consists of 32,000 1.7 x 3.4 cm triangular scintillating plastic strips with phototube readout interleaved with nuclear targets and electromagnetic and hadronic calorimeter absorbers. It is located in the NuMI near hall directly in front of the MINOS near detector, which serves as a momentum analyzer for forward muons produced in MINERvA neutrino interactions. The dedicated fine grained fully active detector allows precise measurements of event kinematics previously only possible with

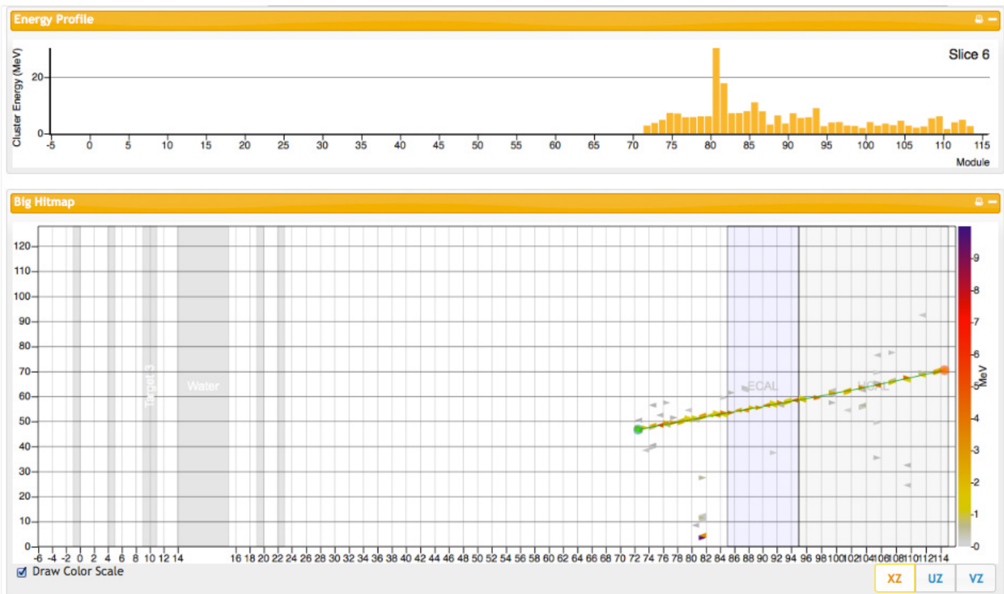

Figure 2: A typical quasi-elastic anti-neutrino scattering candidate from the MINERvA experiment. The beam enters from the left and the interaction occurs in the central scintillator tracker. The x and y axes are plane and strip number respectively and correspond to 1.7 cm segmentation. The signature for the process $\overline{\nu}_\mu + p \rightarrow \mu^+ + n$ is a single muon (the track with hits leaving the detector to the right), very little energy deposited in the vertex region and, possibly, a localized energy deposit far away from the final state neutron.

bubble chambers. The MINERvA experiment was successfully installed 2010 and took both neutrino and anti-neutrino data in the NuMI low energy configuration until the end of April 2012. Data taking resumed in early September 2013 and will continue through anti-neutrino running in 2016-2017.

Schellman served as head of offline computing infrastructure through 2014 and postdoc Laura Fields was the physics coordinator for the experiment until January 2016. Schellman and Patrick were in charge of the data pre-processing, logging of raw data to tape, archiving of reconstructed data and the SAM data catalog. Patrick also served as the gains calibration expert. The Oregon State group took over some of the data processing responsibilities of the Northwestern group and will be taking on more once a postdoc is hired in summer 2016.

Measurements of quasi-elastic anti-neutrino scattering

The major physics effort of the NU group is measurements of the anti-neutrino quasi-elastic cross-section, one of MINERvA 's flagship analyses. Patrick took the lead on this after Field's original work resulted in the first two major physics publications from Minerva[20, 21] in 2013. These have now been followed by measurements of resonant single pion production[32], coherent pion production[33] and the A-dependence for the total scattering cross section [35]. Figure 2 shows a typical anti-neutrino quasi-elastic scattering candidate in the MINERvA detector.

Figure 3 shows the anti-neutrino Q^2 distribution from the first MINERvA publications in 2013[21]. Patrick has now produced the first anti-neutrino double-differential cross-sections in transverse and longitudinal momentum, which will more powerfully discriminate between different models of the nuclear effects that are suggested by the single-differential results discussed in the recent publications.

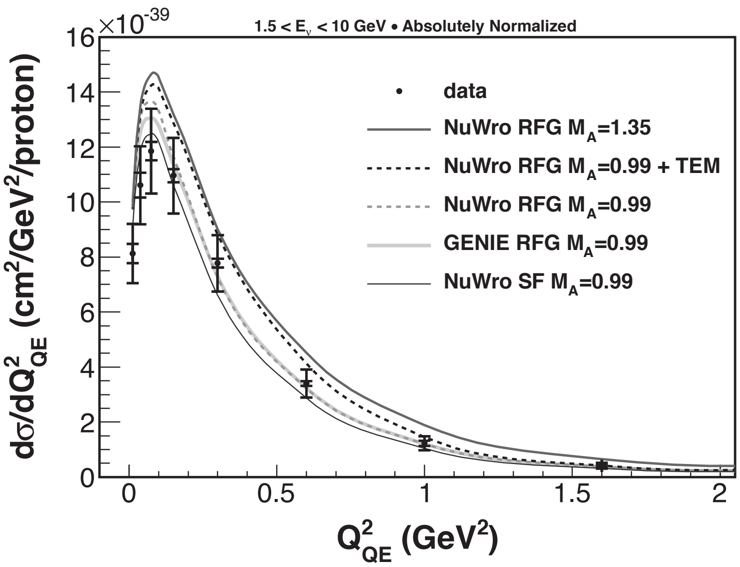

Figure 3: Q^2 distribution of anti-neutrino quasi-elastic interactions from reference [18]. Data from the MINERvA experiment are compared to different theoretical models, there is an 11% uncertainty in normalization due to the anti-neutrino flux. The models include the Relativistic Fermi Gas (RFG) and vary the dipole mass factor M_A and transverse enhancement (TEM). The SF model replaces the RFG with a more sophisticated spectral function calculation. Please see reference [18] for the full model descriptions.

One of the more interesting issues, which has attracted wide attention in the neutrino and electron scattering community[23, 24, 25, 26, 27, 28, 29, 30, 31], is the surprising complexity of the supposedly simple quasi-elastic scattering when it occurs on nucleons in a nucleus. In the MINERvA neutrino CCQE measurement[20] Phillip Rodrigues of the University of Rochester found strong evidence for additional proton production in quasi-elastic neutrino scattering, which could be due to correlated np pairs in the nucleus, as had previously been suggested by electron scattering experiments at Jefferson Lab [37], at lower neutrino energies by the MiniBooNE[39] collaboration and by recent direct observation in a small number of events in a Liquid Argon TPC by the ArgoNeut[38] collaboration. These correlations can both shift the initial nucleon kinematics, leading to distortions in the final state lepton kinematics, and significantly influence the low final state activity one would expect in a quasi-elastic scatter. In particular, the final state activity becomes quite different for neutrinos - where an additional proton might be expected in the final state - than for anti-neutrinos, where an additional neutron is more likely. Figure 4 shows a quasi-elastic

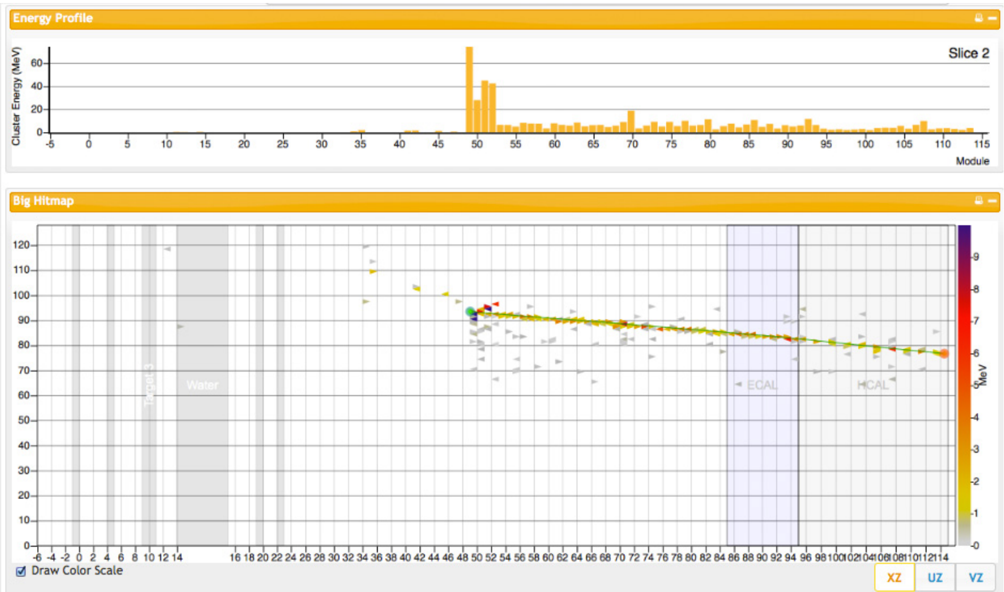

Figure 4: A less typical quasi-elastic anti-neutrino candidate from the MINERvA experiment. Although the quasi-elastic signature of little vertex energy and a final state muon is there, a second track that travels through around 15 cm of scintillator, depositing around 150 MeV is also visible. This could be a final state interaction after a true quasi-elastic scatter or resonance production.

anti-neutrino scattering candidate with an 150 MeV track near the vertex region in addition to the scattered muon. The additional energy deposition is detectable both in the energy distribution per plane and as a short track.

Figure 5 shows the hadronic energy deposited in the first 5 counters of the MINERvA scintillating tracker ($\sim$ 8.5 cm) after an anti-neutrino interaction. Minimum ionizing energy from the muon has been subtracted. Data and a GENIE simulation are compared to get a sense of the source of the observed signal. While the CCQE interactions show a clear signal near zero recoil energy as expected, there is a tail which overlaps the resonance contribution. This tail is probably due to a combination of expected final state neutron energy deposition and additional final state particles, making the definition of a true quasi-elastic signature difficult.

In her thesis [22], Cheryl Patrick has introduced a quasi-elastic like scattering definition which defines the QE-like signal as a final state with no pions and no protons above 120 MeV kinetic energy. This definition mirrors the sensitivity of the MINERvA detector to final state protons and is the closest we can come to a consistent theoretical description of the signatures that the MINERvA experiment is sensitive to. These results were presented in the Fermilab Wine and Cheese on June 2016 (see Figures 6 and CherylRatio). A long paper is in preparation. The MINERvA data favor the complex models of quasi-elastic scattering, including Random Phase Approximation and 2p2h effects. Patrick is now a postdoc on SuperNEMO at University College London.

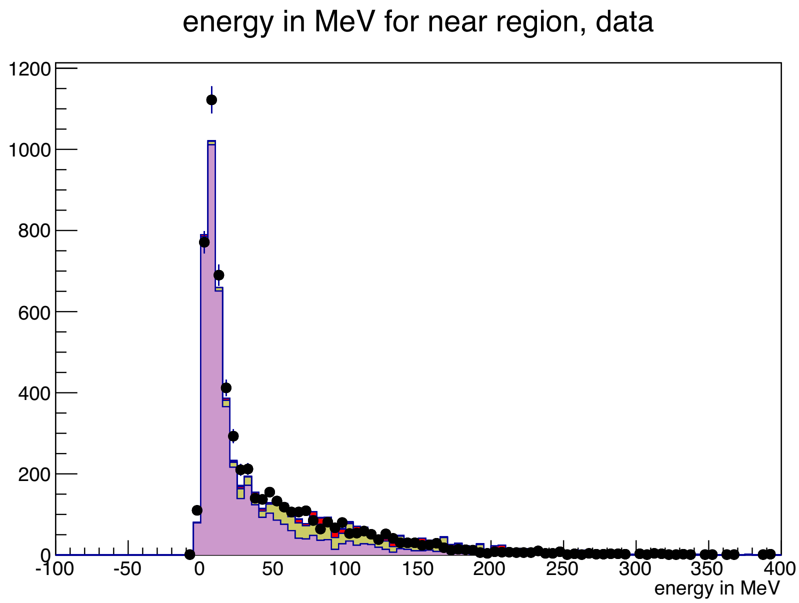

Figure 5: Non-muonic calorimetric energy deposited in the first 5 counters after the event vertex in a MINERvA anti-neutrino quasi-elastic scattering sample. The points are data while the histograms are `GENIE`[36] 2.6 predictions for (bottom to top) CCQE, resonance, DIS and coherent production. Note that a large (17%, and likely poorly known) fraction of the real CCQE events lie above 50 MeV (partially due to energy deposit by the expected final state neutron and partially due to low energy charged particles from nuclear interactions) where resonance production would be expected to dominate.

Technical contributions

Major technical achievements in 2013-2015 were the conversion of the MINERvA data handling systems to the new `samweb` interface and the implementation of new files storage systems based on the new Fermilab small file archive (SFA) and file transfer systems (FTS). Figure 8 illustrates the MINERvA data model using dcache and the FTS system.

The DUNE/LBNF Experiment

The proposed Deep Underground Neutrino Experiment (DUNE)[53] experiment will take a very high intensity neutrino beam from Fermilab and direct it towards a multi-kiloTonne neutrino detector located in the Sanford Underground Research Facility (SURF) in South Dakota. The distance between Fermilab and SURF of 1300 km corresponds to a first oscillation maximum at an energy of around 3.0 GeV. The LBNF (Long Baseline Neutrino Facility) neutrino beamline design is an evolution of the successful NuMI beamline [41] used in the MINOS, MINERvA, ArgoNeut and NOvA experiments but is necessarily new as the baseline and flux requirements for DUNE require a new beam direction and higher beam

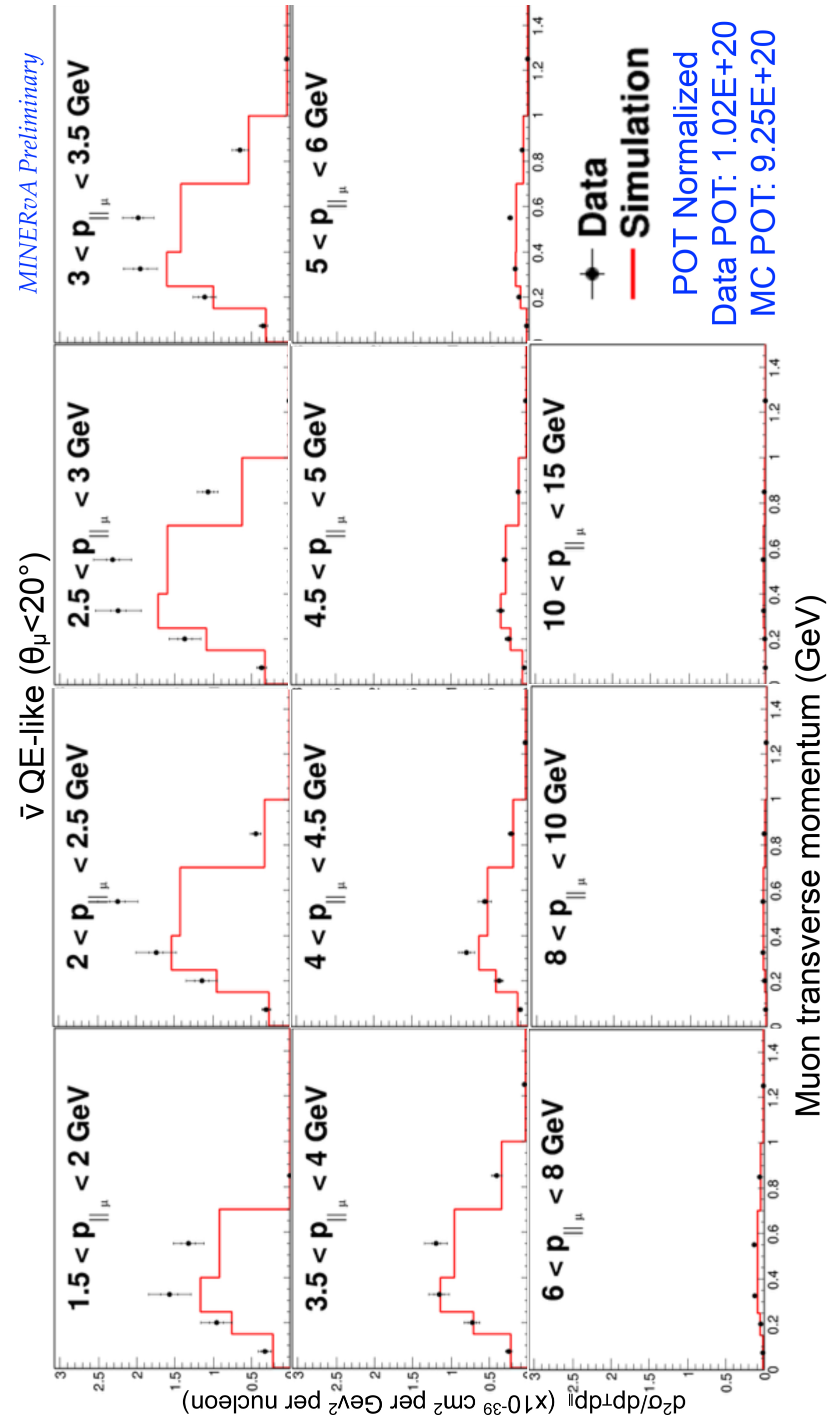

Figure 6: Full 2-D QE-like anti-neutrino cross section results as presented in the Fermilab Wine and Cheese on June 14, 2016 by Cheryl Patrick. The black points show the data while the red lines show the default GENIE simulation. The anti-neutrino flux uncertainty has been reduced to 8% due to recent work by Aliaga et al. [40].

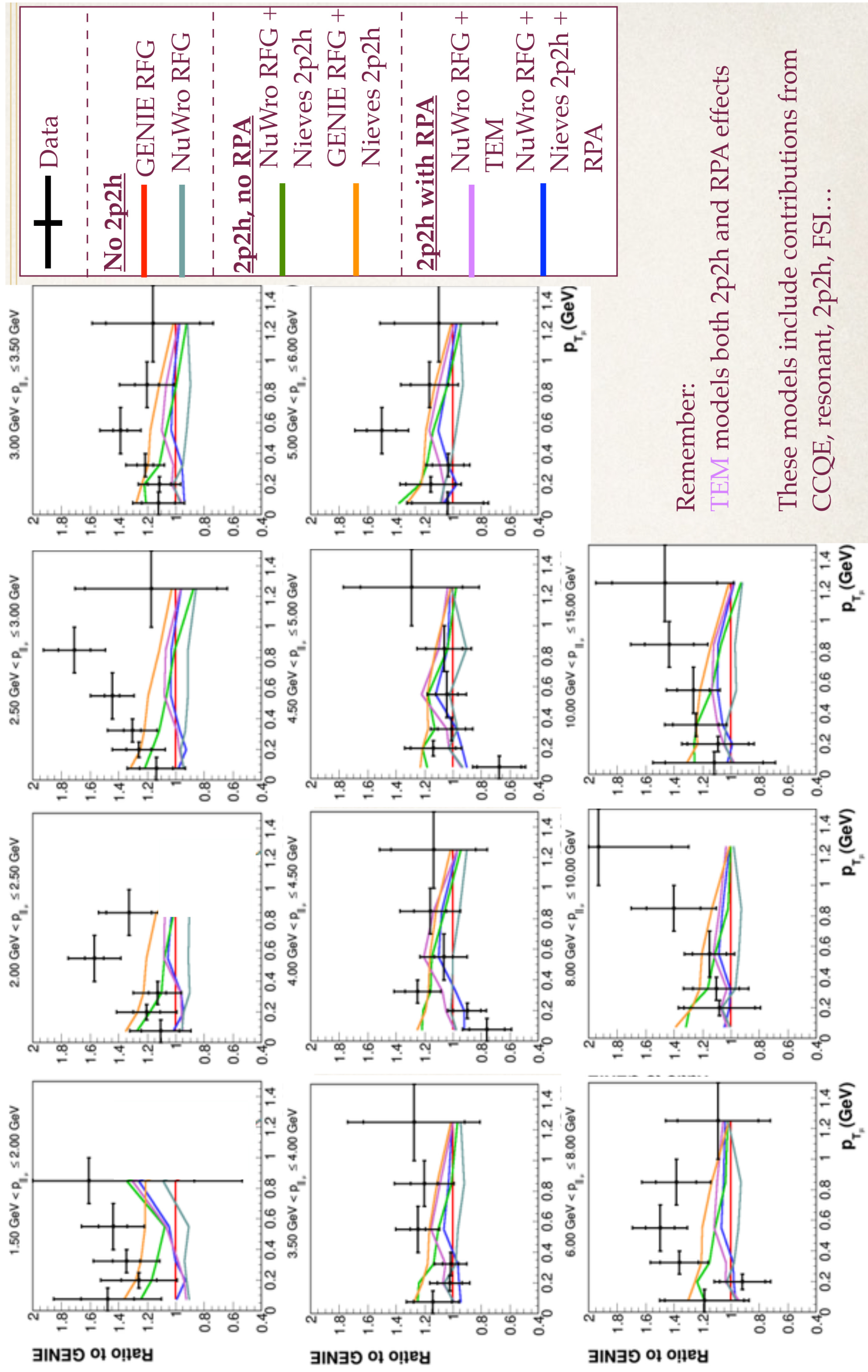

Figure 7: Full 2-D QE-like anti-neutrino cross section compared to default GENIE simulations as presented in the Fermilab Wine and Cheese by Cheryl Patrick. The data points are normalized to the default GENIE predictions (red line at 1). The best χ^2 with correlations taken into account is the blue curve which includes 2p2h correlations from Nieves et al. [29] and includes the random phase approximation.

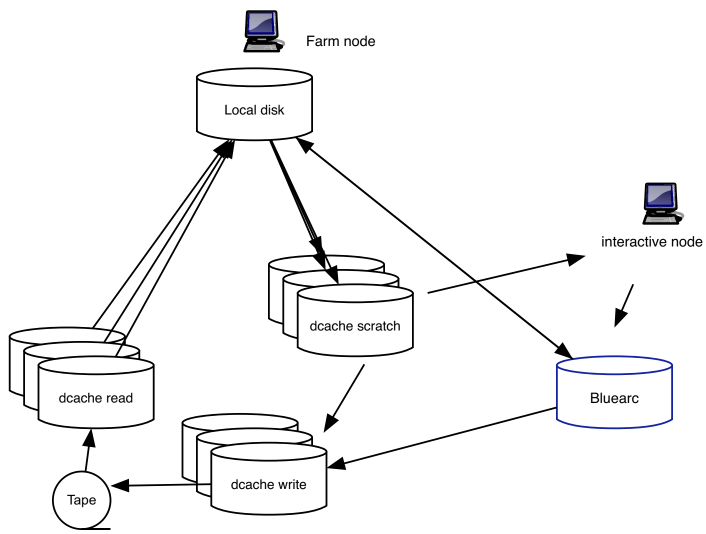

Figure 8: Fermilab data-flow model as of 2014. Data are now stored on tape (lower left), cached on temporary disk dcache and processed on local disk on farm CPU's. User analysis is done on interactive machines that have access to a blue arc disk set for small files and applications. Not shown is the sam metadata-scheme that tracks files as they migrate amongst locations.

power. The need for a new beamline creates an opportunity to use existing experience with the NuMI line to create an improved and optimized system.

Neutrino beamlines consist of a proton source, such as the Fermilab Main Injector (MI), a target system to create pions and kaons, electromagnetic horns to sign-select and focus the mesons, a decay volume, a beam dump to remove residual hadrons, shielding and a near detector to detect unoscillated neutrinos. The DUNE/LBNF Conceptual Design Report[53] includes a preliminary design for the LBNF beamline based largely on the existing NuMi systems. The performance of the beamline for physics was studied using simulations based on `GLoBES`[46], a long-baseline neutrino simulation tool that includes mixing and matter effects, a fast simulation of the DUNE neutrino detectors and on `g4lbne`[49], a `geant4`[48] based beamline simulation that does full ray tracing for particles originating in the target area.

While at Northwestern, Fields introduced a parameter optimization technique[44] based on genetic algorithms that had first been explored by the LBNO studies in Europe [45]. In this work, 40 physical beamline parameters such as beam energy, target length, horn geometry and target placement were varied and the physics performance of the variant neutrino beam - for example the % of CP violation space in δ accessible within 6 years of running - was compared to the baseline. Variants with improved performance were then combined to create "children" which were then "mutated" by varying their parameters slightly and then evaluated for fitness. The process converged after around 100 iterations, corresponding to around 10,000 beam simulations. Because each full simulation of a beamline took several days of CPU time, the fitness variations as a function of neutrino energy and parameter value

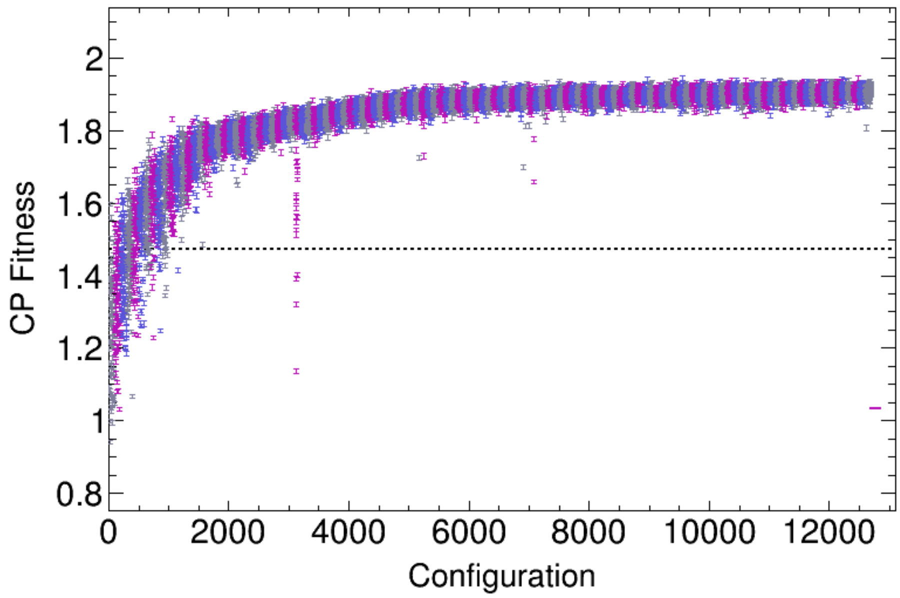

Figure 9: Figure 17 from Fields [44]. The fitness (CP sensitivity estimator) of each beam configuration simulated during the optimization is compared with the original beamline design using 120 GeV protons and 200 kA horn currents. The dotted line at 1.5 shows the sensitivity of the original baseline DUNE beam design.

were first estimated via full simulation and those derivatives were then used to estimate the fitness of the full 10,000 variants in the genetic optimization. This approximation reduced the iteration time to around 4 hrs, allowing fast studies of configurations. The optimal configurations were then validated with the full beamline simulation. Figure 9 illustrates the convergence of the algorithm on a solution which is 30% more fit via this metric than the nominal design.

The algorithm suggests significant changes in the beamline design, favoring a longer target placed entirely within Horn 1 and a very different horn design. Figure 10 illustrates the optimized Horn1 inner conductor compared to the nominal design.

Figure 11 shows an estimate of the average significance of a CP violation signal covering 75% of the CP space for the reference and optimized neutrino beamline designs. The optimized design is equivalent to a 30% reduction in running time or, in principle, target mass. While these results are extremely promising, and suggest that reasonably inexpensive changes to the beamline design could result in significant improvements in the speed with which DUNE achieves precision measurements, they are still based on fast simulation and substantial engineering will be needed to implement them as a physical beamline.

Fields is now an Associate Scientist at Fermilab and the UT Arlington undergraduate student, Amit Bashyal, who worked with her on this project, is now a student with Schellman at Oregon State University. His continuing work with Fields was recently funded by the NSF.

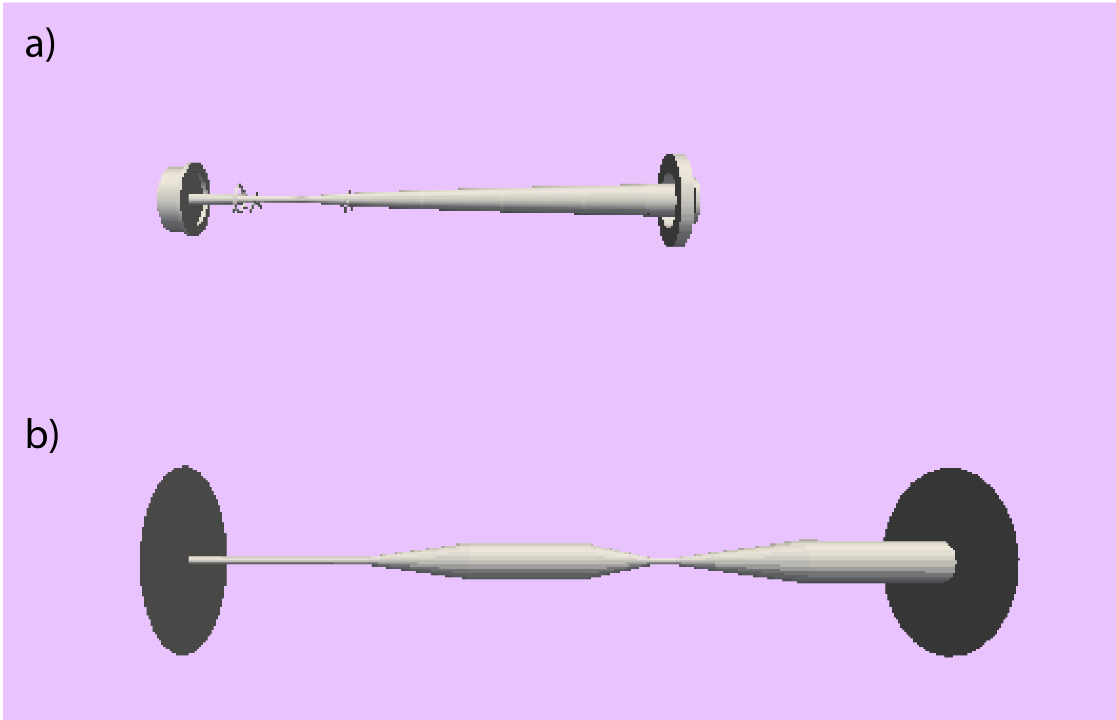

Figure 10: The nominal (a) and optimized (b) configuration for the inner radius of Horn 1 for anti-neutrinos.

Service

Schellman serves on the Jefferson Laboratory and Sanford Underground Laboratory Physics Advisory Panels and recently served on computing reviews for DOE OHEP. She also served as a member of the Nuclear Science Long Range Plan working group that is preparing a strategy for US Nuclear Science. She represents the US on the C11 (HEP) committee of IUPAP and joined the CERN Scientific Policy Committee in 2015. Fields has served as Physics Coordinator for the MINERvA collaboration and as beamline simulations convenor for LBNF/DUNE.

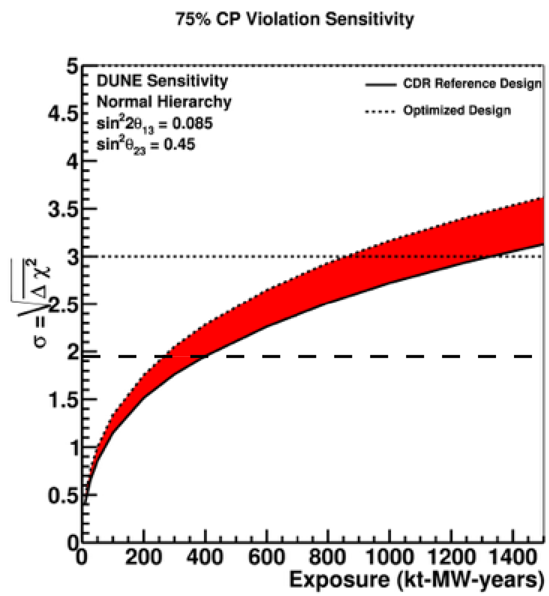

Figure 11: The CP violation sensitivity estimator for the normal hierarchy as a function of exposure for the nominal (lower edge of red band) and optimized (upper edge of red bands). The dashed horizontal line shows the sensitivity for the optimized beam. The increase in sensitivity is equivalent to a reduction in required beam time of around 30%.

References

[1] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of associated production of Z bosons with charm quark jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV," arXiv:1308.4384 [hep-ex].

[2] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of the differential cross section of photon plus jet production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV," Phys. Rev. D **88**, 072008 (2013) [arXiv:1308.2708 [hep-ex]].

[3] V. M. Abazov *et al.* [D0 Collaboration], "Studies of W boson plus jets production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV," arXiv:1302.6508 [hep-ex].

[4] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of the ratio of differential cross sections $\sigma(p\bar{p} \to Z + bjet)/\sigma(p\bar{p} \to Z + jet)$ in $p\bar{p}$ collisions at $\sqrt{(s)} = 1.96$ TeV," Phys. Rev. D **87**, 092010 (2013) [arXiv:1301.2233 [hep-ex]].

[5] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of the differential photon + c-jet cross section and the ratio of differential photon+ c and photon+ b cross sections in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV," Phys. Lett. B **719**, 354 (2013) [arXiv:1210.5033 [hep-ex]].

[6] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of the $p\bar{p} \to W+b+X$ production cross section at $\sqrt{s} = 1.96$ TeV," Phys. Lett. B **718**, 1314 (2013) [arXiv:1210.0627 [hep-ex]].

[7] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of the differential $\gamma + 2$ b-jet cross section and the ratio $\sigma(\gamma + 2\ b\text{-jets})/\sigma(\gamma + b\text{-jet})$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV," Phys. Lett. B **737**, 357 (2014) [arXiv:1405.3964 [hep-ex]].

[8] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of the muon charge asymmetry in ppbar to W + X to mu nu + X events at sqrts = 1.96 TeV," Phys. Rev. D **88**, 091102 (2013) [arXiv:1309.2591 [hep-ex]].

[9] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of the effective weak mixing angle in $p\bar{p} \to Z/\gamma^* \to e^+e^-$ events," Submitted to Phys. Rev. Lett., arXiv:1408.5016 [hep-ex].

[10] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of the W Boson Production Charge Asymmetry in $p\bar{p} \to W + X \to e\nu + X$ Events at $\sqrt{s} = 1.96$ TeV," Phys. Rev. Lett. **112**, 151803 (2014) [arXiv:1312.2895 [hep-ex]].

[11] T. A. Aaltonen *et al.* [CDF and D0 Collaborations], "Combination of CDF and D0 W-Boson Mass Measurements," Phys. Rev. D **88**, 052018 (2013) [arXiv:1307.7627 [hep-ex]].

[12] V. M. Abazov *et al.* [D0 Collaboration], "Measurement of the W boson mass with the D0 detector," Phys. Rev. D **89**, no. 1, 012005 (2014) [arXiv:1310.8628 [hep-ex]].

[13] A. V. Kotwal, H. Schellman and J. Sekaric, "Review of Physics Results from the Tevatron: Electroweak Physics," submitted to IJMPA, arXiv:1409.5163 [hep-ex].

[14] g-2 Experiment Document 879-v1, "Straw Tracker Spacing Study", Heidi Schellman, March 12, 2013

[15] g-2 Experiment Document 1178-v3, "CDR for the Director's Review" B. Lee Roberts et al., July 12, 2013

[16] g-2 Experiment Document 1424-v1, "Tracker Requirements", Leah Welty-Rieger, October 18, 2013. g-2 Experiment Document 879-v1, "Straw Tracker Spacing Study", Heidi Schellman, March 12, 2013 g-2 Experiment Document 1620-v1, "Tracker Data Products", Leah Welty-Rieger February 14, 2014. g-2 Experiment Document 2125-v1 "Module Design & Placement", Leah Welty-Rieger, July 31, 2014. g-2 Experiment Document 1555-v1, "Offset study", Heidi Schellman, December 16, 2013.

[17] M. Rominsky, B. Casey, L. Welty-Rieger, H. Schellman, M. Eads and N. Pohlman, "T-1042: Muon g-2 Straw Tracker," FERMILAB-PROPOSAL-1042.

[18] C. Adams *et al.* [LBNE Collaboration], "Scientific Opportunities with the Long-Baseline Neutrino Experiment," arXiv:1307.7335 [hep-ex].

[19] L. Aliaga *et al.* [MINERvA Collaboration], "Design, Calibration, and Performance of the MINERvA Detector," arXiv:1305.5199 [physics.ins-det].

[20] G. A. Fiorentini *et al.* [MINERvA Collaboration], "Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV," Phys. Rev. Lett. **111**, 022502 (2013) [arXiv:1305.2243 [hep-ex]].

[21] L. Fields *et al.* [MINERvA Collaboration], "Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV," Phys. Rev. Lett. **111**, 022501 (2013) [arXiv:1305.2234 [hep-ex]].

[22] C. Patrick, "Measurement of the Antineutrino Double-Differential Charged-Current Quasi-Elastic Scattering Cross Section at MINERvA," FERMILAB-THESIS-2016-04.

[23] M. Martini, M. Ericson, G. Chanfray and J. Marteau, Phys. Rev. C **81**, 045502 (2010) [arXiv:1002.4538 [hep-ph]].

[24] J. E. Amaro, M. B. Barbaro, J. A. Caballero, T. W. Donnelly and C. F. Williamson, Phys. Lett. B **696**, 151 (2011) [arXiv:1010.1708 [nucl-th]].

[25] O. Benhar, P. Coletti and D. Meloni, Phys. Rev. Lett. **105**, 132301 (2010) [arXiv:1006.4783 [nucl-th]].

[26] A. Bodek, H. S. Budd and M. E. Christy, Eur. Phys. J. C **71**, 1726 (2011) [arXiv:1106.0340 [hep-ph]].

[27] J. T. Sobczyk, Phys. Rev. C **86**, 015504 (2012) [arXiv:1201.3673 [hep-ph]].

[28] T. Golan, C. Juszczak and J. T. Sobczyk, Phys. Rev. C **86**, 015505 (2012) [arXiv:1202.4197 [nucl-th]].

[29] J. Nieves, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Lett. B **721**, 90 (2013) [arXiv:1302.0703 [hep-ph]].

[30] R. Gran, J. Nieves, F. Sanchez and M. J. Vicente Vacas, Phys. Rev. D **88**, 113007 (2013) [arXiv:1307.8105 [hep-ph]].

[31] O. Benhar, A. Lovato and N. Rocco, arXiv:1312.1210 [nucl-th].

[32] B. Eberly *et al.* [MINERvA Collaboration], "Charged pion production in ν_μ interactions on hydrocarbon at $\langle E_\nu \rangle$= 4.0 GeV," Phys. Rev. D **92**, no. 9, 092008 (2015) [arXiv:1406.6415 [hep-ex]].

[33] A. Higuera *et al.* [MINERvA Collaboration], "Measurement of Coherent Production of $\pi^\pm$ in Neutrino and Antineutrino Beams on Carbon from E_ν of 1.5 to 20 GeV," Phys. Rev. Lett. **113**, no. 26, 261802 (2014) [arXiv:1409.3835 [hep-ex]].

[34] T. Walton *et al.* [MINERvA Collaboration], "Measurement of muon plus proton final states in ν_μ interactions on hydrocarbon at $< E_\nu >= 4.2$ GeV," Phys. Rev. D **91**, no. 7, 071301 (2015) [arXiv:1409.4497 [hep-ex]].

[35] B. G. Tice *et al.* [MINERvA Collaboration], "Measurement of Ratios of ν_μ Charged-Current Cross Sections on C, Fe, and Pb to CH at Neutrino Energies 2-20 GeV," Phys. Rev. Lett. **112**, 231801 (2014) [arXiv:1403.2103 [hep-ex]].

[36] C. Andreopoulos, A. Bell, D. Bhattacharya, F. Cavanna, J. Dobson, S. Dytman, H. Gallagher and P. Guzowski *et al.*, "The GENIE Neutrino Monte Carlo Generator," Nucl. Instrum. Meth. A **614**, 87 (2010) [arXiv:0905.2517 [hep-ph]].

[37] K. S. Egiyan et al., Phys. Rev. C 68 (2003) 014313 and Phys. Rev. Lett. 96 (2006) 082501, R. Subedi et al., Science 320 (2008) 1476 and R. Shneor et al., Phys. Rev. Lett. 99 (2007) 072501, M. M. Sargsian et al., Phys. Rev. C 71 (2005) 044615. and R. Schiavilla et al., Phys. Rev. Lett. 98 (2007) 132501.

[38] R. Acciarri *et al.* [ArgoNeuT Collaboration], "The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT detector in the NuMI low energy beam line," Phys. Rev. D **90**, 012008 (2014) [arXiv:1405.4261 [nucl-ex]].

[39] A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], "First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section," Phys. Rev. D **81**, 092005 (2010) [arXiv:1002.2680 [hep-ex]].

[40] L. Aliaga *et al.* [MINERvA Collaboration], "Neutrino Flux Predictions for the NuMI Beam," arXiv:1607.00704 [hep-ex]. 1 citations counted in INSPIRE as of 17 Jul 2016

[41] P. Adamson *et al.*, "The NuMI Neutrino Beam," arXiv:1507.06690 [physics.acc-ph].

[42] C. Albright *et al.*, "Physics at a neutrino factory," hep-ex/0008064.

[43] V. D. Barger *et al.*, "Oscillation measurements with upgraded conventional neutrino beams," hep-ph/0103052

[44] Laura J. Fields, "Genetic Optimization of the LBNF/DUNE Beamline", DUNE Document 56-v3.

[45] M. Calviani, S. Di Luise, V. Galymov and P. Velten, "Optimization of neutrino fluxes for future long baseline neutrino oscillation experiments, arXiv:1411.2418 [physics.ins-det].

[46] P. Huber, M. Lindner and W. Winter, "Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator)," Comput. Phys. Commun. **167**, 195 (2005) [hep-ph/0407333].

[47] https://cdcvs.fnal.gov/redmine/projects/numi-beam-sim/wiki

[48] Nuclear Instruments and Methods in Physics Research A 506, 250-303 (2003), IEEE Transactions on Nuclear Science 53 No. 1, 270-278, (2006)

[49] https://cdcvs.fnal.gov/redmine/projects/lbne-beamsim/wiki

[50] Kuldeep , "Neutrino Flux Studies at NOvA", DPF2015 Conference, Ann Arbor, Michigan, July 2015,Kuldeep.pdf

[51] Laura J. Fields, "Genetic Optimization of the LBNF/DUNE Beamline", DUNE Internal Document 56-v3. September 1, 2015.

[52] V. Papadimitriou *et al.* [LBNF Collaboration], "Design of the LBNF Beamline," FERMILAB-CONF-15-231-AD-ND, IPAC-2015-THPF120.

[53] DUNE Conceptual Design Report