DE-SC0007948

STUDIES IN THEORETICAL HIGH ENERGY PARTICLE PHYSICS

Final Technical Report
for Period July 1, 2012 - March 31, 2017.

Wai–Yee Keung

Department of Physics, M/C 273
University of Illinois at Chicago
845 W. Taylor Street, Rm 2236
Chicago, Illinois 60607–7059

July 2017

Prepared for
THE U.S. DEPARTMENT OF ENERGY
AGREEMENT NO. DE-FG02-12ER41811

ABSTRACT

This is a final technical report for grant no. DE-SC0007948 describing research activities in theoretical high energy physics at University of Illinois at Chicago for the whole grant period from July 1, 2012 to March 31, 2017.

Final Technical Report (Grant No. DE-SC0007948)

In this report, we provide the final technical report on results achieved in various areas of theoretical high energy physics research at University of Illinois at Chicago during the period from July 1, 2012 to March 31, 2017. We summarize and highlight our work published or preprint posted in the following list.

Publications of W.–Y. Keung

K1. Collider Signatures of Goldstone Bosons.
K. Cheung, W. -Y. Keung and T. -C. Yuan,
Phys. Rev. D **89**, 015007 (2014); arXiv:1308.4235 [hep-ph].

K2. Supernova Bounds on Weinberg's Goldstone Bosons.
W. Y. Keung, K. W. Ng, H. Tu and T. C. Yuan,
Phys. Rev. D **90**, 075014 (2014); arXiv:1312.3488 [hep-ph].

K3. Can vanishing mass-on-shell interactions generate a dip at colliders?
Y. Bai and W. Y. Keung,
Int. J. Mod. Phys. A **30**, no. 20, 1550120 (2015) doi:10.1142/S0217751X15501201; arXiv:1407.6355 [hep-ph].

K4. Hyperfine splitting in muonic hydrogen constrains new pseudoscalar interactions.
W.-Y. Keung and D. Marfatia,
Phys. Lett. B **746**, 315 (2015) doi:10.1016/j.physletb.2015.05.025; arXiv:1501.00455 [hep-ph].

K5. Interpretations of the ATLAS Diboson Anomaly.
K. Cheung, W. Y. Keung, P. Y. Tseng and T. C. Yuan,
Phys. Lett. B **751**, 188 (2015) doi:10.1016/j.physletb.2015.10.029; arXiv:1506.06064 [hep-ph].

K6. Leptoquark induced rare decay amplitudes $h \to \tau^{\mp}\mu^{\pm}$ and $\tau \to \mu\gamma$.
K. Cheung, W. Y. Keung and P. Y. Tseng,
Phys. Rev. D **93**, no. 1, 015010 (2016); arXiv:1508.01897 [hep-ph].

K7. Axial Vector Z' and Anomaly Cancellation.
A. Ismail, W.-Y. Keung, K. H. Tsao and J. Unwin,
Nucl. Phys. **B 918** 220-224 (2017); arXiv:1312.3488 [hep-ph].

K8. Lepton-Flavor-violating Z using the electron-muon channel at the LHC.
K. Cheung, W.-Y. Keung and P. Y. Tseng,
Phys. Rev. D **94**, no. 7, 075006 (2016); arXiv:1606.06696 [hep-ph].

K9. Super-heavy Particle Origin of IceCube PeV Neutrino Events.
V. Barger and W. -Y. Keung,
Phys. Lett. B **727**, 190 (2013); arXiv:1305.6907 [hep-ph].

K10. A Reappraisal on Dark Matter Co-annihilating with a Top/Bottom Partner.
W.-Y. Keung, I. Low, and Y. Zhang,
Phys. Rev. D **96**, no. 1, 015008 (2017); arXiv:1703.02977 [hep-ph].

K11. Interpreting the 3 TeV WH Resonance as a W' boson.
Kingman Cheung, Wai-Yee Keung, Chih-Ting Lu, and Po-Yan Tseng,
JHEP **1706**, 105 (2017); arXiv:1704.02087 [hep-ph].

K12. Flavor-Tuned 125 GeV SUSY Higgs Boson at the LHC: MSSM and NATURAL SUSY TESTS.
V. Barger, M. Ishida and W. -Y. Keung,
Phys. Rev. D **87**, 015003 (2013); arXiv:1207.0779 [hep-ph].

K13. Scalar-Top Masses from SUSY Loops with 125 GeV m_h and Precise M_W.
V. Barger, P. Huang, M. Ishida and W. -Y. Keung,
Phys. Lett. B **718**, 1024 (2013); arXiv:1206.1777 [hep-ph].

K14. PeV Neutrino Events at IceCube from Single Top-Quark Production.
V. Barger, E. Basso, Y. Gao and W.-Y. Keung,
Phys. Rev. D **95**, no. 9, 093002 (2017); arXiv:1611.00773 [hep-ph].

Publications of P. Schwaller

S1. Higgs CP Properties From Early LHC Data.
A. Freitas and P. Schwaller,
Phys. Rev. D **87**, 055014 (2013); arXiv:1211.1980 [hep-ph].

S2. Dark Matter and Enhanced Higgs to Di-photon Rate from Vector-like Leptons.
A. Joglekar, P. Schwaller and C. E. M. Wagner,

JHEP **1212**, 064 (2012); arXiv:1207.4235 [hep-ph].

S3. A Supersymmetric Theory of Vector-like Leptons.
A. Joglekar, P. Schwaller and C. E. M. Wagner,
JHEP **1307**, 046 (2013); arXiv:1303.2969 [hep-ph].

S4. Scattering Rates For Leptogenesis: Damping of Lepton Flavour Coherence and Production of Singlet Neutrinos.
B. Garbrecht, F. Glowna and P. Schwaller,
Nucl. Phys. B **877**, 1 (2013); arXiv:1303.5498 [hep-ph].

S5. The Scale of Dark QCD.
Y. Bai and P. Schwaller,
Phys. Rev. D **89**, no. 6, 063522 (2014); arXiv:1306.4676 [hep-ph].

S6. Dark Matter and Vector-like Leptons From Gauged Lepton Number.
P. Schwaller, T. M. P. Tait and R. Vega-Morales,
Phys. Rev. D **88**, 035001 (2013); arXiv:1305.1108 [hep-ph].

Publications of A. Ismail

I1. A Redux on "When is the Top Quark a Parton?"
S. Dawson, A. Ismail and I. Low,
Phys. Rev. D **90**, 014005 (2014); arXiv:1405.6211 [hep-ph].

I2. Complementarity of Dark Matter Searches in the pMSSM.
M. Cahill-Rowley, R. Cotta, A. Drlica-Wagner, S. Funk, J. Hewett, A. Ismail, T. Rizzo and M. Wood,
Phys. Rev. D **91**, no. 5, 055011 (2015); doi:10.1103/PhysRevD.91.055011;
arXiv:1405.6716 [hep-ph].

I3. Dark matter complementarity in the phenomenological MSSM.
A. Ismail,
AIP Conf. Proc. **1604**, 53 (2014).

I4. Lessons and Prospects from the pMSSM after LHC Run I: Neutralino LSP.
M. Cahill-Rowley, J. L. Hewett, A. Ismail and T. G. Rizzo,
Phys. Rev. D **91**, no. 5, 055002 (2015); doi:10.1103/PhysRevD.91.055002;
arXiv:1407.4130 [hep-ph].

I5. Higgs boson coupling measurements and direct searches as complementary probes of the phenomenological MSSM.
M. Cahill-Rowley, J. Hewett, A. Ismail and T. Rizzo,
Phys. Rev. D **90**, no. 9, 095017 (2014); arXiv:1407.7021 [hep-ph].

I6. Deconstructed Transverse Mass Variables.
A. Ismail, R. Schwienhorst, J. S. Virzi and D. G. E. Walker,
Phys. Rev. D **91**, no. 7, 074002 (2015); doi:10.1103/PhysRevD.91.074002;
arXiv:1409.2868 [hep-ph].

I7. Whats in the loop? The anatomy of double Higgs production.
S. Dawson, A. Ismail and I. Low,
Phys. Rev. D **91**, no. 11, 115008 (2015); arXiv:1504.05596 [hep-ph].

I8. ATLAS Z+ missing transverse energy excess in the MSSM.
M. Cahill-Rowley, J. Hewett, A. Ismail and T. Rizzo,
Phys. Rev. D **92**, no. 7, 075029 (2015); arXiv:1506.05799 [hep-ph].

I9. Same-sign dilepton Excesses and light top squarks.
P. Huang, A. Ismail, I. Low and C. Wagner,
Phys. Rev. D **92**, no. 7, 075035 (2015); arXiv:1507.01601 [hep-ph].

I10. Searches for non-SM heavy Higgses at a 100 TeV pp collider.
J. Hajer, A. Ismail, F. Kling, Y.-Y. Li, T. Liu and S. Su,
Int. J. Mod. Phys. A **30**, no. 23, 1544005 (2015).

I11. The CP-violating pMSSM.
J. Berger, M. Cahill-Rowley, D. Ghosh, J. Hewett, A. Ismail and T. Rizzo,
Phys. Rev. D **93**, no. 3, 035017 (2016); doi:10.1103/PhysRevD.93.035017;
arXiv:1510.08840 [hep-ph].

I12. Illuminating New Electroweak States at Hadron Colliders.
A. Ismail, E. Izaguirre and B. Shuve,
Phys. Rev. D **94**, no. 1, 015001 (2016); arXiv:1605.00658 [hep-ph].

I13. Double peak searches for scalar and
pseudoscalar resonances at the LHC.
M. Carena, P. Huang, A. Ismail, I. Low, N. R. Shah and C. E. M. Wagner,
Phys. Rev. D **94**, no. 11, 115001 (2016); arXiv:1606.06733 [hep-ph].

We give below a brief description of the main areas in which new physics results were obtained.

* Wai–Yee Keung

A. *Feeble Goldstone Boson in the Collider physics and in Astrophysics.* (K1,K2)

Recently it was suggested that Goldstone bosons arising from the spontaneous breakdown of some global hidden symmetries can interact weakly in the early Universe and account for a fraction of the effective number of neutrino species $N_{\rm eff}$, which has been reported persistently 1σ away from its expected value of three. In this work, we study in some details a number of experimental constraints on this interesting idea based on the simplest possibility of a global $U(1)$, as studied by Weinberg. We work out the decay branching ratios of the associated light scalar field σ and suggest a possible collider signature at the Large Hadron Collider (LHC). In some corners of the parameter space, the scalar radial field σ can decay into a pair of pions with a branching ratio of order $O(1)\%$ while the rest is mostly a pair of Goldstone bosons. The collider signature would be gluon fusion into the standard model Higgs boson $gg \to H$ or associated production with a W gauge boson $q\bar{q}' \to HW$, followed by $H \to \sigma\sigma \to (\pi\pi)(\alpha\alpha)$ where α is the Goldstone boson.

We calculated the energy loss rates through the emission of these Goldstone bosons in a post-collapse supernova core. Invoking the well established emissivity bound from the Supernova 1987A observations and simulations, we find that nuclear bremsstrahlung processes can notably impose a bound on the Goldstone boson coupling to the Standard Model Higgs, g, dependent on the mass of the associated radial field, m_σ. For m_σ large enough compared with the temperature in the post-collapse supernova core, our bound is $|g| \lesssim 0.011(m_r/500\text{MeV})^2$, very competitive to that derived from collider experiments.

B. *Colliders Physics.* (K3,K5,K6,K11)

In K3, we categorize new physics signatures that manifest themselves as a dip structure at colliders. One potential way to realize a dip is to require interactions to be zero when all particles are mass on-shell, but not if one or more are mass off-shell. For three particle interactions, we have found three interesting cases: one massive gauge boson with two identical scalars; one massless gauge boson with two different scalars; one massive gauge boson with two identical massless gauge bosons. For each case, we identify the relevant effective operators to explore its dip signature at the LHC. Unfortunately, the unstable particle with a vanishing mass-on-shell interaction has a complex mass which is coincident with the complex pole in its propagator. As a result, a contact-like amplitude without a dip is produced. Some interesting collider signatures for fermion-phobic vector bosons are also discussed.

During the last few years and recently, the ATLAS Collaboration recorded interesting anomaly in diboson production with excesses at the diboson invariant mass around 2-3 TeV in boosted jets of diboson channels. In K5,K11 we offer a theoretical interpretation of the anomaly using a phenomenological right-handed model with extra W' and Z' bosons. Constraints from narrow total decay widths, dijet cross sections, and $W/Z + h$ production

are taken into account.

Rare decay modes of the newly discovered standard-model-like Higgs boson h may test the flavor changing couplings in the leptoquark sector through the process $h \to \tau^{\mp}\mu^{\pm}$. Motivated by the recently reported excess in LHC data from the CMS detector, we found in K6 that a predicted branching fraction $\mathrm{Br}(h \to \tau^{\mp}\mu^{\pm})$ at the level of 1% is possible even though the coupling parameters are subjected to the stringent constraint from the null observation of $\tau \to \mu\gamma$, where the destructive cancellation among amplitudes is achievable by fine tuning.

Inspired by the recent single $e^{\pm}\mu^{\mp}$ event at 2.1 TeV invariant mass from the ATLAS at $\sqrt{s} = 13$ TeV with 3.2 fb^{-1} luminosity, we propose in K8 an explanation using a Z' gauge boson, which possesses lepton-flavor-changing neutral currents originated from non-universal couplings to charged leptons. We assume that the left-handed charged-lepton mixing matrix equals to the PMNS matrix and no mixing in the neutrino sector to make this phenomenological Z' model more predictive. There are indeed some parameter regions, where the Z' can generate a large enough $e^{\pm}\mu^{\mp}$ production cross section, while at the same time satisfies various observables from lepton-flavor violation and other constraints from the LHC.

C. *Precision Physics in Muonic Hydrogen.* (K4)

In K4, we constrain the possibility of a new pseudoscalar coupling between the muon and proton using a recent measurement of the 2S hyperfine splitting in muonic hydrogen.

D. *Axial Vector Z′ and Anomaly Cancellation.* (K7)

Whilst the prospect of new Z' gauge bosons with only axial couplings to the Standard Model (SM) fermions is widely discussed, examples of anomaly-free renormalisable models are lacking in the literature. We look to remedy this by constructing several motivated examples. Specifically, we consider axial vectors which couple universally to all SM fermions, as well as those which are generation-specific, leptophilic, and leptophobic. Anomaly cancellation typically requires the presence of new coloured and charged chiral fermions, and we argue that the masses of these new states must generally be comparable to that of the axial vector. Finally, an axial vector mediator could provide a portal between SM and hidden sector states, and we also consider the possibility that the axial vector couples to dark matter. If the dark matter relic density is set due to freeze-out via the axial vector, this strongly constrains the parameter space.

E. *PeV neutrino interaction.* (K9,K14)

In K9, we interpret the PeV shower events observed by the IceCube collaboration as an s-channel enhancement of neutrino-quark scattering by a leptoquark that couples to the τ-flavor and light quarks. With a leptoquark mass around 0.6 TeV and a steep $1/E^{2.3}$ neutrino flux, charged-current scattering gives cascade events at ~ 1 PeV and neutral-current scattering gives cascade events at ~ 0.5 PeV. This mechanism is also consistent with the paucity of muon-track events above 100 TeV.

Deep inelastic scattering of very high-energy neutrinos can potentially be enhanced by the production of a single top quark or charm quark via the interaction of a virtual W-

boson exchange with a b-quark or s-quark parton in the nucleon. In K14, the single top contribution shows a sharp rise at neutrino energies above 0.5 PeV and gives a cross-section contribution of order 5 percent at 10 PeV, while single charm has a low energy threshold and contributes about 25 percent. Semi-leptonic decays of top and charm give di-muon events whose kinematic characteristics are shown. The angular separation of the di-muons from heavy quark production in the IceCube detector can reach up to one degree. Top quark production has a unique, but rare, three muon signal.

F. *Reappraisal on Dark Matter Co-annihilation with a top/bottom partner.* (K10)

We revisit the calculation of relic density of dark matter particles co-annihilating with a top or bottom partner, by properly including the QCD bound-states (onia) effects of the colored partners, as well as the relevant electroweak processes which become important in the low mass region. We carefully set up the complete framework that incorporates the relevant contributions and investigate their effects on the cosmologically preferred mass spectrum, which turn out to be comparable in size to those coming from the Sommerfeld enhancement. We apply the calculation to three scenarios: bino-stop and bino-sbottom co-annihilations in supersymmetry, and a vector dark matter co-annihilating with a fermionic top partner. In addition, we confront our analysis of the relic abundance with recent direct detection experiments and collider searches at the LHC, which have important implications in the bino-stop and bino-sbottom scenarios. In particular, in the bino-stop case recent LHC limits have excluded regions of parameter with a direct detection rate that is above the neutrino floor.

G. *SUSY Higgs boson based on Collider data.* (K12,K13)

In K12, we show that an enhanced two-photon signal of the Higgs boson, h, observed with 125 GeV mass by the ATLAS and CMS collaborations, can be obtained if it is identified principally with the neutral H_u^0 of the two Higgs doublets of minimal Supersymmetry. We focus on sparticles and the pseudoscalar Higgs A at the TeV scale. The off-diagonal element of the (H_u^0, H_d^0) mass matrix in the flavor basis must be suppressed, and this requires both a large Higgsino mass parameter, $\mu \sim$ TeV, and large $\tan(\beta)$. A MSSM sum rule is derived that relates $\gamma\gamma$ and $b\bar{b}$ rates, and the $\gamma\gamma$ enhancement predicts the $b\bar{b}$ reduction. On the contrary, Natural SUSY requires $|\mu| < 0.5$ TeV, for which $\gamma\gamma$ is reduced and $b\bar{b}$ is enhanced. This conclusion is independent of the mA-value and the SUSY quantum correction Δ_b. Relative $\tau\bar{\tau}$ to $b\bar{b}$ rates are sensitive to Δ_b.

In K13, we constrain the masses of scalar-tops (stop) by analyzing the new precision Tevatron measurement of the W-boson mass and the LHC/Tevatron indications of a Higgs boson of mass 125.5 ± 1 GeV.

* Pedro Schwaller

A. *Higgs Boson Phenomenology.* (S1)

In July 2012, both LHC experiments have announced the discovery of a resonance with a mass of 125 GeV and with properties consistent with a standard model (SM) Higgs boson. This marks a tremendous step forward in our understanding of the mechanism of electroweak symmetry breaking, and has therefore triggered several projects that aim to understand the implications of this discovery for the SM and for physics beyond the SM.

Determining the identity of the newly discovered resonance is crucial for our understanding of electroweak symmetry breaking. In S5 we have studied the possibility that the resonance is a superposition of a CP-even and a CP-odd state. Due to symmetries, this leads to modifications of the Higgs production and decay modes, and therefore to signal rates in the different channels that deviate from the SM predictions. We have studied how well the current data can constrain the CP-mixing angle and found that a purely CP-odd resonance can already be excluded at a high confidence level. Finally, we estimate that the mixing angle can be constrained to $\alpha < 1.1$ (0.7) in the full 8 TeV (14 TeV) run of the LHC.

B. *Phenomenology of vector-like leptons.* (S2,S3,S4)

Vector-like leptons were originally introduced in S2 in order to explain the apparent enhancement of the Higgs decay rate in the do-photon channel, and since then have become an active field of study for phenomenology.

One shortcoming of the model introduced in S2 is that the sizeable Yukawa couplings needed to explain an enhanced di-photon rate can destabilize the electroweak vacuum. We have therefore implemented the model of S4 into a grand unified supersymmetric framework, which provides a natural UV-completion. In addition to the vector-like leptons, now also their superpartners contribute to the Higgs to di-photon decay. We have studied the Higgs phenomenology in this model and performed a careful analysis of vacuum stability constraints in S3, and found regions of parameter space that allow for a 50% enhancement of the di-photon rate while at the same time making the model stable up to the GUT scale. The model possesses multiple dark matter candidates whose phenomenology is currently under study.

Another important question in vector-like lepton models is the origin of the mass scale for the Dirac masses, which are independent of the electroweak scale. In models where lepton number L is gauged, vector-like leptons naturally appear since they are required to cancel gauge anomalies in $U(1)_L$. In that case the Dirac mass is related to the lepton number breaking scale, and sub-TeV masses are natural without large tuning in the Yukawa couplings. In S4 such a model was constructed, and it was shown that it also leads to a viable dark matter candidate. Constraints on the model from electroweak precision, LEP data and from dark matter detection were evaluated. At the LHC this model can be probed in direct searches as well as through its indirect effects on Higgs properties.

C. *Leptogenesis.* (S5)

In the last year, significant progress was achieved in the calculation of Higgs Yukawa

interaction rates in the early universe. Good knowledge of these rates is important for an accurate prediction of the baryon asymmetry and a precise understanding of flavor effects. Previous approaches to calculate these rates are plagued by divergences in diagrams where fermions are exchanged in the t-channel, which lead to infinite interaction rates in a finite temperature background, and are usually regularized by ad-hoc introduction of thermal masses into the propagators.

Our method for the calculation is based on a strict 2PI loop expansion in non-equilibrium quantum field theory. Compared with previous approaches, the advantage is that the problematic diagrams are automatically resummed such that a finite result is obtained without any ad-hoc regularization prescription. We find that the interaction rates are dominated by gauge boson contributions that are logarithmically enhanced, while contributions involving the top Yukawa coupling are comparably small. Results for the high temperature limit, with all external legs approximately massless, were published in S5. This also represents the first consistent leading order calculation of the flavor equilibration rate in Leptogenesis, which is crucial to obtain accurate predictions for the baryon asymmetry when it takes place below temperatures of the order of 10^{12} GeV.

D. *Asymmetric dark matter.* (S6)

Asymmetric dark matter is based on the idea that the dark matter relic density is not determined by thermal freeze-out, but by an asymmetry similar to the baryon asymmetry in the visible sector. Since the matter and dark matter energy densities in the universe are of the same order, $\rho_{DM} \sim \rho_B$, this motivates the idea that the two asymmetries are not independent but related through some mechanism.

In recent years many mechanisms were presented that allow one to relate the baryon and the dark matter number densities dynamically, $n_{DM} \sim n_B$. However the origin of the dark matter mass scale is often unclear, and in many cases is left as a free parameter. In S6, we have presented a new mechanism to relate the mass of a composite dark matter particle to the proton mass, m_p, using infrared fixed points of QCD and a new confining gauge group in the dark sector, dark QCD. We have shown that models exist where the dark matter mass is naturally of the order of $(1-10) \times m_p$, and that within this setup a mechanism can be implemented that distributes an asymmetry evenly between the dark and visible sectors. A novel property of these models is the presence of TeV scale states that are both charged under QCD and under dark QCD, and predict new signatures at the LHC involving exotic dark jets. The rich phenomenology of these models, e.g. in flavor physics and in cosmology, will be explored in the future.

* Ahmed Ismail

A. *Heavy Quark Parton Distribution Functions.* (I1)

If a new heavy particle ϕ 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 proton-proton collider. We find that the introduction of a top PDF typically has a small effect even at a center of mass energy of 100 TeV due to three factors: 1) the strong coupling constant α_s at the scale $\mu = m_\phi$ is quite small when $\log(m_\phi/m_t)$ is large, 2) the Bjorken $x \ll 1$ for $m_\phi \lesssim 10$ TeV, and 3) the kinematic region where $\log(m_\phi/m_t) \gg 1$ 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 $pp \to \bar{t}H+$ at next-to-leading logarithm order.

B. *The phenomenological Minimal Supersymmetric Standard Model.* (I2, I3, I4, I5)

The phenomenological Minimal Supersymmetric Standard Model (pMSSM) is a tool to explore the parameter space of minimal supersymmetry (SUSY) that satisfies current experimental bounds at present and future experiments.

As is well known, the search for and eventual identification of dark matter in SUSY requires a simultaneous, multi-pronged approach with important roles played by colliders as well as both direct and indirect dark matter detection experiments. In I2 and I3, we examine the capabilities of these approaches in the pMSSM which provides a general framework for complementarity studies of neutralino dark matter. We summarize the sensitivity of dark matter searches at the 7, 8 (and eventually 14) TeV LHC, combined with those by Fermi, CTA, IceCube/DeepCore, COUPP, LZ and XENON. The strengths and weaknesses of each of these techniques are examined and contrasted and their interdependent roles in covering the model parameter space are discussed in detail. We find that these approaches explore orthogonal territory and that advances in each are necessary to cover the supersymmetric WIMP parameter space. We also find that different experiments have widely varying sensitivities to the various dark matter annihilation mechanisms, some of which would be completely excluded by null results from these experiments.

In I4, we study signatures of SUSY at the 7, 8 and 14 TeV LHC employing the pMSSM with a neutralino LSP. Our results were obtained via a fast Monte Carlo simulation of the ATLAS SUSY analysis suite. The flexibility of this framework allows us to study a wide variety of SUSY phenomena simultaneously and to probe for weak spots in existing SUSY search analyses. We determine the ranges of the sparticle masses that are either disfavored or allowed after the searches with the 7 and 8 TeV data sets are combined. We find that natural SUSY models with light squarks and gluinos remain viable. We extrapolate to 14 TeV with both 300 fb^1 and 3 ab^1 of integrated luminosity and determine the expected sensitivity of the jets + missing energy and stop searches to the pMSSM parameter space. We find that the high-luminosity LHC will be powerful in probing SUSY with neutralino LSPs and can provide a more definitive statement on the existence of natural supersymmetry.

Finally, in I5 we examine the connection between precision measurements of the couplings of the Higgs boson at the LHC/ILC and direct searches for SUSY partners in the pMSSM. Within this scenario, we address two questions: 1) How will potentially null direct searches for SUSY at the LHC influence the predicted properties of the lightest SUSY Higgs boson? 2) What can be learned about the properties of the superpartners from precision measurements of the Higgs boson couplings? We examine these questions by employing three different large sets of pMSSM models with either the neutralino or gravitino being the LSP. We make use of the ATLAS direct SUSY searches at the 7/8 TeV LHC as well as expected results from 14 TeV operations, and the anticipated precision measurements of the Higgs boson couplings at the 14 TeV LHC and at the ILC. We demonstrate that the future Higgs coupling determinations can deeply probe the pMSSM parameter space and, in particular, can observe the effects of models that are projected to evade the direct searches at the 14 TeV LHC with 3 ab^{-1} of integrated luminosity. In addition, we compare the reach of the Higgs coupling determinations to the direct heavy Higgs searches in the M_A–$\tan\beta$ plane and show that they cover orthogonal regions. This analysis further demonstrates the complementarity of direct and indirect approaches in searching for supersymmetry, and the importance of precision studies of the properties of the Higgs boson.

C. *Deconstructed Transverse Mass Variables.* (I6)

Traditional searches for R-parity conserving natural SUSY require large transverse mass and missing energy cuts to separate the signal from large backgrounds. SUSY models with compressed spectra inherently produce signal events with small amounts of missing energy that are hard to explore. We use this difficulty to motivate the construction of "deconstructed" transverse mass variables which are designed to preserve information on both the norm and direction of the missing momentum. We demonstrate the effectiveness of these variables in searches for the pair production of supersymmetric top quark partners which subsequently decay into a final state with an isolated lepton, jets and missing energy. We show that the use of deconstructed transverse mass variables extends the accessible compressed spectra parameter space beyond the region probed by traditional methods. The parameter space can be further expanded to neutralino masses that are larger than the difference between the stop and top masses. In addition, we also discuss how these variables allow for novel searches of single stop production, in order to directly probe unconstrained stealth stops in the small stop and neutralino mass regime. We demonstrate the utility of these variables for generic gluino and stop searches in all-hadronic final states. Overall, we demonstrate that deconstructed transverse variables are essential to any search wanting to maximize signal separation from the background when the signal has undetected particles in the final state.

D. *Higgs Physics at Colliders.* (I7, I10)

Determination of Higgs self-interactions through the double Higgs production from gluon fusion is a major goal of current and future collider experiments. In I1, 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, we find that the spectrum at high hh invariant mass is sensitive to the spin of the particles in the loop.

It is also important to search for extra Higgs bosons. In I4, we summarize the production of non-SM Higgses in the Type II Two Higgs Doublet Model at a 100 TeV pp collider, as well as their decays. We present the reach for $pp \to bbH^0/A \to bbtt, bb\tau\tau$, $pp \to H^0/A \to tt$ as well as $pp \to tbH^\pm \to tbtb, tb\tau\nu$ at the 100 TeV pp collider and outline the possible search channels via Higgs exotic decays. We point out that a combination of these conventional channels yields full coverage for $\tan\beta$ and pushes the exclusion limits from the $\mathcal{O}(1)$ TeV at the LHC to the $\mathcal{O}(10)$ TeV at a 100 TeV pp collider, whereas the exotic decays of a heavy Higgs into two light Higgses or one light Higgs plus one SM gauge boson provide alternative discovery channels.

E. *Interpreting LHC Results.* (I8, I9,I12,I13)

Several potential interesting results appeared at the end of Run 1 of the LHC. In I2, we demonstrate that the 3σ excess observed by ATLAS in the Z+MET channel can be explained within the context of the MSSM. Using the freedom inherent in the phennomenological MSSM, we perform a detailed analysis of the parameter space and find a scenario that describes the excess while simultaneously complying with all other search constraints from the Run 1 data at 7 and 8 TeV, including the Z+MET analysis by CMS. We generate a small sample of simplified models, using promising models from our existing phenomenological MSSM sample as seeds, and study their properties. The successful simplified model is found to be described by the production of $1^{st}/2^{nd}$ generation squark pairs, followed by their decay into a bino-like neutralino which in turn decays into a Higgsino-like LSP triplet by emitting a Z boson, *i.e.*, $\tilde{q} \to \tilde{B} \to \tilde{h}$ with $\tilde{q} = \tilde{Q}_L, \tilde{u}_R$, or $\tilde{d}_R$. The preferred region for the sparticle spectrum is found to have squark masses in the 500-750 GeV range, with bino masses near 350 GeV with a mass splitting of 150-200 GeV with the Higgsino LSP. If this excess holds, then this scenario predicts that a signal will be observed in the $0l$+jets and/or $1l$+jets searches in the early operations of Run 2.

In addition, LHC Run 1 data contain excessive events in the same-sign dilepton channel with b-jets and 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 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.

In I12, we propose a novel powerful strategy to perform searches for new electroweak states. Uncolored electroweak states appear in generic extensions of the Standard Model (SM) and yet are challenging to discover at hadron colliders. This problem is particularly acute when the lightest state in the electroweak multiplet is neutral and all multiplet components are approximately degenerate. In this scenario, production of the charged fields of

the multiplet is followed by decay into nearly invisible states; if this decay occurs promptly, the only way to infer the presence of the reaction is through its missing energy signature. Our proposal relies on emission of photon radiation from the new charged states as a means of discriminating the signal from SM backgrounds. We demonstrate its broad applicability by studying two examples: a pure Higgsino doublet and an electroweak quintuplet field.

Many new physics models contain a neutral scalar resonance that can be predominantly produced via gluon fusion through loops. In such a case, there could be important effects of additional particles, that in turn may hadronize before decaying and form bound states. This interesting possibility may lead to novel signatures with double peaks that can be searched for at the LHC. In I13, We study the phenomenology of double peak searches in diboson final states from loop induced production and decay of a new neutral spin-0 resonance at the LHC. The loop-induced couplings should be mediated by particles carrying color and electroweak charge that after forming bound states will induce a second peak in the diboson invariant mass spectrum near twice their mass. A second peak could be present via loop-induced couplings into gg (dijet), $\gamma\gamma$ and $Z\gamma$ final states as well as in the WW and ZZ channels for the case of a pseudo-scalar resonance or for scalars with suppressed tree-level coupling to gauge bosons.

F. *CP-violating Supersymmetry.* (I11)

In this work, we investigate the sensitivity of the next generation of flavor-based low-energy experiments to probe the parameter space of supersymmetry in the context of the phenomenological MSSM, and examine the complementarity with direct searches for supersymmetry at the 13 TeV LHC in a quantitative manner. To this end, we enlarge the usual pMSSM parameter space to include all physical non-zero CP-violating phases, namely those associated with the gaugino mass parameters, Higgsino mass parameter, and the tri-linear couplings of the top quark, bottom quark and tau lepton. We find that future electric dipole moment and flavor measurements can have a strong impact on the viability of these models even if the sparticle spectrum is out of reach of the 13 TeV LHC. In particular, the lack of signals of new physics in future low-energy probes would exclude values of the phases between $\mathcal{O}(10^{-2})$ and $\mathcal{O}(10^{-1})$. We also find regions of parameter space where large phases remain allowed due to cancellations. Most interestingly, in some rare processes, such as BR($B_s \to \mu^+\mu^-$), we find that contributions arising from CP-violating phases can bring the potentially large SUSY contributions into better agreement with experiment and Standard Model predictions.

ACKNOWLEDGEMENTS

For the past 33 years, our research in the high energy theoretical physics at UIC was supported uninterruptedly by DOE grants, which enabled us to achieve many fruitful results in understanding of the electroweak interaction and in the fundamental physics at the deeper level. We are very thankful for the DOE funding, which has been essential in partially supporting our graduate students, postdocs, and faculty members for their salaries and travel expenses, as well as costs of seminars and workshops, etc. Now the grant finished because

the principal investigator retired from UIC in summer, 2016. However, he finds more time in research, being free from departmental tasks, and continues to be engaged in physics with students and scientists at UIC, and in the HEP community of Chicagoland at large.