Final Report for DE-SC0010078
High Energy Physics Research with the CMS Experiment at CERN
University of California, Riverside

Principal Investigator: Gail G. Hanson

Grant Dates: June 1, 2013 – March 17, 2017

1. Introduction and Overview

The discovery of the Higgs boson by the ATLAS and CMS experiments [1-3] at the CERN Large Hadron Collider (LHC) was announced on July 4, 2012. The Higgs boson was postulated in 1964 [4-6] to explain how elementary particles obtain mass and was the missing piece of the Standard Model. François Englert and Peter Higgs were awarded the 2013 Nobel Prize in Physics in October 2013. However, the Standard Model does not describe everything that we know. There are many unanswered questions, such as how can the Higgs boson have the mass that we have observed, are there more Higgs bosons, why is there more matter than antimatter, and what is the invisible dark matter, which constitutes about 85% of the matter in the universe.

This report period covers the shutdown of about two years beginning in March 2013 to complete repairs needed to run at an energy close to the design energy of 14 TeV. Data taking at 13 TeV (Run 2) began in June 2015. Our group played a significant role in the discovery of the Higgs boson and in subsequent analyses, which extended into the Run 2 data taking period, and Run 2 Higgs$\rightarrow\gamma\gamma$ analysis. We also carried out searches for new physics in Supersymmetry and heavy Majorana neutrinos. Our role in the CMS detector has focused on the pixel inner tracker, including its repairs and re-commissioning during the shutdown; the construction, installation and commissioning of the Phase-I upgrade (the replacement of the entire pixel tracker); and preparing for the Phase-II (HL-LHC) upgrade.

1.1. Personnel

The members of our group during the grant period are listed below:

Teaching Faculty: Gail G. Hanson, Distinguished Professor (PI), John Ellison, Professor (Co-PI) until April 2016.

Postdoctoral Researchers: Martina Malberti until May 2016 (left for Marie Curie Fellowship at Milano Bicocca University).

Graduate Students: Kira Burt, Manuel Olmedo, Weinan Si, and Brent Yates (Yates until April 2016). Burt finished her PhD in June 2017, and Olmedo will finish in August 2017.

1.2. Leading Roles in CMS

Hanson and the other members of the group have played important roles in the experiment both on the pixel tracker and in the physics. Beginning September 1, 2016, Hanson started as one of two Higgs Publication Committee Co-Chairs, responsible for all Higgs publications, and replacing Michel Della Negra, the founding Spokesperson of CMS. She was also one of three members of the Cost Estimate Committee for the Phase-II Technical Proposal. Hanson served as Analysis Review Committee Chair for analyses in Higgs, Supersymmetry, and Exotica until she began as Higgs Publication Committee Co-Chair.

Hanson's recent postdoctoral researcher Martina Malberti joined the group in May 2013 in order to work on the Forward Pixel Detector. She served as Level 3 Operations Coordinator for the Forward Pixel Detector and received a CMS Achievement Award for the Tracker in February 2015. Because of her previous experience on the Run 1 Higgs$\rightarrow\gamma\gamma$ analysis, she was asked to serve as Higgs$\rightarrow\gamma\gamma$ subgroup co-convener beginning in January 2016.

Malberti and graduate students Kira Burt, Manuel Olmedo, and Weinan Si worked as Pixel Detector Expert On-Call (Pixel Doc).

John Ellison was a leader in the search for heavy Majorana neutrinos.

2. Physics Analysis

2.1. Searches for New Physics

2.1.1. Searches for Supersymmetry (SUSY). Hanson and her group have been active in the SUSY Photon working group since 2005. We have performed searches for SUSY in the context of general gauge-mediated (GGM) breaking with the lightest neutralino as the next-to-lightest SUSY particle (NLSP) and the gravitino as the lightest (LSP). The neutralino is assumed to decay promptly to a photon and a gravitino. The GGM model allows the strongly interacting SUSY particles to have large production cross sections at the LHC, permitting the exploration of parameter space inaccessible at previous colliders. Now, however, SUSY searches are interpreted in terms of simplified models.

The discovery of the Higgs boson expanded the realm of SUSY searches into searches for production of a pair of higgsinos, the supersymmetric partners of the Higgs boson. A new development was a search for electroweak production of a pair of higgsinos (NLSP), each of which decays to a Higgs boson and an LSP. The Higgs bosons are reconstructed through their various decays. Graduate student Kira Burt and Hanson worked on such a search in which one of the Higgs bosons decays to $\gamma\gamma$ and the other to $b\bar{b}$, with missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ due to the LSPs. This search was combined with other channels and published [7].

Burt then carried out a search for light sbottoms (the supersymmetric partner of the b quark) and higgsinos using Higgs to diphoton decays. The signature is events with at least two b-jets and a pair of photons whose invariant mass is consistent with that of a Higgs boson. This search constituted her PhD thesis.

2.1.2. Searches for Heavy Majorana Neutrinos. Ellison led the searches for heavy Majorana neutrinos in CMS, working with former graduate student Ferdinando Giordano and others. The paper on the search using the 2011 data [8] was the first CMS paper to be published on heavy neutrino searches. Two more publications [9, 10] using 8 TeV data established UC Riverside as a leader in heavy neutrino physics at CMS. Giordano completed his PhD in March 2013 but continued to work with Ellison as a postdoc at Catania/INFN. Ellison and current graduate student Brent Yates began a search using 13 TeV data taken in 2015; however, it was not finished, and Ellison served as Analysis Review Committee member for the 13 TeV searches.

2.1.3. Dark Matter Searches. Hanson is starting a new search for Self-Interacting Dark Matter (SIDM), working with graduate student Weinan Si and Assistant Professor Hai-Bo Yu, a theorist at UC Riverside, and his collaborators. Possibilities for a signal involve the annihilation decay of the dark matter bound state into light mediators, which decay into leptons, boosted or not, with no missing transverse energy [11, 12]. We are starting to look at related searches in CMS (and ATLAS) and background simulations and will work with Yu's postdoc to model the signal. We are planning to involve other physicists in CMS.

2.2. Higgs Boson Physics

The Higgs$\rightarrow\gamma\gamma$ analysis was one of the principal discovery channels [1]. Hanson and previous members of the group began working on the $H\rightarrow\gamma\gamma$ search around 2009, including the time of the discovery. Hanson has been working on searches for the Higgs boson, both standard model and beyond the standard model for many years before CMS and was invited to write a review of Higgs searches in 2009, just before LHC data taking began [13]. Recent members of the group are Manuel Olmedo, who joined in late 2012, and Martina Malberti, who joined U.C. Riverside in 2013 but worked on the Forward Pixel Tracker until January 1, 2016, when she became Higgs→$\gamma\gamma$ subgroup co-convener. Hanson began serving as Higgs Publication Committee Co-Chair in September 2016.

The final $H \to \gamma\gamma$ analysis for the 7 TeV data taken in 2011 and 8 TeV data in 2012 was finally completed and published in 2014 [14] (the so-called "legacy paper"). The $H \to \gamma\gamma$ channel provides a precise measurement of the Higgs mass as well as very significant excess with a local significance of 5.7 σ, compared with 5.2 σ expected for the standard model (SM) because of this.

Results from the combination of the $H \to \gamma\gamma$ results with the results from the other channels [15] are shown in Fig. 1. From the combination of $H \to \gamma\gamma$ with $H \to ZZ \to 4$ leptons (e or μ), the mass of the Higgs boson was determined to be $125.02^{+0.26}_{-0.27}$ (stat) $^{+0.14}_{-0.15}$ (syst) GeV, and the couplings of the five channels $H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$, $H \to \tau\tau$, $H \to bb$, and $H \to \mu\mu$ were compared with their standard model predictions using the mass determined from $H \to \gamma\gamma$ with $H \to ZZ$. The best-fit signal strengths $\mu = \sigma/\sigma_{SM}$ for groupings of decay modes are shown in Fig. 1. Other combinations of decay modes were also examined, and no significant deviations from the standard model coupling were found.

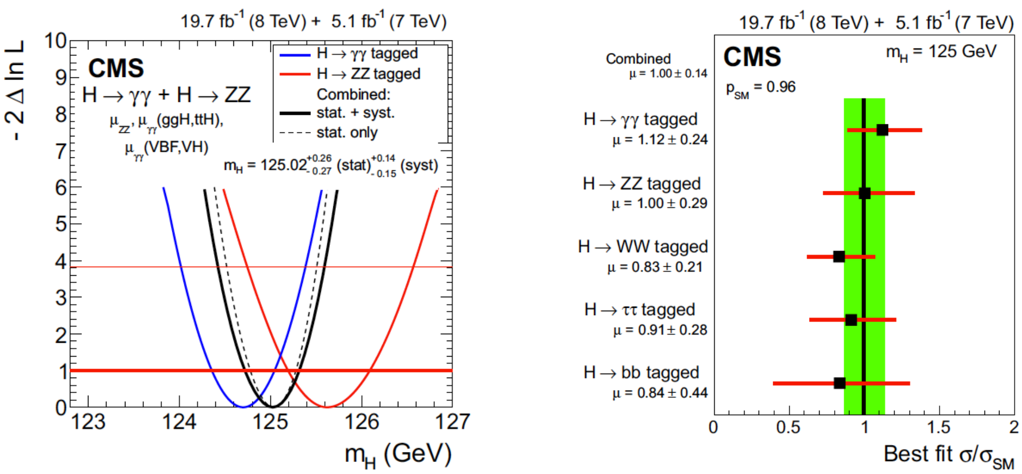

Figure 1: (Left) Scan of the test statistic $q(m_H) = -2\Delta \ln \mathcal{L}$ versus the mass of the boson m_H for the $H \to \gamma\gamma$ and $H \to ZZ \to 4\,\ell$ final states separately and for their combination. (Right) Values of the best-fit σ/σ_{SM} grouped by the dominant decay mode.

The ATLAS and CMS data for the $H \to \gamma\gamma$ and $H \to ZZ \to 4\,\ell$ final states were used to determine a combined measurement of the Higgs boson mass [16]. The results were obtained from a simultaneous fit to the reconstructed invariant mass peaks in the two channels and for the two experiments. The combined measured mass of the Higgs boson was found to be 125.09 ± 0.11 (stat) ± 0.11 (syst) GeV.

Simultaneous fits to the signal strengths for the ATLAS and CMS experiments were obtained [17], and the combined coupling strength was determined to be $\mu = 1.09 \pm 0.11$.

Hanson's group worked to redevelop the $H \to \gamma\gamma$ analysis for the 13 TeV Run 2 data. Making the analysis more centralized and CMS software compatible were the main tasks of the redevelopment. The analysis also needed to be compatible with the new MicroAOD framework. The new framework is called "FLASHgg," for Flexible Lightweight Analysis Steps Hgg. Olmedo played a central role in its development.

Preliminary 13 TeV results were presented at the Moriond conference in March 2016 [18], at ICHEP 2016 in Chicago in August [19], and at LHCP 2017 in Shanghai in May 2017 [20]; the LHCP results are shown in Fig. 2. The LHCP results used 2016 data corresponding to an integrated luminosity of 35.9 fb^{-1}. The best-fit signal strength compared with the SM prediction is $1.16^{+0.15}_{-0.14}$.

These results will be published, but a reconstruction of the data, not planned until the end of 2017, will be needed before the mass can be published.

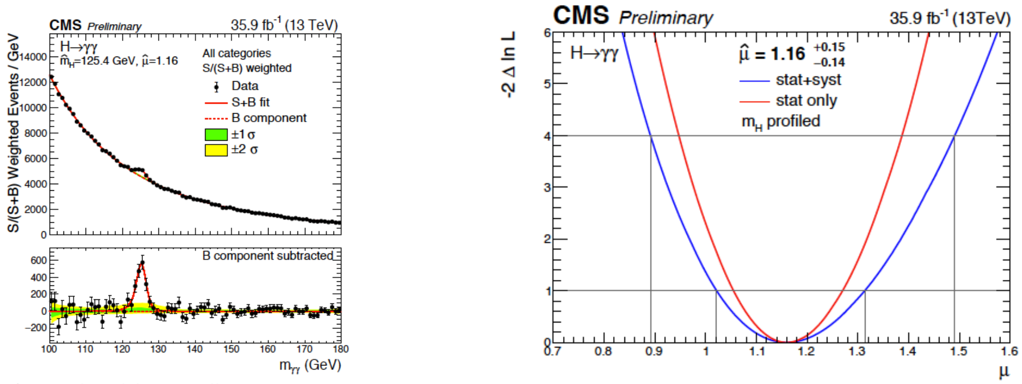

Figure 2: $H\to\gamma\gamma$ results shown at LHCP 2017 [20]. (Left) Data points (black) and signal plus background model fits for all categories summed, where the categories are summed weighted by their sensitivity. The 1 standard deviation (green) and 2 standard deviation (yellow) bands include the uncertainties of the fit. The residuals after background subtraction are shown below. (Right) Likelihood scan for the signal strength where the value of the standard model Higgs boson mass is profiled in the fit.

Olmedo will complete his PhD dissertation in August 2017 on a measurement in the *VH* channel, in which the Higgs boson is produced along with a *W* or a *Z*, as part of the overall $H\to\gamma\gamma$ analysis.

3. Silicon Tracker

3.1. Repairs of Pixel Tracker 2013-2014

Under the direction of Hanson, Kira Burt, Manuel Olmedo, and Martina Malberti carried out the repairs of the forward pixel tracker (FPIX), which was removed from the CMS detector during the long shutdown of 2013-2014, and re-commissioned it after it was re-installed. Their work focused on data acquisition and calibrations. Their work on the repair of the FPIX was highlighted in an article in *Fermilab Today* (see http://www.fnal.gov/pub/today/archive/archive_2013/today13-08-23.html).

3.2. Phase-I Upgrade of Pixel Tracker 2016-2017

The Phase-I upgrade will maintain a high efficiency at an instantaneous luminosity of $2\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, have less material than the previous detector, and will provide four hits per track over the range $|\eta| < 2.5$ [21]. The Phase-I Upgrade pixel detector is shown in Fig. 3. Graduate student Weinan Si joined the group in the summer of 2015 and began working on the Phase-I FPIX Upgrade, doing module testing at Fermilab. He was awarded a US CMS Fellowship to work on the Phase-I FPIX Upgrade. He relocated to CERN in September 2016 to take part in the installation, commissioning, and operation. The Phase-I Upgrade was installed during the Extended Year-End Technical Stop of 2016-2017. Data taking with the new pixel tracker resumed in June. Si has played an important role in the operation, especially on the DAQ. He will give a presentation “Commissioning and Operation of the New CMS Phase I Pixel Detector” at the DPF Meeting at Fermilab in August, the only CMS speaker from UC Riverside.

3.3. Phase-II (HL-LHC) Tracker Upgrade

To fulfill the physics potential of the HL-LHC upgrade, several experimental challenges must be

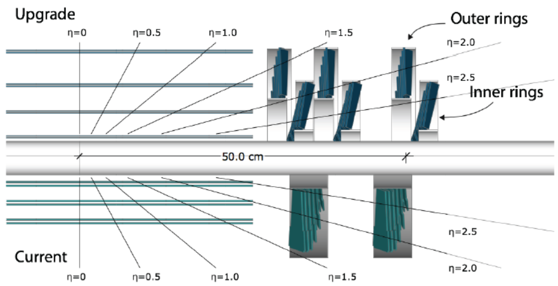

Figure 3: Schematic view of the Phase-I beam pipe and pixel detector layout, showing the current detector and the Upgrade with four barrel layers and three end disks on each side.

met, including radiation damage and high occupancy [22], necessitating the replacement of the entire central tracker and the addition of a Level-1 track trigger, which is required to increase the rejection power of the calorimeter and muon triggers to keep the overall trigger rate at an acceptable level. The layout of the HL-LHC (Phase-II) Tracker is shown in Fig. 4.

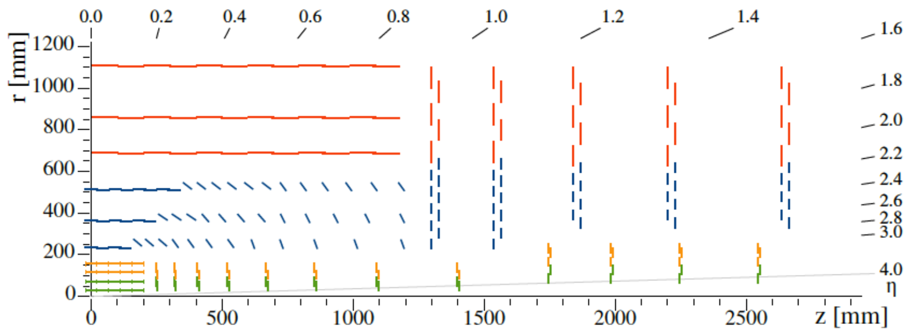

Figure 4: Drawing of one quarter of the Phase-II tracker layout in the *r-z* view. In the Inner Tracker the green lines correspond to pixel modules made of two readout chips and the yellow lines to pixel modules with the four readout chips. In the Outer Tracker the blue and red lines represent two types of modules.

Ellison and his graduate student Brent Yates worked on simulations of the so-called “tracklet” approach to the Level-1 track trigger, in which Field-Programmable Gate Arrays (FPGAs) are used to implement a track finding algorithm that is seeded by finding pairs of stubs (“tracklets”) in neighboring layers. Yates worked under the supervision of Louise Skinnari, a postdoc at Cornell University.

Hanson and her group are working on the forward pixel detector upgrade (now called TFPX), a US-led project, which has obtained major funding as part of the US CMS National Science Foundation (NSF) MREFC.

Hanson was one of three members of the Phase-II Cost Estimate Committee 2014-2015 for the Technical Proposal [22] and was nominated as Deputy Upgrade Coordinator. She also worked on bases of estimates for the TFPX cost estimates. The Technical Design Report (TDR) will be submitted to the LHCC on July 1, 2017; Hanson was a member of the Phase-II Tracker TDR team.

The group, including graduate student Weinan Si and hopefully expanding after the completion of two PhD dissertations, will work on sensor development, including beam tests, and design of the detector. A beginning graduate student or undergraduate will also work on whole-detector simulations of physics performance. The group will also work on module testing at one of the other institutions that already has an installation and technical support.

Appendix A: Bibliography and References Cited

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Appendix B: Other Contributions to the CMS Experiment

- G. Hanson, Higgs Publication Committee Co-Chair, beginning September 1, 2016.

- M. Malberti, $H \rightarrow \gamma\gamma$ subgroup co-convener beginning January 1, 2016.

- G. Hanson, member of the CMS Cost Estimate Committee for the Phase-II Technical Proposal, February 2014 – September 2015.

- M. Malberti, L3 Operations Coordinator for the Forward Pixel Detector 2013-2014; CMS Achievement Award for the Tracker February 2015.

- J. Ellison, Member of Analysis Review Committee for "Search for a heavy composite Majorana neutrino in the final state with two leptons and two quarks at $\sqrt{s}$ = 13 TeV," EXO-16-026, submitted to *Phys. Lett. B*, June 2017.

- G. Hanson, Chair of Analysis Review Committee for "Search for resonant Higgs boson production in the $b\bar{b}\tau^{+}\tau^{-}$ final state using 2016 data," HIG-16-029, public Physics Analysis Summary prepared for ICHEP 2016.

- G. Hanson, Chair of Analysis Review Committee for "Search for non-resonant Higgs boson production in the $b\bar{b}\tau^{+}\tau^{-}$ final state using 2016 data," HIG-16-028, public Physics Analysis Summary prepared for ICHEP 2016.

- G. Hanson, Chair of Analysis Review Committee for "Search for supersymmetry in events with photons and missing transverse energy in pp collisions at 13 TeV," SUS-15-012, public Physics Analysis Summary prepared for Moriond 2016, published in *Phys. Lett. B* June 2017.

- G. Hanson, Chair of Analysis Review Committee for "Search for resonant Higgs boson production in the $b\bar{b}\tau^{+}\tau^{-}$ final state," HIG-16-013, public Physics Analysis Summary prepared for Moriond 2016.

- G. Hanson, Chair of Analysis Review Committee for "Search for non-resonant Higgs boson production in the $b\bar{b}\tau^{+}\tau^{-}$ final state," HIG-16-012, public Physics Analysis Summary prepared for Moriond 2016.

- J. Ellison, Chair of Analysis Review Committee for "Search for Type-III Seesaw Heavy Fermions with Multilepton Final States using 2.3 fb^{-1} of $\sqrt{s}$ = 13 TeV proton-proton Collision Data," EXO-16-002, public Physics Analysis Summary prepared for Moriond 2016.

- J. Ellison, Member of Analysis Review Committee for "Search for dark matter, extra dimensions, and unparticles in monojet events in proton-proton collisions at $\sqrt{s}$ = 8 TeV," published in *Eur. Phys. J. C* 2015.

- J. Ellison, Analysis Review Committee Member, “Search for top squarks decaying to a charm quark and a neutralino in events with a jet and missing transverse momentum,” CMS Physics Analysis Summary, CMS PAS SUS-13-009, 2014.

- G. Hanson, Chair of Analysis Review Committee for “Searches for third generation squark production in fully hadronic final states in proton-proton collisions at $\sqrt{s}$ = 8 TeV,” CMS-SUS-14-001, published in *J. High Energy Phys.* June 2015.

- G. Hanson, Chair of Analysis Review Committee for “Search for charged Higgs bosons with the $b\bar{b}\tau^{+}\tau^{-}$ decay channel in the fully hadronic final state at $\sqrt{s}$ = 8 TeV,” CMS-HIG-14-020, public Physics Analysis Summary.

- G. Hanson, Chair of Analysis Review Committee for “Search for direct production of a pair of bottom squarks,” SUS-13-018, public Physics Analysis Summary prepared for Moriond 2014.

- G. Hanson, Chair of Analysis Review Committee for “Search for the Standard Model Higgs Boson Decaying to Tau Pairs in Association with a *W* or *Z* Boson with the CMS Experiment in *pp* Collisions at $\sqrt{s}$ = 7 and 8 TeV,” CMS-PAS-HIG-12-053, public Physics Analysis Summary prepared for Moriond 2013 and combined with HIG-13-004 for publication.

- G. Hanson, Chair of Analysis Review Committee for “Evidence for the Standard Model Higgs Boson Decaying to Tau Pairs in Proton-Proton Collisions at $\sqrt{s}$ = 7 and 8 TeV,” HIG-13-004, public Physics Analysis Summary prepared for Moriond 2013, published in *J. High Energy Phys.* May 2014.

Appendix C: PhD Theses

- Kira Burt, "A Search for a Simplified Model of Supersymmetry with Light Sbottoms and Higgsinos Using Higgs to Diphoton Decays ," defense June 7, 2017. Will begin a tenure-track faculty position at Spokane Falls Community College, Spokane, Washington.

Invited Presentations by Group Members

- M. Olmedo, "Higgs to two photons in CMS," poster presentation, 3rd Annual Large Hadron Collider Physics Conference (LHCP2015), St. Petersburg, Russia, August 31 – September 5, 2015.

- M. Malberti, "Search for the Higgs boson decaying to two photons in CMS," 20th International Conference on Particles and Nuclei (PANIC 14), Hamburg University, Hamburg, Germany, 25-29 August 2014.

- G. Hanson, "Searches for SUSY in Final States with Photons," 22nd International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY2014), Manchester, England, 21-26 July 2014.

- M. Malberti, "Operation and performance of the CMS tracker," poster presentation at the Third International Conference on Technology and Instrumentation in Particle Physics (TIPP'14), Amsterdam, The Netherlands, 2-6 June 2014.

Publications During the Grant Period with Significant Input from Our Group

1. CMS Collaboration, “Measurements of the properties of the Higgs boson in the diphoton decay channel with the full 2016 data set,” CMS Physics Analysis Summary CMS-PAS-HIG-16-040 (2017).
2. CMS Collaboration, “Updated measurements of Higgs boson production in the diphoton decay channel at $\sqrt{s}$ = 13 TeV in *pp* collisions at CMS,” CMS Physics Analysis Summary CMS-PAS-HIG-16-020 (4 August 2016).
3. V. Khachatryan *et al.*, CMS Collaboration, “Search for heavy Majorana neutrinos in $e^{\pm}e^{\pm}$ + jets and $e^{\pm}\mu^{\pm}$ + jets events in proton-proton collisions at $\sqrt{s}$ = 8 TeV,” *JHEP* **1604** (2016) 169, doi: 10.1007/JHEP04(2016)169.
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