Research on the Theory of the Terascale

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SCIPP Theory
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SCIPP Particle Theory Group

- **Thomas Banks**: supersymmetry, string theory, gravity, and the early universe
- **Michael Dine**: supersymmetry, string theory, and the early universe
- **Howard Haber**: Higgs bosons, collider physics, new physics beyond the Standard Model at the terascale (including supersymmetry)
- **Stefano Profumo**: Theories of particle dark matter and their implications for astrophysics and collider phenomenology

In addition, Anthony Aguirre and Joel Primack work on a variety of topics overlapping particle theory and astroparticle theory, including dark matter, early universe cosmology, inflation, ...
The Standard Model (SM) of Particle Physics

The elementary particles consists of three generations of spin-1/2 quarks and leptons and the gauge bosons of SU(3)xSU(2)xU(1).

Technically, massive neutrinos require an extension of the Standard Model, but most likely the relevant scale of the new physics lies way beyond the terascale.
Naively, an SU(3)xSU(2)xU(1) gauge theory yields massless gauge bosons and massless quarks and leptons, in conflict with observation. The Standard Model introduces the Higgs mechanism for mass generation. The gauge invariance is spontaneously broken. In the simplest implementation, a spinless physical Higgs scalar is predicted.
explain it in 60 seconds

**The Higgs boson** is a fundamental particle predicted by theorist Peter Higgs, which may be the key to understanding why elementary particles have mass. Explaining the connection, I am reminded of the puzzler, “If sound cannot travel in a vacuum, why are vacuum cleaners so noisy?”

This riddle actually touches on a profound insight of modern physics: the vacuum—or empty space—is far from empty. It is indeed “noisy” and full of virtual particles and force fields. The origin of mass seems to be related to this phenomenon.

In Einstein’s theory of relativity, there is a crucial difference between massless and massive particles: All massless particles must travel at the speed of light, whereas massive particles can never attain this ultimate speed. But, how do massive particles arise? Higgs proposed that the vacuum contains an omnipresent field that can slow down some (otherwise massless) elementary particles—like a vat of molasses slowing down a high-speed bullet. Such particles would behave like massive particles traveling at less than light speed. Other particles—such as the photons of light—are immune to the field: they do not slow down and remain massless.

Although the Higgs field is not directly measurable, accelerators can excite this field and “shake loose” detectable particles called Higgs bosons. So far, experiments using the world’s most powerful accelerators have not observed any Higgs bosons, but indirect experimental evidence suggests that particle physicists are poised for a profound discovery.

*Howard E. Haber, University of California, Santa Cruz*
Higgs production at hadron colliders

At hadron colliders, the relevant processes are

\[ gg \rightarrow h^0, \quad h^0 \rightarrow \gamma \gamma, \ VV^{(*)}, \]

\[ qq \rightarrow qqV^{(*)}V^{(*)} \rightarrow qqh^0, \quad h^0 \rightarrow \gamma \gamma, \ \tau^+ \tau^-, \ VV^{(*)}, \]

\[ q\bar{q}^{(t)} \rightarrow V^{(*)} \rightarrow Vh^0, \quad h^0 \rightarrow b\bar{b}, \ WW^{(*)}, \]

\[ gg, q\bar{q} \rightarrow t\bar{t}h^0, \quad h^0 \rightarrow b\bar{b}, \ \gamma \gamma, \ WW^{(*)}. \]

where \( V = W \) or \( Z \).
Probability of Higgs boson decay channels
Question: why not search for Higgs bosons produced in gluon-gluon fusion that decay into a pair of b-quarks?

Answer: The Standard Model background is overwhelming. There are more than $10^7$ times as many b-quark pairs produced in proton-proton collisions as compared to b-quark pairs that arise from a decaying Higgs boson.

Roughly 250,000 Higgs bosons per experiment were produced at the LHC from 2010—2013.
SM Higgs decays at the LHC for $m_h \sim 125$ GeV

1. The rare decay $h^0 \rightarrow \gamma\gamma$ is the most promising signal.

2. The so-called golden channel, $h^0 \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ (where one or both $Z$ bosons are off-shell) is a rare decay for $m_h \sim 125$ GeV, but is nevertheless visible.

3. The channel, $h \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\overline{\nu}$ is also useful, although it does not provide a good Higgs mass determination.
On July 4, 2012, the discovery of a new boson is announced which may be the long sought after Higgs boson.

The discovery papers are published two months later in Physics Letters B.

ATLAS Collaboration:

Physics Letters B716 (2012) 1—29

CMS Collaboration:

A boson is discovered at the LHC by the ATLAS Collaboration

Invariant mass distribution of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The result of a fit to the data of the sum of a signal component fixed to \(m_H = 126.8\) GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays the residuals of the data with respect to the fitted background component. Taken from ATLAS-CONF-2013-012 (March, 2013).

The distribution of the four-lepton invariant mass for the selected candidates, compared to the background expectation in the 80 to 170 GeV mass range, for the combination of the 7 TeV 8 TeV data. The signal expectation for a Higgs boson with \(m_H = 125\) GeV is also shown. Taken from ATLAS-CONF-2013-013 (March, 2013).
A boson is discovered at the LHC by the CMS Collaboration

The diphoton invariant mass distribution with each event weighted by the $S/(S+B)$ value of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of the unweighted invariant mass distribution. Taken from Physics Letters B716 (2012) 30—61.

Distribution of the four-lepton reconstructed mass in full mass range for the sum of the 4e, 4μ, and 2e2μ channels. Points represent the data, shaded histograms represent the background and unshaded histogram the signal expectations. The expected distributions are presented as stacked histograms. The measurements are presented for the sum of the data collected at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. [70-180] GeV range - 3 GeV bin width. Taken from CMS-PAS-HIG-13-002 (March, 2013).
Values of the best-fit $\sigma/\sigma_{\text{SM}}$ for the combination (solid vertical line) and for subcombinations by predominant decay mode and additional tags targeting a particular production mechanism. The vertical band shows the overall $\sigma/\sigma_{\text{SM}}$ uncertainty. The $\sigma/\sigma_{\text{SM}}$ ratio denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The horizontal bars indicate the ±1 standard deviation uncertainties in the best-fit $\sigma/\sigma_{\text{SM}}$ values for the individual modes; they include both statistical and systematic uncertainties. Taken from arXiv:1412.8662 (December, 2014).

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ATLAS evidence for a SM-like Higgs boson (from a CERN seminar October 7, 2014)
Winners of the 2013 Nobel Prize in Physics

François Englert
and
Peter Higgs
Research program 1: theory and phenomenology of Higgs bosons
Research program 2: theory and phenomenology of TeV-scale supersymmetry (SUSY)

Research program 3: explorations of the Terascale at present and future colliders (LHC and ILC)

- Studies of the non-minimal Higgs sector
- Precision measurements of new physics observables
- Distinguishing among different theoretical interpretations of new physics signals
- Employing the ILC as a precision Higgs factory
- Terascale footprints of lepton-number-violating physics (e.g. R-parity-violation or the SUSY seesaw)
- New sources for CP-violation (Higgs and/or SUSY mediated)
CMS search for deviations from SM-Higgs couplings

Summary plot of likelihood scan results for the different parameters of interest in benchmark models separated by dotted lines. The BR_{BSM} value at the bottom is obtained for the model with three parameters (κ_g, κ_γ, BR_{BSM}). The inner bars represent the 68% CL confidence intervals while the outer bars represent the 95% CL confidence intervals. Taken from arXiv:1412.8662 (December, 2014).

2D test statistics q(κ_V, κ_f) scan for individual channels (colored swaths) and for the overall combination (thick curve). The cross indicates the global best-fit values. The dashed contour bounds the 95% CL region for the combination. The yellow diamond shows the SM point (κ_V, κ_f) = (1, 1). Two quadrants corresponding to (κ_V, κ_f) = (+,+), (+,-) are physically distinct. Taken from arXiv:1412.8662 (December, 2014).
Implications of a SM-like Higgs boson

Typically, none of the scalar states of the 2HDM will resemble a SM-Higgs boson. However, a SM-like Higgs boson ($h_{SM}$) can arise in two different ways:

- **The decoupling limit** (Haber and Nir 1990, Gunion and Haber 2003)

All but one of the scalar states ($h$) are very heavy ($M \gg m_h$). Integrating out the heavy states below the mass scale $M$ yields an effective one-Higgs-doublet theory—i.e. the Standard Model, and $h \simeq h_{SM}$.

- **The alignment limit without decoupling** (Craig, Galloway and Thomas 2013, Haber 2013)

In the Higgs basis $\{H_1, H_2\}$, the vacuum expectation value $v = 246$ GeV resides completely in the neutral component of one of the Higgs doublets, $H_1$. In the limit where the mixing between $H_1$ and $H_2$ in the mass matrix goes to zero, one of the neutral mass eigenstates aligns with $\text{Re}(H_1^0 - v)$. This state $h$ is nearly indistinguishable from the SM Higgs boson. This limit can be attained even if all Higgs scalar masses are of the same order of magnitude.
Is it possible that the Higgs coupling to bottom quarks and tau leptons have the expected magnitude but the opposite sign to their predicted SM values?

In collaboration with P. Ferreira, J.F. Gunion and R. Santos, we have scanned the 2HDM parameter space, imposing theoretical constraints, direct LHC experimental constraints, and indirect constraints (from precision electroweak fits, $B$ physics observables, and $R_b$). The latter requires that $m_{H^\pm} \gtrsim 340$ GeV in the Type-II 2HDM.

Given a final state $f$ resulting from Higgs decay, we define

$$\mu^h_f(\text{LHC}) = \frac{\sigma^{2\text{HDM}}(pp \rightarrow h) BR^{2\text{HDM}}(h \rightarrow f)}{\sigma^{\text{SM}}(pp \rightarrow h_{\text{SM}}) BR(h_{\text{SM}} \rightarrow f)}.$$

Our baseline will be to require that the $\mu^h_f(\text{LHC})$ for final states $f = WW, ZZ, b\bar{b}, \gamma\gamma$ and $\tau^+\tau^-$ are each consistent with unity within 20% (blue), which is a rough approximation to the precision of current data. We will then examine the consequences of requiring that all the $\mu^h_f(\text{LHC})$ be within 10% (green) or 5% (red) of the SM prediction.
The main effects of the wrong-sign $h\overline{D}D$ coupling is to modify the $hgg$ and $h\gamma\gamma$ loop amplitudes due to the interference of the $b$-quark loop with the $t$-quark loop (and the $W$ loop in the case of $h \rightarrow \gamma\gamma$). In addition, the possibility of a contributing non-decoupling charged Higgs contribution can reduce the partial width of $h \rightarrow \gamma\gamma$ by as much as 10%.

The absence of a red region for $\sin \alpha > 0$ (the wrong-sign $h\overline{D}D$ Yukawa regime) demonstrates that a precision in the Higgs data at the 5% level is sufficient to rule out this possibility.

Is alignment without decoupling in the MSSM viable?

Analysis strategy:

- Make use of model-independent CMS search for $H, A \rightarrow \tau^+\tau^-$ in the regime $m_A > 200$ GeV. Both $gg$ fusion and $b\bar{b}$ fusion production mechanisms are considered. CMS also considers specific MSSM Higgs scenarios. Recent ATLAS results are similar to those of CMS (although CMS limits are presently the most constraining).

- Analyze various benchmark MSSM Higgs scenarios and deduce limits on $\tan\beta$ as a function of $m_A$.

- Compare resulting limits to the constraints imposed by the properties of the observed Higgs boson with $m_h \approx 125$ GeV.

- Extrapolate to future LHC runs. Determine what is needed to rule out alignment without decoupling in the MSSM.
The \( m^\text{alt}_h \) scenario (for large \( \mu \)) has been chosen to exhibit a region of the MSSM parameter space where the alignment limit is approximately realized.

For \( m_Q = 1 \) TeV, \( m_h = 125.5 \pm 3 \) GeV for \( \tan \beta > 6 \) and \( m_A > 200 \) GeV. Here, we regard the \( \pm 3 \) GeV as the theoretical error in the determination of \( m_h \). Thus, for \( \tan \beta < 6 \), we increase \( m_Q \) such that \( m_h \) falls in the desired mass range for all \( m_A > 200 \) GeV.

The alignment limit is most pronounced at large $\mu$ in the $m_h^{\text{alt}}$ scenario. Taking values of $\mu$ much larger than $3M_Q$ would result in color and charge violating vacua, which suggests that alignment for $\tan \beta$ values below 10 is not viable in the MSSM.

As a member of the Particle Data Group, I am the author of the biennial Supersymmetry Theory review.
My recent Ph.D. students and their thesis projects

Douglas Pahel (2005): CP-Violating Effects in W and Z Boson Pair Production at the ILC in the Minimal Supersymmetric Standard Model


Where are they now?

D. Pahel – working in industry
J. Mason – following a three-year post doctoral research associate in particle theory at Harvard University, John accepted a position as an assistant professor of physics at Western State College of Colorado
D. O’Neil – assistant professor of physics at Bridgewater College (in Virginia)
My current Ph.D. students and their projects

Laura Fava: Precision measurements of couplings at the LHC and tests of theories of UED (universal extra dimensions).

Eddie Santos: Renormalization group running in the general CP-violating two-Higgs doublet model; predictions for Higgs-mediated flavor changing neutral current processes.

I am also working with:

Laurel Stephenson Haskins: Puzzle in the relation between the quark anomalous dimension and the mass anomalous dimension in supersymmetric non-abelian gauge theory.
**Project with Laura Fava:** study the potential for precision coupling measurements in the minimal Universal Extra Dimensions (mUED) model. Look for events with like-sign dileptons, associated hadronic jets and missing transverse energy.

![Diagram](image)

**FIG. 2:** The $n=1$ KK decay chain. Solid lines represent the dominant transitions (BRs ≥ %). From Ref. [7].

We draw the reader’s attention to one particular feature of the model. In mUED, the couplings are independent of $n$. Because the SM fields are the $n = 0$ modes, the mUED couplings are the same as those of the SM, for example:

$$g_{sm}(qqg) = g_{sm}(Q_1 Q_1 g) = g_{ued}(q Q_1 g_1).$$

(3)

We may use this feature in conjunction with other predictions from the theory to determine to within what precision mUED couplings can be measured at the LHC. The goal of this analysis is to estimate this precision for the mUED strong coupling $g_{ued}$ for the range $800$ GeV $\leq R^{-1} \leq 1200$ GeV at $\Delta R = 20$, and a special case of $R^{-1} = 800$ GeV at $\Delta R = 5$, energies which will be accessible to the LHC during the 14 TeV run.
**Preliminary results**

- **S** = number of signal events observed
- **c** = ratio of the strong UED coupling to the QCD coupling
- **R** = compactification radius of the extra dimension
- **Λ** = cutoff energy scale of the mUED model

Brazil plots:
- Green — 68% CL
- Yellow — 95% CL

FIG. 4: \( c \) vs. \( S \) for \( R^{-1} = (a) 800 \text{ GeV}, \) (b) 900 GeV, (c) 1000 GeV, (d) 1100 GeV, and (e) 1200 GeV with \( \Lambda R = 20 \), and for (f) \( R^{-1} = 800 \text{ GeV} \) with \( \Lambda R = 5 \). The assumed integrated luminosity is 100 fb\(^{-1}\) at \( \sqrt{s} = 14 \text{ TeV} \). In each plot, the vertical line denotes the number of signal events for \( c = 1 \).
Implication of the Higgs data for the stability of the vacuum

Figure 5: Regions of absolute stability, meta-stability and instability of the SM vacuum in the $M_t-M_h$ plane. Right: Zoom in the region of the preferred experimental range of $M_h$ and $M_t$ (the gray areas denote the allowed region at 1, 2, and 3σ). The three boundaries lines correspond to $\alpha_s(M_Z) = 0.1184 \pm 0.0007$, and the grading of the colors indicates the size of the theoretical error. The dotted contour lines show the instability scale $\Lambda$ in GeV assuming $\alpha_s(M_Z) = 0.1184$.

Taken from G. Degrassi et al., arXiv:1205.6497
Project with Eddie Santos: Investigate whether stability up to the Planck scale is possible in the two-Higgs-doublet model (2HDM)

A partial scan over 2HDM parameter space

\[ \alpha = 0 \]

\[ \alpha = 0.8 \]

- red—stability bound
- blue—Landau pole