Physics Beyond the SM and LHC Searches

“A (brief and not unweighted) random walk through the theory landscape”

Maxim Perelstein, Cornell
PPP Ph.D. Program, NBI, Copenhagen, Oct 3 2011
• **Standard Model:** Electroweak gauge symmetry SU(2) x U(1) is fundamental, but spontaneously broken at low energies down to e&m U(1)

• Uncovering the **mechanism** of electroweak symmetry breaking (EWSB) is the central question for the LHC

• The Standard Model explanation of EWSB: **Higgs phenomenon**

• Postulate a new particle – the **Higgs boson** – of spin 0

• Vacuum is filled with **Higgs condensate**, which breaks the symmetry
• Standard Model with a light Higgs provides a good fit to all data, indirect determination of H mass:

\[ M_H < 186 \text{ GeV} \quad (95\% \text{ c.l.}) \]
Direct Search for the Higgs

**ATLAS SM Higgs Combination – statistical procedure**

- The profile likelihood ratio is used as test statistics.
- One-sided variants of the test statistic are used for upper-limits and discovery.
- The distribution of the test statistic is obtained in two ways:
  - Ensemble tests with toy Monte Carlo using a fully frequentist procedure.
  - Using asymptotic distribution of likelihood ratio (improved $\chi^2$ method).
- Nuisance parameters are "profiled" based on the data.
- Primary result based on $CL_s$, conservatism introduced to protect against downward fluctuations.
- Additional comparisons with Bayesian procedure with a uniform prior on $\mu$.

The combined upper limit on the Standard Model Higgs boson production cross section divided by the Standard Model expectation as a function of $m_H$ is indicated by the solid line. This is a 95% CL limit using the $CL_s$ method in the entire mass range.

Standard Model Higgs boson mass excluded at 95% C.L.:
- $146 < m_H < 232$, GeV
- $256 < m_H < 282$, GeV
- $296 < m_H < 466$, GeV

The exclusion Confidence Level (CLs) is about 99% in the region between 160 GeV and 220 GeV and exceeds 99% between 300 GeV and 420 GeV.

**Lepton-Photon Conference, August 2011**
Higgs Sensitivity: 1, 2, 5 and 10 fb\(^{-1}\) @ 7 TeV

[V. Sharma, CMS, LP-11 talk]
Radiative Corrections

• Quantum mechanics allows for energy non-conservation for short periods of time:

\[ \Delta E \Delta t \sim \hbar \]

• A particle-antiparticle pair may spontaneously appear from the vacuum, and then disappear after \( \Delta t < 1/M \)

• The vacuum is full of such “virtual” pairs!

• The virtual pairs can interact with particles: this is described by Feynman diagrams with loops (”radiative corrections”)

\[ \sim \]

• Computing radiative corrections involves integration over the lifetime of the virtual pair, in principle down to \( t=0 \) (or equivalently energy up to infinity)
Beyond the SM

- Computing radiative corrections in most quantum field theories (including the SM) involves integrals which **diverge** at high virtual energies.

- Mathematically, this can be dealt with by **renormalization**.

- Physically, divergences mean that we’re applying the theory in a regime where it is **no longer valid**.

Expect a deeper layer of structure beneath the SM!
Light Higgs $\rightarrow$ NP at TeV!

- No elementary spin-0 particles are known to exist: scalar mass is unstable with respect to radiative corrections.

- In SM,
  \[ V(H) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2 \]
  \[ v^2 = \frac{\mu^2}{\lambda}, \quad m_h^2 = 2\mu^2 \]

- Renormalization:
  \[ \mu^2(M_{ew}) = \mu^2(\Lambda) + c_1 \frac{1}{16\pi^2} \Lambda^2 + c_2 \frac{1}{16\pi^2} \log \left( \frac{\Lambda}{M_{ew}} \right) + \text{finite} \]
  with \( c_1 \sim 1 \) and \( \Lambda \) is the scale where loop integrals are cut off by new physics.

- Expect \( \mu \sim \Lambda/(4\pi) \) $\rightarrow$ \( \Lambda \sim 1 \text{ TeV} \) (naturalness)
  
  [But NB: \( \Lambda \sim 10 \text{ TeV} \) if 1% fine-tuning is allowed!]

Monday, October 3, 2011
Thermal Dark Matter

• Dark matter (non-luminous, non-baryonic, non-relativistic matter) well-established by a variety of independent astro observations, ~20% of the universe

• None of the SM particles can be dark matter

• Assume new particle, in thermal equilibrium with the cosmic plasma in the early universe

• Measured DM density $\rightarrow$ interaction cross section DM-SM

\[
\sigma \approx 1 \text{ pb } \sim \frac{\alpha}{(\text{TeV})^2}
\]

independent hint for new physics at the TeV scale!

[figure: Birkedal, Matchev, MP, hep-ph/0403004]
Options for New Physics @ TeV

• Models with light Higgs, addressing naturalness:
  • New particles, related to SM by symmetry, cut off loops (ex. SUSY, Little Higgs, gauge-higgs unification)
  • Higgs not elementary, bound state resolved at ~TeV (ex. warped [Randall-Sundrum] extra dimensions)
  • Point-like SM particles resolved as TeV-scale strings (ex. large extra dimensions)

• Models without light Higgs, necessarily strongly-coupled at the TeV scale (ex.: Technicolor, Higgsless)

• Models that do not improve naturalness, but have other interesting features or unusual signatures (ex. hidden valley, unparticles, split SUSY)
Supersymmetry

- In supersymmetric theories scalar masses do not receive quadratic divergences
- SUSY not symmetry of nature must be broken
- “Soft” breaking at the TeV scale loops cut off at the TeV scale, naturalness restored
- “Minimal” supersymmetric SM (MSSM): superpartner for each SM d.o.f., plus 2nd Higgs doublet and its superpartners

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34 new particles waiting to be discovered!

Table 7.1: The undiscovered particles in the Minimal Supersymmetric Standard Model (with fermion mixing for the first two families assumed to be negligible).

SUSY as an Extra (Fermionic) Dimension

• Grassmann (anticommuting) numbers:
  \[ \theta : \{\theta_1, \theta_2\} = 0 \Rightarrow \theta^2 = 0 \]
  cf normal numbers:
  \[ x : [x, y] = 0 \]

• In quantum field theory, fields of fermions (e.g. electrons) are Grassmann-valued - Pauli exclusion principle built in!

• Imagine a space with 1 or more G-valued coordinates, in addition to the usual 4: superspace

• “Superfield” lives in this superspace: \( \Phi(x^\mu, \theta) \)

• Taylor expand to obtain usual 4D fields: \( \Phi(x^\mu, \theta) = \phi(x) + \theta \psi(x) \)

• Supersymmetry is the generalization of Poincare group (rotations, translations, boosts) to this new superspace
Gauge Coupling Unification: a Hint for Supersymmetry?

• The three lines do not meet in the SM (but, considering the extrapolation range, come close!)

• There is at least one example of non-SUSY model where unification occurs with roughly same precision
MSSM and Its 100 Parameters

- **Arbitrary** soft terms \(\mathcal{O}(100)\) free parameters, affecting spectrum, branching ratios, etc.

\[
\mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2} \left( M_{3g} g + M_2 \bar{W} W + M_1 \bar{B} B + \text{c.c.} \right) \\
- \left( \bar{\nu}_{au} Q H_u - \bar{d}_{au} \bar{H} d - \bar{\tau}_{au} \bar{L} H_d + \text{c.c.} \right) \\
- \bar{Q} m_{\tilde{Q}} \bar{Q} - \bar{L} m_{\tilde{L}} \bar{L} - \bar{\nu} m_{\tilde{\nu}} \bar{\nu} - \bar{d} m_{\tilde{d}} \bar{d} - \bar{\tau} m_{\tilde{\tau}} \bar{\tau} \\
- m_{\tilde{H}_u} H_u - m_{\tilde{H}_d} H_d - b H_u H_d + \text{c.c.}.
\]

- **Models** of SUSY breaking “predict” some parameters (or relations among them), **reduce** the freedom

- **But:** **Many** such models (e.g. gravity mediation, gauge mediation, anomaly mediation, etc.), each has strengths and weaknesses, **no clear “winner” emerged over ~25 years of model-building** \(\Rightarrow\) **NEED DATA!!!**

- **Search strategies** must be designed with this in mind - “cover” the 120-dimensional parameter space as well as experimental limitations allow
SUSY: Generic Predictions

- Extra discrete symmetry - R parity - imposed to avoid rapid proton decay (may be relaxed, but very artificial)

- All SM states R-even, superpartners R-odd \(\rightarrow\) lightest superpartner (LSP) stable

- Strong limits on colored/charged relics in the universe prefer neutral LSP (also a WIMP dark matter candidate!)

- Generic signature: missing energy in every event with superpartner production

- Inclusive search for stable (neutral or not) objects plus high-pT jets and/or leptons is the best mod.-ind. strategy

- Production cross sections for strongly interacting superpartners - gluinos and squarks - are usually the largest (could be 1 - 10 pb \(\rightarrow\) \(10^4 - 10^5\) events/year at the LHC)
• Direct decays ("guaranteed") give jets+MET:

\[ \tilde{q} \rightarrow q + \chi_1^0 \quad , \quad \tilde{g} \rightarrow q\bar{q}\chi_1^0 \]

• Cascade decays (spectrum-dependent) may give lepton(s) + jets+MET: for example

\[ \tilde{q} \rightarrow q + \chi_2^0, \quad \chi_2^0 \rightarrow \mu^+ + \bar{\mu}^-, \quad \bar{\mu}^- \rightarrow \mu^- + \chi_1^0 \]

iff \( M(\tilde{q}) > M(\chi_2^0) > M(\bar{\mu}) > M(\chi_1^0) \)

\( H_T = \text{scalar sum of all jet } E_T \)

\( \int L \, dt \approx 1.04 \, \text{fb}^{-1} \)

\( \geq 4 \text{ jets} \)

\[ m_{\text{eff}} = H_T + \text{Missing } E_T \, [\text{GeV}] \]

\( \text{SM: Etmiss from neutrinos:} \)

\[ Z \rightarrow \nu\bar{\nu}, \quad t\bar{t}, \ldots \]

"Reality": Etmiss from detector malfunctioning, jet energy mismeasurements, etc.
So, the bounds on gluino and squark masses are already above 1 TeV.

Does this imply that SUSY is “disfavored” (i.e. sparticles must be too heavy to eliminate fine-tuning)?

Plot credit: H. Bachacou talk at LP-11
LHC results put supersymmetry theory 'on the spot'

Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Researchers failed to find evidence of so-called "supersymmetric" particles, which many physicists had hoped would plug holes in the current theory.
• Renormalization:

\[ \mu^2(M_{\text{ew}}) = \mu^2(\Lambda) + c_1 \frac{1}{16\pi^2} \Lambda^2 + c_2 \frac{1}{16\pi^2} \log \left( \frac{\Lambda}{M_{\text{ew}}} \right) + \text{finite} \]

where \( \Lambda \) is the scale where loop integrals are cut off by new physics

• Expect \( \mu \sim \Lambda/(4\pi) \rightarrow \Lambda \sim 1 \text{ TeV} \) (naturalness) IF \( c_1 \sim 1 \)

• However, \( c_1 \) depends on the coupling constants and different particles in loops contribute differently!
So: only Higgsinos and **3rd gen. squark** really must be below TeV

Other squarks/sleptons may be a factor of **5 or more** heavier with no effect on fine-tuning

**Gluino** first appears at 2 loops, suppressing its effect on fine-tuning
What About the LHC?

Stops have small cross sections:
\[ \sigma(\tilde{t}\tilde{t}^*) \approx 30 \text{ fb} \]
at 500 GeV

Chargino/neutralino (e.g. higgsino) cross sections are even smaller

All searches so far rely on producing gluinos and/or 1st, 2nd gen. squarks, different decay channels

Plot credit: H. Bachacou talk at LP-11
LHC Searches

**BOTTOM LINE:** 1st/2nd gen. squark/gluino bounds have essentially **NO impact** on fine-tuning in the MSSM

[Not so in specific SUSY breaking models, e.g. where three gen. of squarks have common mass term at some scale]

Plot credit: H. Bachacou talk at LP-11
LHC Searches

ATLAS-CONF-2011-130  17 August 2011

Don’t they search for stops?

This search relies on gluino pair-production to make stops, and has no impact on fine-tuning so far.

$m_{\tilde{g}} \gtrsim 500 \text{ GeV} \quad m_{\tilde{t}} \gtrsim ?$
Wouldn’t stops show up in other channels? Yes, but the limits so far are not strong enough to impact fine-tuning.

[Re-interpretation of 1 fb−1 searches presented at summer conferences, by Papucci, Ruderman, Toro and Weiler]

- Good news: SUSY, as a solution to the hierarchy problem, is alive and well despite lack of LHC discovery so far
MSSM, Higgs and Naturalness

• Non-observation of the Higgs at LEP2 presents a significant problem for the MSSM

• At tree level, a firm upper bound (ind. of 120 parameters) on the mass of the lighter CP-even Higgs boson: \( m(h^0) < M_Z \)

• Experimentally, \( m(h^0) > 114 \text{ GeV} \) (except corners)

• Loop corrections to \( m(h^0) \) must be large (25%)

• Same loops induce large corrections to Higgs vevs, which need to be canceled precisely - fine-tuning of \( O(1\%) \)

• In any case, \( m(h^0) \leq 135 \text{ GeV} \) in the MSSM - will be tested within a year!

• Caveat: If SUSY is realized, it may well be a non-minimal version (e.g. extra scalars coupled to the Higgs sector, non-standard Higgs phenomenology)
MSSM Pheno: Some Caveats

- **Caveat 1**: R-parity may be broken (e.g. either L or B would be sufficient to ensure proton stability) → no MET signature

- **Caveat 2**: next-to-lightest SUSY particle (nLSP) may be long-lived enough to decay outside of the detector ($10^{10}$ yrs $> \tau_{nLSP} > 10^{-8}$ sec) → no missing energy, a massive charged-particle (CHAMP) track or a decay of a particle stopped inside the detector instead

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Quantum Gravity at TeV

- In string theory, all divergent integrals cut off at $M_S$: Higgs and other particles turn into finite-size strings!

- If $M_S \sim 1\text{ TeV}$, there is no hierarchy problem! But $M_S \sim M_{Pl}$

- ADD model: SM on a 4D “brane” inside higher-D space, with extra dimensions compactified with

$$R \sim M_{Pl}^{-1} \left( \frac{M_{Pl,4}}{M_{Pl}} \right)^{2/n} \gg M_{Pl}^{-1}$$

- At $E < M_{Pl}$, missing energy signature due to graviton emission into the extra dimensions

Black Holes & Strings at LHC?

- If two partons collide at super-plankian energies $E \gg M_{P1}$, a black hole must form.

- Given existing constraints on $M_{P1}$, it seems pretty unlikely that the LHC will probe the region $E \gg M_{P1}$.

- In any (weakly coupled) string theory, Regge excitations of SM particles lie below Planck scale $M_n = \sqrt{n} M_S$, $M_S < M_{P1}$.

- Reggeons appear as s-channel resonances in SM scattering processes: Easy to see, more realistic target than BHs.

- Distinguish from Zprimes etc.: spin “Regge gluon” is spin-2!

- Excited Reggeons have spin > 2, at present not handled by general-purpose MC generators!
QCD Redux: Composite Higgs, Technicolor, and Their Cousins

- All these models involve **new strong dynamics at TeV (or 10 TeV)**, a la QCD confinement at GeV, but with interesting new twists!
Composite Higgs

• Many spin-0 particles exist in nature - mesons

• They are composite, made of spin-1/2 quarks, bound by QCD strong force

• Above the QCD confinement scale, the good degrees of freedom are quarks ➡️ no hierarchy problem!

• Can the Higgs be a meson bound by a new strong force?

• Old idea, but difficult to build models - non-perturbative physics!

• New insight: AdS/CFT duality ➡️ some strongly coupled 4D models are “dual” to weakly coupled, calculable models with an extra dimension!

• Setup: Randall-Sundrum (RS) 5D model
**Warped (RS) Extra Dimension**

- Original model had the SM on the TeV brane, solves the hierarchy problem

\[ (ds)^2 = e^{-2kr_c|\theta|} \eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\theta^2 \]

\[ k \sim M_{Pl}, \ \theta = 0..\pi. \]

\[ k \sim \frac{10}{r_c} \Rightarrow \text{natural EWSB: } M_W \sim ke^{-k\pi r_c} \]

- New states: KK gravitons at the TeV scale

- Couplings: \[ \mathcal{L} \sim \frac{1}{(\text{TeV})^2} T_{\mu\nu} G_{KK}^{\mu\nu} \]
Kaluza-Klein Particles from Extra Dimensions

• Suppose that space-time has an extra spatial dimension, which is circular, with radius $R$

• Free field can be decomposed into momentum eigenstates (waves): $\phi \sim e^{i(p \cdot x + p_5 y)}$

• Periodicity $\Rightarrow$ momentum quantization: $p_5 (2\pi R) = 2\pi n \Rightarrow p_5 = \frac{n}{R}$

• Fourier expansion = Kaluza-Klein decomposition:

$$\phi(x, y) \sim \sum_{n=0}^{\infty} \phi^n(x) e^{iny/R}$$

• Each KK mode behaves like a 4D particle, with mass $M_n = \frac{n}{R}$

• SM fields can be fundamentally 5D, if $\frac{1}{R} > 500$ GeV
RS: LHC Searches

RS graviton ($k/M_{Pl} = 0.1$):
$m(G) > 1.8$ TeV at 95% C.L.

[a similar bound is obtained from 2-photon resonance search]
It was subsequently realized that models with SM gauge fields and fermions in the “bulk” are more interesting:

- natural solution to fermion mass hierarchy problem
- natural suppression of flavor-changing neutral currents
- possibility of gauge coupling unification, as in the MSSM

figure credits: G. Perez, G. Servant
RS with Bulk Matter: Pheno

• Good: all SM states now have KK modes!
• Bad: the KKs do not couple to light quarks and leptons much...
• Worse: PEW constraints force KK masses > 3 TeV or so
• KK gluon is probably the easiest target at the LHC

\[ \text{Final state: A pair of highly-boosted tops (''top jets'')} \]

Agashe et al., hep-ph/0612015; Lillie et al., hep-ph/0701166
Gauge-Higgs Unification

• A zero-mass photon does not require fine-tuning - mass is protected by gauge symmetry

• In a 5D theory, the gauge field $A_M(x) \rightarrow A_\mu(x), A_5(x)$

• If the 5th dimension is infinite, $A_5$ is naturally massless!

• After compactification, $m(A_5) \sim 1/R \Rightarrow$ good if $1/R \sim M_W \sim M(W')$

• Higgs mass quadratic divergences are canceled by KK modes:

• A realistic GHU implementation, using a warped extra dimension, predicts KK states at 2 TeV and $m_h < 140$ GeV

[Agashe, Contino, Pomarol, hep-ph/0412089]
**Little Higgs**

- Quadratic divergence cancellation by *same-spin states* can also occur in a purely 4D theory - Little Higgs

[LH ↔ effective theory of the first two KK modes in GHU!]

- In LH, Higgs is a *Goldstone boson* arising from a global symmetry breaking [a la *pions* in QCD]

- If the global symmetry is *exact*, $m_h = 0$ naturally!

- Goldstones only interact derivatively need to break the global symmetry explicitly by gauge and Yukawa interactions

- Generically explicit breaking *reintroduces* quadratic divergences

- “Collective” breaking pattern in LH avoids quad. div. *at one loop*

[Arkani-Hamed, Cohen, Georgi, 2002]
EWSB in Littlest Higgs Model

- Higgs mass is dominated by top and Top loops:

\[ m_t^2(H) = -\frac{3\lambda_t^2 M_T^2}{8\pi^2} \log \frac{\Lambda^2}{M_T^2}. \]

- This contribution is log-divergent and negative:

- All other contributions are generically subdominant

- EWSB is triggered radiatively - simple mechanism!

- Similar to the MSSM but with no tree-level potential at all - e.g. no \( \mu \) problem!
LH models are weakly coupled at the TeV scale, predictive!

The “first-generation” LH models strongly disfavored by precision electroweak data

Best solution: introduce “T Parity”: new TeV-scale particles T-odd and only appear in loops in PEWO [a la R parity of the MSSM]

Littlest Higgs with T Parity (LHT) passes PEW tests without significant fine-tuning

[Hubisz, Meade, Noble, MP, hep-ph/0506042]
LHT Collider Phenomenology

- The Lightest T-Odd Particle (LTP) is stable, typically the neutral, spin-1 “heavy photon” - WIMP DM candidate
- Symmetry structure forces introduction of T-odd partners for each SM (weak doublet) fermion - “T-quarks” and “T-leptons”
- Hadron collider signature: T-quark production, decays to LTP+jets

[Carena, Hubisz, MP, Verdier, 2006]  [MP, Shao, 2011]

A “SUSY look-alike” candidate!
LHT or SUSY?

- Only looked at one channel, generic in both models
- Simulated SUSY+SM sample = “data”, try to fit with LHT+SM, varying LHT parameters (T-quark and LTP masses)
- Fit to 10 observables: $\langle p_T \rangle, \langle H_T \rangle$, moments, asymmetries

[T他的 study point is now ruled out... Still, the strategy may well be useful]
What if There is No Higgs?

• If physics at TeV scale is strongly coupled, a symmetry-breaking condensate can exist without a physical Higgs boson in the theory - technicolor!

• TC with QCD-like dynamics at TeV is strongly disfavored by precision electroweak data

• Difficult to explore model space due to strong coupling

• New insight: AdS/CFT duality → some strongly coupled 4D models are “dual” to weakly coupled, calculable models with an extra dimension!

• 5D “Higgsless” models have been constructed, with EWSB by boundary conditions in RS-like setup, passes precision electroweak tests with ~1% fine-tuning

• Fermion masses can be straightforwardly incorporated
Higgsless Phenomenology

- Best place to search for all higgsless models is $W/Z$ scattering
- Unitarity must be restored, typically resonances appear
- 5D Higgsless model predicts narrow, light (sub-TeV) resonances

$W^\pm \rightarrow q q'$

$Z \rightarrow V^\pm, q q'$

$V^\pm \rightarrow W \rightarrow j j$

$Z \rightarrow W^\pm, W^\pm \rightarrow j j$

[Gold-Plated Channel: $2j+3l+\text{Et}_{\text{miss}}$]

[Birkedal, Matchev, MP, hep-ph/0412278]
Closing Remarks

- Since the SM became accepted (~30 years), theorists have been able to provide very **precise guidance** for new physics searches at the energy frontier (e.g. W, Z, top)

- This is **NOT** the case in the BSM physics hunt:
  - Number of “**ideas**” is finite (SUSY, xdim, TC, ...)
  - Number of “**implementations**” is essentially infinite
  - Number of “**free parameters**” in each implementation is typically large
  - **Inclusive** (signature-based whenever possible) searches are the best bet
  - “**Model space**” will **evolve** very quickly once there is evidence for BSM in the data!
Build a Model

Identify Collider Signatures

Compute Signal Cross Sections

Compute Backgrounds and Optimize Cuts

Confront with Data

“NEW PHYSICS PIPELINE”

(iterate the loop until it converges)
Monte Carlo Tools for BSM

• Monte Carlo predictions from models are essential for theory/experiment connection

• Old model: MC developers implement models in general-purpose generators, users use these tools (slow!)

• New model (over the last ~3-4 years):
  • users implement models in parton-level matrix element generators (e.g. Madgraph), output Les Houches Accord-compatible files
  • LHA files are passed on to the rest of the simulation chain (same as SM, except if long-lived BSM states)
Monte Carlo Tools for Beyond the Standard Model Physics

6th Workshop: MAR 22 - 24, 2012 (CORNELL)

ORGANIZERS email:
mc4bsm.AT.nbi.dk

RESOURCES:
- BSM tool repository
- Les Houches Accord for BSM Generators
- Video Lectures on Monte Carlo for the LHC
- Summary of MC4BSM-1 Discussion sessions

5th workshop: APR 14-16, 2010 (NBI, COPENHAGEN)
Organizing committee: Poul Henrik Damgaard, Christophe Grojean, Peter Hansen, Jørgen Beck Hansen, Rasmus Mackeprang, Konstantin Matchev, Stephen Mrenna, Maxim Perelstein, Peter Skands.

4th workshop: APRIL 3-4, 2009 (UC DAVIS)
Organizing committee: Hsin-Chia Cheng, Christophe Grojean, Konstantin Matchev, Stephen Mrenna, Maxim Perelstein, Peter Skands.

3rd workshop: MARCH 10-11, 2008 (CERN)
Organizing committee: Georges Azuelos, Christophe Grojean, Jay Hubisz, Borut Kersevan, Joe Lykken, Fabio Maltoni, Konstantin Matchev, Filip Moortgat, Stephen Mrenna, Maxim Perelstein, Peter Skands, James Wells.

2nd workshop: MARCH 21-24, 2007 (PRINCETON)
Organizing committee: Jay Hubisz, Konstantin Matchev, Stephen Mrenna, Maxim Perelstein, Peter Skands.

1st workshop: MARCH 20-21, 2006 (FERMILAB)
Organizing Committee: Marcela Carena, Mu Chun Chen, Bogdan Dobrescu, Chris Hill, Jay Hubisz, Joe Lykken, Konstantin Matchev, Stephen Mrenna, Maxim Perelstein, Jose Santiago, Peter Skands.
Conclusions

• The mechanism which breaks electroweak symmetry remains a fundamental, unsolved mystery

• All natural models of EWSB predict new physics at the TeV scale

• Tevatron is at the frontier, discovery possible every day

• LHC is on its way!

• Lots of interesting possibilities - exciting physics ahead!

• Widely open theory space brings challenges as well:
  • Making sure no new physics is missed (triggers, cuts)
  • Experiment-theory communication issues