Continuum Top Partners

Seung J. Lee

With C. Csaki, S. Lombardo; work in progress
With C. Csaki, S. Lombardo, G. Lee, O. Telem; work in progress
With J. Terning and amazing students; work in progress
With M. Park and Z. Qian; work in progress
Naturalness Paradigm Under Pressure

Naturalness $\Rightarrow$ new colored partners, potentially within the LHC reach.

\[
\frac{\delta m_h^2}{m_h^2} \sim \left( \frac{\tilde{m}_t}{400 \text{ GeV}} \right)^2
\]

2 leading frameworks of naturalness

- Supersymmetry
  - top partners = stops

Well, Higgs is just another fundamental scalar bosons, and more is coming…!

$\tilde{m}_{\text{stop}} > 1 \text{ TeV}$

- Composite Higgs
  - top partners = ”T”

AdS/CFT
- warped extra dimension

No, Higgs is just another composite resonance we are familiar with …!
Naturalness Paradigm Under Pressure

Naturalness => new colored partners, potentially within the LHC reach.

*Neutral Naturalness is not discussed in this talk

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Composite Higgs
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SUSY top partner searches

see Greg Landsberg’s and Lucia MASETTI’s talk today
same-sign dileptons

W tag:
2 subjets,
$M_j[60,130]$

CMS top tag

---

Composite Top Partner Searches

Simone, Matsedonski, Rattazzi, Wulzer `12
Azatov, Son, Spannowsky `13
Matsedonski, Panico, Wulzer `14

Composite Top Partner Searches

same-sign dileptons

W tag: 2 subjets, $M_j[60,130]$  
CMS top tag

Oblique parameter fits of LEP & Tevatron data gave $f \gtrsim 800\text{GeV}$

Grojean, Matsedonskyi, Panico '13

Ciuchini, Franco, Mishima, Silvestrini '13
Composite Top Partner Searches

same-sign dileptons

W tag: 2 subjets, $M_j[60,130]$ 

CMS top tag

Simone, Matsedonski, Rattazzi, Wulzer `12
Azatov, Son, Spannowsky `13
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Composite Top Partner Searches

same-sign dileptons

How about Run 2?

Single production with Boosted Analysis becomes more important!

Backovic, Flacke, SL, Perez `14
Backovic, Flacke, Kim, SL (x2), `15
Flacke, SL, Serodio, Parolini, `16

W tag: 2 subjets, $M_{jj}[60,130]$

CMS top tag

Simone, Matsedonski, Rattazzi, Wulzer `12
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W tag: 2 subjets, $M_j[60,130]$ (CMS top tag)

Simone, Matsedonski, Rattazzi, Wulzer '12
Azatov, Son, Spannowsky '13
Matsedonski, Panico, Wulzer '14

Pair VLQ:
- $TT \rightarrow bW+x$
- $TT \rightarrow tZ+x$
- $TT (T \rightarrow tW, bZ, bH) \rightarrow tH+x$
- $BB \rightarrow tH+x$
- $XX \rightarrow tWtW$

Single VLQ:
- $T \rightarrow tH$
- $T/Y \rightarrow bW$
- $T \rightarrow tZ, B \rightarrow bZ$

Excluding masses $X_{53}^{RH} < 1.16 \text{ TeV}$

Excluding masses $T/Y \rightarrow bW (100\%) < 1.295 \text{ GeV}$

Excluding masses $X_{53}^{RH} < 1.32 \text{ TeV}$
No Resonance, No New Physics? Naturalness?

$M_{KKG} = 3 \text{ TeV}$

![Graph showing the distribution of events vs. mass for different models and measurements.](image)

**ATLAS Preliminary**
- $\sqrt{s} = 13 \text{ TeV}$, $36.1 \text{ fb}^{-1}$
- Fiducial phase space

**CMS**
- Preliminary
- $35.8 \text{ fb}^{-1}$ (13 TeV)

**Data**
- POWHEG+Py8
- POWHEG+H7
- MG5 aMC@NLO+Py8
- Sherpa 2.2.1
- Stat. Unc.
- Stat. & Syst. Unc.

**Theory**
- Data
- Stat
- Sys @ stat
- Sys
- Stat
- POWHEG P8
- NNLO QCD+NLO EW
- POWHEG H++
- MG5 P8 [FxFx]
No Resonance, No New Physics? Naturalness?

New Physics for EWSB in the tail?

picture adapted from Francesco Riva
No Resonance, No New Physics? Naturalness?

- New Physics may appear solely as a continuum
  - approximately conformal sector (i.e. CFT broken by IR cutoff)
  - multi-particle states with strong dynamics (branch cut at $4m_{\pi}^2$ in $\pi\pi \rightarrow \pi\pi$ scattering)
No Resonance, No New Physics? Naturalness?

♦ New Physics may appear solely as a continuum
- approximately conformal sector (i.e. CFT broken by IR cutoff)
- multi-particle states with strong dynamics (branch cut at $4m_{\pi}^2$ in $\pi\pi\to\pi\pi$ scattering)

\[ \sigma / f_0(500) \]

\[ \rho \]

\[ M_\sigma = 450 \text{ MeV} \quad \Gamma_\sigma = 550 \text{ MeV} \]

\[ M_\rho = 770 \text{ MeV} \quad \Gamma_\rho = 145 \text{ MeV} \]
New Physics may appear solely as a continuum

- If the new strong dynamics responsible for furnishing a composite Higgs is near a quantum critical point, the composite spectrum may effectively consist of a continuum with a mass gap.

- In this scenario, poles corresponding to the composite top partner (and vector meson) excitations have merged into a branch cut in the scattering amplitude.
Ising Model

\[ H = -J \sum s(x)s(x + n) \]

\[ s(x) = \pm 1 \]

\[ \langle s(0)s(x) \rangle = e^{-|x|/\xi} \]

at \( T = T_c \) \( \xi \to \infty \)

Courtesy of J. Terning
Critical Ising Model is Scale Invariant

\[ \langle s(0)s(x) \rangle \propto \frac{1}{|x|^{2\Delta - 1}} \]

at \( T = T_c \)


Courtesy of J. Terning
At $T = T_c$, \[ \langle s(0) s(x) \rangle \propto \frac{1}{|x|^{2\Delta - 1}} = \int d^3p \frac{e^{ip \cdot x}}{|p|^{4-2\Delta}} \]

Critical exponent


Courtesy of J. Terning
Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs.
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**@2nd order QPT, @ critical point,** all masses vanish & the theory is scale invariant, characterized by the **dimensions** of the field,

and at low energies we will see the universal behavior of some fixed point that constitutes the low-energy EFT.

Sachdev, arXiv:1102.4268
What is the nature of electroweak phase transition?

Does the underlying theory also have a QPT?

If so, is it more interesting than mean-field theory?
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Does the underlying theory also have a QPT?

If so, is it more interesting than mean-field theory?

\[ G(p) \sim \frac{\imath}{p^2} \quad \text{vs.} \quad G(p) \sim \frac{\imath}{(p^2)^{2-\Delta}} \quad \text{or} \quad G(p) \sim \frac{\imath}{(p^2-\mu^2)^{2-\Delta}} \]
Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs. At a 2nd order QPT, at a critical point, all masses vanish and the theory is scale invariant, characterized by the scaling dimensions of the field, and at low energies we will see the universal behavior of some fixed point that constitutes the low-energy EFT.

What is the nature of electroweak phase transition?

Does the underlying theory also have a QPT?

If so, is it more interesting than mean-field theory?

\[ G(p) \sim \frac{i}{p^2} \quad \text{vs.} \quad G(p) \sim \frac{i}{(p^2)^{2-\Delta}} \quad \text{or} \quad G(p) \sim \frac{i}{(p^2 - \mu^2)^{2-\Delta}} \]
\[ \left\langle e^{\int d^4x \phi_0(x) \mathcal{O}(x)} \right\rangle_{\text{CFT}} \approx e^{S_{5\text{Dgravity}}[\phi(x,z)|_{z=0}=\phi_0(x)]} \]

\[ ds^2 = \frac{R^2}{z^2} \left( dx_\mu^2 - dz^2 \right) \]

\[ \mathcal{O} \subset \text{CFT} \leftrightarrow \phi \text{ AdS}_5 \text{ field} \]
\[ ds^2 = \frac{R^2}{z^2} \left( dx_{\mu}^2 - dz^2 \right) \]
\[ z > \epsilon \]
\[ S_{\text{bulk}} = \frac{1}{2} \int d^4 x dz \sqrt{g} \left( g^{\alpha \beta} \partial_\alpha \phi \partial_\beta \phi + m^2 \phi^2 \right) \]
\[ \phi(p, z) = a z^2 J_\nu(pz) + b z^2 J_{-\nu}(pz) \]
\[ \Delta[\mathcal{O}] = 2 \pm \nu = 2 \pm \sqrt{4 + m^2 R^2} \]
\[ \langle \mathcal{O}(p) \mathcal{O}(p) \rangle \propto \frac{\delta^{(4)}(p+p')}{(2\pi)^2} (p^2)^{\Delta-2} \]

Witten, Klebanov 99’
broken CFT

- Randall Sundrum 2 (only UV brane and bulk): cuts from 0 (CFT)
- RS1: putting IR cutoff at TeV
- New type of IR cutoff (soft wall) gives rise to a different phenomenology

The usual RS scenario involves AdS space with an IR brane and a UV cutoff. The soft wall scenario replaces the IR brane with a curvature singularity, where the metric vanishes. This leads to a continuous KK spectrum above the mass gap. Note: UV brane is the only place to put Higgs quartic, Higgs is fundamental $\Rightarrow$ fine-tuning.
• Randall Sundrum 2 (only UV brane and bulk): cuts from 0 (CFT)
• RS1: putting IR cutoff at TeV
• New type of IR cutoff (soft wall) gives rise to a different phenomenology

scalar getting VEV => marginal deformation of CFT
broken CFT

- Randall Sundrum 2 (only UV brane and bulk): cuts from 0 (CFT)
- RS1: putting IR cutoff at TeV
- New type of IR cutoff (soft wall) gives rise to a different phenomenology

\[ ds^2 = a(z)^2 \left( dx^\mu dx_\mu - dz^2 \right) \]

IR-brane models confinement, cuts off CFT
- discrete spectrum

\[ a(z) = \frac{R}{z} \]

IR brane is replaced by curvature singularity, at which metric vanishes

UV brane is the only place to put Higgs quartic, Higgs is fundamental ⇒ fine-tuning
broken CFT by IR cutoff

\[ S_{\text{int}} = \frac{1}{2} \int d^4xdz \sqrt{g} \phi \mathcal{H}^\dagger \mathcal{H} \]

\[ \phi = \mu z^2 \]

\[ z^5 \partial_z \left( \frac{1}{z^3} \partial_z \mathcal{H} \right) - z^2(p^2 - \mu^2)\mathcal{H} - m^2 R^2 \mathcal{H} = 0 \]

\[ \langle \mathcal{O}(p) \mathcal{O}(p) \rangle \propto \frac{\delta^{(4)}(p+p')}{(2\pi)^2} (p^2 - \mu^2)^{\Delta-2} \]

\[ [\partial^2 - \mu^2]^{2-\Delta} \delta(x - y) \]
soft wall (AdS/QCD)

\[ ds^2 = a(z) \left( dx^\mu dx_\mu - dz^2 \right) \]
\[ a(z) = \frac{R}{z} e^{-\frac{2}{3} \mu (z-R)} \]
\[ S_{\text{gauge}} = \int d^5 x - \frac{1}{4} a(z) F_{M N}^2 \]

EOM:
\[ (a^{-1} \partial_z (a \partial_z) + p^2) f = 0 \]
\[ f = a^{-\frac{1}{2}} \Psi \]

"Schrödinger Eqn": \[ (-\partial_z^2 + V(z)) \Psi = p^2 \Psi, \quad V(z) = \frac{a''}{2a} - \frac{a'^2}{4a^2} \]

\[ V(z) \bigg|_{z \to \infty} \to \left( \frac{\mu}{3} \right)^2 \]

=> continuum begins at:
\[ p^2 = \left( \frac{\mu}{3} \right)^2 \]

\[ \to \infty \] (infinite well)

=> just like IR brane:
KK towers

Note: UV brane is the only place to put Higgs quartic, Higgs is fundamental \ensuremath{\Rightarrow} fine-tuning

soft wall cuts off CFT
continuous KK spectrum above mass gap

5D UnHiggs: Falkowski, Perez-Victoria '08
soft wall (AdS/QCD)

\[ ds^2 = a(z) \left( dx^\mu dx_\mu - dz^2 \right) \]
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\[ S_{gauge} = \int d^5 x - \frac{1}{4} a(z) F_{MN}^2 \]

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\[ p^2 = \left( \frac{\mu}{3} \right)^2 \]

\[ \Rightarrow \text{continuum begins at:} \]

\[ \Rightarrow \infty \quad (\text{infinite well}) \]

\[ \Rightarrow \text{just like IR brane:} \]

KK towers
soft wall (AdS/QCD)

\[ \hat{V}(z) \]

**Regge:** \( M^2 \sim \frac{1}{n} \)

\[ \hat{V}(z) \]

**RS like:** \( M^2 \sim n^2 \)

EOM:

\[ (a^{-1} \partial_z (a \partial_z \phi) + p^2) \phi = 0 \]

**"Schrödinger Eqn":**

\[ (-\partial_z^2 + V(z)) \Psi = p^2 \Psi, \quad V(z) = \frac{a''}{2a} - \frac{a'^2}{4a^2} \]

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(\( \Rightarrow \) just like IR brane: KK towers)

\( \Rightarrow \) just like IR brane: KK towers

\[ \rightarrow \infty \quad \text{(infinite well)} \]

5D UnHiggs: Falkowski, Perez-Victoria ‘08

Note: UV brane is the only place to put Higgs quartic, Higgs is fundamental \( \Rightarrow \) fine-tuning
soft wall (AdS/QCD)

EOM:
\[
(a^{-1} \partial_z (a \partial_z f) + p^2) f = 0
\]

Regge: \( M^2 \sim n \)

continuum with mass gap

“Schrödinger Eqn”:
\[
(-\partial_z^2 + V(z)) \Psi = p^2 \Psi, \quad V(z) = \frac{a''}{2a} - \frac{a'^2}{4a^2}
\]

\[ V(z) \bigg|_{z \to \infty} \to \left(\frac{\mu}{3}\right)^2 \]

\[ \to \infty \] (infinite well)

\[ \Rightarrow \text{continuum begins at:} \quad p^2 = \left(\frac{\mu}{3}\right)^2 \]

\[ \Rightarrow \text{just like IR brane: KK towers} \]

usual RS scenario

- AdS
- \( u(z) = \frac{R}{z} \)
- IR-brane models confinement, cuts off CFT
- discrete spectrum

UV

IR

\( z = R \)

\( z = R' \)

\( m^{(0)} \)

\( m^{(1)} \)

\( m^{(2)} \)
EOM: \( (a^{-1} \partial_z (a \partial_z) + p^2) f = 0 \) \n
\[ ds^2 = a(z) \left( dx^\mu dx_\mu - dz^2 \right) \]

Regge: \( M^2 \sim \frac{n^2}{R^2} \)

\( V(z) \) \bigg|_{z \to \infty} \to \left( \frac{\mu}{3} \right)^2 \)

Schrödinger Eqn: \( \left( -\partial_z^2 + V(z) \right) \Psi = p^2 \Psi, \quad V(z) = \frac{a''}{2a} - \frac{a'^2}{4a^2} \)

Continuum with mass gap

\[ \hat{V}(z) \]

Soft wall (AdS/QCD)

5D UnHiggs: Falkowski, Perez-Victoria '08

Batell, Gherghetta, Sword '08

Cabrer, Gersdorff, Quiros '09

Stabilization of this setting:

\[ m^{(0)} \to \infty \quad \text{(infinite)} \]
soft wall (AdS/QCD)

\[ \hat{V}(z) \]

\[ \text{Regge: } M^2 \sim n \]

EOM:
\[ (a^{-1} \partial_z (a \partial_z) + \frac{p^2}{a^2}) f = 0 \]
\[ f = \frac{a''}{2a} - \frac{a'^2}{4a^2} \]

```
"Schrödinger Eqn": \[ (-\partial_z^2 + V(z)) \Psi = p^2 \Psi, \quad V(z) = \frac{a''}{2a} - \frac{a'^2}{4a^2} \]
```

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=> continuum begins at:

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=> just like IR brane: KK towers
Modeling the QCH: generalized free fields

Generalized Free Fields

Polyakov, early ‘70s- skeleton expansions

CFT completely specified by 2-point function - rest vanish

Scaling - 2-point function:
\[ G(p^2) = -\frac{i}{(-p^2 + i\epsilon)^{2-\Delta}} \]

Can be generated from:
\[ \mathcal{L}_{GFF} = -\hat{h}^\dagger (\partial^2)^{2-\Delta} \hat{h} \]

Branch cut starting at origin - spectral density purely a continuum:

\[ G(p) \sim \int_{\mu^2}^\infty dM^2 \frac{\rho(M^2)}{p^2 - M^2} \]
Quantum Critical Higgs (Generalized Free Fields)  
Bellazzini, Csaki, Hubisz, SL, Serra, Terning

5D model:

\[
S = \int d^4xdz\sqrt{g}\left[ |D_M H|^2 - \frac{1}{4g_4^2} W_{MN}^a W^a_{MN} - \phi(z) |H|^2 + L_{\text{int}}(H) \right] + \int d^4x L_{\text{perturbative}}.
\]

\[
d s^2 = a(z)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2) \]

\[
a(z) = \frac{R}{z} e^{-\frac{2}{3} \mu (z-R)}
\]

With the discovery of Higgs, we need a pole (125 GeV) and a gap to BSM continuum

Soft wall terminates CFT with continuum, not set of KK modes
Quantum Critical Higgs (Generalized Free Fields)
Bellazzini, Csaki, Hubisz, SL, Serra, Terning

- 5D model:

\[ S = \int d^4x d^2z \sqrt{g} \left[ |D_M H|^2 - \frac{1}{4g_4^2} W_{MN}^a \cdot \phi(z) |H|^2 + \mathcal{L}_{\text{int}}(H) \right] + \int d^4x \mathcal{L}_{\text{perturbative}}. \]

\[ ds^2 = a(z)^2 \left( \eta_{\mu\nu} dx^\mu dx^\nu - dz^2 \right) \]

\[ a(z) = \frac{R}{z} e^{-\frac{2}{3} \mu (z - R)} \]

With the discovery of Higgs, we need a pole (125 GeV) and a gap to BSM continuum

Soft wall terminates CFT with continuum, not set of KK modes

The momentum space propagator for the physical Higgs scalar can be written as

\[ G_h(p) = -\frac{i Z_h}{(\mu^2 - p^2 + i\varepsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}} \]

\[ Z_h = \frac{(2 - \Delta)}{(\mu^2 - m_h^2)^{\Delta - 1}} \]

c.f. unparticle propagator
Quantum Critical Higgs (Generalized Free Fields)
Bellazzini, Csaki, Hubisz, SL, Serra, Terning


5D model:

\[
S = \int d^4x dz \sqrt{g} \left[ |D_M H|^2 - \frac{1}{4g_4^2} W_{MN}^a W^{a, MN} - \phi(z) |H|^2 + \mathcal{L}_{\text{int}}(H) \right] + \int d^4x \mathcal{L}_{\text{perturbative}}.
\]

\[
d s^2 = a(z)^2 (\eta_{\mu \nu} dx^\mu dx^\nu - dz^2)
\]

\[
a(z) = \frac{R}{z} e^{-\frac{2}{3} \mu (z-R)}
\]

With the discovery of Higgs, we need a pole (125 GeV) and a gap to BSM continuum

Soft wall terminates CFT with continuum, not set of KK modes

Generally:

\[
G_h(p^2) = \frac{i}{p^2 - m_h^2} + \int_{\mu^2}^\infty dM^2 \frac{\rho(M^2)}{p^2 - M^2}
\]

SM recovered in limits \( \mu \to \infty \) and/or \( \Delta \to 1 \)
Probing Naturalness by the Tail of the Off-shell Higgs via Polarization Tagging

SL, Park, Qian; to appear soon
Probing Naturalness by the Tail of the Off-shell Higgs via Polarization Tagging

SL, Park, Qian; to appear soon

Z Polarization ↔ Angle $\cos \theta$ dist. from decay

Transverse: \[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta} = \frac{3}{8} (1 + \cos^2 \theta)
\]

Longitudinal: \[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta} = \frac{3}{4} (1 - \cos^2 \theta)
\]

To optimize the longitudinal over transverse mode significance:

\[-0.68 < \cos \theta < 0.68\]

$\cos \theta_C = 0.68$

$\{\epsilon_L, \epsilon_T\} = 86\%, 59\%$
Probing Naturalness by the Tail of the Off-shell Higgs via Polarization Tagging

1. Theoretical discriminant:

\[
\frac{\sigma_{LL}/\sigma_{TT}}{\frac{\sigma}{|\cos \theta| < \cos \theta_C}} \quad \frac{\sigma}{|\cos \theta| > \cos \theta_C}
\]

2. Experimental observable:

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<th>Theory Cross Section (fb)</th>
<th>Observable (# events)</th>
<th>14 TeV 3000 fb⁻¹</th>
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3. Pseudo experiment that make use of the whole polarization angle spectra in real analysis.
Quantum Critical Higgs

- soft wall cuts off CFT
- continuous KK spectrum above mass gap

Note: UV brane is the only place to put Higgs quartic, Higgs is fundamental $\Rightarrow$ fine-tuning
A Natural Quantum Critical Higgs: 5D model

Csaki, SL, Lombardo, work in progress
A Natural Quantum Critical Higgs: 5D model
Higgs arises from CFT with a domain wall (IR brane)

Csaki, SL, Lombardo, work in progress

\[ a(z) = \frac{R}{z} e^{-\frac{2}{3} \mu(z-R)} \]

light SM particles

UV

AdS

IR

IR-localized Higgs Potential

Higgs, W, Z, \gamma, g

t_L, \ t_R

soft wall

deep IR
A Natural Quantum Critical Higgs: 5D model

Higgs arises from CFT with a domain wall (IR brane)

Higgs, \( W, Z, \gamma, g \)

t-t

IR-localized Higgs Potential

taking a pole (physical Higgs) out of CFT

\[ a(z) = \frac{R}{z} e^{-\frac{2}{3} \mu(z-R)} \]

Csaki, SL, Lombardo, work in progress
A “more” Natural Quantum Critical Higgs: 5D model

SU(2) × U(1)$_{\gamma}$

light SM particles

SU(3)$_c$ × SO(5) × U(1)$_x$

AdS

bulk gauge symmetry broken down to

SU(3)$_c$ × SO(4) × U(1)$_x$

UV

light SM particles

AdS

UV

IR

IR

top partners

position of IR brane controls whether KK poles or continuum begins first

W, Z, γ, g

IR

soft wall

IR

deep IR

Csaki, Lombardo, Lee, SL, Telem; appear soon
A “more” Natural Quantum Critical Higgs: 5D model

**PNGB Higgs: as an A5 (IR brane)**

- **UV**
  - SU(2) X U(1)γ
  - light SM particles

- **AdS**
  - SU(3)c X SO(5) X U(1)x

- **IR**
  - PNGB Higgs
  - bulk gauge symmetry broken down to
  - SU(3)c X SO(4) X U(1)x

- **soft wall**

- **deep IR**

- **top partners**

- **W, Z, γ, g**

- **tL**

- **tR**

Position of IR brane controls whether KK poles or continuum begins first

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Continuum Naturalness?

Csaki, Lombardo, Lee, SL, Telem (appear soon)

♦ New Physics (e.g. Top partner) appear solely as a continuum
- KK gluon / colored octet example
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Continuum Naturalness?

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-Similar stories for continuum top partners
-Set of EFT operators searches
MCHM (Agashe, Contino, Pomarol) $\Rightarrow$ continuum version
- elementary fields which mix with the composite operators and the form factors:

$$\mathcal{L}_{\text{top}} = \bar{t}_L \not\! p \Pi_L(p) t_L + \bar{t}_R \not\! p \Pi_R(p) t_R + \bar{t}_L M(p) t_R + h.c.$$  

- 2-point function $\langle \not\! t \not\! t \rangle$ is given by

$$-i P_t(p) = \frac{1}{\not\! p - \frac{M(p)}{\sqrt{\Pi_L(p) \Pi_R(p)}}} = \int dm^2 \frac{\not\! p + m}{p^2 - m^2} \rho_t(m^2)$$
MCHM (Agashe, Contino, Pomarol) \Rightarrow \text{continuum version}

- elementary fields which mix with the composite operators and the form factors:
  \[ \mathcal{L}_{\text{top}} = \bar{t}_L \phi \Pi_L(p) t_L + \bar{t}_R \phi \Pi_R(p) t_R + \bar{t}_L M(p) t_R + h.c. \]

- 2-point function \( \langle \bar{t}t \rangle \) is given by
  \[
  -i P_t(p) = \frac{1}{\phi - \frac{M(p)}{\sqrt{\Pi_L(p)\Pi_R(p)}}} = \int dm^2 \frac{\phi + m}{p^2 - m^2} \rho_t(m^2)
  \]

- non-local effective action:
  \[ S_{\text{eff}} = \int d^4x \, d^4y \, \bar{\psi}(x)(i\gamma^\mu \partial_\mu - m) \Sigma(x - y) \psi(y) \]
MCHM (Agashe, Contino, Pomarol) \implies \text{continuum version}
- elementary fields which mix with the composite operators and the form factors:
  \[ \mathcal{L}_{\text{top}} = \bar{t}_L \not{\phi} \Pi_L(p) t_L + \bar{t}_R \not{\phi} \Pi_R(p) t_R + \bar{t}_L M(p) t_R + h.c. \]
- 2-point function \(<tt>\) is given by
  \[ -iP_t(p) = \frac{1}{\not{\phi} - \frac{M(p)}{\sqrt{\Pi_L(p)\Pi_R(p)}}} = \int dm^2 \frac{\not{\phi} + m}{p^2 - m^2} \rho_t(m^2) \]
- non-local effective action:
  \[ S_{\text{eff}} = \int d^4x d^4y \bar{\psi}(x)(i\not{\phi}y - m)\Sigma(x - y)\psi(y) \]
- gauge invariant way:
  \[ S_{\text{eff}} = \int \frac{d^4p}{(2\pi)^8} \frac{d^4k}{(2\pi)^8} \bar{\psi}(k)(\not{\phi} - m)\Sigma(p^2)F(k - p, p) \]

\[ \rho_h = \frac{1}{\pi} \text{Im} \Sigma^{-1} \]
\[ F(x, y) = \mathcal{P} \exp \left( -igT^a \int_x^y A^a \cdot dw \right) \psi(y) \]
Can we hide top partners at the LHC?

- depending on profile of the spectral density
- calculate top partner production for a given $\rho_h = \frac{1}{\pi} \text{Im} \Sigma^{-1}$

- quadratic divergence cancellation: the discrete sum rule turns into a continuous integral over the top partners
New Physics (e.g. Top partner) appear solely as a continuum

- SUSY + soft-wall (CFT with IR cutoff):

- combined to give gaugino mediation (solving flavor problem): hiding gaugino decaying into multiple leptons and missing ET

Cai, Cheng, Medina, Terning (09')
The presence of a continuum can drastically change the LHC phenomenology of new BSM resonances

we provided a model where the strong dynamics of confinement furnishes a continuum and bound states which mix together

new signals:
- enhancements to off-shell behavior of SM DOFs from mixing with continuum
- top partners and New Physics may be hidden in the tail!