Unhiggs

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Outline

Based on Stancato, Terning [0807.1954] , AA, Perez-Victoria [0810.4940] , AA, Perez-Victoria [0901.3777]

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Why New Physics?

Astrophysics

- Dark Matter is around (rotation curves, WMAP, bullet cluster(s))
- PAMELA positron excess
- Less established signals: ATIC/PPB-BETS, EGRET, WMAP haze
- Controversial signals: INTEGRAL, DAMA

Collider physics

- Less established signals: muon g-2?

Why new physics in the LHC reach?

- Tja...
- Hierarchy problem - stabilizing the weak scale needs weak scale particles
- Thermal dark matter coincidence ?
- ATIC/PPB-BETS peak???

Stronger case for *no* new physics in the LHC reach

- Electroweak precision observables (S,T,e^4): $M_{NP} \gtrsim 10\,\mathrm{TeV}$
- Flavor Physics (Δm_K): $M_{NP} \gtrsim 10^3 - 10^4\,\mathrm{TeV}$
- CP violation (ϵ_K): $M_{NP} \gtrsim 10^5\,\mathrm{TeV}$
- Baryon conservation: $M_{NP} \gtrsim 10^{12}\,\mathrm{TeV}$

The case for the Standard Model Higgs

Light SM Higgs is pretty well motivated:

- Simple
- Breaks electroweak symmetry
- Unitarizes WW scattering
- Standard Model can be extrapolated to high scales
- Consistent with precision tests

Problems:

- Hierarchy problem
- Tension between the LEP limit $m_h > 114\,\mathrm{GeV}$ and the electroweak fit $m_h = 77^{+28}_{-22}$.
  - Leptonic data prefer a very light Higgs
  - If tau data used, electroweak fit moves toward lighter Higgs Passera,Marciano,Sirlin [0804.1142]

Alternatives to Standard Model Higgs

Those adressing the hierarchy problem

- Higgsless: Technicolor, Topcolor. *Problems with EWPT and flavor*
- Pseudo-Goldstone Higgs. *Little hierarchy problem*
- Supersymmetric Higgs. *Little hierarchy problem + scenario-specific problems*

But

- None of the above clarifies why new physics is strangely elusive
- Most of them (except Higgsless of course) are uncomfortable with the Higgs mass bound $m_h > 114\,\mathrm{GeV}$

New physics, if within reach, is stealthy...

Enter Unparticles

- Georgi [hep-ph/0703260] : Unparticles (or more generally hidden valleys) are an example of stealthy new physics
- But, as far today, it is unclear if they could address any nagging problems of the Standard Model

Enter Unhiggs

Stancato,Terning [0807.3961] Unhiggs is a Higgs with a non-local action, and a continuous spectrum (branch cut in the propagator, rather than a simple pole)

$$p^2 \to (p^2)^{2-d}$$

Unparticle sector charged under the electroweak gauge group, unlike previous studies of Higgs+unparticles Kikuchi,Okada [0707.0893] , Delgado,Espinosa,Quirós [0707.4309]

- A new consistent scenario of EW breaking
- Maybe Higgs *was* at LEP but we missed it?
- Maybe clarifies the elusiveness of new physics

At this point Unhiggs is at the same footing as unparticles, hidden valley, quirks, etc: Theoretically viable and phenomenologically distinctive scenario that deserves further study....

Unhiggs

Stancato,Terning [0807.3961] Quadratic action in the momentum space

$$\int \frac{d^4p}{(2\pi)^4} h(-p) \left[\mu^{4-2d} - (-p^2+\mu^2)^{2-d} - (2-d)\mu^{2-2d} m_{uh}^2\right] h(p)$$

This is Georgi's unparticle with dimension d, plus the mass gap μ, plus the mass term m_{uh}. Non-local action in position space:

$$\int d^4x d^4y h(x) D(x,y) h(y)$$

and $D(x,y)$ is NOT proporional to $\delta^4(x-y)$. Propagator:

$$P = \frac{1}{\mu^{4-2d} - (-p^2+\mu^2)^{2-d} - (2-d)\mu^{2-2d} m_{uh}^2}$$

- Far below the mass gap, (rescaled) particle propagator

$$P \approx (2-d)\mu^{2d-2} \frac{i}{p^2 - M^2}$$

- Branch cut for $p^2 > \mu^2$ announcing continuum of degrees of freedom

Unhiggs: Results

- ST action can be made gauge-invariant using the Mandelstam construction Mandelstam ['62]
- Electroweak symmetry can be broken (W and Z acquire mass terms) by the Unhiggs vev
- Interaction vertices of Unhiggs modified wrt the Standard Model
- Interactions with arbitrary high number of gauge fields exist!
- Unhiggs vev modifes 3-, 4- and higher gauge vertices!!
- In spite of that, longutidinal WW scattering unitarized by Unhiggs exchange!!!

The Unhiggs can do what the Standard Model Higgs does:
break electroweak symmetry AND unitarize WW scattering

What about contributing to S and T?

Unhiggs

Cleary a new direction in model building, but many issues are unclear

- Gauge invariance
- What are the new degrees of freedom?
- What is the cut-off?
- What is the amount of fine-tuning?
-

Try another approach where these question can be unambiguously addressed

Holographic Unhiggs

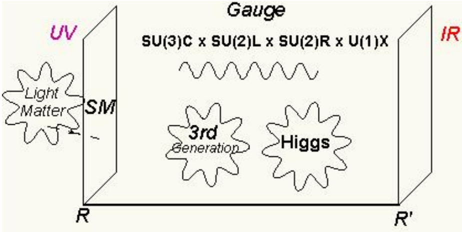
Non-local Unhiggs action as a boundary effective action of a local gauge theory in 5D

Why bother:

- Well understood local physics. Usual perturbative methods of QFT apply
- Consistency for free
- Gauge invariance for free
- Fine-tuning and cut-off understood
- Clean calculation of WW scattering and electroweak precision observables
- Wider spectrum of phenomenological possibilities

5D Electroweak Breaking on a Hard Wall

Agashe, Delgado, May, Sundrum [2003]



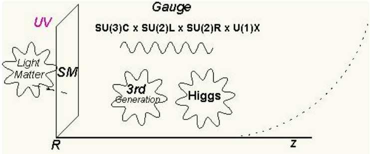
- 5D model on an interval, warped metric

$$ds^2 = a^2(z)\left(dx_\mu dx_\mu - dz^2\right)$$

- $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$ gauge symmetry and fermions in bulk
- Custodial R-symmetry to control contributions to the T parameter
- UV brane boundary conditions breaking $SU(2)_R \times U(1)_X$ to $U(1)_Y$, so that UV preserves only SM gauge symmetries
- Higgs bi-doublet on the IR brane breaking $SU(2)_L \times SU(2)_R$ to $SU(2)_V$ so that IR dynamics preserves custodial symmetry

5D Electroweak Breaking on a Soft Wall

AA, Perez-Victoria [0806.1737] , Batell, Gherghetta, Sword [0808.3977]



- 5D model with and a warped metric

$$ds^2 = a^2(z)\left(dx_\mu dx_\mu - dz^2\right)$$

- No IR brane! Mass gap from IR dynamics of warp factor

Higgs equation of motion

$$\left[a^{-3}\partial_z(a^3\partial_z) - \hat{M}^2 + p^2\right] h = 0, \qquad \hat{M}^2 = a^2 R V''$$

can be rewritten for $h = a^{-3/2}\Psi$ as Schrodinger equation

$$\left(-\partial_z^2 + V_h\right)\Psi = p^2\Psi\,, \qquad V_h = \hat{M}^2(z) + \frac{3a''}{2a} + \frac{3(a')^2}{4a^2}.$$

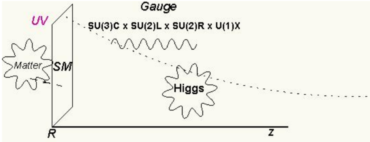
Quantum mechanical problem: $\lim_{z\to\infty} V_h = \infty$ (infinite well) when

$$a(z) \sim e^{-(\rho z)^\alpha} \qquad \alpha > 1$$

Note, in AdS $a(z) = 1/z$, $\alpha = 0$ and no mass gap

5D Electroweak Breaking with unparticle Higgs

Cacciapaglia, Marandella, Terning [0804.0424] , AA, Perez-Victoria [0810.4940]



- Warped metric $ds^2 = a^2(z)\left(dx_\mu dx_\mu - dz^2\right)$
- No IR brane.

Choose the warp factor such that the Schrodinger potential asymptotes to a positive constant $V_h \to \mu^2$ in far IR. Higg has continuous excitations (*unparticle*) which however need $p^2 = \mu^2$ to get excited (*mass gap*). For example

$$a(z) = e^{-2\mu z/3}$$

interpolating between flat space in UV and unparticle type background with mass gap μ, or

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

interpolating between AdS in UV and unparticle type background with mass gap μ

p/z propagator

How to deal with 5D theory with no well-defined KK modes

Equation of motion

$$\left[a^{-3}\partial_z(a^3\partial_z) - \hat{M}^2 + p^2\right] h = 0, \qquad \hat{M}^2 = a^2 R V''$$

has two solutions

- $K(z, p^2)$ regular in IR, $K(z, p^2) \sim a^{-3/2} e^{-\sqrt{-p^2+\mu^2} z}$ at large z.
- $S(z, p^2)$ regular in UV, $S(R, p^2) = 0$

Mixed p/z propagator: propagation of all from point z to point $z' > z$ with 4-momentum p

$$P(p^2, z, z') = \frac{K(z, p^2) K(z', p^2)}{R \Pi_h(p^2)} - S(z, p^2) K(z', p^2), \quad \Pi_h(p^2) = R^{-1} K'(R, p^2) - M^2_{\rm UV}.$$

- Well-behaved in IR because, by definition, $K(z')$ is well-behaved in IR
- M^2_{UV} from boundary Higgs potential $M^2_{UV} = V''_{UV}$. In general, M^2_{UV} can be replaced by a *local* function of p^2

Boundary Effective Action

Leave light degrees of freedom, integrate out heavy degrees of freedom Barbieri,Pomarol,Rattazzi [hep-ph/0310285] : rather than Higgs zero-mode, better use boundary value $\bar{h}(p) = R^{1/2} h(p, R)$. Effective action is an inverse of boundary-to-boundary propagator

$$S_{eff} = \frac{1}{2} \int \frac{d^4 p}{(2\pi)^4} \bar{h}(-p) \Pi_h(p^2) \bar{h}(p) + \ldots .$$

$\Pi_h(p^2) = R^{-1} K'(R, p^2) - M_{\mathrm{UV}}^2$ is called the *kinetic function*:

- Non-trivial analytic structure with poles and/or cuts due to integrating-out heavy stuff
- At low momenta $p^2 \ll \mu^2$, as usual $\Pi_h(p^2) \approx Z(p^2 - m_{uh}^2)$
- For $p^2 > \mu^2$, $K(z, p^2)$ becomes imaginary, thus $\Pi_h(p^2)$ is imaginary too, announcing production of continuum of bulk degrees of freedom

SM fermions and Yukawa interactions

$$Y_* \hat{v}(R) \overline{\psi}_L \psi_R + Y_* \bar{h} \overline{\psi}_L \psi_R$$

Almost likes in SM, but $Y_* = m_f / \hat{v}(R)$ instead of $Y_* = m_f / v$.

Uniggs Boundary Action - example 0

$$a(z) = e^{-2\mu(z-R)/3} \qquad \hat{M}(z) = 0$$

Solutions

$$K(z, p^2) = e^{-(z-R)(\sqrt{-p^2+\mu^2}-\mu)}$$

$$S(z, p^2) = e^{(z-R)\mu} \frac{\sinh\left((z-R)\sqrt{-p^2+\mu^2}\right)}{\sqrt{-p^2+\mu^2}}$$

Kinetic function

$$\Pi_h(p^2) = R^{-1}\mu - R^{-1}\sqrt{\mu^2 - p^2} - M_{UV}^2$$

Square root type branch cut for $p^2 > \mu^2$. Plus a pole at $p^2 = \mu^2 - (\mu - RM_{UV}^2)^2$.

Uniggs Boundary Action - example 1

$$a(z) = \frac{R}{z} e^{-2\mu(z-R)/3} \qquad \hat{M}^2(z) = \frac{\nu^2 - 4}{z^2}$$

Solution

$$K(z, p^2) = a^{-3/2}(z) \frac{W(\kappa, \nu, \sqrt{\mu^2 - p^2} z)}{\bar{W}(\kappa, \nu, \sqrt{\mu^2 - p^2} R)}$$

where W is the Whittaker function (rescaled hypergeometric of the 2nd kind), and $\kappa = -\frac{3\mu}{2\sqrt{\mu^2 - p^2}}$

The kinetic function at for $p \ll 1/R$, and $0 < \nu < 1$

$$\Pi_h(p^2) \approx C(\nu) R^{2\nu-2} \left[m^{2\nu} + \frac{\Gamma(1/2 + \nu - \kappa)}{\Gamma(1/2 - \nu - \kappa)} (\mu^2 - p^2)^\nu \right]$$

Looks very much like Stancato-Terning Unhiggs, with $\nu = 2 - d$. Gamma's irrelevant for $p^2 \gg \mu^2$, though different dynamics near the mass gap.

Uniggs Boundary Action - example 2

$$a(z) = \frac{R}{z} e^{-2\mu(z-R)/3} \qquad \hat{M}^2(z) = \frac{\nu^2 - 4}{z^2} - \frac{3\mu}{z}$$

$$K(z,p^2) = a^{-3/2}(z)(z/R)^{1/2} \frac{K_\nu(\sqrt{\mu^2 - p^2}z)}{K_\nu(\sqrt{\mu^2 - p^2}R)}.$$

The kinetic function

$$\Pi_h(p^2) = \frac{\mu K_{1-\nu}(\mu R)}{R K_\nu(\mu R)} - \frac{\sqrt{\mu^2 - p^2} K_{1-\nu}(\sqrt{\mu^2 - p^2}R)}{R K_\nu(\sqrt{\mu^2 - p^2}R)} - Z m_{uh}^2$$

For $p \ll R^{-1}$, and $0 < \nu < 1$

$$\Pi_h(p^2) \approx (\mu R)^{2\nu - 2} C_\nu \left[\mu^2 - \frac{(\mu^2 - p^2)^\nu}{\mu^{2\nu-2}} - m_{uh}^2 \right]$$

Exactly Stancato and Terning with $\nu = 2 - d$. $\Lambda = 1/R$ can be thought of as the cut-off of the Unhiggs scenario. But valid also outside the open interval $0 < \nu < 1$. For example, for $\nu = 0$,

$$\Pi_h(p^2) \approx \frac{1}{R^2 \log(e^\gamma \sqrt{\mu^2 - p^2} R/2)} - \frac{1}{R^2 \log(e^\gamma \mu R/2)} - \tilde{m}_{uh}^2.$$

Vector and Pseudoscalar Continuum

In 5D there are also KK modes of SM gauge bosons and bulk Higgs...

- Vector resonances propagate in Schrodinger potential:

$$V_{\rm v} = M^2(z) + \frac{a''}{2a} - \frac{(a')^2}{4a^2} \qquad M^2(z) = g_*^2 a^2 \hat{v}^2/2$$

  - Typically, mass gap $\sim \mu/3$ (smaller than that of Unhiggs!)
  - They can take over unitarizing WW scattering (Unhiggsless models ;-)

- Pseudoscalar resonances propagate in Schrodinger potential:

$$V_{\rm p} = M^2(z) + \frac{a''_{eff}}{2a_{eff}} - \frac{(a'_{eff})^2}{4a_{eff}^2} \qquad a_{eff}(z) = a^{-3}(z)\hat{v}^{-2}(z)$$

  - Typically, mass gap $\sim \mu$

- Graviton resonances propagate in Schrodinger potential:

$$V_{\rm g} = \frac{3a''}{2a} + \frac{3(a')^2}{4a^2}$$

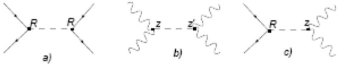
  - Typically, mass gap $\sim \mu$

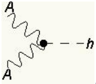
Unhiggs scenario

- 5D Holographic Unhiggs predicts vector, pseudoscalar, graviton and radion continuum to appear along with the Unhiggs continuum
- That's OK - if the Unhiggs continuum originates from a strong sector one expects other degrees of freedom too
- *In the following:* Zoom in on Unhiggs
  - Gravity can be formally decoupled by taking $M_5 \to \infty$ (one proceeds with 5D non-gravitational theory)
  - Vector resonances can propagate in a different metric (perfectly allowed in a non-gravitational theory) that leads to a parametrically larger mass gap
  - Pseudoscalars can be decoupled with the help of fine-tuning

Interesting questions brushed under carpet - e.g. the holographic dual....

Computing with Holographic Unhiggs





$i\eta_{\mu\nu} R^{1/2} g_*^2 a^3(z)\hat{v}(z)/4$

- In the SM, the Higgs-Gauge-Gauge vertex is $g^2 v/4$, and the Higgs propagator is $1/(s - m_h^2)$
- The Unhiggs, interacts with two gauge fields anywhere in the bulk, with a z-dependent vertex. Physical amplitudes integrate over all possible positions of the vertex in the bulk.
- One can define the effective propagator

$$P_{\rm eff}^{[gg]}(p^2) = \frac{2\int_R^\infty dz' \int_R^{z'} dz a^3(z)\hat{v}(z)a^3(z')\hat{v}(z')P(p^2, z, z')}{Rv^2}$$

  that encompasses the effects of the z-dependent vertex and the z-dependent propagator.
- `THE RULE:` To get the Unhiggs amplitude, in the SM amplitude trade the Higgs propagator for the effective propagator.

Computing with Holographic Unhiggs

By the same logic one can also define the effective gauge-fermion propagator and the effective fermion-fermion propagator

$$P_{\rm eff}^{[gg]}(p^2) = \frac{2\int_R^\infty dz' \int_R^{z'} dz a^3(z)\hat{v}(z)a^3(z')\hat{v}(z')P(p^2,z,z')}{Rv^2}$$

$$P_{\rm eff}^{[ff]}(p^2) = \frac{\hat{v}(R)^2}{v^2}\frac{1}{\Pi(p^2)}.$$

$$P_{\rm eff}^{[gf]}(p^2) = \frac{\int_R^\infty a^3(z)\hat{v}(z)K(z,p^2)}{R\hat{v}(R)\Pi(p^2)}.$$

THE RULE: To get the Unhiggs amplitude, in the SM amplitude trade the Higgs propagator for the *corresponding* effective propagator.

Computing with Holographic Unhiggs

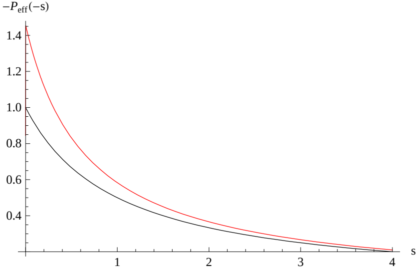
For the particular background corresponding to the Stancato-Terning Unhiggs

$$P_{\rm eff}^{[ff]}(s) = \frac{Z}{\Pi_0(s) - Z m_{\rm uh}^2} \qquad P_{\rm eff}^{[gf]}(s) = \frac{\Pi_0(s)}{s} \frac{1}{\Pi_0(s) - Z m_{\rm uh}^2}$$

$$P_{\rm eff}^{[gg]}(s) = \frac{1}{s} + \frac{\Pi_0(s)}{p^4} \frac{m_{\rm uh}^2}{\Pi_0(s) - Z m_{\rm uh}^2}$$

$$\Pi_0(s) = \frac{\mu K_{1-\nu}(\mu R)}{R K_\nu(\mu R)} - \frac{\sqrt{\mu^2 - s} K_{1-\nu}(\sqrt{\mu^2 - s} R)}{R K_\nu(\sqrt{\mu^2 - s} R)} \sim (\mu^2 - s)^\nu$$

`Important`: In UV, when $\Pi_0 \gg Z m_{uh}^2$, the gauge-gauge and the gauge-fermion propagators asymptote to $1/p^2$. UV properties of amplitudes involvig the SM gauge bosons are the same as in the SM!



WW scattering

Gauge self-interactions contribute to longitudinal WW scattering

$$M_g(s) \approx \frac{g_L^2}{4m_W^2} s$$

In SM, "bad" UV behavior is cancelled for $s > m_h^2$ by Higgs exchange

$$M_h(s) \approx -\frac{g_L^2}{4m_W^2} \frac{s^2}{s - m_h^2}$$

Unhiggs exchange contributes

$$M_{uh}(s) \approx -\frac{g_L^2}{4m_W^2} s^2 P_{eff}^{[gg]}(s)$$

Since $P_{eff}^{[gg]}(s) \approx 1/s$ in UV, unitarity restored as in the SM!

S and T parameter at 1-loop

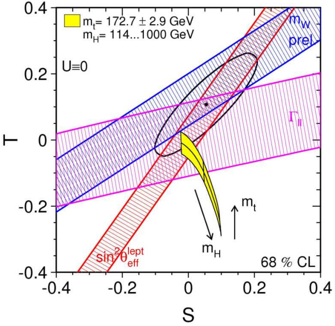
Higgs contribution to S and T parameters at one loop

$$T_{\rm SM} = \frac{3}{8\pi\cos^2\theta_W}\int dk \frac{k^5}{(k^2+m_W^2)(k^2+m_Z^2)}\frac{1}{(k^2+m_h^2)} \sim -\frac{3}{8\pi\cos^2\theta_W}\log(\Lambda/m_h)$$

$$S_{\rm SM} = -\frac{1}{6\pi}\int dk k^3 \frac{k^4+3k^2m_Z^2+12m_Z^4}{(k^2+m_Z^2)^3}\frac{1}{(k^2+m_h^2)} \sim \frac{1}{6\pi}\log(\Lambda/m_h)$$

Log divergence cancelled against gauge loops. Define $\Delta T_{SM} = T_{\rm SM}(m_h) - T_{\rm SM}(m_{ref})$

$$\Delta T_{SM} \sim -\frac{3}{8\pi\cos^2\theta_W}\log(m_h/m_{ref}) \qquad \Delta S_{SM} \sim \frac{1}{6\pi}\log(m_h/m_{ref})$$



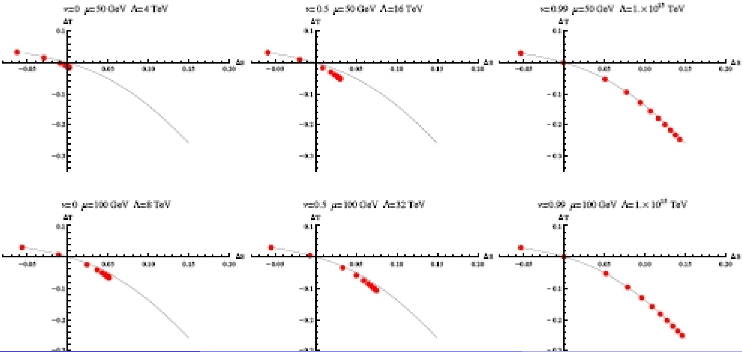
S and T parameter at 1-loop

AA, Perez-Victoria [0901.3777] Unhiggs contribution to S and T parameters

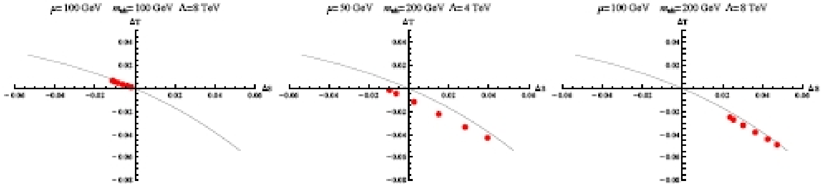
$$T_{\rm SM} = -\frac{3}{8\pi \cos^2\theta_W}\int dk \frac{k^5}{(k^2+m_W^2)(k^2+m_Z^2)} P_{eff}^{[gg]}(-k^2)$$

$$S_{\rm SM} = \frac{1}{6\pi}\int dk k^3 \frac{k^4+3k^2m_Z^2+12m_Z^4}{(k^2+m_Z^2)^3} P_{eff}^{[gg]}(-k^2)$$

Since $P_{eff}^{[gg]}(s) \approx 1/s$ in UV, the loops are log divergent and the divergence is cancelled against gauge loops, as in the SM !



S and T parameter at 1-loop



- The Unhiggs is consistent with the LEP constraints on S and T in a large portion of its parameter space. In particular, electroweak precision observables do not exclude the conformal dimension $d = 2$ ($\nu = 0$), nor a mass gap smaller than $100\,\mathrm{GeV}$.
- Typically, the Unhiggs mimics the SM Higgs, in the sense that its contributions to ΔS and ΔT are similar to the SM Higgs contribution for *some* Higgs mass.
- If the Unhiggs mass parameter m_{uh} is much smaller than the mass gap μ, then the Unhiggs mimics the SM Higgs with mass $m_h \sim m_{\mathrm{uh}}$. If, $m_{\mathrm{uh}} \gg \mu$ and d is away from 1, the Unhiggs mimics the SM Higgs with mass $m_h \sim \mu$.

Outlook

- New direction in electroweak symmetry breaking beyond the SM
- Consistent with unitarity of WW scattering *and* electroweak precision observables
- Visible to electroweak precisions tests, but unvisible to colliders
- Can this be a part of a more symmetric scheme? Pseudo-Goldstone boson, or supersymmetry?

If Unhiggs is out there, CERN has a wrong machine ;-)

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