Quantum Critical Higgs Models

in the $gg \to ZZ \to 4\ell$ channel

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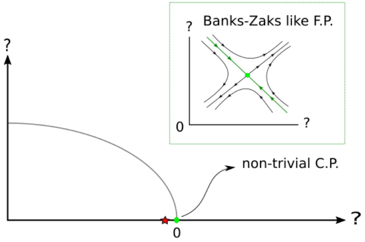
Why QCH?

- Hierarchy problem + LHC: we need to explore new directions.
- Georgi on unparticles: "it's different; not just more particles"
- What is QCH?
  - Non-trivial critical point: Higgs sector is described by a (strongly coupled) CFT



  - The strongly coupled theory produces a weakly coupled effective theory
  - Scaling dimension is $1 < \Delta < 2$ (In SM $\Delta = 1 + \mathcal{O}(\alpha)$)
  - The CFT is softly broken at $\mu > m_h$
  - No new massless particles (dilaton)

The 1PI Effective Action

$$S = S_{CFT} + S_{mix} + S_{elem.}$$

$$S \quad \rightarrow \quad S_{1PI} = \frac{1}{2\mathcal{Z}_h} \int \frac{d^4p}{(2\pi)^4} h(p) \Sigma(p^2, \mu, \Delta) h(-p) + \dots$$

- S_{1PI} is weakly coupled

  Higgs observed pole:
- $S_{CFT} \rightarrow S_{1PI}$: hierarchy solved.
  or
- $S_{CFT} + S_{mix} \rightarrow S_{1PI}$: the case in our models.

The CFT

- At high energies the CFT is restored:

$$\langle h(p)h(-p)\rangle = \frac{-i}{p^{2(2-\Delta)}}.$$

- consequently

$$\Sigma(p^2) = p^{2(2-\Delta)} \quad \text{as} \quad p^2 \to \infty$$

- Unitarity requires: $1 < \Delta$
- In QCH we have an action: $\Delta < 2$ (unparticles)

unHiggs

A 4D example: unparticles model with mass gap

- We break the CFT using the ansatz:

$$\langle h(p)h(-p)\rangle \propto \int_{\mu^2}^{\infty} (M^2-\mu^2)^{\Delta-2} \frac{i}{p^2-M^2+i\epsilon} dM^2,$$

- The Kinetic term is

$$\Sigma(p^2) = -(\mu^2-p^2)^{2-\Delta} + (\mu^2-m_h^2)^{2-\Delta}$$

- Unitarizes $WW \to WW$

Higgs from AdS

- n-point functions can be calculated from:

$$\left\langle e^{-\int d^4x \phi_0 \mathcal{O}} \right\rangle_{CFT} = e^{-S_{gravity}[\phi]},$$

- The dual field has the scaling dimension

$$\begin{aligned} ds^2 =& e^{-2A(z)}\left(\eta^{\mu\nu} dx_\mu dx_\nu - dz^2\right) \\ \Delta =& 2 - \nu, \\ \nu =& \sqrt{m^2 R^2 + 4}, \qquad M^2(z) = m^2 + f(z) \end{aligned}$$

-

$$\boxed{\Sigma(p^2) = \frac{R^3}{\epsilon^{3-2\Delta}} \partial_z \mathcal{K}(p^2, z = \epsilon) - m_{UV}^2} \qquad h_\epsilon = \epsilon^\Delta h_{QCH}, \quad p\epsilon \to 0$$

Model I

"Holographic unHiggs" hep-ph/0810.4940

- The background is assumed:

$$\begin{cases} A(z) = & \log(\frac{z}{R}) + \frac{2}{3}\mu(z-R), \\ M^2(z) = & e^{\frac{4}{3}\mu(z-R)}\left(m^2 - \frac{3z}{R^2}\right). \end{cases}$$

- After redefining the field and removing the regulating brane

$$h_\epsilon^2 = \frac{\epsilon^{4-2\nu}2^{2\nu}\Gamma(\nu)}{R^3\Gamma(1-\nu)}h^2$$

$$\boxed{\Sigma(p^2) = -(\mu^2 - p^2)^\nu + (\mu^2 - m_h^2)^\nu}$$

Model II

"Dynamical Soft-Wall AdS/QCD" hep-ph/0801.4383

- Constructed to study AdS/QCD
- Background is solved in the presence of a dilaton, Φ, and a Tachyonic mode.

$$\begin{cases} A(z) = & \log\left(\frac{z}{R}\right) \\ M^2(z) = & m^2 \\ \Phi(z) = & (2\mu z)^\alpha \end{cases} \leftarrow \begin{cases} \boxed{\alpha = 1, \quad \text{continuum}} \\ \alpha = 2, \quad \text{Regge} \end{cases}$$

$$S_5 = \int d^5x\sqrt{g}e^{-\Phi}\mathcal{L}$$

$$\boxed{\Sigma(p^2) = (\mu^2 - p^2)^\nu \frac{\Gamma\left(\frac{1}{2} + \frac{3\mu}{2\sqrt{\mu^2-p^2}} + \nu\right)}{\Gamma\left(\frac{1}{2} + \frac{3\mu}{2\sqrt{\mu^2-p^2}} - \nu\right)} - (p^2 \to m_h^2)}$$

Model III

" The AdS/CFT/Unparticle Correspondence" hep-ph/0804.0424

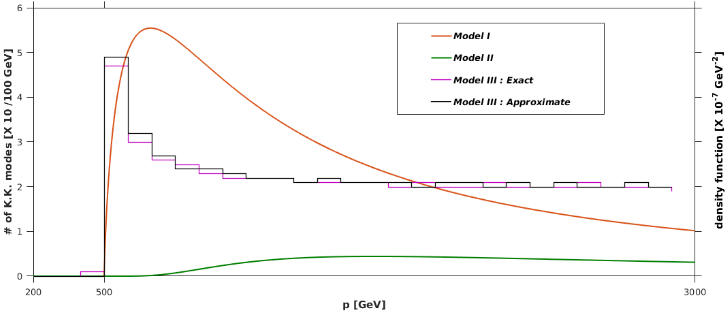
- An addition scalar field was added in the bulk
- The scalar acquires a z-dependent VEV

$$\begin{cases} A(z) = & \log(\frac{z}{R}) \\ \phi(z) = & \mu^2 R^{1/2}\left(\frac{z}{R}\right)^2 \\ M^2(z) = & m^2 + R^{1/2}\phi(z) \end{cases}$$

- We further investigate the back-reaction of the scalar field on the geometry
- There is a singularity at $z_s \approx (RM_5)^{3/4}/\mu$

$$\Sigma(p^2) = (\mu^2 - p^2)^\nu \left(1 + \frac{2}{\Gamma(1-\nu)\Gamma(\nu)} \frac{K_\nu(\sqrt{\mu^2 - p^2} z_s)}{I_\nu(\sqrt{\mu^2 - p^2} z_s)}\right) - (p^2 \to m_h^2)$$

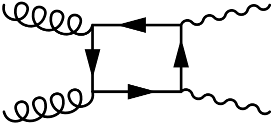
The generic behavior of the spectral density functions



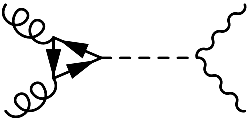
$$\langle h(p)h(-p)\rangle \propto \int_{\mu^2}^{\infty} \rho(M^2)\frac{i}{p^2 - M^2 + i\epsilon}dM^2,$$

Interactions

- $gg \to ZZ$:



$+$ *crossings* $+$



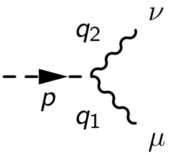
- We will focus on the hZZ coupling.

Gauging the non-local action

- We can gauge the non-local action using Mandelstam's method (Wilson line)

$$S = \int d^4x \int d^4y \quad h(x)\Sigma(x-y) P \cdot e^{-ig\int_x^y A_\mu du^\mu} h(y)$$

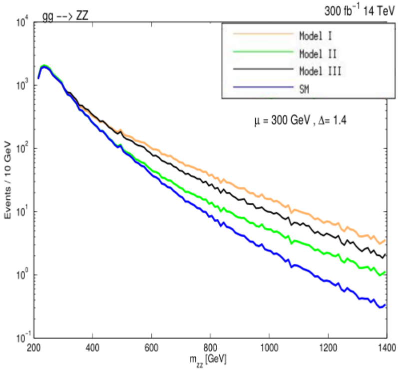
- hZZ (Stancato's PhD thesis)

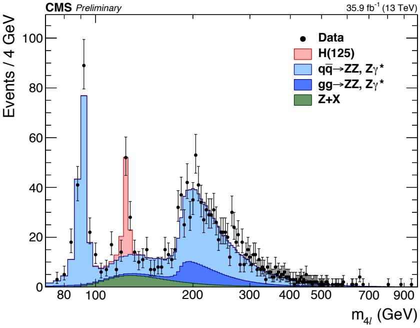


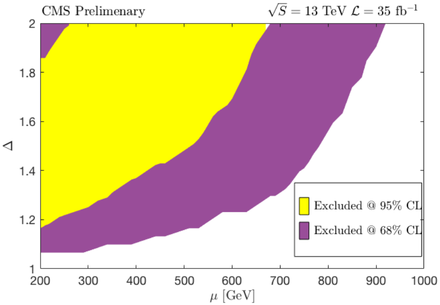
$$= -i\frac{gM_Z}{2c_w\mathcal{Z}_h}\Big[2\eta^{\mu\nu}\frac{\Sigma(p)-\Sigma(0)}{p^2} + (2q_2+q_1)^\mu q_2^\nu * \# + \dots\Big]$$

Results

- Plot has been generated using *ggZZ* program
- The Zs are on-shell
- No background




CMS Preliminary
35.9 fb^{-1} (13 TeV)
Events / 4 GeV
Data
H(125)
$q\bar{q}\to ZZ, Z\gamma^*$
$gg\to ZZ, Z\gamma^*$
Z+X
m_{4l} (GeV)

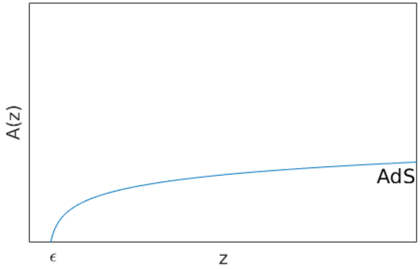

CMS Prelimenary
$\sqrt{S} = 13$ TeV $\mathcal{L} = 35$ fb^{-1}
Δ
μ [GeV]
Excluded @ 95% CL
Excluded @ 68% CL

AdS/Broken-CFT

$$ds^2 = e^{-2A(z)}\left(\eta^{\mu\nu} dx_\mu dx_\nu - dz^2\right)$$

AdS$\Longleftrightarrow$CFT energy scale $\Longleftrightarrow 1/z$

5D



4D dual

- UV cut-off$= 1/\epsilon$
- CFT not broken in IR
- e.g. RS II model

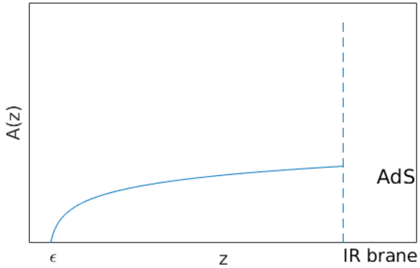
$A(z)_{AdS} = \log(z/R)$, R : radius of AdS

AdS/Broken-CFT

$$ds^2 = e^{-2A(z)}\left(\eta^{\mu\nu}dx_\mu dx_\nu - dz^2\right)$$

AdS$\Longleftrightarrow$CFT energy scale $\Longleftrightarrow 1/z$

5D



4D dual

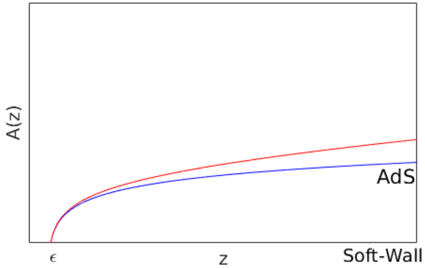
- UV cut-off$= 1/\epsilon$
- hard breaking of CFT
  - K.K. modes
- e.g. RS I model

AdS/Broken-CFT

$$ds^2 = e^{-2A(z)}\left(\eta^{\mu\nu}dx_\mu dx_\nu - dz^2\right)$$

AdS$\Longleftrightarrow$CFT energy scale $\Longleftrightarrow 1/z$

5D



4D dual

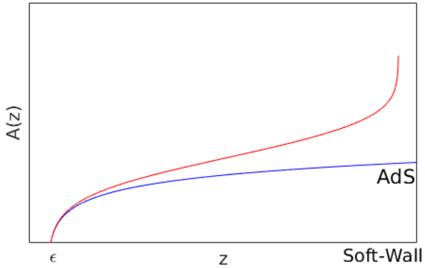
- UV cut-off$= 1/\epsilon$
- soft breaking of CFT
  - mass gap + no K.K. modes
- e.g. models I & II

AdS/Broken-CFT

$$ds^2 = e^{-2A(z)}\left(\eta^{\mu\nu} dx_\mu dx_\nu - dz^2\right)$$

AdS $\Longleftrightarrow$ CFT   energy scale $\Longleftrightarrow$ $1/z$

5D



4D dual

- UV cut-off$= 1/\epsilon$
- soft + hard breaking of CFT
  - mass gap + K.K. modes
- e.g. model III

Interactions from the bulk

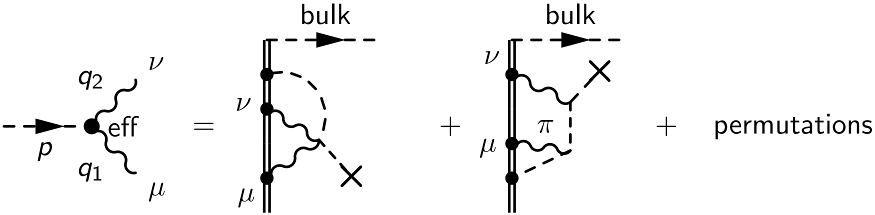
- We need to check for further contributions in AdS picture
- We remove the unwanted gauges by b.c.:
  $SU(2)_L \times SU(2)_R \to SU(2)_L \times U(1)_Y$
- Boundary potential for the Higgs ignites SB in the bulk

$$\mathcal{L}_H = \frac{1}{2}\partial_M h \partial^M h - \frac{1}{2}M(z)^2 h^2 + \frac{1}{2}(V(z)+h)^2 \Big(L^a_M - R^a_M\Big)^2 + \dots$$

where

$$L^3_{UV\mu} - R^3_{UV\mu} = \frac{g}{c_w} Z_\mu$$

Interactions from the bulk



- These will give what we already have found by imposing gauge invariance
- We can add gauge invariant coupling that further contribute to hZZ:

$$\mathcal{L}_{int} \propto H^2 F^2$$

- Our philosophy is to keep few free parameters and so will ignore these
- No further contribution at tree level

Unitarity of $t\bar{t}WW$ scattering

hep-ph/1203.0312

- Non conformal case

$$\mathcal{L}_{Y,NC} = -\frac{m_t}{\mathcal{V}} h t \bar{t}$$

$$\mathcal{M}(t\bar{t} \to WW) = \sqrt{2} G_F m_t m_h^{4-2\Delta} (-1)^{\Delta-2} s^{\Delta-3/2}$$

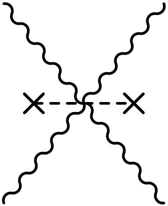
- The amplitude diverges for $\Delta > 3/2$
- Propagating the top into the bulk we find

$$\mathcal{L}_{Y,C} = -\frac{m_t}{\mathcal{V}} F(p^2) h t \bar{t}$$

$$\lim_{p^2 \to \infty} F(p^2) \propto p^{1-\Delta}$$

unitarity of WW scattering

- vertices with arbitrary number of gauge bosons



- The crosses indicate insertion of Higgs VEV

SB in the Bulk

$$S = \int d^4xdz\sqrt{g}\left[|D_M H|^2 - \frac{1}{4g_L^2} {L^a_{MN}}^2 - \frac{1}{4g_R^2} {R^a_{MN}}^2 - M(z)^2 + \mathcal{L}_{int}(H)\right] + \int d^4x\mathcal{L}_{boundary}$$

$$\mathcal{L}_{boundary} \supset - m^2_{UV} H_0^2 + \lambda/4 H_0^4$$

$$\mathcal{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h+V \end{pmatrix} + \Pi$$

Peskin-Takeuchi S and T

$$T = 0$$

$$\alpha S = 4 s_w^2 g^2 \partial_{p^2} \Pi_{WB}(p^2 = 0)$$

$$\Pi_{WB} = \frac{1}{g_L^2 + g_R^2} \left(\frac{v'(p^2, z = z_{UV})}{v(p^2, z = z_{UV})} - \frac{a'(p^2, z = z_{UV})}{a(p^2, z = z_{UV})} \right)$$

- a and v are the solution to the axial and vector 5D fields

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

"The Schrödinger potential"

- After a field re-difination

$$-\bar{h}'' + V\bar{h} = p^2\bar{h}$$
$$V = \frac{9}{4}A'^2 - \frac{3}{2}A'' + e^{-2A}M^2$$

- as $z \to \infty$:

$V \to \infty$	discretuum
$V \to 0$	continuum w/o mass gap
$V \to \mu$	continuum w/ mass gap