Dilaton vs Higgs: Nearly Conformal Physics

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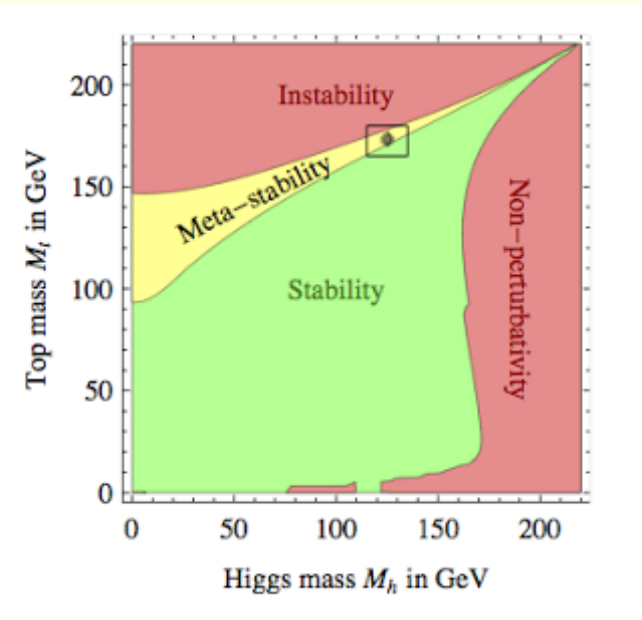
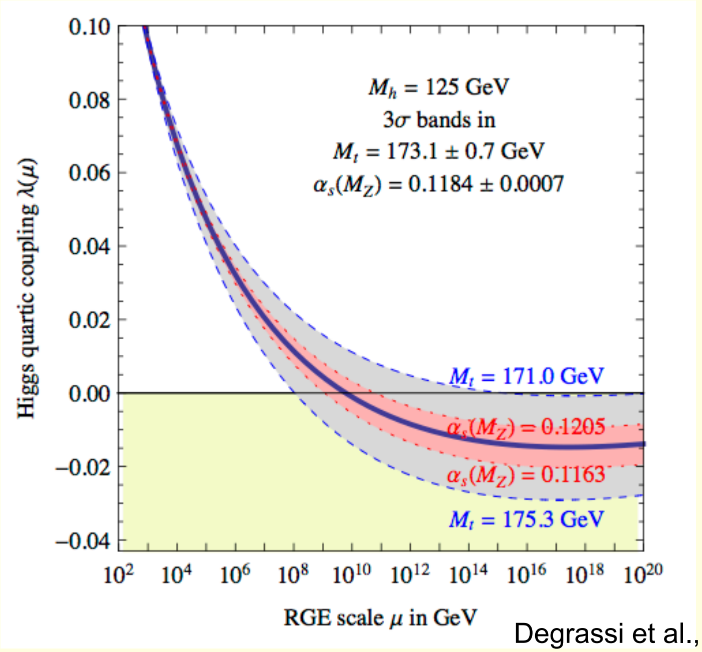
"Live or die" on whether Higgs is about 125 GeV

The SM vacuum Stability bound/ $\lambda\left(M_{Planck}\right) > 0$
The only 1 GeV (!) differences may destroy the Universe





Degrassi et al., 2013

$$m_h\left[GeV\right] > 129.4 + 1.4\left(\frac{m_t\left[GeV\right] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s - 0.1184}{0.0007}\right) \pm \underbrace{1\ \mathrm{GeV}}_{THEORY}$$

Something else – not in terms of Higgs?

- In the absence of an explicit sector that breaks gauge invariance, the SM are approximately conformal down to QCD scale

The question of what triggers gauge symmetry breaking in the SM is tied to the dynamical breaking of scale invariance.

Main message: EWSB could be triggered by a spontaneously broken, nearly conformal sector at $Q \sim f > v = 246\ GeV$ E Gildener, S Weinberg (1976)

- **The spectrum of states at EW scale $Q \sim v$ would then contain a scalar resonance, the pseudo-dilaton PsD (pseudo-Goldstone boson) of conformal symmetry breaking.**
- **Higgs-like properties are usual.**

PsD may be a source of DM, $PsD \to \gamma\ \gamma_U^*$, Dark photons

Scale invariant hidden world?

Sample: combined LHC+Tevatron excess in $\gamma\gamma$ channel

$$\sigma^{LHC,Tevatron}(s)BR(s \to \gamma\gamma)/\sigma BR(SM) > 1$$ **Origin?**

No enhanced di-photon rate in MSSM, NMSSM, others

Turn to Hidden sector?

DILATON $\sigma(x)$ as a possible candidate for s-particle observed

Why? - pseudo-Goldstone boson, $m_\sigma \sim O(\Lambda_{QCD})$

- need to preserve a non-linear realization of scale symmetry

-serves as a portal to HIDDEN sector

-guarantees ReN of the theory/$\sigma(x) = (h^+ h)^{1/2}(x)$ if $f = v$

The Higgs interpretation of a discovery at the LHC is not the only possibility

Dilaton: couplings to SM particles

Key point: SM$\in$ Conf. Sector , $L_{trace} = \frac{\sigma}{f}\left[T_{\mu}^{\mu}(SM)^{tree} + T_{\mu}^{\mu}(SM)^{anom}\right]$

By conformal invariance: $\sum_{light} b_0 + \sum_{heavy} b_0 = 0, \quad \beta_i(g) = b_0^i g^3 / 16\pi^2$

Split scale over color particles: $light - m_\sigma - heavy$

Non-perturbative generalization (sufficient for exp. application)

Dilaton: $L_{\sigma gg}^{1-loop} = -\frac{\alpha_s}{8\pi} b_0^{light} \frac{\sigma}{f}\left(G_{\mu\nu}^a\right)^2, \quad m_q < m_\sigma, \quad b_0^{light} = -11 + \frac{2}{3} n_{light}$

- If $m_\sigma \sim 125$ GeV, no top-quark contribution are in the loop!
- Instability catastrophe avoided

Collider phenomenology:

- **Effective theory @ energy** $\Lambda_{CFT} \sim 4\pi f\,,\ EWCh \xrightarrow{replm't} v \to v(\sigma / f)$

Crucial point:

- **Loop-induced couplings to** $\gamma\,\gamma$ **or** $g\,g$ **below** Λ_{CFT}

CFT/SM loop: tenfold increase of coupling strength! LHC!

$$\left(\frac{\sigma\, gg}{H\ gg}\right)_{coupling} = \left(\frac{33}{2} - n_{light}\right)_{factor} = \begin{matrix} 11 + \varepsilon,\ n_{light} = 5 \\ 10 + \varepsilon,\ n_{light} = 6 \end{matrix}$$

σ **discovery possible, if** $\left(11 - \frac{2n_{light}}{3}\right)\frac{v}{f} > O(0.3)$ @ $100\, fb^{-1}$ ATLAS (2004)

for $m_\sigma < m_t$

Estimated upper limit: $f < 6$ TeV **for light dilaton**

Kozlov, Gorbunov, Int. J. Mod. Phys. (2011)

Dark photon(s)? $\sigma \to \gamma_U^* \gamma$

- $L = L_\sigma + L_{O_U}$ small explicit breaking of conformal symmetry
- $$L_\sigma = -B\partial_\mu A^\mu + \frac{1}{2\xi}B^2 - \frac{1}{\Lambda_U^{d-3}}\left(A_\mu - \partial_\mu \sigma\right)O_U^\mu +$$ $$+\bar{\psi}\left(i\hat{\partial} - m + g\hat{A}\right)\psi - \frac{\sigma}{f}\sum_\psi \left(m + \varepsilon\, y_\psi v\right)\bar{\psi}\psi$$
- $$L_{O_U} = \frac{1}{\Lambda_U^{d-1}}\left[\sum_\psi \bar{\psi}\left(c_v\gamma^\mu - a_v\gamma^\mu\gamma_5\right)\psi\, O_{U\mu} + \frac{1}{\Lambda_U^2}W_{\mu\alpha}^a W_\beta^{a\mu}\left(\partial^\alpha O_U^\beta + \partial^\beta O_U^\alpha\right)\right]$$

- Scale symmetry is violated by ψ-operators. Yukawa shift appears.
- $\varepsilon = m_\sigma^2 / f^2 < 1$ controls the deviation from exact scale symmetry.

Dilaton mass m_σ is the measure of the symmetry breaking size.

$$\lim_{m_\sigma \to 0} \left[\Delta + m_\sigma^2\right]^2 \sigma(x) \approx 0$$ **Dipole field** G Kozlov (2012)

Dilaton propagator (l^{-1} distinguishes the model from EW theory)

$$\tilde{W}(p) = \frac{-1}{4\xi} i \frac{\partial^2}{\partial p^2} \left[\frac{\ln e^{2\gamma}\left(-p^2 l^2 - i\varepsilon\right)}{-p^2 - i\varepsilon} \right]$$

D Zwanziger (1978)

G Kozlov (2010)

Lowest order energy of the dilaton "charge"/F.T. of "static" $\tilde{W}(p)$

$$E(r) = i \int d_3 p \, e^{i\vec{p}\vec{x}} \tilde{W}\left(p^0 = 0, \vec{p}\right) \sim \frac{M^2}{8\pi\xi} r \left[const + 3\ln(r/l)\right]$$

- **Energy of the dilaton is linearly rising with distance** $r = |\vec{x}|$

The result is stable both at short & large r **/any finite order of P.T.**

Confinement ?! **Mediator field in a heavy quark sector!**

Dilaton as a force carrier

$$V(r) \to g_{dil} \frac{e^{-\varepsilon f \cdot r}}{r}, \quad 4\pi v < Q < \Lambda < \Lambda_{UV} = 4\pi f, \quad g_{dil} \propto \left(\frac{m_q}{f}\right)^2$$

Important $\varepsilon \to 0 \; as \; \Lambda \to \Lambda_{UV} = 4\pi f$

For short-range interaction between quark and antiquark

$r < (\varepsilon f)^{-1}, \quad f \sim O(1\ \mathrm{TeV})$ compared to OGE

G. Kozlov et al. J. Phys. G. (2004)

$$SU(3): \quad m_q > \frac{f}{\eta_{\sigma q}} \left(\frac{16}{3}\pi \alpha_s\right)^{1/2}, \eta_{\sigma q} = 1(SM) + \delta, \quad \delta < 1$$

Lower bound for m_q can exceed m_{top}, even if $f \cong v$. ***4^{th} q's?***

A new force if discovered, the first ever seen not related to a gauge symmetry

Hidden sector / $\gamma\gamma$ Decays / Oscillations.

- SM γ may oscillate into DP γ^* and then $\gamma^* \to \bar{\nu}\nu$ invisible

$$SM \Rightarrow SM \times U_B^{'}(1) = SU_L(2) \times U_Y(1) \times U_B^{'}(1)$$

DM, DP, pseudophoton

$$S \to \gamma\ \gamma \Rightarrow S \to \gamma\ \underset{dark}{\gamma^*} \to \gamma\ \bar{\nu}_e \nu_e,$$ $S : H$, dilaton σ (contin. mass spectrum!)

- DP γ^* mixes with γ: kinetic term $\sim \varepsilon F_{\mu\nu} B^{\mu\nu}$, $\varepsilon = 10^{-12} - 10^{-2}$?

$$BR(H \to \gamma\gamma) \sim \left(1 + a\ \varepsilon^2\ \Omega\right) BR^{SM}(H \to \gamma\gamma),$$

$$\Omega = \left(1 - \frac{m_{\gamma^*}^2}{m_H^2}\right)^b, \quad b > 0 \quad \swarrow$$

if enhanced rate does exist

DM sector on observable(s) & Restrictions

Mixing strength ε is restricted by $\varepsilon < \frac{s^d}{\left(v^2 M^{d-2}\right)^2}$

NP signals with DM increase with $\sqrt{s},\ d$

Below $Q \sim v$ DM becomes the standard particle stuff

Assume $\varepsilon \sim O(3\%)$, DM visible @ LHC for $M < 10^3$ TeV, d=4

For $H \to \gamma\gamma^*$: $L \sim O_{SM} O_{IR} \sim \varepsilon \bar{\psi}\,\gamma_\mu \psi\; H\;\; B^\mu M^{-1}$

Relevant energy scale $Q \sim m_q,\ \ q: top, \ldots$

Result: $\varepsilon < 10^{-5},\ \ q: top,\ \ \ d = 4$

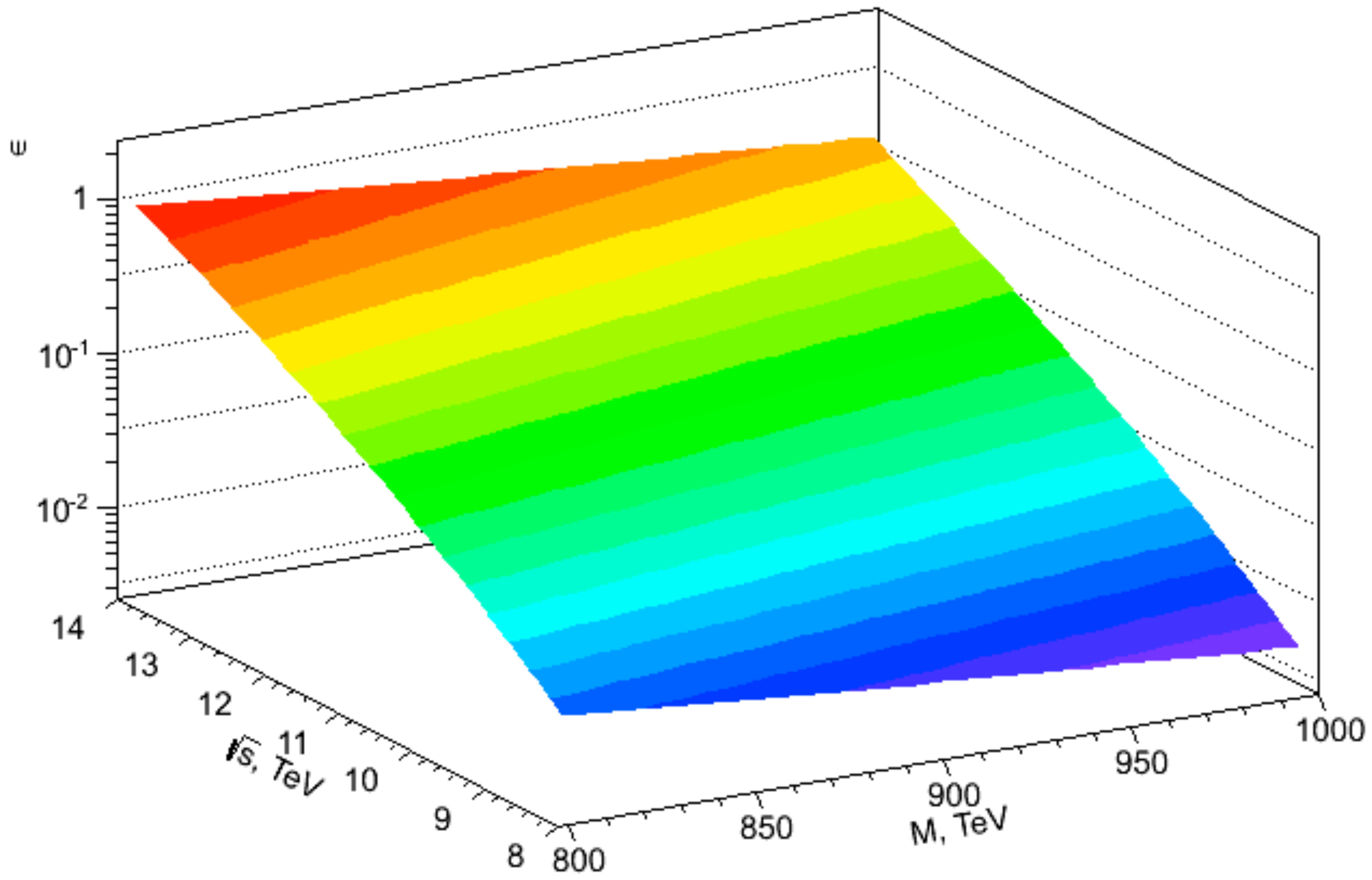
$\varepsilon < 6 \cdot 10^{-2},\ \ q: top, 4q \sim O(0.5\ TeV)\ \ \ d = 4$

LHC is a very good facility where the DM Physics can be tested well

Upper limit on $\varepsilon < \dfrac{s^d}{\left(v^2 M^{d-2}\right)^2}$,

$\sqrt{s} = 8 - 14\ TeV,\ \ M = 800 - 1000\ TeV,\ \ d = 4$

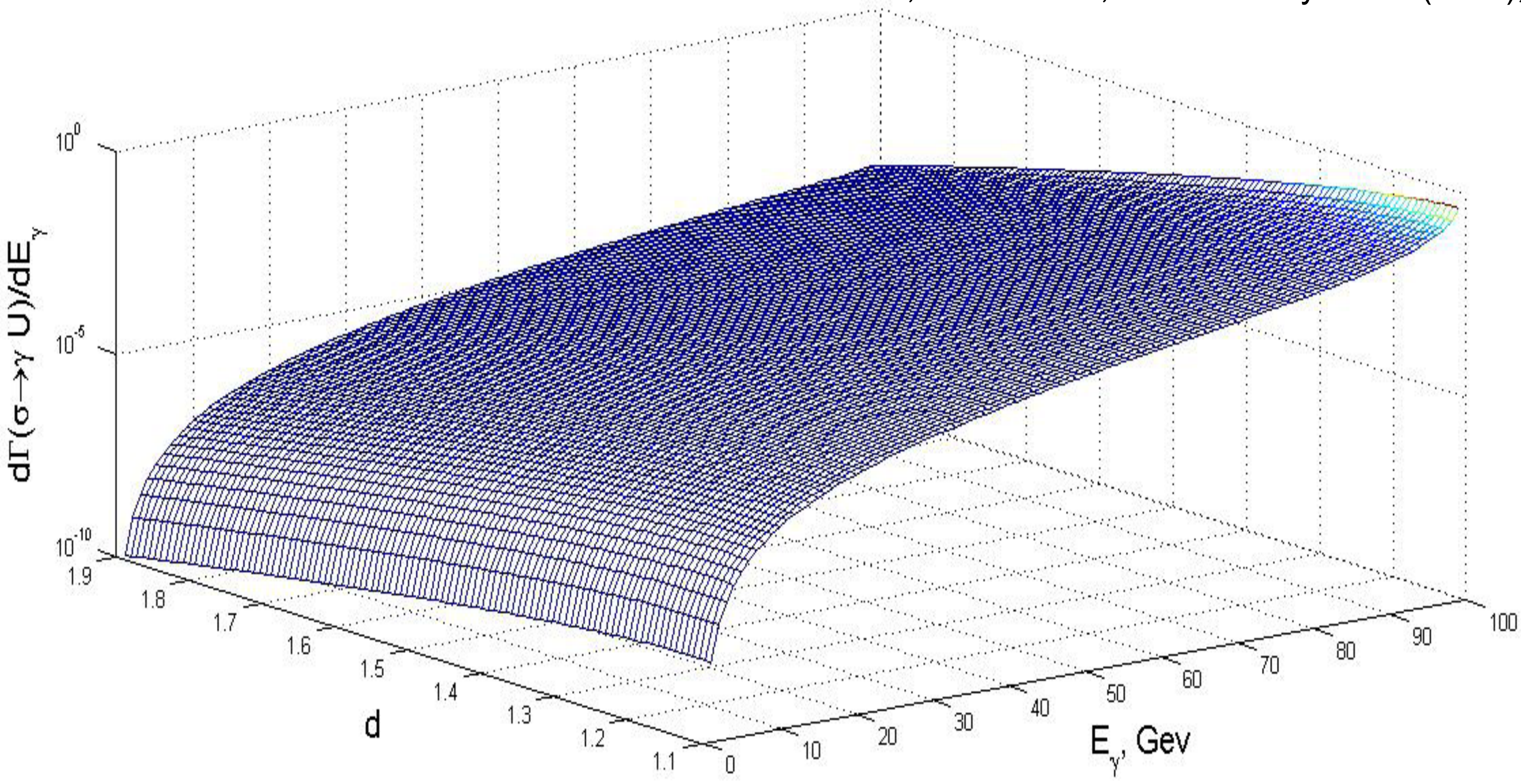
G. Kozlov (2014)



Energy spectrum of a real emitted photon in $\sigma \to \gamma\ \gamma_U^*$

Energy of a photon: $E_\gamma = \left(m_\sigma^2 - P_{\gamma_U^*}^2\right) / \left(2m_\sigma\right):\quad \left[0,\ m_\sigma / 2\right]$

G. Kozlov, I. Gorbunov, I.J. Mod. Phys. A26 (2011), 3987



Conclusions

- **A scalar dilaton could also be the subject of bright results at HE colliders, in particular for extended SM and DM search.**

- **One of the main prospects for distinguishing the dilaton from the minimal Higgs-boson at the LHC:**
  An enhancement of couplings to massless SM gauge bosons, $\sim \mathcal{O}(100)$ **of the gluon fusion production cross-section compared to that of the SM Higgs.** **Overcome the suppression factor** $\sim (v/f)^2$

- **A light, narrow resonance if observed, is distinguishing feature of a nearly conformal dynamics.**

- **The** $\gamma\gamma$ **final state is very instructive to search for "conformal Higgs", a dilaton, because of the dimension of operators dependence. The approach leads to differentiation of dilaton from Higgs at the ILC.**