Dilaton vs Higgs: Nearly Conformal Physics @ the LHC

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Triumph

ATLAS (P.L.B716 (2012) 1) CMS (P.L.B716 (2012) 30)

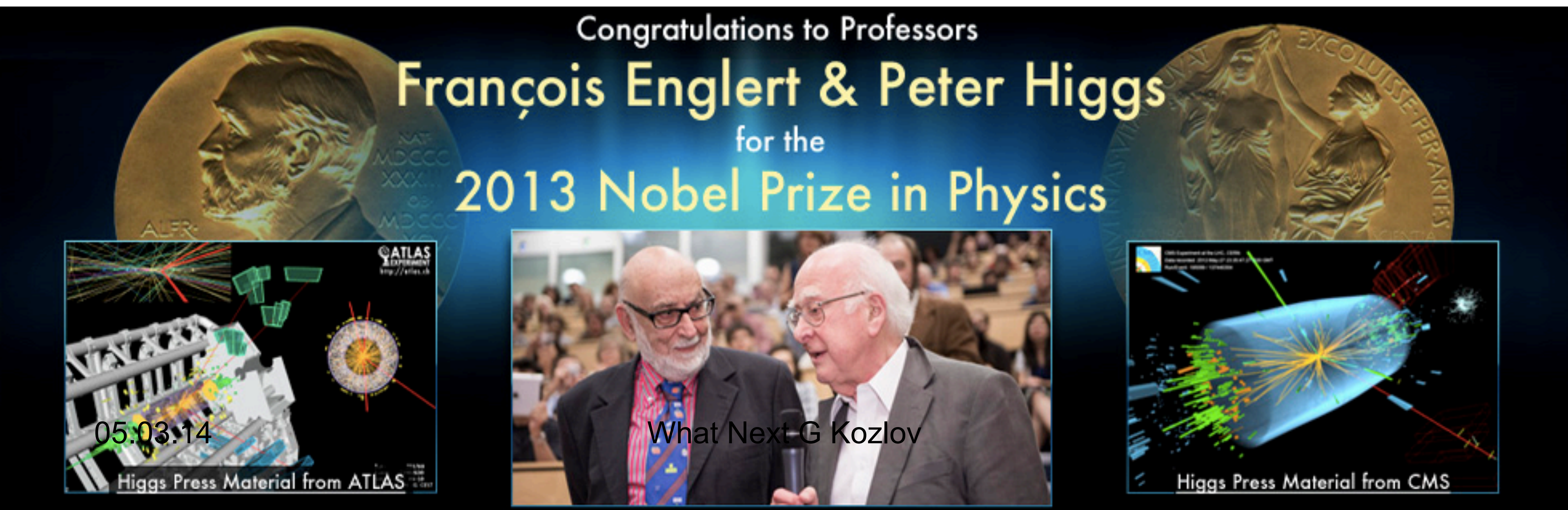
have observed a new boson with a mass around 125-126 GeV

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Belgium

Peter W. Higgs
University of Edinburgh, UK

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"



However, the only 1 GeV (!) differences may destroy the Universe

- A 125-126 GeV Higgs is quite heavy for minimal SUSY !

Some theorists favorite SUSY frameworks “live or die” on whether the mass is 125 or 126 GeV

The SM vacuum must be stable!

- Important: a 125-126 GeV Higgs in the SM means one is close to the vacuum stability bound (NNLO):

expect even the meta-stability of the vacuum

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

- Could we see something else – not in terms of Higgs?

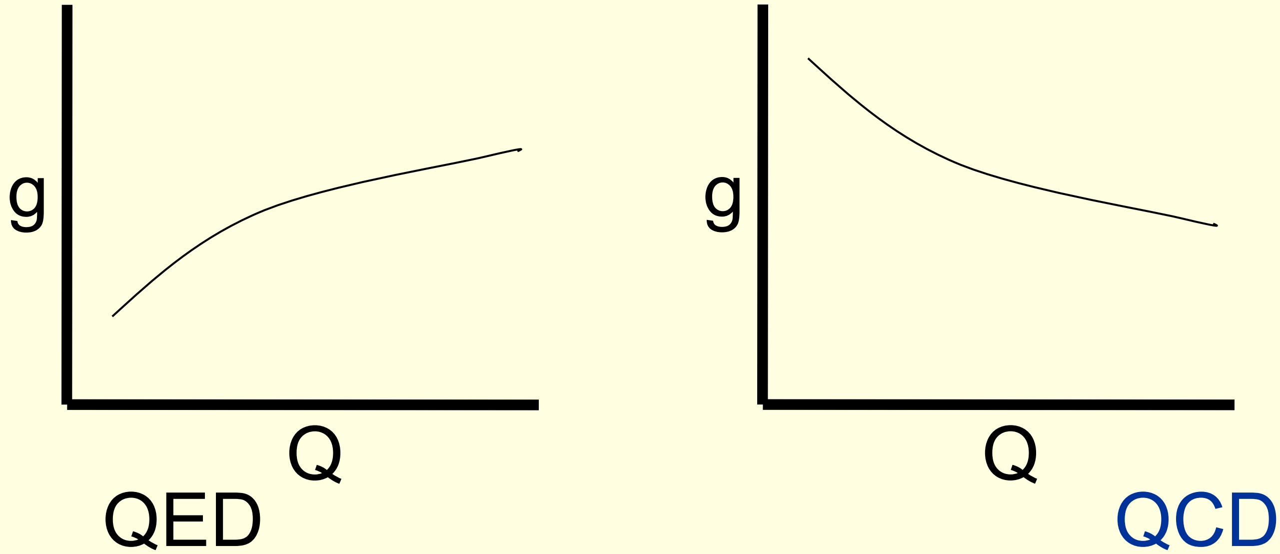
In the absence of an explicit sector that breaks gauge invariance, the interactions of SM gauge bosons with fermions are approximately conformal down to QCD scale.

- Should one expect new scalar particle(s) ? Great!
- **Scale invariant hidden world?**

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

No CONFORMAL INVARIANCE

- At the quantum level, dimensionless couplings depend on scale: renormalization group evolution



are not conformal theories

Couplings of hidden & SM sectors.

Hidden sector: conservation or not the dilatation current

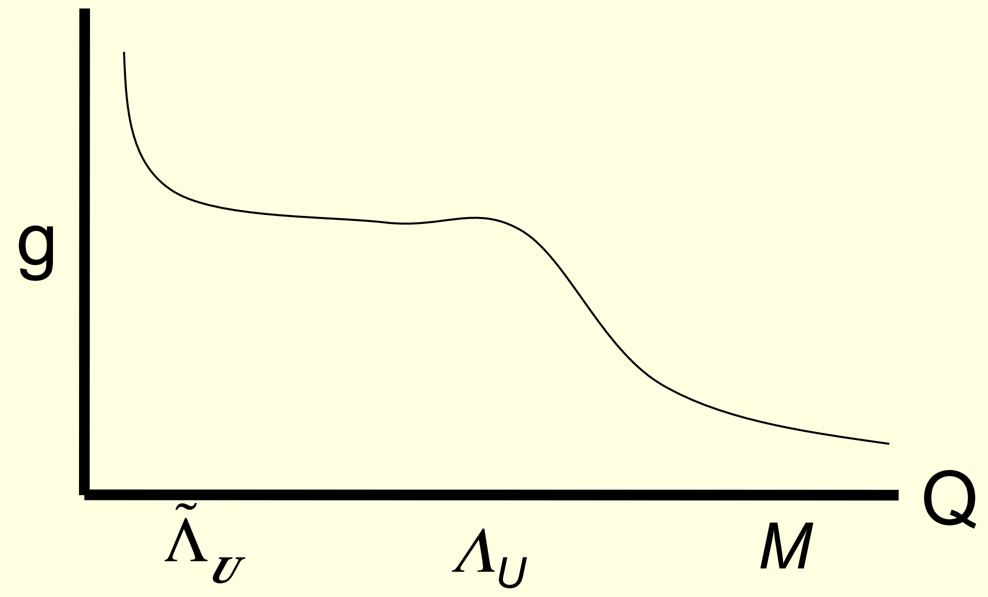
3 characteristic scales: $M, \Lambda_U, \tilde{\Lambda}_U$

-Hidden sector couples at M

- Conformal $\tilde{\Lambda}_U < \Lambda_U < M$

- EWSB $\rightarrow$ CSB at $Q < \tilde{\Lambda}_U$

Conformal anomaly appears



- The hidden scalar particles (dilatons as well the unparticle) physics is only possible in the conformal valley
- Width of this valley depends on $d, \tilde{\Lambda}_U, \Lambda_U, M$

Dilaton origin

At classical scale invariant scheme at very high energies

Dilaton appearance: Gravity action

$$S = \int d^4x \sqrt{-\tilde{g}}\ \frac{1}{2}\left[\kappa r^2 + \left(\partial_\mu \bar{\sigma}\right)^2 - \eta \bar{\sigma}^2 r\right];\ \ \kappa,\ \eta > 0$$

Once the Conformal symmetry breaking $\rightarrow \langle \bar{\sigma} \rangle = f$

at $\Downarrow$

$$\Lambda_{CFT} = 4\pi f$$

$\Downarrow$ triggers EWSB at $\Lambda_{EW} = 4\pi v$

f and v different except for Higgs

Dilaton origin:

- Beyond the SM

Full theory $\sqsubseteq$ some sector (scale invariant) with SB(Scale) invar's,

Dilaton arises as PsGoldstone boson Bardeen (1986), Csaki (2007)

Dilaton mass:

Due to explicit Breaking Scale invar's in scale inv. sector at $\sqrt{q^2} < f$

Dilaton couplings:

- with $T_\mu^\mu(x)$ (all the fields) in scale-invariant sector
- pick up add. coupl's at loop level from scale anomaly

Simplest example of effective Dilaton :

Higgs-boson of the SM, $m_H < v = 246$ GeV, $v = f$!

Dilaton: couplings to SM particles

- Because of the pseudo-Goldstone nature, dilaton is the messenger between the SM fields & the hidden sector (DM, …)
- Dilaton is the dominant origin in the unparticle stuff production via SM fields

In the exact scale symmetry, e.g., for SM

$$L_{Trace} = \frac{\sigma}{f}\left[T_{\mu}^{\mu}\left(SM\right)^{tree} + T_{\mu}^{\mu}\left(SM\right)^{anom}\right]$$

$$T_{\mu}^{\mu}\left(SM\right)^{tree} = \sum_{q} m_q \bar{q}q - 2m_W^2 W_{\mu}^{+} W^{-\mu} - m_Z^2 Z_{\mu} Z^{\mu} + 2m_h^2 h^2 - \partial_{\mu} h \partial^{\mu} h$$

$$T_{\mu}^{\mu}\left(SM\right)^{anom} = -\frac{\alpha_s}{8\pi} b_{QCD} \sum_{a} F_{\mu\nu}^{a} F^{a\mu\nu} - \frac{\alpha}{8\pi} b_{EM} F_{\mu\nu} F^{\mu\nu}$$

Higgs: $L_{hgg} = \frac{\alpha_s}{8\pi} \sum_i b_0^i \frac{h}{v} \left(G_{\mu\nu}^a \right)^2, \quad m_q > m_h, \quad b_0(top) = 2/3$

Heavy quarks contributions: $\beta_i(g) = b_0^i g^3 / 16\pi^2$

QCD $\subset$ conformal sector. UV insensitive predictions.

$$\sum_{light} b_0 + \sum_{heavy} b_0 = 0$$

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

Non-perturbative generalization

$$L_{\sigma gg} = -\frac{\beta(g)}{2g} \frac{\sigma}{f} \left(G_{\mu\nu}^a \right)^2 \qquad \begin{array}{l} n_{light} = 5, m_\sigma < m_{top} \\ n_{light} = 6, m_\sigma > m_{top} \end{array}$$

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

$$\sigma^{LHC,Tevatron}(s)BR(s\to\gamma\gamma)/\sigma BR(SM)\approx 1.7\pm 0.4,$$

Origin?

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

Turn to Hidden sector?

We suppose the DILATON as a possible candidate for s-particle observed

Why? - provides the most natural way to interpret the data
-serves as a portal to HIDDEN sector
-guarantees ReN of the theory

The key is the trace of EMT $T^{\mu}_{\mu}=T^{\mu}_{\mu}(SM)^{tree}+T^{\mu}_{\mu}(SM)^{anom}\neq 0$

Collider phenomenology:

- **Effective theory @ energy** $\Lambda_{CFT} \sim 4\pi f$
- **Below** Λ_{CFT} **scale symmetry spontaneously broken**
- **SB scale symmetry triggers EWSB at** $\Lambda_{EW} \sim 4\pi v \leq \Lambda_{CFT}$

Collider phenomenology crucial point:

- **Loop-induced couplings to** $\gamma\,\gamma$ **or** $g\,g$

$$\frac{\sigma}{8\pi f}\left[c_{EM} F_{\mu\nu} F^{\mu\nu} + c_s G^a_{\mu\nu} G^{a,\mu\nu}\right], \quad \begin{array}{l} c_{EM} = -\alpha \cdot 17/9,\ m_W < m_\sigma < m_t \\ c_{EM} = -\alpha \cdot 11/3,\ m_\sigma > m_t \end{array}$$

$$c_s = \alpha_s \left(1 - 2 n_{light}/3\right)$$

CFT/SM loop: tenfold increase of coupling strength!

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

- **Production of the dilaton. Upper limit of f**

- $gg \to \sigma$ - dominant production

Dilaton signal significance: Significance of Higgs signal by rescaling

$$\left(\frac{S}{\sqrt{B}}\right)_\sigma = \frac{c_s^2}{\alpha_s^2}\frac{v^2}{f^2}\left(\frac{S}{\sqrt{B}}\right)_{Higgs}$$

Goldberger, Grinstein, Skiba P.R.L. (2008)

Lower bound: $\left(\frac{c_s^2}{\alpha_s^2}\right)\left(\frac{v^2}{f^2}\right) > \frac{1}{8}$ @ $100\, fb^{-1}$ **for** $m_\sigma > 160\, GeV$

Estimated upper limit: $\begin{cases} f < 5.33\ TeV,\ m_\sigma < m_t \\ f < 4.87\ TeV,\ m_\sigma > m_t \end{cases}$

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

How to search the dilaton? In decays? E.g., $\sigma \to \gamma^*_U \gamma$

- $L = L_\sigma + L_{O_U}$ in the nearly conformal sector

$$L_\sigma = -B\partial_\mu A^\mu + \frac{1}{2\xi}B^2 - \frac{1}{\Lambda_U^{d-3}}\left(A_\mu - \partial_\mu \sigma\right)O_U^\mu +$$

- $$+\bar{\psi}\left(i\hat{\partial} - m + g\hat{A}\right)\psi - \frac{\sigma}{f}\sum_\psi \left(m + \varepsilon\, y_\psi v\right)\bar{\psi}\psi$$

- $$L_{O_U} = \frac{1}{\Lambda_U^{d-1}}\left[\sum_\psi \bar{\psi}\left(c_v \gamma^\mu - a_v \gamma^\mu \gamma_5\right)\psi\, O_{U\mu} + \frac{1}{\Lambda_U^2} W^a_{\mu\alpha} W^{a\mu}_\beta \left(\partial^\alpha O_U^\beta + \partial^\beta O_U^\alpha\right)\right]$$

- Scale symmetry is violated by ψ-operators
- Size of scale symmetry deviation $\varepsilon = m_\sigma^2 / f^2 < 1$ (or even <<1)

Dilaton mass m_σ is the measure for the symmetry breaking size

Basic Equations of Motion

- $\partial_\mu \sigma \approx A_\mu - \frac{1}{\Lambda_U^2}\bar{\psi}\left(c_v \gamma_\mu - a_v \gamma_\mu \gamma_5\right)\psi$
- $\partial_\mu A^\mu = \xi^{-1} B$
- $\partial_\mu B = -J_\mu + \frac{1}{\Lambda_U^{d-3}} O_{U\mu}, \quad J_\mu = g\bar{\psi}\gamma_\mu \psi$
- $\frac{1}{\Lambda_U^{d-3}}\partial_\mu O_U^\mu + \frac{1}{f}\left(m + \varepsilon\, y_\psi v\right)\bar{\psi}\psi = 0$

✓ **In the nearly Conformal Sector:**

$$\lim_{m_\sigma \to 0}\left[\Delta + m_\sigma^2\right]^2 \sigma(x) \approx 0, \quad \Delta \equiv \partial^2 / \partial x_\mu^2$$ **Dipole-type field! Flat!**

Supported by: weakly changing operator $O_U^\mu(x)$ in x_μ

current conservation

More theory…

$$\lim_{m_\sigma \to 0}\left[\Delta + m_\sigma^2\right]^2 \sigma(x) \approx 0, \quad \Delta \equiv \partial^2 / \partial x_\mu^2$$ **Dipole-type field**

CCR's for all x_μ and y_μ:

$$\left[\sigma(x), \sigma(y)\right] = -i\xi^{-1} F(x-y)$$

$$F(x) = (8\pi)^{-1}\theta\left(x^2\right)\mathbf{sgn}\left(x^0\right)$$

Propagator of the dilaton field in nearly conformal sector:

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

D. Zwanziger, Phys.Rev.D (1978)

G. Kozlov, Phys. Part. Nucl. (2010)

l^{-1} is the renorm. mass/ distinguishes the model from the SM EW

More theory…

G Kozlov, PoS (Confinement X) 086

Lowest order energy of the dilaton "charge"

$$E(r) = i\int d_3p\, e^{i\vec{p}\vec{x}}\tilde{W}\left(p^0 = 0, \vec{p}\right) \sim \frac{M^2}{8\pi\xi} r\left[const + 3\ln\left(r/l\right)\right]$$

RESULT: In Nearly Conformal sector:

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

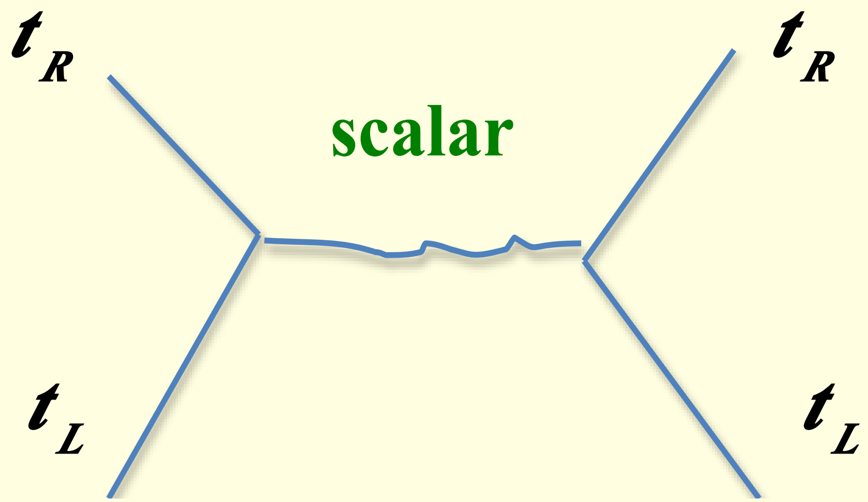
Confinement ?!

Mediator field in a (super) heavy quark sector!

Higgs/Dilaton = Force carrier

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

- Its mediator looks a lot like the SM scalar



The dominant effective potential

Mediators: heavy quarks bound states

- **Light dilaton (nearly conformal sector), small distances**

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

$m_{dil} = \varepsilon f$ **Conformal symmetry breaking parameter**

$f \geq v \quad \Downarrow \quad$ ***CSB*** **triggers EWSB**

- **Light Higgs (EW sector) effective potential, larger distances**

$$V(r) \to g_{Higgs} \frac{e^{-m_{Higgs} \cdot r}}{r}, f = v, \quad \mathbf{Q} < \tilde{\Lambda} \approx 4\pi v, \quad \mathbf{g}_{Higgs} \propto \left(\frac{m_q}{v}\right)^2$$

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

Heavy quark masses restriction

For short-range interaction between quark and antiquark:

$$m_q > \frac{f}{\eta_{\sigma q}}\left(4\pi C_F \alpha_s\right)^{1/2}, \eta_{\sigma q} = 1\left(SM\right) + \delta, \quad \delta < 1$$

Lower bound for m_q can exceed m_{top}, even if $f \cong v$

Fourth generation quarks ?

From Theory through Phenomenology… to exp't?

Amplitude for the transition $\sigma \to \gamma_U^* \gamma$

$$Am\left(x_q, y_q\right) = \frac{3\,\alpha\,v}{\pi\, m_W s_W \Lambda_U^{d-1} f} \sum_q c_v e_q \left[I\left(x_q, y_q\right) - J\left(x_q, y_q\right) \right]$$

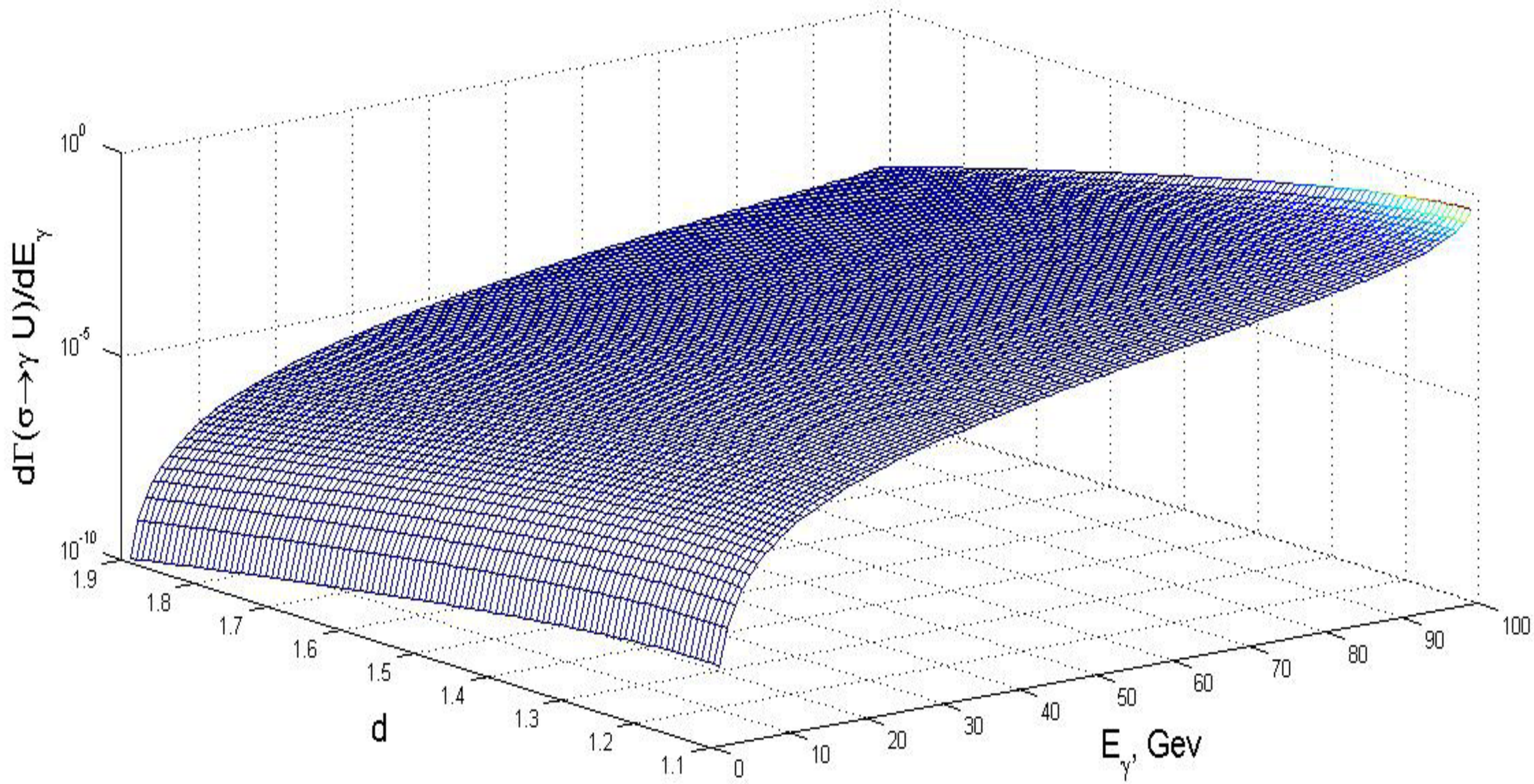
- **No W - boson contribution in the loop.**

Why? $L_{O_U} \sim \frac{1}{\Lambda_U^{d+1}} W_{\mu\alpha}^a W_\beta^{a\mu} \left(\partial^\alpha O_U^\beta + \partial^\beta O_U^\alpha \right)$ **suppression by** $\frac{1}{\Lambda_U^{d+1}}$ **factor**

$$\Lambda_U \sim O(f),\ f \sim O(TeV),\ d_U \geq 1$$

- **The quarks contribution only**

$$x_q = 4m_q^2 / m_\sigma^2, \quad y_q = 4m_q^2 / P_U^2$$


10^0
10^{-5}
10^{-10}
$d\Gamma(\sigma \to \gamma\ U)/dE_\gamma$
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
d
0
10
20
30
40
50
60
70
80
90
100
E_γ, Gev

Hidden sector: Dark Photons in Higgs decays

$$H \to \gamma\ \gamma \Rightarrow H \to \gamma\ \gamma^* \to \gamma\ \bar{\nu}_e \nu_e$$

$$\qquad\qquad\qquad dark$$

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

DM, DP, pseudophoton

Ex., GUT, ExtraD, Superstrings, Little Higgs, …

- SM γ may oscillate into DP γ^* and then $\gamma^* \to \bar{\nu}\nu$ invisible
- DP γ^* mixes with γ: $\sim \varepsilon F_{\mu\nu} B^{\mu\nu}, \quad \varepsilon = ?$

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

$$\left(1 - \frac{\boldsymbol{m}_{\gamma^*}^2}{\boldsymbol{m}_H^2}\right)^{\boldsymbol{b}}, \ \boldsymbol{b} > 0$$

Couplings & Constraints

To collider physics @ O(10 TeV): UV flows to IR

UV <-> SM interaction/via UV messenger (heavy)

$$L_{\text{int}} \sim \left(\frac{1}{M^{d-4}} O_{SM}\right)\left(\frac{1}{M^{d_{UV}}} O_{UV}\right)$$

No masses allowed

All mass scales generated dynamically in IR

The hidden sector is formed when dilaton $\tilde{\sigma}$ coupled to $U(1)$ gauge theory $L \sim \frac{1}{M^{d_{UV}-2}} |\tilde{\sigma}|^2 O_{UV}$

DM operator

scaling symmetry broken $L \sim const \frac{\Lambda^{d_{UV}-d_{IR}}}{M^{d_{UV}-2}} |H|^2 O_{IR}$

Energy Constraints

Once $H(x)$ acquires v, theory becomes non-conformal

at $Q < \tilde{\Lambda}$, where $\tilde{\Lambda}^{4-d_{IR}} = \frac{\Lambda^{d_{UV}-d_{IR}}}{M^{d_{UV}-2}} v^2$

Below $\tilde{\Lambda}$, DM becomes the standard particle stuff

Collider Physics: $\tilde{\Lambda} < \sqrt{s} < \Lambda$

Energy constraints for NP

$$s^{2-d_{IR}/2} > \left(\frac{\Lambda}{M}\right)^{d_{UV}-d_{IR}} M^{2-d_{IR}} v^2$$

New observable (mixing strength ε in kinetic term $\sim \varepsilon F_{\mu\nu} B^{\mu\nu}$)

$$L_{\text{int}} \sim \frac{1}{M^{d-4}} O_{SM} \frac{1}{M^{d_{UV}}} O_{UV} \Rightarrow \quad \varepsilon = \left(\frac{\sqrt{s}}{M}\right)^{2(d-4)} \left(\frac{\sqrt{s}}{\Lambda}\right)^{2d_{IR}} \left(\frac{\Lambda}{M}\right)^{2d_{UV}}$$

Effect of DM sector on observable(s)

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

Important: no dependence on $d_{UV},\ d_{IR},\ \Lambda$

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

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

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

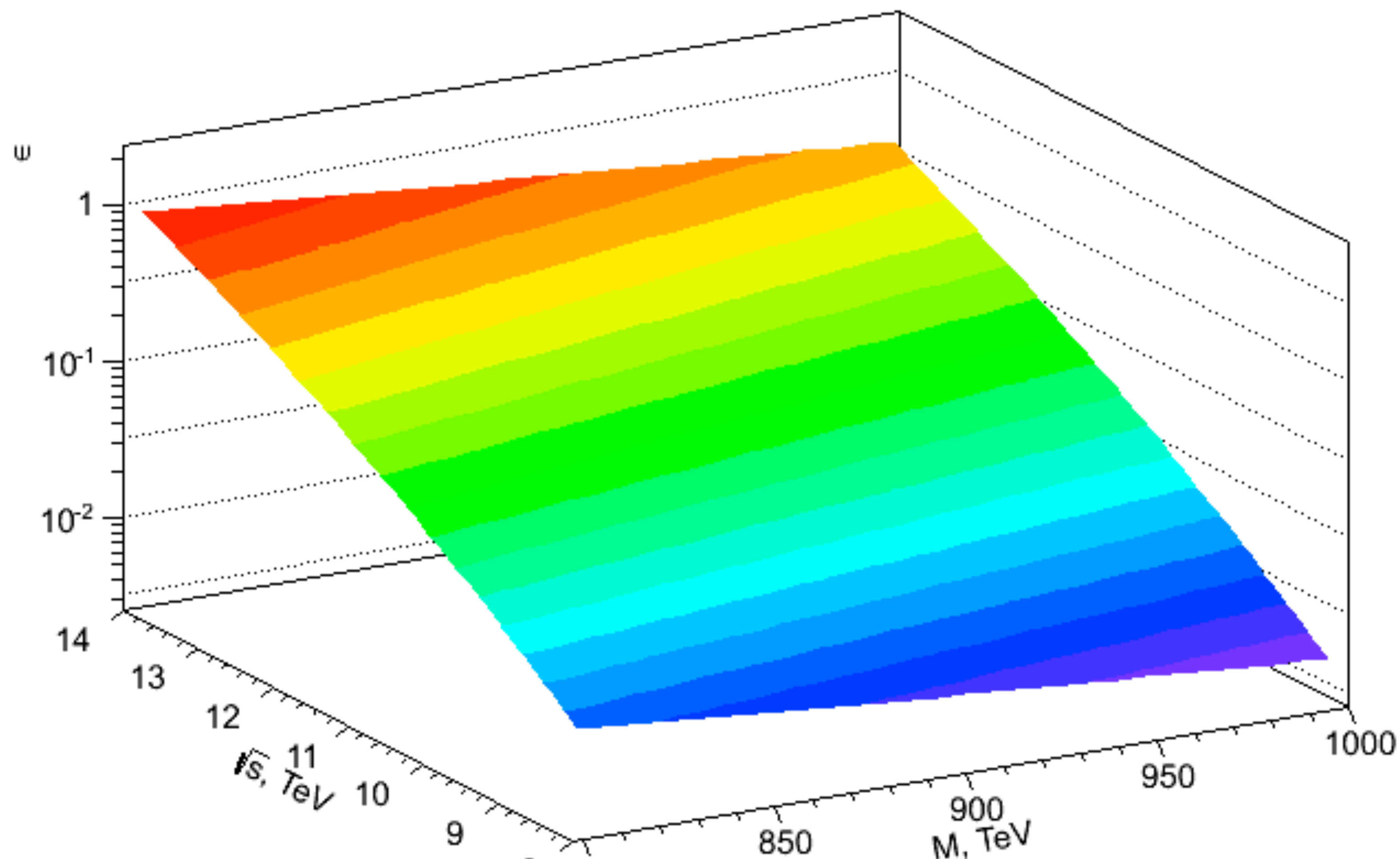
Relevant energy scale $Q \sim m_q,\ \ q : top, \ldots$

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 $\varepsilon < \dfrac{s^d}{\left(v^2 M^{d-2}\right)^2}$, $\sqrt{s} = 8-14\ TeV,\ \ M = 800-1000\ TeV,\ \ d = 4$



Conclusions

- **Dilaton could also be the candidate to explain the LHC results.**

- **Heavy quark sector: mediator field.**

- **The enhancement about $\sim O(100)$ of the gluon fusion production cross-section compared to that of the SM Higgs.**

  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.

- **An instructive & useful to probe (test) the nearly conformal sector containing the dilaton and the unparticle stuff @ the LHC.**