中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

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Theoretical indications on a new scalar boson near 0.5 TeV

Sergei Afonin

Based on: S.S. Afonin, Phys. Lett. B840 (2023) 137882 [arXive: 2211.07500];
S.S. Afonin, arXive: 2306.16972

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Saint Petersburg State University

Petersburg Nuclear Physics Institute

The Higgs potential looks like a phenomenological construction

BSM - ?

<u>Our assumptions</u>:

- The Higgs potential arises from a strong BSM sector

- This sector lies in the same universality class as non-perturbative QCD

- One singlet extra-Higgs is enough to solve several fundamental problems of the SM.

  Its mass - ?

The main obstacle: the <u>strong coupling</u> problem arises

⇨ Non-perturbative approaches are needed!

A possible direction for model building - the <u>holographic approach</u>

AdS/CFT correspondence
(= gauge/gravity duality = holographic duality)

Qualitatively:

Strong coupling problems in non-abelian QFT	⟺	Classical Problem in a curved higher-dimensional space
g^2, N_c		$g_s, \alpha' = l_s^2$ String coupling and string tension
$\lambda \equiv g^2 N$ T'Hooft coupling		

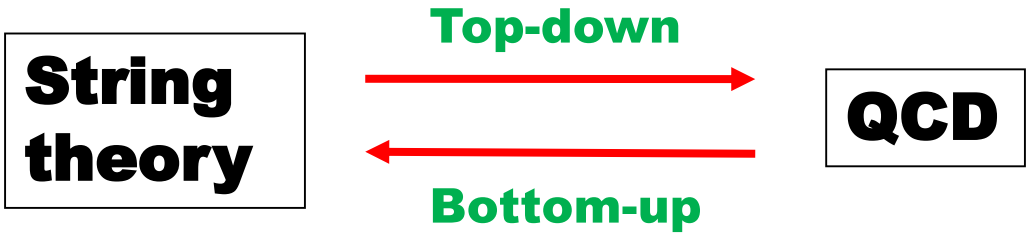
Source for major inspiration! (a great number of related models in the last 25 years)

(Maldacena, 1997 - *the most cited work in theoretical physics*!)

Although the holographic duality was not proven, it motivated construction of numerous phenomenological models for non-perturbative strong interactions which often had an unexpected predictability comparable with old traditional approaches

AdS/QCD approach
(“holographic QCD”)

A program for implementation of holographic duality for QCD following some recipies from the AdS/CFT correspondence



Some applications

- ❑ Meson, baryon and glueball spectra
- ❑ Low-energy strong interactions (chiral dynamics)
- ❑ Hadronic formfactors
- ❑ Thermodynamic effects (QCD phase diagram)
- ❑ Description of quark-gluon plasma
- ❑ Condensed matter (high temperature superconductivity *etc.*)
- ❑ ...

Confinement $\Rightarrow$ **linear Regge trajectories** $\boxed{m_n^2 \sim n}$

Realization of linear Regge trajectories in the bottom-up holographic approach to QCD?

Soft-wall holographic model

A. Karch, E. Katz, D. T. Son, M. A. Stephanov, PRD 74, 015005 (2006)

$$S = \int d^4x\, dz \sqrt{g}\, \underline{e^{-cz^2}}\, \mathcal{L}$$

"Dilaton" background

$$g = |\mathrm{det} g_{MN}|$$

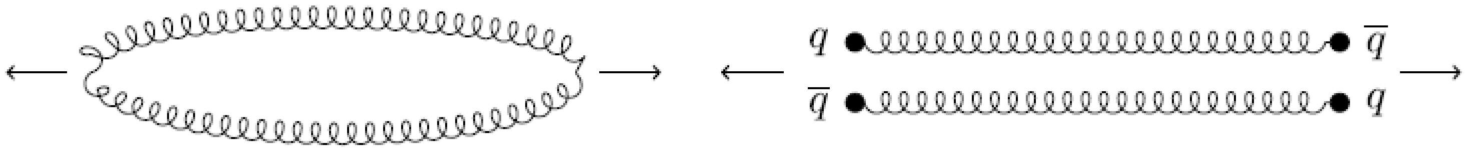
AdS$_5$: $ds^2 = \frac{R^2}{z^2}(dx_\mu dx^\mu - dz^2), \qquad z > 0$

AdS/CFT: operators of 4D theory <-> fields in 5D theory

In a sense, the background in holographic action provides a phenomenological model for non-perturbative gluon vacuum in QCD

Holographic string breaking

(S.S. Afonin and T.D. Solomko, Phys. Lett. B831 (2022) 137185)

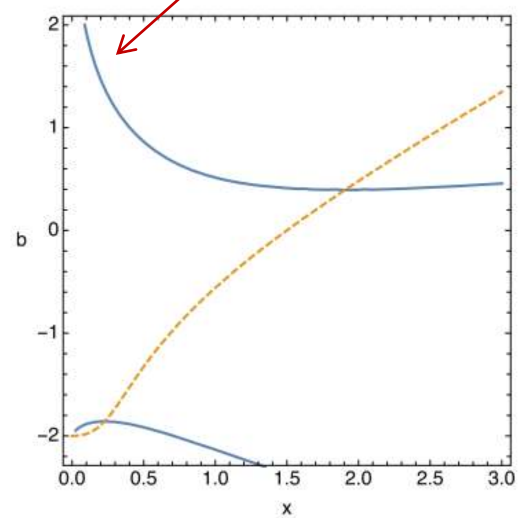


$$\boxed{\sigma_{\text{mes}} = \frac{1}{2}\sigma_{\text{gl}}}$$

due to quarks

$$M^2_{\text{mes}}(n) = \frac{1}{2}a(n + 2 + b_0) \quad \Longrightarrow \quad \sigma(b_0) = \frac{1}{2}\sigma(0)$$

selfconsistency



2 solutions:

$$b_1 \approx -1.859, \qquad b_2 \approx 0.394$$

$\Longrightarrow$ 2 ground states!

Proposal: **This model can be applied to a holographic description of hypothetical BSM strong sector**

Conjecture: Only the ground states (*n=0*) can really be seen and affect the BSM physics

Then in the scalar sector we have the following relation,

$$M_{h'}^2 = \frac{2+b_2}{2+b_1} M_h^2$$

Inserting the higgs mass

$$M_h = 125 \ \text{GeV}$$

we get the following estimate for the mass of "second higgs"

$$\boxed{M_{h'} \approx 515 \ \text{GeV}}$$

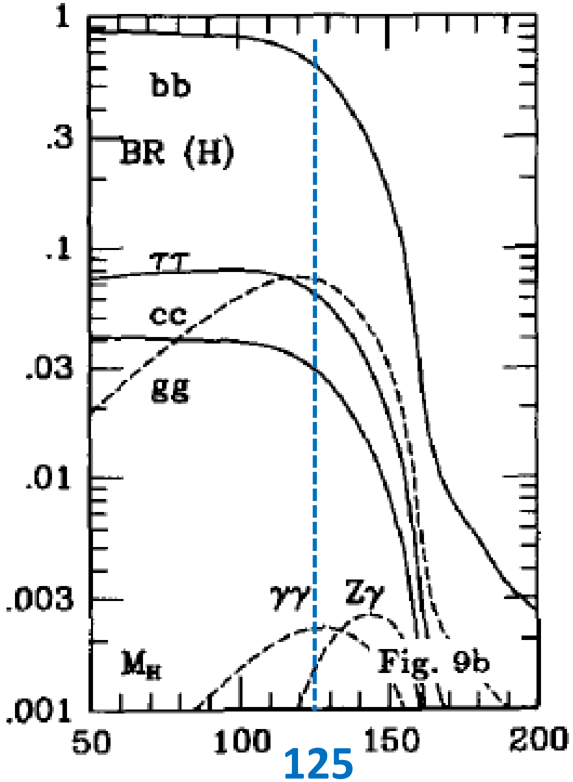
$\Rightarrow$ $\boxed{M_{h'} \approx 4M_h}$ (numerically)

Towards understanding masses of higgses...

Higgs boson production at the LHC

M. Spira[a], A. Djouadi[b,c], D. Graudenz[d], P.M. Zerwas[c] Nuclear Physics B 453 (1995) 17–82

Fig. 9a



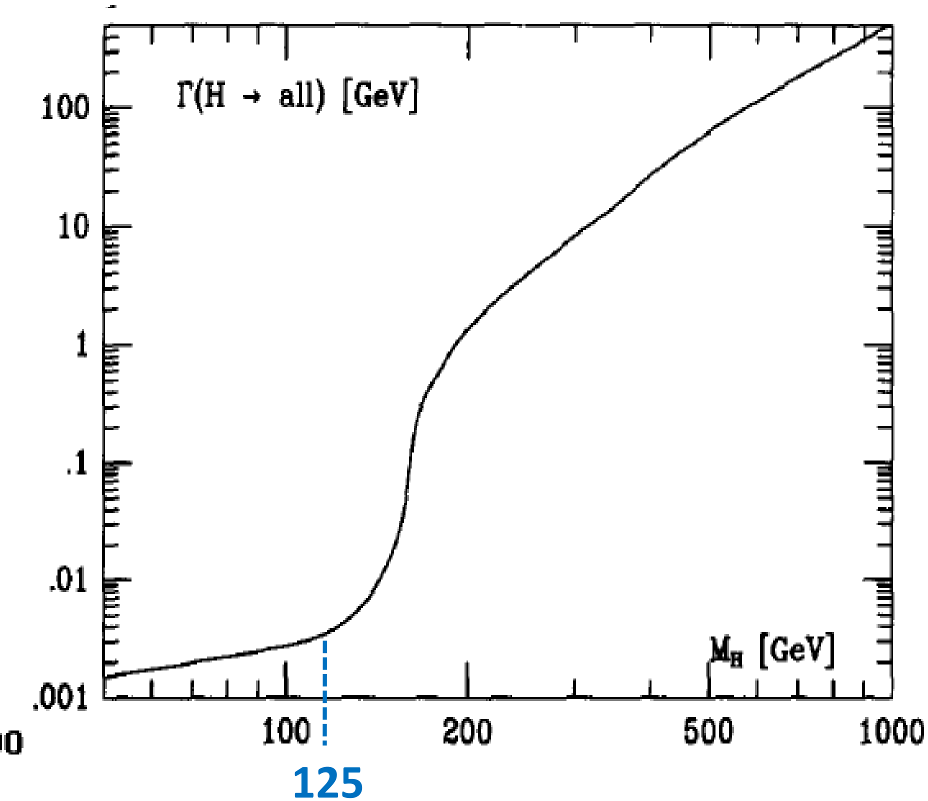


Fig. 9b

Fig. 9. (a) Total decay width (in GeV) of the Standard Model Higgs boson as a function of its mass, and (b) the branching ratios (in %) of the dominant decay modes (m_t = 174 GeV). All known QCD and leading electroweak radiative corrections are included.

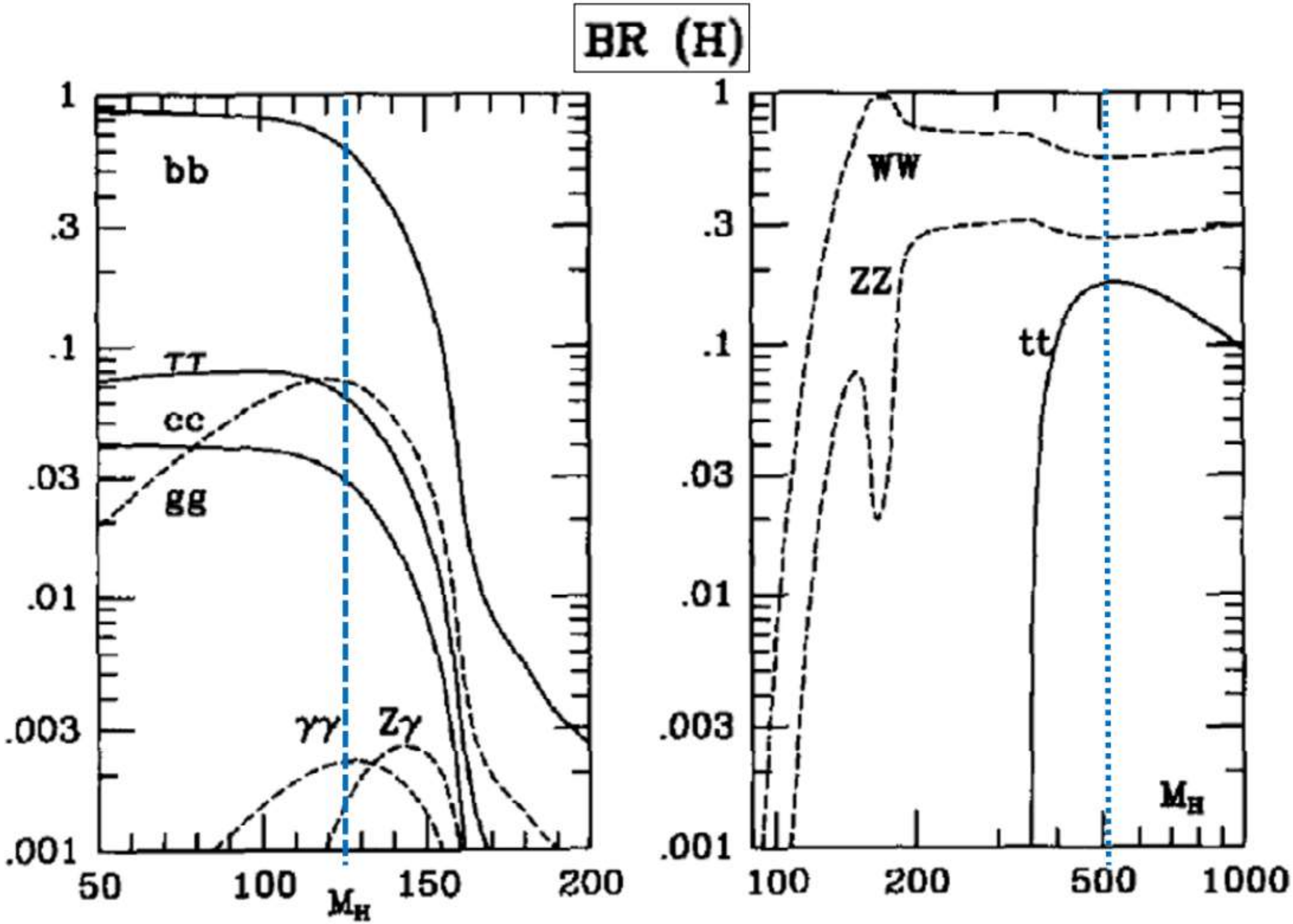
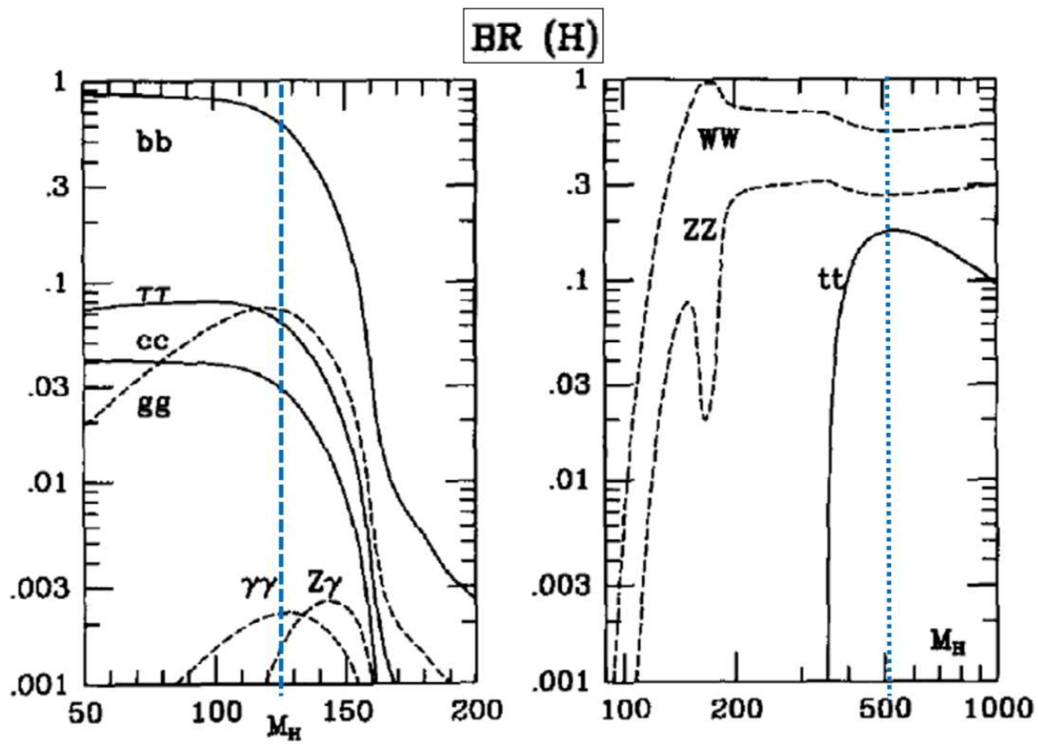


Fig. 2. The branching ratios of the dominant decay modes of SM Higgs boson as a function of its mass (in GeV). All known QCD and leading electroweak radiative corrections are included. The plot is taken from Ref.

M. Spira, A. Djouadi, D. Graudenz and P. M. Zerwas, *Higgs boson production at the LHC*, Nucl. Phys. B **453** (1995), 17-82, [hep-ph/9504378]

This observation might shed light on the physical reason for the existence of two composite Higgs bosons: One can construct two gauge and renormalization group invariant scalar operators in the standard gauge theories, $O_1 = \beta G^2_{\mu\nu}$, where β is the Gell-Mann–Low beta-function, and $O_2 = m_\psi \bar{\psi}\psi$. Both operators have the canonical dimension $\Delta = 4$. The two-point correlation functions $\Pi_1 = \langle O_1 O_1 \rangle$ and $\Pi_2 = \langle O_2 O_2 \rangle$ calculated in the background of BSM strong sector may have poles. Then M_h and $M_{h'}$ could arise form poles of different correlation functions, Π_1 and Π_2.



Does the predicted relation

$$\boxed{M_{h'} \approx 4M_h}$$

have a QCD analogue?

If the SM higgs represents a composite pseudogoldstone boson arising from a strongly-interacting BSM dynamics (as is often assumed) then the higgs is analogous to the pion in QCD

$$M_{\pi^0} = 135\,\mathrm{MeV}$$
$$M_\eta = 548\,\mathrm{MeV}$$
$$\Rightarrow \quad \boxed{M_\eta \approx 4M_\pi}$$

The matter looks as if the *t*-quark in *h'* played a role analogous to the *s*-quark in the eta-meson

Also $M_\eta \approx M_\sigma \quad \Rightarrow \quad \boxed{M_\sigma \approx 4M_\pi}$ (hh-resonance?)

$\sigma \doteq f_0(500)$ - the lightest scalar in PDG

⇨ Even if ***eta*** and ***sigma*** were mixed, this would not change the mass!

Spectral sum rules

$$\Pi(q^2) = i\int d^4x\, e^{iqx}\, \langle 0|\mathrm{T}\{j(x), j(0)\}|0\rangle \quad \Longleftrightarrow \quad \Pi(Q^2) = a_0 Q^2 \ln\frac{Q^2}{\mu^2} + \sum_{n=1}^{\infty} a_n \frac{C_n}{Q^{2n}}$$

Ansatz for the spectral density

$$\mathrm{Im}\Pi = f_h^2 s\delta(s - m_h^2) + a_0 s\Theta(s - s_0)$$ where $$\langle 0|j|h\rangle = f_h m_h$$

One can show that in the scalar case, an approximate relation holds

$$j = \bar{\psi}\psi \quad \Rightarrow \quad \boxed{m_h^2 \simeq \frac{2}{3} s_0}$$ "perturbative threshold"

The analogue of "perturbative threshold" in the BSM case?

Our proposal: this is the **"triviality bound"**.

From non-perturbative lattice simulations: $m_h \lesssim 640 \pm 20\ \mathrm{GeV}$

$$\Rightarrow \quad \boxed{m_{h'} \simeq 523 \pm 18\ \mathrm{GeV}}$$

Cancelation of quadratic divergence in vacuum energy

In the limit of free fields, the vacuum energy density can be easily written by summing up the zero-point energies of free harmonic oscillators, $\pm\frac{1}{2}\hbar\omega(k)$

$$\rho_{\rm vac} = \sum_n (-1)^{2S_n} g_n \frac{1}{2} \int_0^\Lambda \frac{d^3k}{(2\pi)^3} \sqrt{k^2 + m_n^2}$$

Integrating and expanding the answer at $\Lambda \gg m_n$

$$\rho_{\rm vac} = \sum_n (-1)^{2S_n} g_n \left\{ \frac{\Lambda^4}{16\pi^2} + \frac{\Lambda^2 m_n^2}{16\pi^2} - \frac{m_n^4}{32\pi^2} \left[\ln\frac{\Lambda}{m_n} - \frac{1}{4} + \ln 2 + O\left(\frac{m_n}{\Lambda}\right)^2 \right] \right\}$$

Pauli–Zeldovich condition $\boxed{\rho_{\rm vac} = 0}$

The main contribution to the quadratic divergence from the SM particles

$$\sum_n (-1)^{2S_n} g_n m_n^2 \approx m_h^2 + 3(2m_W^2 + m_Z^2) - 12 m_t^2 \approx -526^2\ \mathrm{GeV}^2$$

With one extra scalar singlet we can impose

$$\sum_n (-1)^{2S_n} g_n m_n^2 \approx \underline{m_{h'}^2} + m_h^2 + 3(2m_W^2 + m_Z^2) - 12 m_t^2 \approx 0$$

$$\Rightarrow \qquad \boxed{m_{h'} \approx 526\ \mathrm{GeV}}$$

Nambu-Jona-Lasinio model

$$\mathcal{L} = \overline{\psi}\,(i\partial\!\!\!/ - m_0)\,\psi + G\left[(\overline{\psi}\psi)^2 + (\overline{\psi}i\gamma_5\psi)^2\right] \quad \Rightarrow \quad M = m_0 - 2G\langle\overline{\psi}\psi\rangle$$

In the Pauli-Villars regularization: the inputs

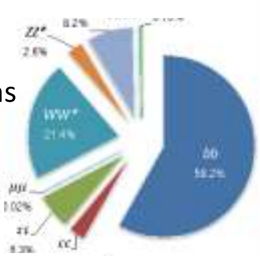
$$\langle\overline{\psi}\psi\rangle = -(240 \pm 10\,\mathrm{MeV})^3\,,\ f_\pi = 93\ \mathrm{MeV},\ m_0 = 5.2\ \mathrm{MeV},\ m_\pi = 135\,\mathrm{MeV}$$

lead to $M \simeq 260 \mp 20$ MeV, $\Lambda \simeq 800 \mp 60$ MeV $\quad \boxed{m_\sigma = 530^{-30}_{+60}\ \mathrm{MeV}}$

Now moving on to the Higgs sector we note an intriguing feature: The presented fits suggest that if we replace "MeV" by "GeV" then the value of m_π looks like the Higgs mass m_h, m_0 — like the b-quark mass m_b, $|\langle\overline{\psi}\psi\rangle|^{1/3}$ — like the v.e.v. of the Higgs field $v = 246$ GeV, and Λ — like the known upper bound on m_h from the perturbative unitarity. In addition, in numerical solutions above one has with a good accuracy $\langle\overline{\psi}\psi\rangle \simeq -M^3$. Then the analogue of the Nambu relation $m_\sigma \simeq 2M$ (which is exact in the chiral limit $m_0 = 0$) takes the form $m_{h'} \simeq 2v$, hence, predicting the second scalar boson near 0.5 TeV. More accurately, with the inputs $m_h = 125$ GeV and $\langle\overline{\psi}\psi\rangle = -(246\,\mathrm{GeV})^3$ we get $\Lambda = 835$ GeV and

$$\boxed{m_{h'} \simeq \sqrt{4v^2 + m_h^2} \approx 508\,\mathrm{GeV}}$$

Relative fractions of higgs decays:



The given suggestion implies that $M_b \simeq v$ plays the role of "constituent" mass of b-quark, i.e., the mass b-quark "dressed" by new strong BSM interactions

Experimental signatures?

If h' couples to the SM only via mixing with the ordinary Higgs boson h then one expects a considerable suppression of h' production cross section compared to that for the SM higgs boson, roughly about factor 10 according to the analysis in Ref. [6].

S.I. Godunov, A.N. Rozanov, M.I. Vysotsky, E.V. Zhemchugov, Extending the Higgs sector: an extra singlet, Eur. Phys. J. C 76 (2016) 1, arXiv:1503.01618.

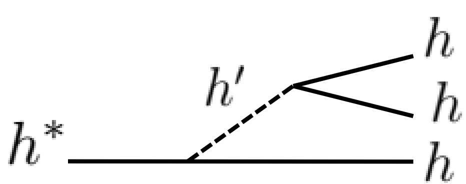
Some time ago the CMS and ATLAS Collaborations announced a pronounced excess of events near 650 GeV

T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. Weiglein, Possible indications for new Higgs bosons in the reach of the LHC: N2HDM and NMSSM interpretations, Eur. Phys. J. C 82 (2) (2022) 178, arXiv:2109.01128.

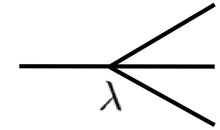
An observation: $m_{H(650)} \simeq m_h + m_{h'} \simeq 125\ \mathrm{GeV} + 525\ \mathrm{GeV}$

$H(650)$- a threshold of simultaneous production of h and h' ?

A possible interpretation: If for some reasons the direct production $hh \to h'$ is highly suppressed (e.g., because the higgs-higgs interaction is very short-ranged), the dominant mechanism can consist in emission via the same vertex, $\boxed{h \to hh'}$



A contribution to the higgs selfcoupling?



CONCLUSION

If a singlet extra higgs particle indeed exists and arises from a strongly-coupled BSM sector then various non-perturbative approaches give estimates on its mass near 0.5 TeV (= 4 higgs masses)

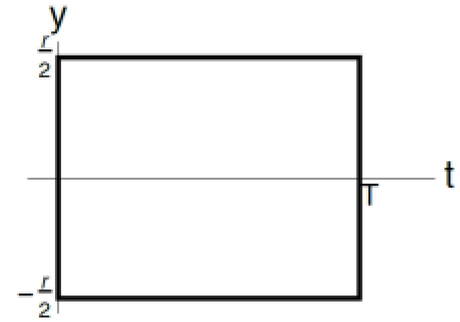
Backup

Holographic Wilson loop

"Dilaton" background -> modified AdS metric (O. Andreev, PRD (2006))

$$g_{MN} = \mathrm{diag}\left\{\frac{R^2}{z^2}h, \ldots, \frac{R^2}{z^2}h\right\}, \quad h = e^{-2cz^2}$$

The main steps (J. Maldacena, PRL (1998)):
Consider the Wilson loop placed in the 4D boundary



$$T \to \infty \quad \Longrightarrow \quad \langle W(\mathcal{C})\rangle \sim e^{-TE(r)}$$

Alternatively $$\langle W(\mathcal{C})\rangle \sim e^{-S} \quad \Longrightarrow \quad \boxed{E = \frac{S}{T}}$$

area of a string world-sheet

This formulation is convenient to study the confinement properties. In particular, a Cornell like confinement potential for heavy quarks was derived (O. Andreev, V. Zakharov, PRD (2006))

string tension

$$E(r) = -\frac{\kappa}{r} + \sigma r + \mathrm{const}$$

Mass spectrum of vector SW model is $$m_n^2 = 4|c|n, \qquad n = 1, 2, \ldots.$$

Generalization to the arbitrary intercept, $$m_n^2 = 4|c|(n + b)$$

within this formulation, is achieved via (S.S. Afonin and T.D. Solomko, EPJC (2022))

$$h = e^{-2cz^2} \quad \Rightarrow \quad h = e^{-2cz^2} U^4(b, 0, |cz^2|)$$

Tricomi function

The final result for this generalization is

$$r = 2\sqrt{\frac{\lambda}{c}} \int_0^1 dv \, \frac{U^4(b,0,\lambda)}{U^4(b,0,\lambda v^2)} \frac{v^2 e^{2\lambda(1-v^2)}}{\sqrt{1 - v^4 e^{4\lambda(1-v^2)} \frac{U^8(b,0,\lambda)}{U^8(b,0,\lambda v^2)}}},$$

$$E = \frac{R^2}{\pi\alpha'}\sqrt{\frac{c}{\lambda}} \left[\int_0^1 \frac{dv}{v^2} \left(\frac{e^{2\lambda v^2} U^4(b,0,\lambda v^2)}{\sqrt{1 - v^4 e^{4\lambda(1-v^2)} \frac{U^8(b,0,\lambda)}{U^8(b,0,\lambda v^2)}}} - D \right) - D \right]$$

Here $D = U^4(b, 0, 0)$

The same calculation can be made for the scalar SW model, where

$$h = e^{2cz^2/3} U^{4/3}(b, -1, cz^2)$$

$$r = 2\sqrt{\frac{\lambda}{c}} \int_0^1 dv \, \frac{U^{4/3}(b,-1,\lambda)}{U^{4/3}(b,-1,\lambda v^2)} \frac{v^2 e^{2\lambda(1-v^2)/3}}{\sqrt{1 - v^4 e^{4\lambda(1-v^2)/3} \frac{U^{8/3}(b,-1,\lambda)}{U^{8/3}(b,-1,\lambda v^2)}}},$$

$$E = \frac{R^2}{\pi\alpha'} \sqrt{\frac{c}{\lambda}} \left[\int_0^1 \frac{dv}{v^2} \left(\frac{e^{2\lambda v^2/3} U^{4/3}(b,-1,\lambda v^2)}{\sqrt{1 - v^4 e^{4\lambda(1-v^2)/3} \frac{U^{8/3}(b,-1,\lambda)}{U^{8/3}(b,-1,\lambda v^2)}}} - D \right) - D \right]$$

Here $D \equiv U^{4/3}(b, -1, 0)$

The SM phase diagram in terms of Higgs and top masses