Heavy Quarks bound states

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Outline

The masses, decay constants, spectrum and binding energy of mesons containing at least one heavy quark.

- Heavier than the top quark of Standard model i.e., isosinglet D quark of E_6, T quark of little Higgs, Golino of Supersymmetry and Fourth generation quarks b' and t'.....

Outline

- Among the mysteries of nature is the number of generations. We observe three generations, however...
- Data from the LHC-CMS (under some circumstances) restricts the masses of the t' and b' quarks in a fourth generation to be greater than about 500 GeV.
- The constraints on this scenario arise either directly, via the search for production of fourth generation quarks and leptons at colliders (Aad 2012), or indirectly, through their effect on the oblique electroweak parameters(Peskin 1991,Kribs 2007 ,Hashimoto 2010) and on the Higgs boson production and decay partial widths(Chen 2012).
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4th quarks can enhance the Higgs production by $\mathcal{O}(10)$ (Georgi 1977) and Higgs decay suppress by $\mathcal{O}(100)$ (Denner 2011). via this diagrams:

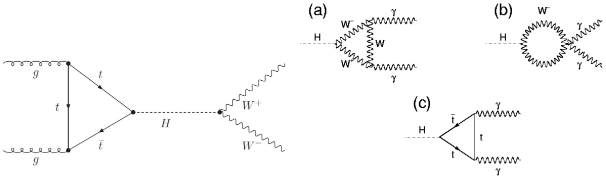

Figure: (left): Gluon fusion, (right): Diagrams corresponding to $H \to \gamma\gamma$.

As a consequence, precise measurements of the Higgs production rate and branching ratios can strongly constrain the existence of a fourth generation.

- Recently, the ATLAS, CMS, CDF and D0 experiments have reported new result (ATLAS 2012,Chatrchyan 2012,D0 2012) which hint on the existence of a light Higgs boson with a mass of order 125 GeV. Several Higgs decay channels have been probed, including the $\gamma\gamma$, ZZ^* and WW^* channels dominated by the gluon fusion production mode, $b\bar{b}$ in the associated production mode, and the diphoton channel dominated by the vector boson fusion (VBF) production mode.
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- bound state condition:$Q \to qW$ $m_Q < 100|V_{Qq}|^{-2/3}$ (see Bigi 1986 PLB)
- $|V_{Qq}| < 0.1$ If it is!!?
- If the heavy quarks have a very small mixing with the ordinary quarks, they can be long enough lived and the production of bound states become possible. In this case the production of these bound states at the LHC may have important experimental consequences.

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- Bound states come with different color, spin and flavor quantum numbers.
- These bound states can be: scalar, pseudoscalar, vector and axial vector type ground states or higher states mesons. The masses and bound states spectrum can be calculated in different methods, for instance, using the Schroedinger equation (Ishiwata et al PRD 2011) or QCD sum rule Methods (Bashiry et al PRD 2012).

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- Heavy quarks feel a strong attractive force from Higgs exchange in both the $\bar{q}'q'$ and $q'q'$ channels that gives rise to bound states Hung et al PRD.
- Heavy quarks feel force from gluon exchange(QCD).
- $H = \frac{\mathbf{p}^2}{m_{q'}} - \left(\sqrt{2}G_F m_{q'}^2\right)\frac{e^{-m_h r}}{4\pi r} - \frac{4}{3}\alpha_s\left(\frac{1}{r}\right) + \ldots,$

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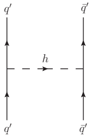

Figure: t-channel Higgs exchange. $V_{Higgs} = -\left(\sqrt{2}G_F m_{q'}^2\right)\frac{e^{-m_h r}}{4\pi r}$,

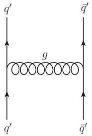

Figure: Gluon exchange. $V_{\rm QCD}(r) = -\frac{4}{3}\alpha_s\left(\frac{1}{r}\right)$

Using the variational method, minimizing $E[a] = \langle\psi|H|\psi\rangle/\langle\psi|\psi\rangle$ for trial wave functions $\psi \propto e^{-r/a}$.

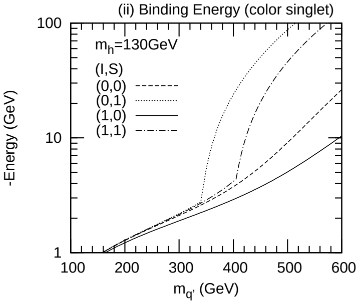

Figure: Variational binding energy of color singlet channels as the function of the heavy quark mass. Here we set $a = a_0$.

- QCD Sume Rules Can be applied just for the ground states.
- In oneside we have QCD language where everything can be calculated in terms quarks, gluon parameters. In the other side we have hadronic parameters. The result of the QCD calculation is then matched, via dispersion relation, to a sum over hadronic states.

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The two point correlation function corresponding to the scalar (S) and pseudoscalar (PS) cases can be written as:

$$\Pi^{S(PS)} = i\int d^4x e^{ip.x}\langle 0 \mid \mathcal{T}\left(J^{S(PS)}(x)\bar{J}^{S(PS)}(0)\right) \mid 0\rangle, \qquad (1)$$

where $\mathcal{T}$ is the time ordering product and $J^S(x) = \overline{u}_4(x)q(x)$ and $J^{PS}(x) = \overline{u}_4(x)\gamma_5 q(x)$ are the interpolating currents of the heavy scalar and pseudoscalar bound states, respectively.

Similarly for the vector (V) and axial vector (AV), the correlation function can be written as:

$$\Pi_{\mu\nu}^{V(AV)} = i \int d^4 x e^{ip.x} \langle 0 \mid \mathcal{T}\left(J_\mu^{V(AV)}(x) \bar{J}_\nu^{V(AV)}(0)\right) \mid 0 \rangle, \qquad (2)$$

where, the currents $J_\mu^V = \overline{u}_4(x)\gamma_\mu q(x)$ and $J_\mu^{AV} = \overline{u}_4(x)\gamma_\mu\gamma_5 q(x)$ are responsible for creating the vector and axial vector quarkonia, respectively from the vacuum with the same quantum numbers as the interpolating currents.

- The aforesaid correlation functions must be treated in two alternative ways.
- In physical or phenomenological side, we calculate them in terms of hadronic parameters such as masses and decay constants.
- In QCD or theoretical side, they are calculated in terms of QCD degrees of freedom such as quark masses and gluon condensates by the help of operator product expansion (OPE) in deep Euclidean region.

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- Equating these two representations of the correlation function through dispersion relations, we acquire the QCD sum rules for the masses and decay constants.

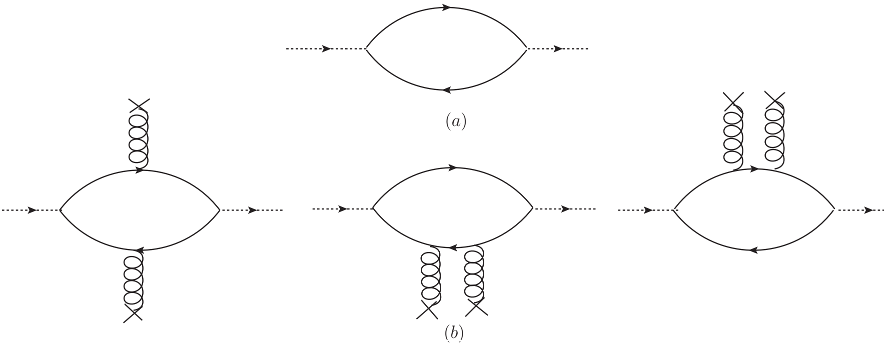

Figure: (a): Bare loop diagram (b): Diagrams corresponding to gluon condensates.

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- Perform the integral over x and isolating the ground state, we obtain

$$\Pi^{S(PS)} = \frac{\langle 0 \mid J^{S(PS)}(0) \mid S(PS)\rangle\langle S(PS) \mid J^{S(PS)}(0) \mid 0\rangle}{m^2_{S(PS)} - p^2} + \cdots \quad (3)$$

where $\cdots$ represents the contributions of the higher states and continuum and $m_{S(PS)}$ is mass of the heavy scalar(pseudoscalar) meson. From the similar manner, for the vector (axial vector) case, we obtain

$$\Pi_{\mu\nu}^{V(AV)} = \frac{\langle 0 \mid J_\mu^{V(AV)}(0) \mid V(AV)\rangle\langle V(AV) \mid J_\nu^{V(AV)}(0) \mid 0\rangle}{m_{V(AV)}^2 - p^2} + \cdots \quad (4)$$

To proceed, we need to know the matrix elements of the interpolating currents between the vacuum and mesonic states. These matrix elements are parametrized in terms of the leptonic decay constants as:

$$\begin{aligned}
\langle 0 \mid J(0) \mid S \rangle &= f_S m_S, \\
\langle 0 \mid J(0) \mid PS \rangle &= f_{PS} \frac{m_{PS}^2}{m_{u4} + m_q}, \\
\langle 0 \mid J_\mu(0) \mid V(AV) \rangle &= f_{V(AV)} m_{V(AV)} \varepsilon_\mu,
\end{aligned} \quad (5)$$

Using the summation over the polarization vectors in the $V(AV)$

$$\epsilon_\mu \epsilon^*_\nu = -g_{\mu\nu} + \frac{p_\mu p_\nu}{m^2_{V(AV)}}, \tag{6}$$

The physical sides of the correlation functions as:

$$\Pi^S = \frac{f_S^2 m_S^2}{m_S^2 - p^2} + \cdots$$

$$\Pi^{PS} = \frac{f_{PS}^2 \left(\frac{m_{PS}^2}{m_{u4}+m_q}\right)^2}{m_{PS}^2 - p^2} + \cdots$$

$$\Pi^{V(AV)}_{\mu\nu} = \frac{f^2_{V(AV)} m^2_{V(AV)}}{m^2_{V(AV)} - p^2} \left[-g_{\mu\nu} + \frac{p_\mu p_\nu}{m^2_{V(AV)}} \right] + \cdots,$$

For each correlation function we write

$$\Pi^{QCD} = \Pi_{pert} + \Pi_{nonpert} . \quad (8)$$

The bare loop diagram in figure (5) part (a)). The long distance contributions (diagrams shown in figure (5) part (b)) are parameterized in terms of gluon condensates.

$$\Pi^{QCD} = \int \frac{ds\rho(s)}{s-p^2} + \Pi_{nonpert} , \quad (9)$$

where, $\rho(s)$ is called the spectral density.

Outline

The Feynman amplitude of the bare loop diagram is calculated by the help of the Cutkosky rules, where the quark propagators are replaced by Dirac delta function, i.e., $\frac{1}{p^2-m^2} \rightarrow (-2\pi i)\delta(p^2-m^2)$.

$$\rho(s) = \frac{3s}{8\pi^2}\left(1-\frac{(m_1 \pm m_2)^2}{s}\right)\sqrt{1-2\frac{m_1^2+m_2^2}{s}+\frac{(m_1^2-m_2^2)^2}{s^2}} \quad (10)$$

where $+$ sign in $(m_1 \pm m_2)$ is chosen for scalar and axial vector cases and $-$ sign is for psoduscalar and vector channels. Here, $m_1 = m_{u_4}$ and m_2 is either m_{u_4} or $m_{c(b)}$.

Outline

we calculate the gluon condensate diagrams represented in part (b) of figure (5). The vacuum gluon field is expressed as:

$$A^a_\mu(k') = -\frac{i}{2}(2\pi)^4 G^a_{\rho\mu}(0)\frac{\partial}{\partial k'_\rho}\delta^{(4)}(k'), \tag{11}$$

where k' is the gluon momentum and the quark-gluon-quark vertex as:

$$\Gamma^a_{ij\mu} = ig\gamma_\mu\left(\frac{\lambda^a}{2}\right)_{ij}, \tag{12}$$

After straightforward but lengthy calculations, the non-perturbative part for each case in momentum space is obtained as:

$$\Pi^i_{nonpert} = \int_0^1 \langle \alpha_s G^2 \rangle \frac{\Theta^i + \Theta^i(m_1 \leftrightarrow m_2)}{96\pi(m_2^2 + m_1^2 x - m_2^2 x - p^2 x + p^2 x^2)^4} dx \quad (13)$$

where $\Theta^i(m_1 \leftrightarrow m_2)$ means that in Θ^i, we exchange m_1 and m_2. The explicit expressions for Θ^i are given as:

$$
\begin{aligned}
\Theta^S &= \frac{1}{2}x^2\Big\{3m_1^4x(m_2^2(x(17-2x(2x(9x-26)+47))+8)\\
&+p^2x(x(27x-25)-7)(x-1)^2)+2m_2m_1^3(m_2^2(x(x(x(21x-58)+39)\\
&+12)-15)-p^2(x-1)x(x(x(7x-13)-3)+12))\\
&+m_1^2(-m_2^2p^2(x-1)x(x(x(2x(81x-242)+455)-96)-33)\\
&+m_2^4(x(x(x(3x(36x-145)+652)-414)+72)+15)+3p^4(x-1)^3\\
&x^2(24x^2-22x-5))-m_2m_1(x-1)(-m_2^2p^2(x^2-2)(x(14x-27)+15)\\
&+m_2^4(3x-5)(x(7x-12)+6)+p^4(x-1)x(x(2x(7x-13)+3)+12))\\
&+(x-1)(-m_2^2p^4(x-1)x(2x(x(2x(18x-55)+109)-30)-9)\\
&+m_2^4p^2(x(x(x(x(81x-328)+490)-299)+42)+15)\\
&-m_2^6(2x-3)(x(6x(3x-8)+47)-15)+3p^6(x-1)^3x^2(6(x-1)x-1))\\
&+9m_1^6(x-1)^2x^2(4x+1)+3m_2m_1^5x(x((8-7x)x+2)-4)\Big\},
\end{aligned}
\qquad (14)
$$

The next step is to match the phenomenological and QCD sides of the correlation functions to get sum rules for the masses and decay constants of the bound states. To suppress the contribution of the higher states and continuum, Borel transformation over p^2 as well as continuum subtraction are performed. As a result of this procedure, we obtain the following sum rules:

$$
\begin{aligned}
m^2_{S(V)(AV)} f^2_{S(V)(AV)} e^{\frac{-m^2_{S(V)(AV)}}{M^2}} &= \int_{(m_1+m_2)^2}^{s_0} ds\, \rho^{S(V)(AV)}(s)\, e^{-\frac{s}{M^2}} + \hat{B}\Pi^{S(V)(AV)}_{nonpert}, \\
\frac{m^4_{PS} f^2_{PS}}{(m_{u_4}+m_q)^2} e^{\frac{-m^2_{PS}}{M^2}} &= \int_{(m_1+m_2)^2}^{s_0} ds\, \rho^{PS}(s)\, e^{-\frac{s}{M^2}} + \hat{B}\Pi^{PS}_{nonpert}, \qquad (15)
\end{aligned}
$$

where M^2 is the Borel mass parameter and s_0 is the continuum threshold. The sum rules for the masses are obtained applying derivative with respect to $-\frac{1}{M^2}$ to the both sides of the above sum rules and dividing by themselves. i.e.,

$$m^2_{S(PS)(V)(AV)} = \frac{-\frac{d}{d(\frac{1}{M^2})}\left[\int_{(m_1+m_2)^2}^{s_0} ds\, \rho^{S(PS)(V)(AV)}(s)\, e^{-\frac{s}{M^2}} + \hat{B}\Pi^{S(PS)(V)(AV)}_{nonpert}\right]}{\int_{(m_1+m_2)^2}^{s_0} ds\, \rho^{S(PS)(V)(AV)}(s)\, e^{-\frac{s}{M^2}} + \hat{B}\Pi^{S(PS)(V)(AV)}_{nonpert}}, \qquad (16)$$

where

$$\hat{B}\Pi^i_{nonpert} = \int_0^1 e^{\frac{m_2^2+x(m_1^2-m_2^2)}{M^2 x(x-1)}} \frac{\Delta^i + \Delta^i(m_1 \leftrightarrow m_2)}{\pi 96 M^6 (x-1)^4 x^3} \langle \alpha_s G^2 \rangle dx, \qquad (17)$$

and

$$\begin{aligned}
\Delta^S &= -m_2 m_1^3 (x-1) x^2 (m_2^2(14x^2-29x+14) \\
&+2M^2 x(7x^2-13x+6)) + m_1^4 (x-1)x^3 (m_2^2(9x^2-14x+6) \\
&+3M^2x(3x^2-4x+1)) + m_2 m_1 (x-1)(m_2^2 M^2 x \\
&(14x^4-53x^3+71x^2-36x+6) + m_2^4(7x^4-28x^3+40x^2-25x+6) \\
&+2M^4x^2(14x^4-40x^3+29x^2+9x-12)) + m_1^2 x(m_2^2 M^2 x \\
&(-18x^5+70x^4-105x^3+77x^2-27x+3) + m_2^4(-9x^5+37x^4 \\
&-61x^3+52x^2-21x+3) - 12M^4x^2(3x+1)(x-1)^4) - (x-1) \\
&(-2m_2^2M^4x^3(18x^4-76x^3+123x^2-89x+24) \\
&+m_2^4M^2x(-9x^5+40x^4-71x^3+68x^2-33x+6) + m_2^6(-3x^5+14x^4 \\
&-27x^3+29x^2-15x+3) + 6M^6(x-1)^3x^3(6x^2-6x-1)) \\
&-3m_1^6(x-1)x^5 + m_2 m_1^5 x^3(7x^2-8x+1),
\end{aligned} \quad (18)$$

we take the mass of the u_4 in the interval $m_{u_4} = (450 - 550)\, GeV$, $m_b = 4.8\, GeV$, $m_c = 1.3\, GeV$ and $\langle 0 \mid \frac{1}{\pi}\alpha_s G^2 \mid 0\rangle = 0.012\, GeV^4$. The sum rules for the masses and decay constants also contain two auxiliary parameters, namely Borel mass parameter M^2 and continuum threshold s_0. The standard criteria in QCD sum rules is that the physical quantities should be independent of the auxiliary parameters. Therefor, we should look for working regions of these parameters such that our results be approximately insensitive to the variation of auxiliary parameters.

The working region for the Borel mass parameter is determined demanding that not only the higher state and continuum contributions are suppressed but also the contributions of the highest order operators should be small, i.e., the sum rules for the masses and decay constants should converge. As a result of the above procedure, the working region for the Borel parameter is found to be 500 $GeV^2 \leq M^2 \leq 900\ GeV^2$ for $\bar{u}_4 b$ and $\bar{u}_4 c$, and 1200 $GeV^2 \leq M^2 \leq 2000\ GeV^2$ for $\bar{u}_4 u_4$ heavy SM_4 mesons.

The continuum threshold s_0 is not completely arbitrary but it is related to the energy of the first exited states with the same quantum numbers as the interpolating currents. Our numerical calculations show that in the interval $(m_1 + m_2 + 0.3)^2\ GeV^2 \leq s_0 \leq (m_1 + m_2 + 0.5)^2\ GeV^2$ for the continuum threshold, our results have very weak dependency on this parameters.

The following values for the mass and the decay constant of $h_b(1P)$, which is recently observed by Belle, are obtained(Bashiry PRD 2012):

$$m[h_b(1P)] = (9940 \pm 37)\ MeV \quad (19)$$

$$f[h_b(1P)] = (94 \pm 10)\ MeV \quad (20)$$

Note that,The experimental value of the mass $m[h_b(1P)] = (9898.25 \pm 1.06^{+1.03}_{-1.07})$ Mev (Belle 2011).

mass (GeV)	$u_4\bar{c}$	$u_4\bar{b}$	$u_4\bar{u}_4$
Scalar	552.82 ± 0.31	556.27 ± 0.31	1101.67 ± 0.60
Pseudoscalar	552.43 ± 0.18	555.78 ± 0.18	1101.11 ± 0.36
Axial Vector	552.81 ± 0.31	556.25 ± 0.31	1101.68 ± 0.60
Vector	552.42 ± 0.18	555.77 ± 0.18	1101.12 ± 0.36

Table: The values of masses of different bound states obtained using $m_{u_4} = 550\ GeV$.

Leptonic decay constant f (GeV)	$u_4\bar{c}$	$u_4\bar{b}$	$u_4\bar{u}_4$
Scalar	0.10 ± 0.01	0.12 ± 0.01	0.26 ± 0.03
Pseudoscalar	0.14 ± 0.01	0.27 ± 0.01	4.19 ± 0.20
Axial Vector	0.10 ± 0.01	0.12 ± 0.01	0.26 ± 0.03
Vector	0.14 ± 0.01	0.27 ± 0.01	4.18 ± 0.20

Table: The values of decay constants of different bound states obtained using $m_{u_4} = 550\ GeV$.

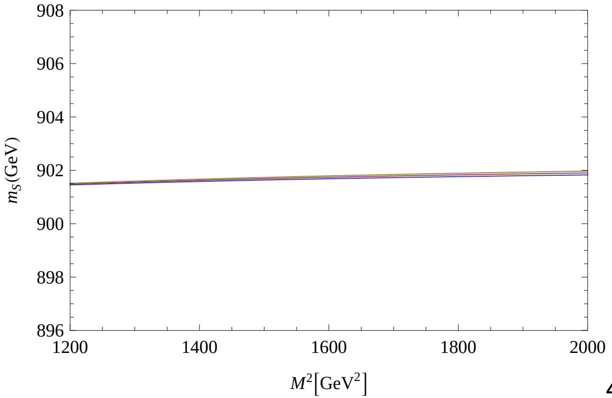

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Figure: Dependence of mass of the scalar $\bar{u_4}u_4$ on the Borel parameter, M^2 at three fixed values of the continuum threshold. The upper, middle and lower lines belong to the values $s_0 = (m_1 + m_2 + 0.5)^2\ GeV^2$, $s_0 = (m_1 + m_2 + 0.4)^2\ GeV^2$ and $s_0 = (m_1 + m_2 + 0.3)^2\ GeV^2$, respectively.

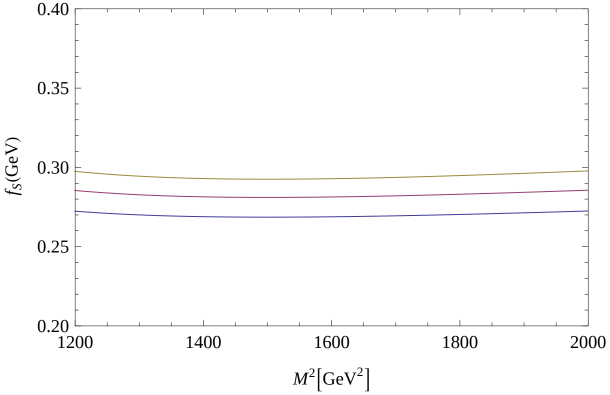

Figure: Dependence of the decay constant of the scalar $\bar{u}_4 u_4$ on the Borel parameter, M^2 at three fixed values of the continuum threshold. The upper, middle and lower lines belong to the values $s_0 = (m_1 + m_2 + 3.7)^2\ GeV^2$, $s_0 = (m_1 + m_2 + 3.5)^2\ GeV^2$ and $s_0 = (m_1 + m_2 + 3.3)^2\ GeV^2$, respectively.

To sum up, the heavy quarks that have sufficiently small mixing with the three known family SM quarks can form hadrons. Considering the arguments mentioned in the text, the production of such bound states will be possible at LHC. Hopping this possibility, we calculated the masses and decay constants of the bound state objects containing two quarks either both heavy quarks or one from heavy and the other from observed SM bottom or charm quarks in the framework of the QCD sum rules. The obtained numerical results approach to the known masses and decay constants of the $\bar{b}b$ and $\bar{c}c$ heavy quarkonia, when the heavy quarks are replaced by the bottom or charm quark.