heavy quark pair production for 750GeV diphoton resonance

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based on the work with
Chengcheng Han, Koji Ichikawa, Shigeki Matumoto Michihisa Takeuchi
(1602.08100. Published in JHEP)
Another possibility: bound state of heavy fermion

$1S(J^{PC} = 0^{-+})$ at $750 GeV$

$m_T : 375 \sim 380 GeV$

To explain signal, need to evade from current searches

$2m_T - E_0$
heavy scalar/fermion bound state as the origin of diphoton excess

- If the life time of a heavy colored particle $X$ is longer than time scale forming $XX$ bound state, there are a channel

- $pp \rightarrow X \bar{X} \rightarrow S \rightarrow gg, \gamma \gamma, ZZ$ we take $X$ SU(2) singlet

\[
\sigma(pp \rightarrow S \rightarrow \gamma \gamma) = \frac{K}{m_{S_0}} \frac{\Gamma_{\gamma \gamma} \Gamma_{gg}}{\Gamma_{\text{tot}}} \left[ \frac{\pi}{8} \int dx_1 dx_2 \delta(x_1 x_2 - m_{S_0}^2 / s) f_g(x_1) f_g(x_2) \right]
\]

\[
\Gamma_{\text{tot}} = \Gamma_{\gamma \gamma} / c_W^4 + \Gamma_{gg} + 2\Gamma_X, \quad \text{X width must be small}
\]

\[
\Gamma_{\gamma \gamma} = 48 \pi Y_X^4 \alpha^2 |\psi_0(0)|^2 / m_{S_0}^2,
\]

\[
\Gamma_{gg} = 32 \pi \alpha_s^2 |\psi_0(0)|^2 / (3m_{S_0}^2),
\]

wave function of $XX$ system at origin

4th power of hypercharge ($\cdots$ fit anything)
bound state of $X$

- wave function at origin

$$\left[-\frac{\nabla^2}{m_X} + V(r) - E_0\right] \psi_0(r) = 0,$$

- numerically solve and fit

(consistent with Hagiwara Kato Martine, Ng 1990 for $Y=0$)

$$|\psi_0(0)| = \sum_{n=0}^{4} a_n \left[ \ln(m_S/750\text{GeV}) \right]^n, \quad E_0 = \sum_{n=0}^{4} b_n \left[ \ln(m_S/750\text{GeV}) \right]^n,$$

QED part + linear part

$$V(r) = -\frac{\alpha}{|r|} + V_{\text{QCD}}(|r|).$$

<table>
<thead>
<tr>
<th>$Y_X$</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_4$</th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
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<tbody>
<tr>
<td>0</td>
<td>87.78</td>
<td>114.4</td>
<td>76.85</td>
<td>37.76</td>
<td>10.71</td>
<td>4.119</td>
<td>2.458</td>
<td>0.9314</td>
<td>0.2429</td>
<td>0.04078</td>
</tr>
<tr>
<td>1/3</td>
<td>88.44</td>
<td>115.3</td>
<td>77.54</td>
<td>38.14</td>
<td>10.82</td>
<td>4.145</td>
<td>2.481</td>
<td>0.9416</td>
<td>0.2461</td>
<td>0.04143</td>
</tr>
<tr>
<td>2/3</td>
<td>90.44</td>
<td>118.1</td>
<td>79.64</td>
<td>39.30</td>
<td>11.17</td>
<td>4.226</td>
<td>2.552</td>
<td>0.9726</td>
<td>0.2557</td>
<td>0.04341</td>
</tr>
<tr>
<td>1</td>
<td>93.82</td>
<td>122.9</td>
<td>83.20</td>
<td>41.25</td>
<td>11.76</td>
<td>4.363</td>
<td>2.672</td>
<td>1.026</td>
<td>0.2721</td>
<td>0.04682</td>
</tr>
<tr>
<td>4/3</td>
<td>98.64</td>
<td>129.8</td>
<td>88.28</td>
<td>44.05</td>
<td>12.61</td>
<td>4.559</td>
<td>2.845</td>
<td>1.102</td>
<td>0.2960</td>
<td>0.05180</td>
</tr>
<tr>
<td>5/3</td>
<td>105.0</td>
<td>138.8</td>
<td>95.01</td>
<td>47.76</td>
<td>13.73</td>
<td>4.822</td>
<td>3.077</td>
<td>1.206</td>
<td>0.3285</td>
<td>0.05858</td>
</tr>
<tr>
<td>2</td>
<td>112.6</td>
<td>150.7</td>
<td>104.5</td>
<td>51.83</td>
<td>14.40</td>
<td>5.162</td>
<td>3.366</td>
<td>1.322</td>
<td>0.3812</td>
<td>0.07999</td>
</tr>
</tbody>
</table>
Abnormal candidate remains

Figure 1: Red stars are predictions of our model on the $(|C_{gg}|, |C_{BB}|)$-plane with $Y_X$ being 2/3, 1, 4/3, 5/3 and 2, respectively. Contours of the diphoton cross section as a function of $|C_{gg}|$ and $|C_{BB}|$ are also shown by gray-dashed lines. Darker (lighter) green-shaded region corresponds to the cross section experimentally favored by the diphoton excess at 1σ (2σ) level [3].

Numerically tough calculation, completely relay on Ishikawa-san
Thoughts about X decay

- There are no dim 4 operator involving X and SM particles →The X decay must be suppressed by some cutoff scale Λ →Consistent with small width assumption to get signal

- If X is Z₂ odd in some conserved parity, decaying into lightest Z₂ odd particle (dark matter)
  - X: strongly interacting particle with (3,0,-4/3)
  - χ: weakly interacting particle. X and χ interact through some higher dim operators such as

\[ \mathcal{O}_F \sim \left( Xu^c \right) \left( \bar{\chi} u^c \right) / \Lambda^2 \quad \mathcal{O}_S \sim \left( \bar{X} d^c \right) \left( u^c d^c \right) \bar{\chi} / \Lambda^3 \]


dark matter density

effective pair annihilation cross section

\[ \langle \sigma v \rangle = \sum_{ij} \langle \sigma_{ij} v \rangle \frac{g_i g_j}{g_{\text{eff}}} (1 + \Delta_i)^{3/2} (1 + \Delta_j)^{3/2} \exp[-x(\Delta_i + \Delta_j)], \]

\[ x = \frac{m_\chi}{T}, \]

\[ \Delta_i = \frac{(m_i - m_\chi)}{m_\chi} \text{ mass difference} \]

for our case

\[ \langle \sigma v \rangle \approx 2 \frac{43 \pi \alpha_s^2}{27 m_\chi^2} \frac{36 (1 + \Delta_\chi)^3 \exp(-2x\Delta_\chi)}{g_\chi + 12 (1 + \Delta_\chi)^{3/2} \exp(-x\Delta_\chi)}^2 \]


“Three exceptions in the calculation of relic abundance”

dark matter density is the function of \( m_X - m_\chi \)

It is enough to exclude this region

dark matter density is small enough here
Collider Constraints

X decay pattern
\[ X \rightarrow \chi (jj, jjj) \chi = \text{DM} \]

Other possibility
1. X\rightarrow Wj, Zj, Hj etc is not allowed because of Q=4/3
2. X\rightarrow 2j, 3j (Kats and Strassler 1602.08819) weaker

\[ \sigma (pp \rightarrow XX) \]

collider bound: large QCD background fat jet search at 13TeV?

\[ \text{signal!} \]

relatively light particle with huge cross section

need to evade from current searches

recast light squark search at LHC
degenerate BSM search
hard ISR (better prediction)

SM particle rather difficult to be seen
monojet searches at 8 and 13 TeV are relevant
generate $p p \rightarrow X X$ upto 2jet matched sample.

force $X$ to decay into $X \rightarrow \chi jj$ or $\chi jjj$ to obtain efficiency.

signature is therefore jet (ISR, hard) + missing + soft activities

compare with ATLAS and CMS SUSY searches results using checkmate

8TeV stop-LSP degenerate

<table>
<thead>
<tr>
<th>Region</th>
<th>$\not E_T$ [GeV]</th>
<th>$p_{T,j}$ [GeV]</th>
<th>$\Delta \phi (j, \not E_T)$</th>
<th>$n_j$</th>
<th>$\not E_T / \sqrt{H_T}$</th>
<th>$m_{\text{eff}}$ (incl.)</th>
<th>$\sigma_{\text{95%}}^{\text{obs}}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>340</td>
<td>340</td>
<td>0.4</td>
<td>$\leq 3$</td>
<td>-</td>
<td>-</td>
<td>28.4 fb</td>
<td>[44]</td>
</tr>
<tr>
<td>SR5</td>
<td>350</td>
<td>0.5 $\not E_T$</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21 fb</td>
<td>[45]</td>
</tr>
<tr>
<td>SR6</td>
<td>400</td>
<td>0.5 $\not E_T$</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12 fb</td>
<td>[45]</td>
</tr>
<tr>
<td>SR2jm</td>
<td>200</td>
<td>300</td>
<td>0.4</td>
<td>$\geq 2$</td>
<td>15 GeV$^{1/2}$</td>
<td>1.2 TeV</td>
<td>21 fb</td>
<td>[46]</td>
</tr>
</tbody>
</table>

Table 3: Signal regions and upper bounds on the signal cross sections at 95% C.L. Here, $p_{T,j}$, $H_T$, and $m_{\text{eff}}$ (incl.) are the leading jet $p_T$, the scalar $p_T$ sum of all jets and $H_T + \not E_T$, respectively.

13TeV data

all the other limits included in Checkmate are investigated.
background modeling at 13TeV

Background Estimation at LHC: NNLO cross section and +NLO multijet for some process

Biggest uncertainty comes from the process calculated only up to one loop

Signal cross section is NNLO level but not ready for NLO multi jet

<table>
<thead>
<tr>
<th>Channel</th>
<th>2jl</th>
<th>2jm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total bkg</td>
<td>237</td>
<td>163</td>
</tr>
<tr>
<td>Total bkg unc.</td>
<td>±22 [9%]</td>
<td>±20 [12%]</td>
</tr>
<tr>
<td>MC statistics</td>
<td>–</td>
<td>±1.8 [1%]</td>
</tr>
<tr>
<td>(\Delta \mu_{Z+jets})</td>
<td>±6 [3%]</td>
<td>±5 [3%]</td>
</tr>
<tr>
<td>(\Delta \mu_{W+jets})</td>
<td>±4 [2%]</td>
<td>±4 [2%]</td>
</tr>
<tr>
<td>(\Delta \mu_{Top})</td>
<td>±1.2 [1%]</td>
<td>±1.6 [1%]</td>
</tr>
<tr>
<td>(\Delta \mu_{Multi-jet})</td>
<td>±0.05 [0%]</td>
<td>±0.09 [0%]</td>
</tr>
<tr>
<td>CR(\gamma) corr. factor</td>
<td>±8 [3%]</td>
<td>±6 [4%]</td>
</tr>
<tr>
<td>Theory (W)</td>
<td>±1.4 [1%]</td>
<td>±2.3 [1%]</td>
</tr>
<tr>
<td>Theory (Z)</td>
<td>±6 [3%]</td>
<td>±3.2 [2%]</td>
</tr>
<tr>
<td>Theory Top</td>
<td>±2.7 [1%]</td>
<td>±2.1 [1%]</td>
</tr>
<tr>
<td>Theory Diboson</td>
<td>±16 [7%]</td>
<td>±16 [10%]</td>
</tr>
<tr>
<td>(Jet/E_T^{miss})</td>
<td>±1.5 [1%]</td>
<td>±2.1 [1%]</td>
</tr>
</tbody>
</table>
The limit depends on signal error assumptions (we take 16%).

13 TeV data gives best limit, and the limit is weaker than expected.

Limit is weaker here because mono-jet condition (pT1 vs ETmiss) two body decay case (X->jχ) is excluded by multi-jet search+

Tight mono-jet requirement leads worse sensitivity for heavy quark: (more ISR). Stop search is optimize for M2.
summary

- **Heavy quark and dark matter for 750GeV resonance:** We proposed a effective theory with rather few number of particles. It turns out this is a new class of effective DM theory with **almost Model independent prediction of DM density.**

- **Our case** still barely survives from mono-jet search constraints. More stringent constraint this year, if scale dependence of the signal can be controlled.

- **LHC will exclude narrow width heavy fermion** though $\gamma \gamma$ channel.