# Heavy Fermion Bound States for Diphoton Excess at 750GeV

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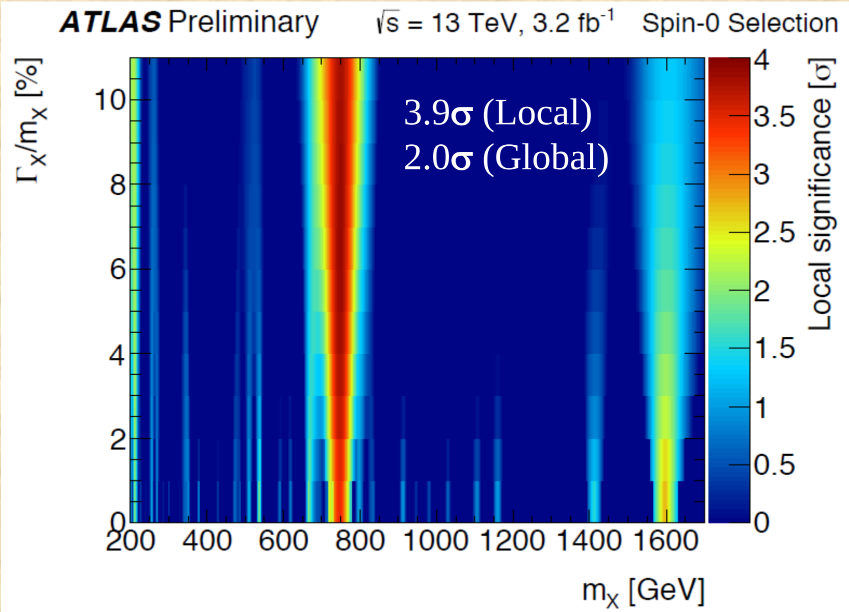
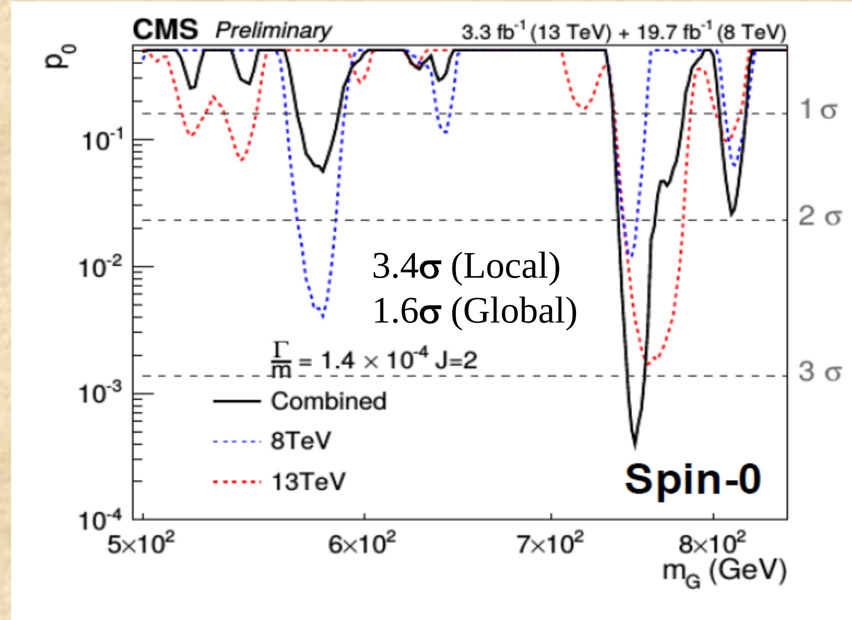
[Arxiv:1602.08100]

1. Summarizing the diphoton excess at 750GeV
2. An interpretation by fermion bound states
3. Is it still phenomenologically viable?

# The excess @ 750GeV




- ✓ The Mass of the resonance should be around 750GeV.
- ✓ Its width seems large (45GeV) for ATLAS, while small for CMS.
- ✓ Its spin should not be one when the final state is $2\gamma$.
- ✓ The CP property of the resonance (odd or even) is unknown.
- ✓ The production cross section should be around 4—5fb (see next).
- ✓ The events are not accompanied by ETmiss, nor leptons or jets.
- ✓ Does the resonance give other signals like WW, ZZ, $Z\gamma$, and so on?

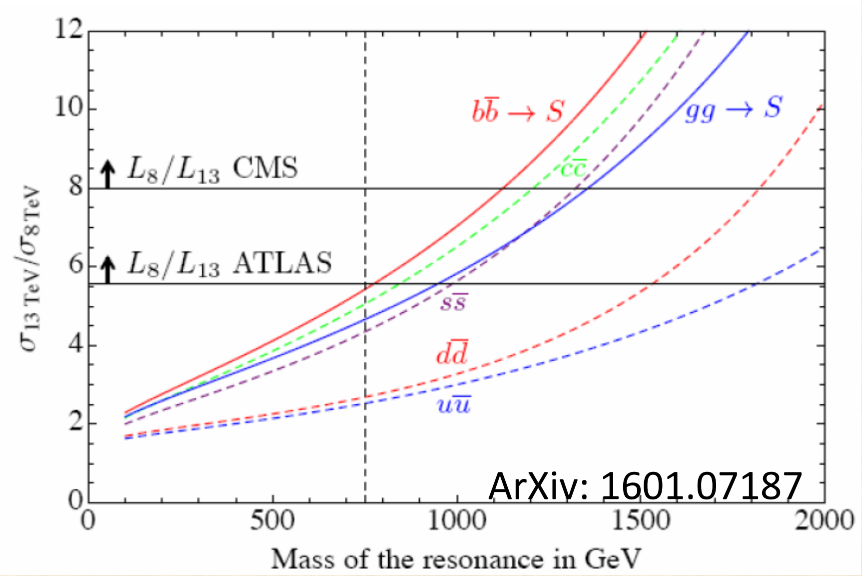
[$\sigma_{WW} < 40$fb, $\sigma_{ZZ} < 12$fb, $\sigma_{Z\gamma} < 4$fb, $\sigma_{gg} < 2.5$pb at 8TeV.]

# The excess @ 750GeV

Let us focus on the simplest case, namely $pp \to$ (Resonance) $\to \gamma\gamma$.

↓

Which parton (inside a proton) actually produces the resonance?




When $q\bar{q}$ produces the resonance,

$\sigma$(13TeV)/$\sigma$(8TeV) = 2.5

When gg produces the resonance,

$\sigma$(13TeV)/$\sigma$(8TeV) = 4.5

$\sigma$(8TeV) should be < 1—2fb!

while

$\sigma$(13TeV) of 4—5fb is required.

The resonance seems to be produced by the gluon fusion in this case!

↓

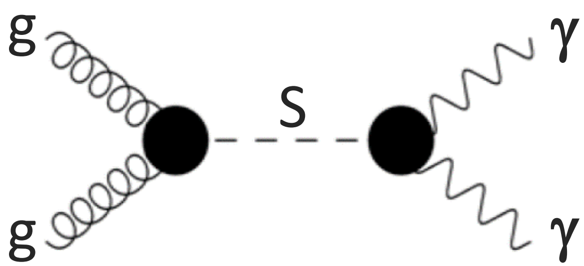
Production cross section of the diphoton process is simply given by

Scaler case:

$$\sigma(pp \to S \to \gamma\gamma) \sim 5 \times 10^6\, K\, \frac{\Gamma(S \to gg)}{\Gamma_{\rm tot}} \frac{\Gamma(S \to \gamma\gamma)}{m_S}\ \mathrm{fb}$$

# The excess @ 750GeV

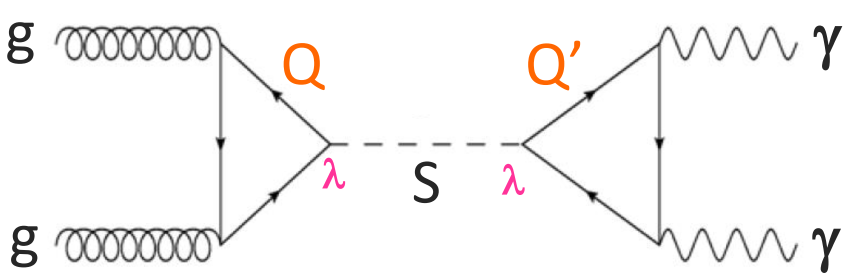
**The cross section is rephrased by a diagram or effective interactions.**




$$\mathcal{L}_{\rm int} = \frac{C_{BB}}{\Lambda} S\, B_{\mu\nu} \overset{(\sim)}{B}{}^{\mu\nu} + \frac{C_{WW}}{\Lambda} S\, W^a_{\mu\nu} \overset{(\sim)}{W}{}^{a\mu\nu} + \frac{C_{GG}}{\Lambda} S\, G^a_{\mu\nu} \overset{(\sim)}{G}{}^{a\mu\nu}$$

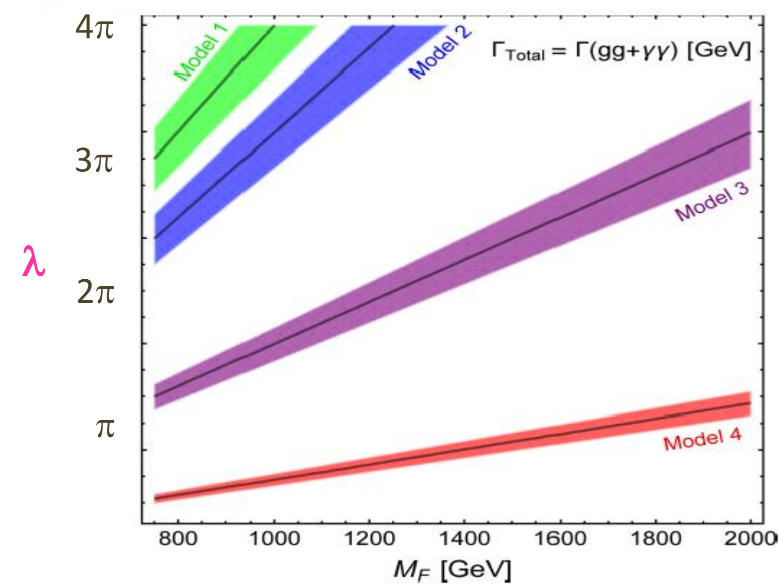
**Which fundamental physics gives the interactions?**

**For example, a naive answer is …**




**New particles (Q, Q' ) could be**

- ✓ Vector-like quarks
- ✓ Charged scalars
- ✓ Massive gauge bosons, …




1: $Q = Q' = (3, 1)_{3/2}$

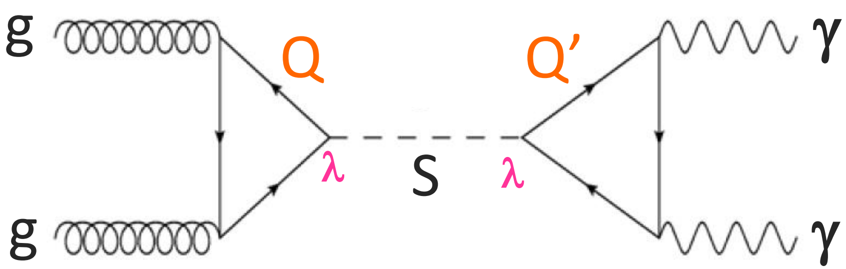
2: $Q = Q' = (3, 2)_{1/6}$

3: $Q = Q' = (3,1)_{3/2} + (3,1)_{-1/3} + (3,2)_{1/6}$

4: $Q = Q' = \text{Model } 3 + (1,1)_{-1} + (1,2)_{-1/2}$

# Fermion bound state for Excess

**The scalar particle S does not have to be introduced, for Q is colored!**

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$$\mathcal{L}_X = \bar{X}(i\not{D} - m_X)X$$

$$D_\mu = \partial_\mu + i g_s (\lambda^a/2) G^a_\mu + i g' Y_X B_\mu$$

**$SU(2)_L$ singlet!**

## About $^1S_0$ bound states

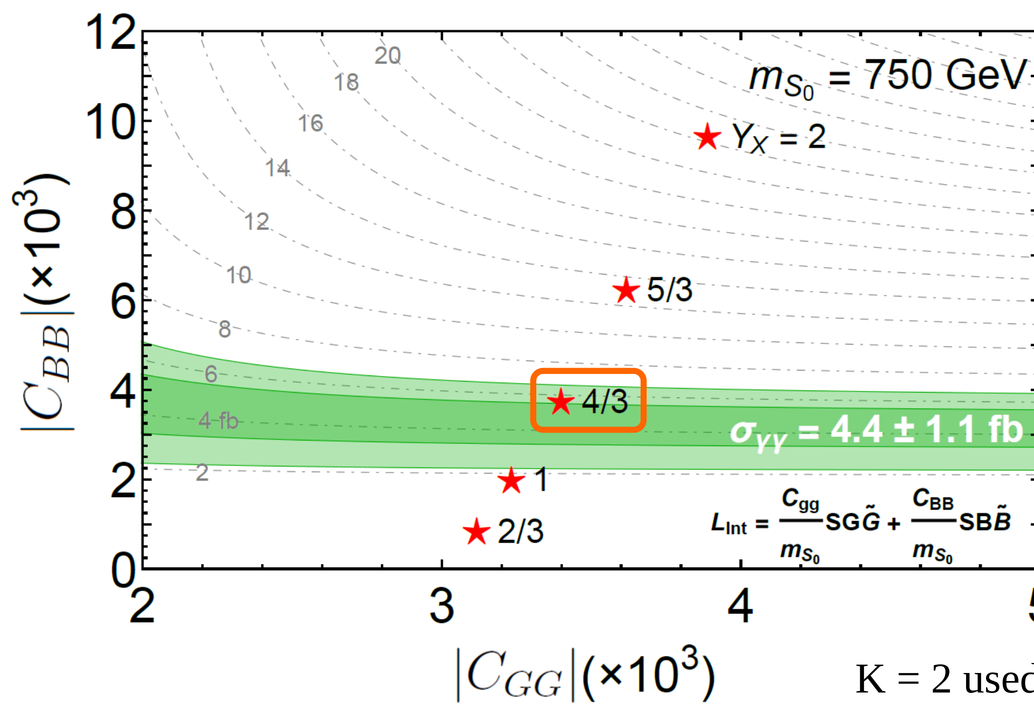
$$|C_{BB}| = (8\sqrt{3}\,\pi\, Y_X^2\, \alpha / c_W^2)\,(|\psi_0(0)|/m_{S_0}^{3/2})$$

$$|C_{GG}| = (4\,\pi\,\alpha_s/\sqrt{3})\,(|\psi_0(0)|/m_{S_0}^{3/2})$$

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

$$V(\boldsymbol{r}) = -Y_X^2 \frac{\alpha}{|\boldsymbol{r}|} + V_{\rm QCD}(|\boldsymbol{r}|)$$

[K. Hagiwara, K. Kato, A. D. Martin, C. K. Ng, NPB344 1990]




K = 2 used.

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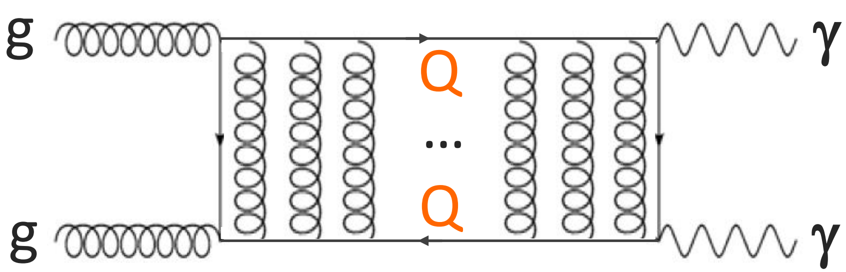


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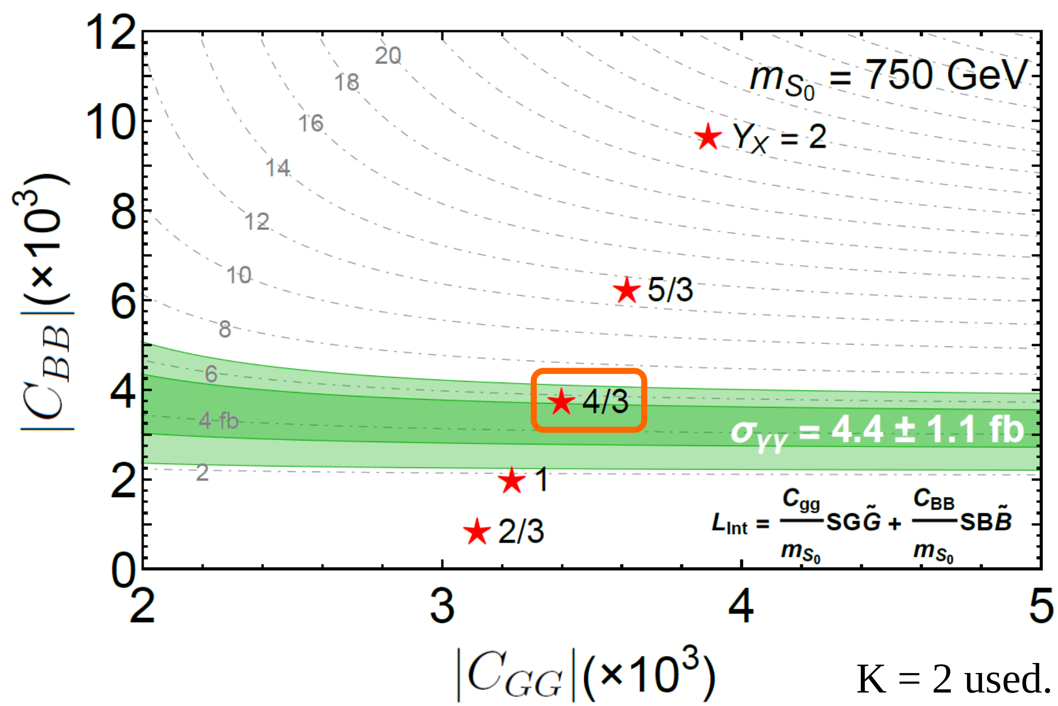


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# Constraints on the Scenario

*Are there some constraints from other decay modes of bound states?*

| @8TeV | Prediction | Limit |
|---|---|---|
| $S_0 \to Z\gamma$ | 0.74 fb | 4.0 fb |
| $\to ZZ$ | 0.11 fb | 12 fb |
| $S_1 \to \ell^+\ell^-$ | 0.13 fb | 1.2 fb |
| $\to \tau^+\tau^-$ | 0.064 fb | 12 fb |
| $\to t\bar{t}$ | 0.072 fb | 550 fb |
| $\to b\bar{b}$ | 0.021 fb | 1 pb |
| $S_0 + S_1 \to jj$ | 7 fb | 2.5 pb |

$S_0$ = Colorless para-quarkonium
$S_1$ = Colorless ortho-quarkonium

$S_1$ is produced from $q\bar{q}$ collisions and decays mainly into fermions.

No color octet bound states exist, for QCD gives a repulsive force.

*Is there a constraints from direct X searches?* *It depends on X decay!*

Quantum numbers of $X = (3, 1)_{4/3}$

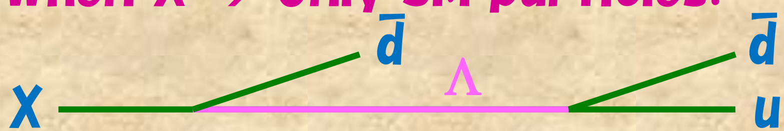
↓

Its decay must be described by higher dimensional operators.

↓

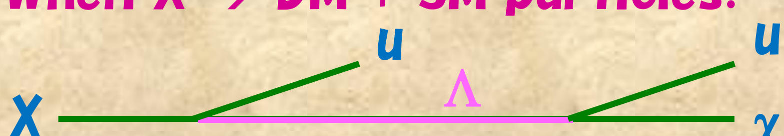
The width will be suppressed.
[It is phenomenologically nice, otherwise $S_0$ is very unstable.]

When X → Only SM particles:




Operator $\sim X\, u^c\, d\, d/\Lambda^2$

When X → DM + SM particles:




Operator $\sim X\, u^c\, u^c\, \chi/\Lambda^2$

# Constraints on the Scenario

✓ When $\Delta m = m_X - m_\chi$ is large enough, we have the following signal:

$pp \to XX \to (j\, j\, \chi)\, (j\, j\, \chi)$ [Multi-jet + ETmiss]

$m_X$ = 375GeV has been ruled out when $\Delta m >$ about one hundred GeV.

8TeV LHC: [The ATLAS collaboration, arXiv:1507.05525.]
13TeV LHC: [The ATLAS collaboration, ATLAS-CONF-2015-062.]

✓ When $\Delta m = m_X - m_\chi$ is small enough, we have the following signal:

$pp \to XXj_{ISR} \to (j\, j\, \chi)\, (j\, j\, \chi)\, j_{ISR}$ [Mono-jet + ETmiss]

$m_X$ = 375GeV has been ruled out when $\Delta m <$ a few tens of GeV.

8TeV LHC: [The ATLAS collaboration, PRD90, 052008 (2014).]
8TeV LHC: [The ATLAS collaboration, EPJ C75, 299 (2014).]
13TeV LHC: [The ATLAS collaboration, ATLAS-CONF-2015-062.]

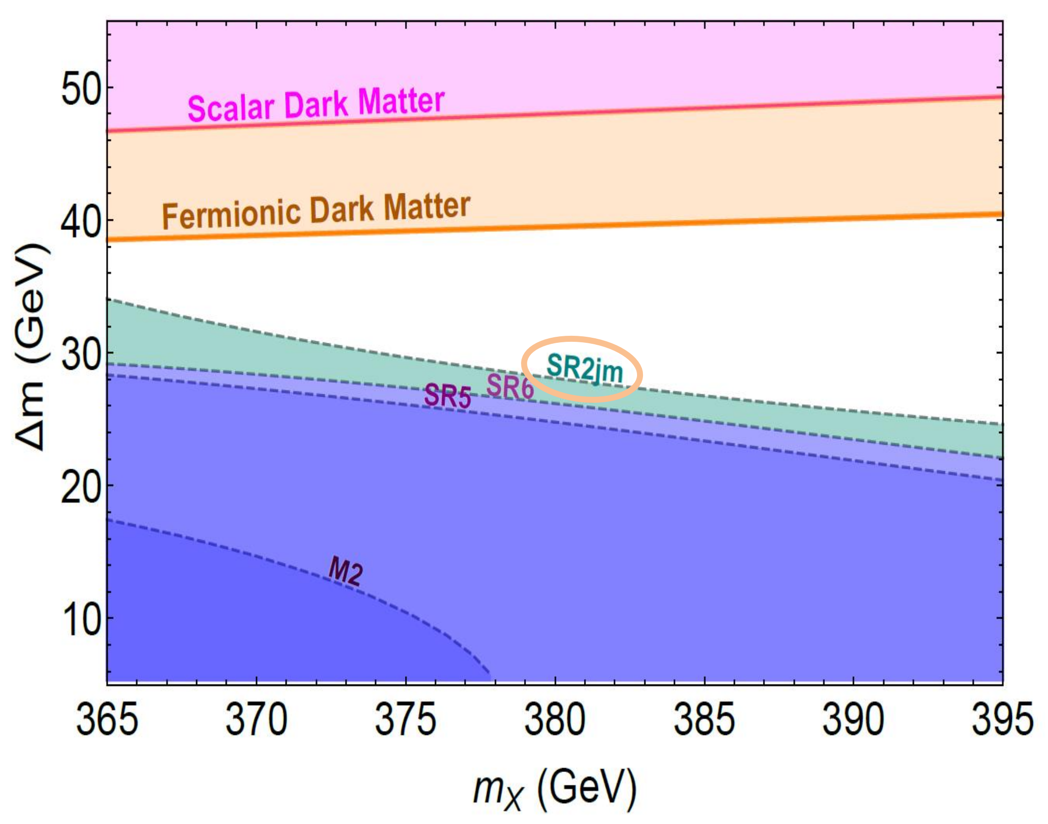
✓ When $\Delta m = m_X - m_\chi$ is large, we have a cosmological constraint:

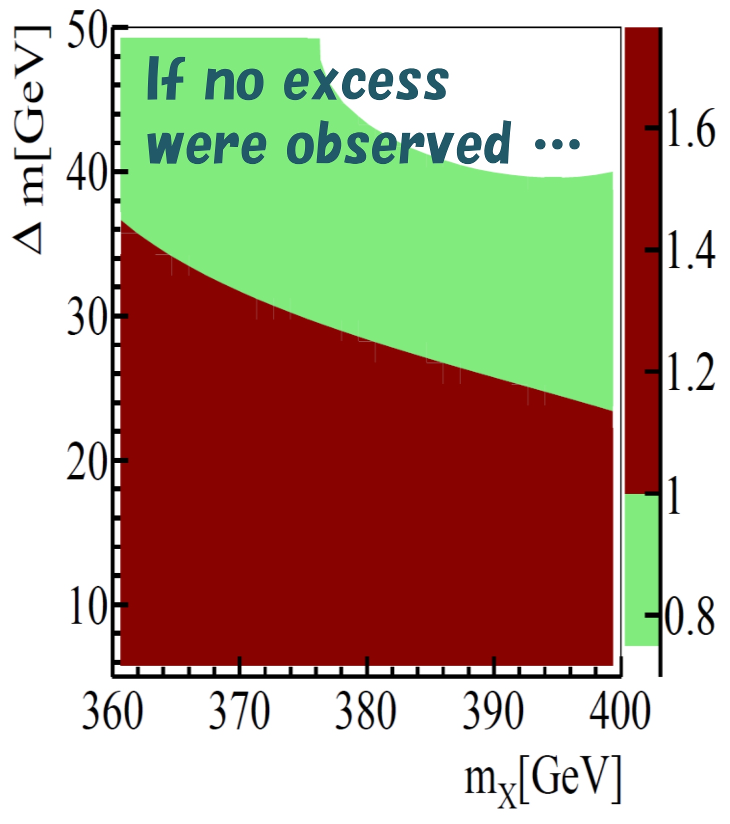
$\Omega_{DM}h^2 \propto 1/\langle\sigma_{eff}v\rangle$ & $\langle\sigma_{eff}v\rangle \propto \mathrm{Exp}(-2\Delta m/T_f)$ with $T_f \sim m_X/25$.

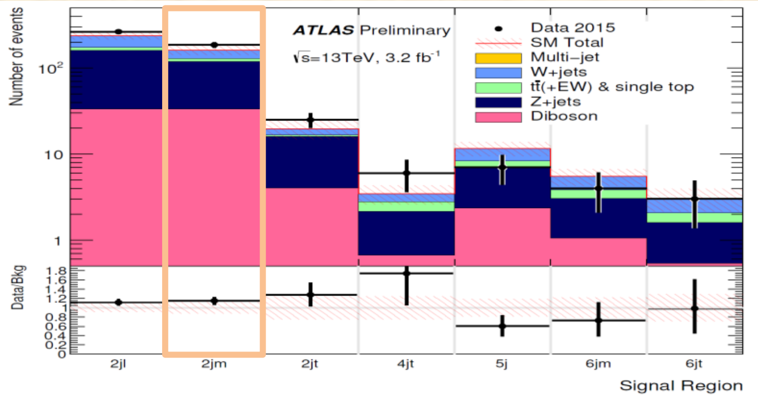
This is because $\chi$ does not have any renormalizable interactions.

Coannihilation: [K. Griest and D. Seckel, PRD43, 3191 (1991).]

# Constraints on the Scenario




| Signal Region | 2jl | 2jm | 2jt | 4jt | 5j | 6jm | 6jt |
|---|---|---|---|---|---|---|---|
| MC expected events | | | | | | | |
| Diboson | 33 | 33 | 4.0 | 0.7 | 2.4 | 1.1 | 0.5 |
| $Z/\gamma^*$+jets | 151 | 94 | 12 | 1.8 | 4.9 | 2.5 | 1.3 |
| W+jets | 72 | 42 | 4.5 | 0.9 | 3.0 | 1.6 | 0.9 |
| $t\bar{t}$(+EW) + single top | 18 | 17 | 1.2 | 0.9 | 2.7 | 1.6 | 1.1 |
| Multi-jet | 0.6 | 0.8 | 0.03 | – | – | – | – |
| Total MC | 275 | 188 | 22 | 4.3 | 13 | 6.7 | 3.8 |
| Fitted background events | | | | | | | |
| Diboson | 33 ± 17 | 33 ± 17 | 4.0 ± 2.0 | 0.67 ± 0.35 | 2.4 ± 1.3 | 1.1 ± 0.6 | 0.5 ± 0.4 |
| $Z/\gamma^*$+jets | 127 ± 12 | 85 ± 8 | 12 ± 4 | 1.5 ± 0.6 | 4.5 ± 1.3 | 2.0 ± 0.7 | 1.1 ± 0.6 |
| W+jets | 61 ± 4 | 32 ± 5 | 2.9 ± 0.8 | 0.7 ± 0.4 | 3.3 ± 1.0 | 1.7 ± 0.7 | 1.0 ± 0.6 |
| $t\bar{t}$(+EW) + single top | 14.6 ± 2.9 | 10.5 ± 2.6 | 0.7 ± 0.5 | 0.6 ± 0.4 | 1.4 ± 0.5 | 0.8 ± 0.4 | 0.46 ± 0.33 |
| Multi-jet | 0.51 ± 0.06 | 0.6 ± 0.5 | – | – | – | – | – |
| Total bkg | 237 ± 22 | 163 ± 20 | 20 ± 5 | 3.5 ± 0.8 | 11.7 ± 2.2 | 5.5 ± 1.2 | 3.1 ± 0.9 |
| Observed | 264 | 186 | 25 | 6 | 7 | 4 | 3 |
| $\langle\epsilon\sigma\rangle^{95}_{obs}$ [fb] | 24 | 21 | 5.9 | 2.5 | 2.0 | 1.6 | 1.6 |
| $S^{95}_{obs}$ | 76 | 67 | 19 | 8.2 | 6.3 | 5.3 | 5.0 |
| $S^{95}_{exp}$ | $52^{+22}_{-15}$ | $46^{+19}_{-12}$ | $14.1^{+5.1}_{-3.1}$ | $5.7^{+2.2}_{-1.6}$ | $8.5^{+3.3}_{-2.1}$ | $6.5^{+2.5}_{-1.6}$ | $5.0^{+2.3}_{-1.4}$ |
| $p_0$ (Z) | 0.11 (1.20) | 0.12 (1.15) | 0.18 (0.93) | 0.14 (1.08) | 0.5 (0.0) | 0.5 (0.0) | 0.5 (0.0) |

# Summary

- ✓ Non-relativistic bound state can be responsible for the diphoton excess at 750GeV. Considering the color triplet fermion which is singlet under $SU(2)_L$, its hypercharge $Y_X$ is suggested to be 4/3 by the strength of the excess, though some uncertainties remain.
- ✓ Such an exotic hypercharge $Y_X$ makes the constituent fermion X unstable through higher dimensional operators. In spite of this exotic nature, it is phenomenologically nice, since otherwise the strength of the diphoton signal would be much weaker.
- ✓ Decay scenario of X into a dark matter and some SM particles is interesting, for it is consistent with cosmology and all LHC data. It survives thanks to a small excess in the X search at 13TeV!