Higgs singlet as a diphoton resonance in a vector-like quark model

Takaaki Nomura (KIAS)

Based on : Chuan-Hung Chen, T. N. arXiv:1512.06028 and work in progress

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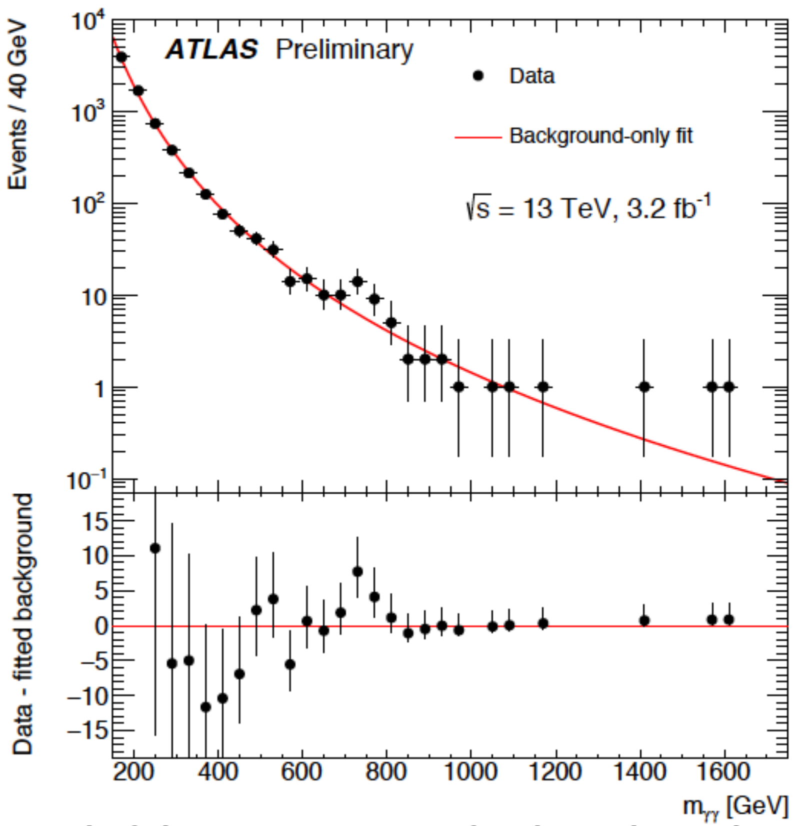
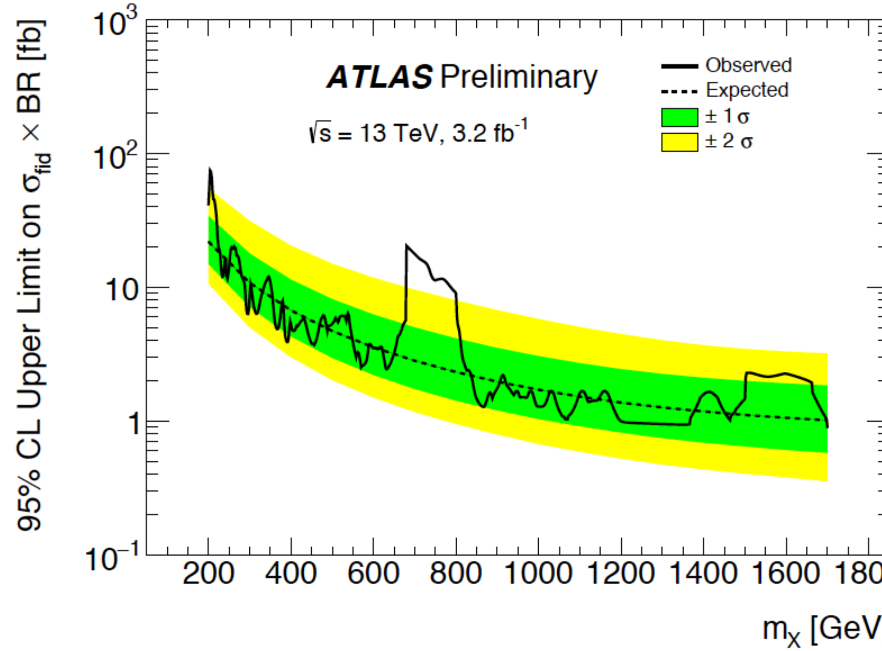
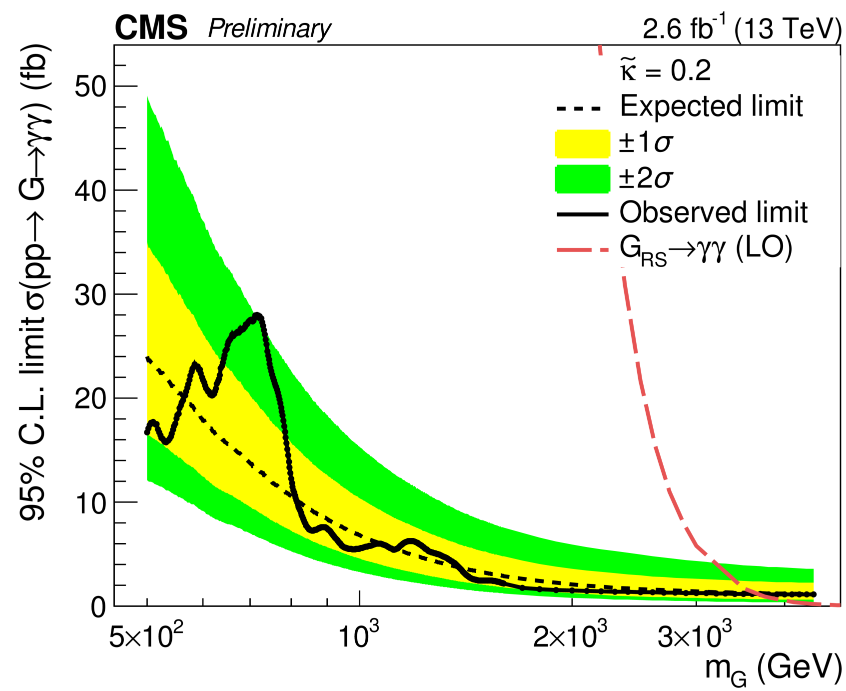
1. Introduction
2. A model & diphoton excess
3. Checking constraint
4. VLQ production
5. Summary

Diphoton excess at 750 GeV





ATLAS-CONF-2015-081, CMS-PAS-EXO-15-004



Both ATLAS and CMS observed bump on diphton invariant mass distribution

3.6 σ : ATLAS
2.6 σ : CMS

(Local significance)

How we can interpret the diphoton excess?

- It could be new particle : spin 0 or 2

  - **Let us consider scalar particle S with m_S = 750 GeV**

- Cross section to produce a new particle S

$$\sigma(pp \to S)BR(S \to \gamma\gamma) \approx 3-10 \text{ fb}$$

- Width of S?

  Best fit value by ATLAS : Γ~45 GeV

  CMS : Narrow width is preffered

- S → other modes : not observed

  ➡ BRs of S are constrained

Properties of the diphoton excess

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[6, 7]	$< 0.8\ (r/5)$
$e^+e^- + \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[8]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	15 fb	[9]	$< 6\ (r/5)$
$Z\gamma$	< 4.0 fb	< 3.4 fb	[10]	$< 2\ (r/5)$
ZZ	< 12 fb	< 20 fb	[11]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[12]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[13]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[14, 15]	$< 20\ (r/5)$
$t\bar{t}$	< 550 fb	-	[16]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[17]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[18]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[5]	$< 1300\ (r/5)$

$$r = \sigma_{13TeV} / \sigma_{8TeV}$$

$$\Gamma / M \approx 0.06$$

From Table 1 of arXiv:1512.04933 (Franceschini et. al.)

- S → other modes : not observed

⇒ BRs of S are constrained

We consider a simple scenario to explain the excess

SM+Vector-like triplet quarks(VLTQ) + scalar singlet(S)

SU(2)

Our strategy

- **S does not mix with SM Higgs**
- **gg→S and S→γγ are induced by VLTQ loop**
- **VLTQs are heavy as O(1) TeV : S does not decay into them**
- **Sizable Yukawa coupling of S and VLTQ enhance the process**
- **Two triplet give # of quark = 6 → enhance Sgg and Sγγ coupling**

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Our Model

SM + vector-like triplet quarks (F_1,F_2)+singlet scalar (S)

VLTQ

F_1 : (3,3)(2/3), F_2 : (3,3)(-1/3) {(SU(3),SU(2))(U(1)$_Y$)}

$$F_1 = \begin{pmatrix} U_1/\sqrt{2} & X \\ D_1 & -U_1/\sqrt{2} \end{pmatrix}, \quad F_2 = \begin{pmatrix} D_2/\sqrt{2} & U_2 \\ Y & -D_2/\sqrt{2} \end{pmatrix}$$

$\left(\begin{array}{l} Q_X = 5/3 \\ Q_Y = -4/3 \end{array} \right)$

(Y.Okada, L.Panizzi (2013))

Yukawa couplings of VLTQ

$$L_{VLTQ}^{Yukawa} = Y_1 \bar{Q}_L F_{1R} \tilde{H} + Y_2 \bar{Q}_L F_{2R} H + y_1 Tr(\bar{F}_{1L} F_{1R}) S + y_2 Tr(\bar{F}_{2L} F_{2R}) S + h.c.$$

Our Model

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Q_X=5/3
Q_Y=-4/3

(Y.Okada, L.Panizzi (2013))

Yukawa couplings of VLTQ

$$L^{Yukawa}_{VLTQ} = \underline{Y_1 \bar{Q}_L F_{1R} \tilde{H} + Y_2 \bar{Q}_L F_{2R} H} + \underline{y_1 Tr(\bar{F}_{1L} F_{1R}) S + y_2 Tr(\bar{F}_{2L} F_{2R}) S} + h.c.$$

gg →S and S→γγ

It induces decay of F_i & mixing of VLQ and SM quarks

*We assume Z_2: S→-S, F_{iL}→-F_{iL} to forbid S-H mixing (softly broken by F mass term)

Gauge interactions of VLTQs

$$L_{VFF}=-g\left[(\bar{X}\gamma^{\mu}U_1+\bar{U}_1\gamma^{\mu}D_1+\bar{D}_2\gamma^{\mu}Y+\bar{U}_2\gamma^{\mu}D_2)W_{\mu}^{+}+h.c.\right]$$
$$-\left[\frac{g}{c_W}\bar{F}_1\gamma^{\mu}(T^3-s_W^2Q_1)F_1+e\bar{F}_1\gamma^{\mu}Q_1F_1A_{\mu}+(F_1\to F_2,Q_1\to Q_2)\right]$$

$$F_1^T=(X,U_1,D_1);\ \ F_2^T=(U_2,D_2,Y)$$

❖ Isospin of VLTQ is different from the SM quarks

➡ Z-mediated FCNC is induced since CKM matrix is not unitary

$$\mathcal{L}_{Wud}=-\frac{g}{\sqrt{2}}\bar{u}_L\gamma^{\mu}V_{\rm CKM}^{L}d_LW_{\mu}^{+}-\frac{g}{\sqrt{2}}\bar{u}_R\gamma^{\mu}V_{\rm CKM}^{R}d_RW_{\mu}^{+}+h.c.$$
$$\mathcal{L}_{Zqq}=-\frac{g}{c_W}C_{ij}^{q_L}\bar{q}_{iL}\gamma^{\mu}q_{jL}Z_{\mu}-\frac{g}{c_W}C_{ij}^{q_R}\bar{q}_{iR}\gamma^{\mu}q_{jR}Z_{\mu}$$

$$C_{ij}^{q_L}=(I_3-s_W^2Q_q)\delta_{ij}+\frac{1}{2}\left(-V_{Li4}^{q}V_{Lj4}^{q*}+V_{Li5}^{q}V_{Lj5}^{q*}\right)$$
$$C_{ij}^{q_R}=-s_W^2Q_q\delta_{ij}+\epsilon_q(V_R^q)_{i\alpha_q}(V_R^{q*})_{\alpha_q j}$$

$$V_{\rm CKM}^{L}=V_L^u\left(\begin{array}{c|c}(V_{\rm CKM})_{3\times3} & 0_{3\times2}\\ \hline 0_{2\times3} & \sqrt{2}\mathbb{1}_{2\times2}\end{array}\right)V_L^{d\dagger}\quad V_{\rm CKM}^{R}=V_R^u\left(\begin{array}{c|c}0_{3\times3} & 0_{3\times2}\\ \hline 0_{2\times3} & \sqrt{2}\mathbb{1}_{2\times2}\end{array}\right)V_R^{d\dagger}$$

Gluon fusion and decay modes of S

Gluon fusion and decay of S via VLTQ loop

gg → S → VV

$$L_{sgg} = \frac{\alpha_s}{8\pi}\left(\sum_{F_i}\frac{3y_i}{2m_{F_i}}A_{1/2}(\tau_{F_i})\right)\phi G^{a\mu\nu}G^a_{\mu\nu}$$

Decay widths

$$\Gamma(S \to gg) = \frac{\alpha_s^2 m_S^3}{32\pi^3}\left|\sum_i \frac{y_i}{2m_{F_i}}A_{1/2}(\tau_i)\right|^2$$

$$\left(\tau_i = \frac{4m_{F_i}^2}{m_S^2}\right)$$

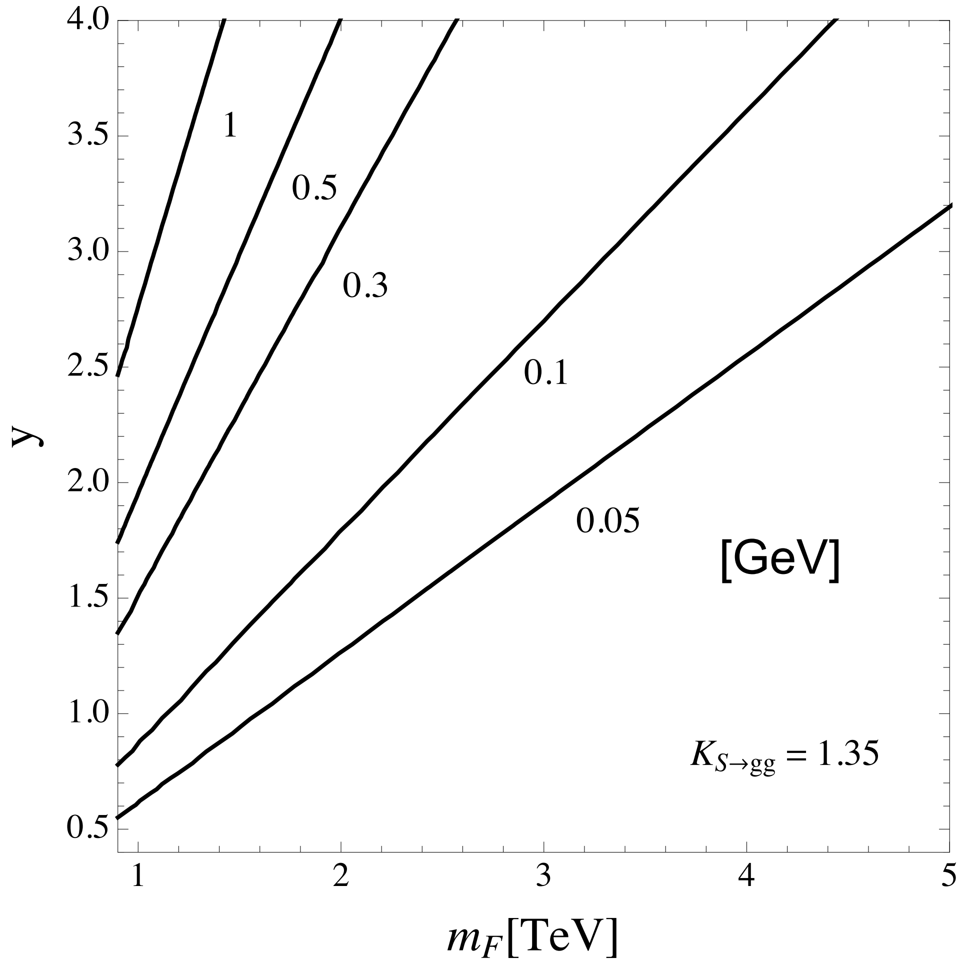
$$\Gamma(S \to \gamma\gamma) = \frac{\alpha^2 m_S^3}{256\pi^3}\left|\sum_i \frac{3y_i Q_{F_i}^2}{m_{F_i}}A_{1/2}(\tau_i)\right|^2$$

$$\Gamma(S \to Z\gamma) = \frac{9m_S^3}{32\pi^3}\left|A_F\right|^2\left(1-\frac{m_Z^2}{m_S^2}\right)^3$$

$$\Gamma(S \to WW) = \frac{\alpha^2 m_S^3}{256\pi^3}\left|\sum_i \frac{6y_i}{m_{F_i}s_W^2}A_{1/2}(\tau_i)\right|^2$$

$$\Gamma(S \to ZZ) = \frac{\alpha^2 m_S^3}{256\pi^3}\left|\sum_i \frac{3y_i(T_{F_i}^3 - s_W^2 Q_{F_i})^2}{m_{F_i}s_W^2 c_W^2}A_{1/2}(\tau_i)\right|^2$$

Total decay width of S and BR



$$BR(S \to gg) \approx 0.67$$

$$BR(S \to W^+W^-) \approx 0.15$$

$$BR(S \to ZZ) \approx 0.095$$

$$BR(S \to Z\gamma) \approx 0.039$$

$$BR(S \to \gamma\gamma) \approx 0.017$$

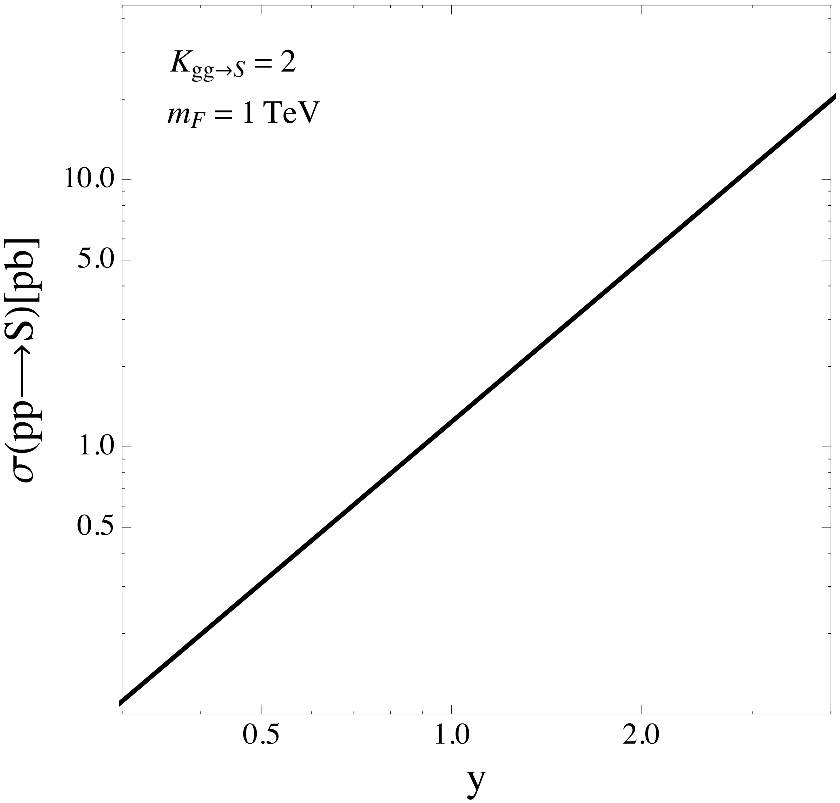
$$\left(\begin{array}{l} BR(S \to hh) \approx 0.007 \\ BR(S \to t\bar{t}\,) \approx 0.018 \end{array} \right)$$

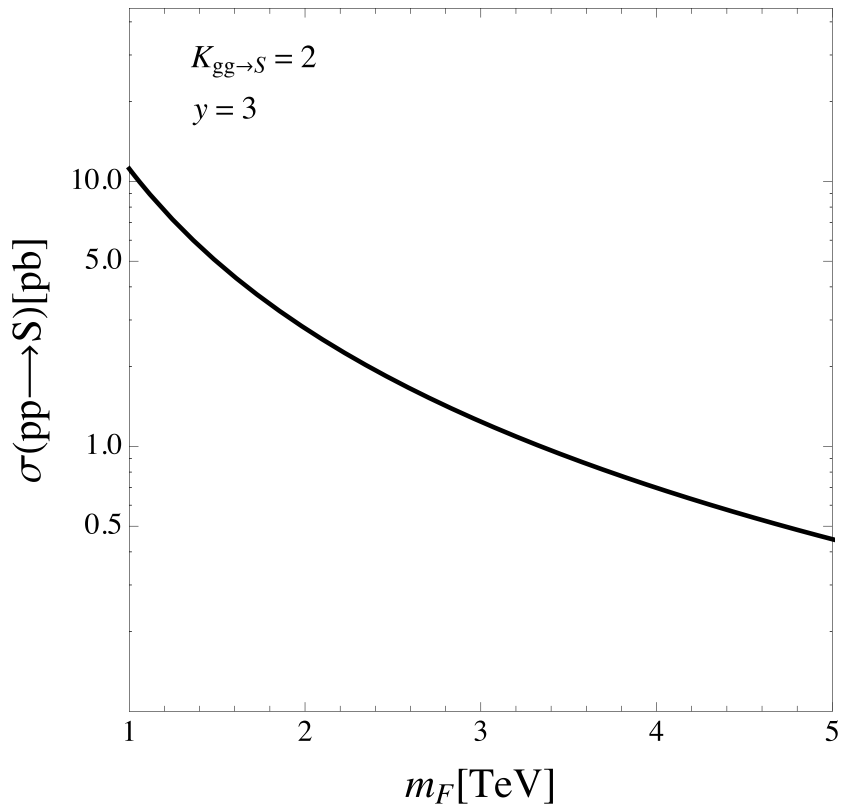
- The with is mostly less than 1 GeV : narrow width
- BRs are almost independent of VLTQ mass

$K_{s\to gg}$=1.35

(Djouadi Phys. Rep. 457, 1)

Gluon fusion production cross section at 13 TeV





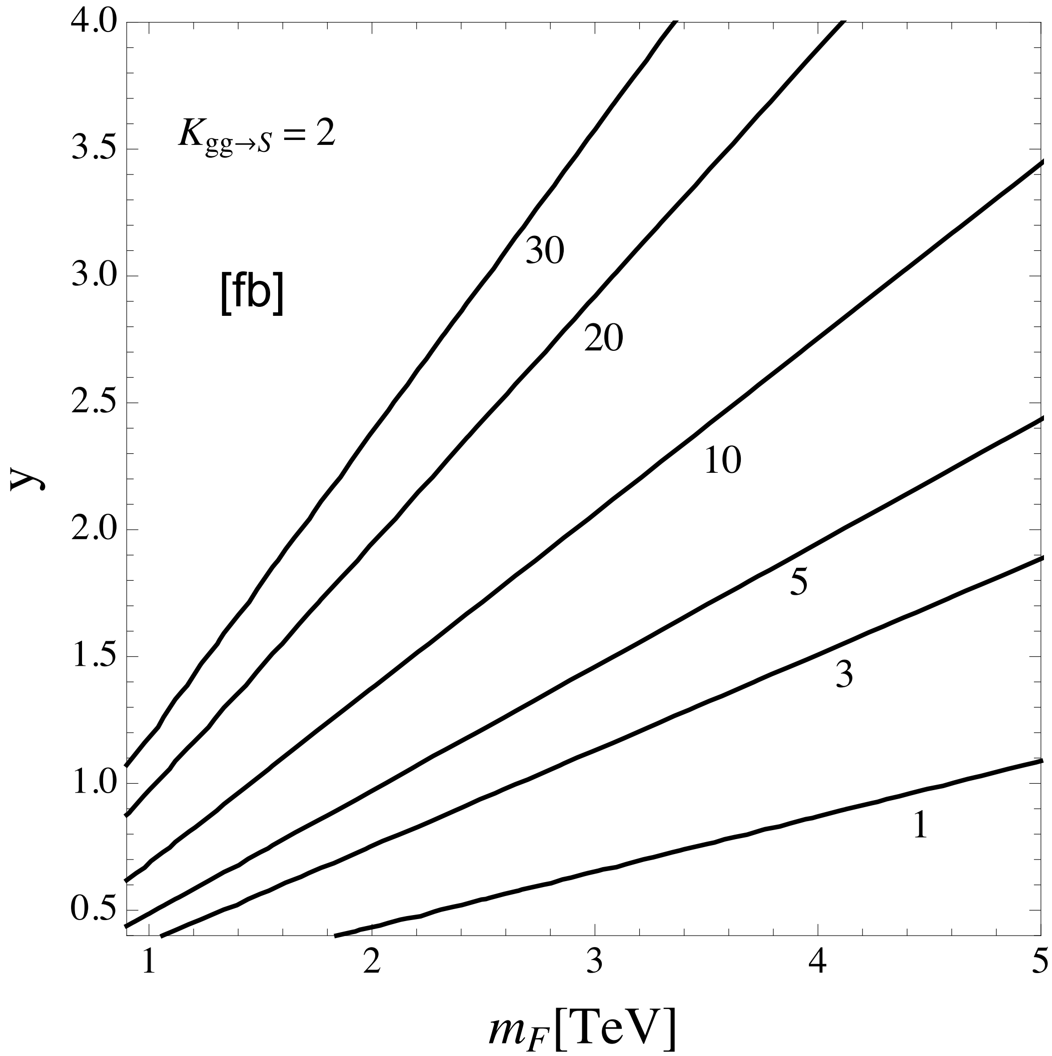
- **The VLTQ masses are universal for simplicity**
- **Cross section is estimated with CalcHEP**
- **The cross section can be O(1) pb with O(1) Yukawa**

$K_{gg\to s}=1.35$

(Djouadi Phys. Rep. 457, 1)

2.Model & diphoton excess

$\sigma(gg\to S)\times BR(S\to\gamma\gamma)$



~5 fb cross section is possible with O(1) TeV m_F and O(1) Yukawa couling

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Checking constraints: 8TeV data

final state f	σ at $\sqrt{s}=8$ TeV observed	expected	ref.
$\gamma\gamma$	<1.5 fb	<1.1 fb	[6, 7]
$e^+e^- + \mu^+\mu^-$	<1.2 fb	<1.2 fb	[8]
$\tau^+\tau^-$	<12 fb	15 fb	[9]
$Z\gamma$	<4.0 fb	<3.4 fb	[10]
ZZ	<12 fb	<20 fb	[11]
Zh	<19 fb	<28 fb	[12]
hh	<39 fb	<42 fb	[13]
W^+W^-	<40 fb	<70 fb	[14, 15]
$t\bar{t}$	<550 fb	-	[16]
invisible	<0.8 pb	-	[17]
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[18]
jj	$\lesssim 2.5$ pb	-	[5]

From Table 1 of arXiv:1512.04933

$$\sigma(gg \to S)_{13TeV} BR(S \to \gamma\gamma) \approx 6\,fb$$

$BR(S \to \gamma\gamma) \approx 0.017$

$$\Rightarrow \sigma(gg \to S)_{13TeV} \approx 350\,fb$$

$$\left[\ \sigma(gg \to S)_{13TeV} / \sigma(gg \to S)_{8TeV} \approx 5\ \right]$$

$$\sigma(gg \to S)_{8TeV} BR(S \to gg) \approx 49\,fb$$

$$\sigma(gg \to S)_{8TeV} BR(S \to W^+W^-) \approx 10\,fb$$

$$\sigma(gg \to S)_{8TeV} BR(S \to ZZ) \approx 7.0\,fb$$

$$\sigma(gg \to S)_{8TeV} BR(S \to Z\gamma) \approx 2.8\,fb$$

$$\sigma(gg \to S)_{8TeV} BR(S \to \gamma\gamma) \approx 1.2\,fb$$

Our scenario can satisfy all constraints!

$$\left(\begin{array}{l} BR(S \to gg) \approx 0.67 \\ BR(S \to W^+W^-) \approx 0.15 \\ BR(S \to ZZ) \approx 0.095 \\ BR(S \to Z\gamma) \approx 0.039 \\ BR(S \to \gamma\gamma) \approx 0.017 \end{array}\right)$$

Checking constraints: FCNC

❖ t→ch

$$\mathcal{L}_{hQq} = \frac{Y_{1i}}{\sqrt{2}}(v+h)\left(\frac{1}{\sqrt{2}}\bar{u}_{Li}U_{1R} + \bar{d}_{Li}D_{1R}\right) + \frac{Y_{2i}}{\sqrt{2}}(v+h)\left(\bar{u}_{Li}U_{2R} - \frac{1}{\sqrt{2}}\bar{d}_{Li}D_{2R}\right)$$

- SM Higgs mediated FCNC induces **t→(u,c)h**
- $\mathbf{Y_{11},Y_{21}}$ contribute to D-$\bar{\text{D}}$, K-$\bar{\text{K}}$, B_d-$\bar{B}_d$ mixing → we assume $\mathbf{Y_{11}=Y_{21}=0}$
- $\mathbf{Y_{12},Y_{13},Y_{22},Y_{23}}$: constrained by B_s-$\bar{B}_s$ mixing
- When we assume $\mathbf{Y_{12}\sim Y_{13}\sim Y_{22}\sim Y_{23}}$

$$\mathcal{L} = -C_{sb}\bar{s}P_R bh - \frac{m_t}{m_b}C_{sb}\bar{c}P_R th + H.c.$$

$$\left(C_{sb} = \frac{m_b}{4v}(2\zeta_{12}\zeta_{13} + \zeta_{22}\zeta_{23}) \quad \varsigma_{ij} = \frac{vY_{ij}}{m_F} \right)$$

- Assuming Δm_{Bs} =1.1688×10^{-11}GeV, we get $|C_{sb}|$<5.2×10^{-4} → ζ^2<0.036

$$\Gamma(t\to ch) = \frac{m_t}{32\pi}\left|\frac{m_t}{m_b}C_{bs}\right|^2\left(1-\frac{m_h^2}{m_t^2}\right)^2 \Rightarrow BR(t\to ch) < 1.1\times 10^{-4}$$

$$\Gamma_t = 1.41\ \text{GeV}$$

Checking constraints: h →γγ

Flavor mixing effect $\mathbf{Y_{1j}}$ and $\mathbf{Y_{2j}}$ contribute σ(gg→h)BR(h→γγ)

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to h)_{\text{VLTQ}}}{\sigma(pp \to h)_{\text{SM}}} \frac{BR(h \to \gamma\gamma)_{\text{VLTQ}}}{BR(h \to \gamma\gamma)_{\text{SM}}}$$
$$\approx \left|1 + \frac{3}{4}\zeta_{gg}\right|^2 \left|1 + \frac{N_c A_{1/2}(x_F)\zeta_{\gamma\gamma}}{A_1(x_W) + 4/3 A_{1/2}(x_t)}\right|^2$$

$$\zeta_{gg} = \zeta_{12}^2 + \zeta_{13}^2 + \zeta_{22}^2 + \zeta_{23}^2 \,,$$
$$\zeta_{\gamma\gamma} = \frac{Q_u^2 + 2Q_d^2}{4}(\zeta_{12}^2 + \zeta_{13}^2) + \frac{2Q_u^2 + Q_d^2}{4}(\zeta_{22}^2 + \zeta_{23}^2)$$

We assume $\zeta_{12}=\zeta_{13}=\zeta_{22}=\zeta_{23}=\zeta$

(*)

$$m_t, m_F >> m_h,\ x_W = 4m_W^2 / m_h^2,\ x_t = 4m_t^2 / m_h^2$$
$$x_F = 4m_F^2 / m_h^2,\ A_1(x_W) \approx -8.3,\ A_{1/2}(x_t) \approx 1.38$$

For $\zeta^2 < 0.036 \to \mu_{\gamma\gamma} < 1.18$

Consistent with LHC data

- $\mu_{\gamma\gamma} < 1.17 \pm 0.27$ (ATLAS)
- $\mu_{\gamma\gamma} < 1.13 \pm 0.24$ (CMS)

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Production of VLTQs at LHC 13 TeV

(work in progress)

Signature of our model: VLTQ production
VLTQ components: $U_{1,2}$, $D_{1,2}$, X, Y

→ X, Y production would be interesting

$$\varsigma_{11} = \varsigma_{21} = 0.02$$

$$\varsigma_{12} = \varsigma_{13} = \varsigma_{22} = \varsigma_{23} \equiv \varsigma = 0.2$$

❖X, Y pair production cross section

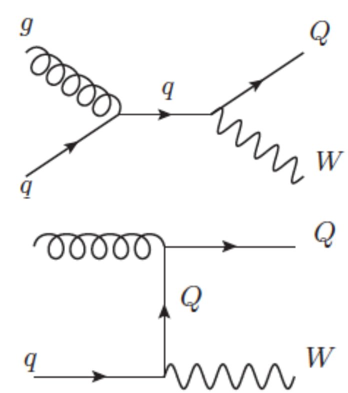
$Q = X_{5/3}, Y_{-4/3}$.

m_F [GeV]	800	900	1000	1100	1200
$\sigma(pp \to Q\bar{Q})$ [fb]	88	42	22	11	6

❖X, Y single production cross section via QCD process

TABLE III: Production cross section for $X_{5/3}W^-$ and $Y_{-4/3}W^+$ with various values of m_F, where $\sqrt{s} = 13$ TeV, $\zeta_{11,21} = 0.02$, and $\zeta = 0.2$ are used.

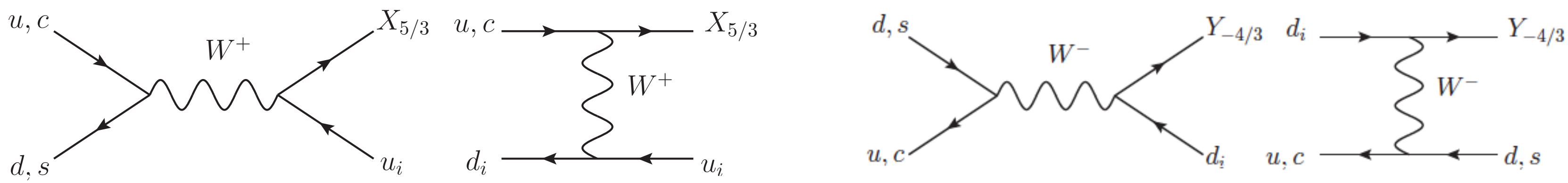
m_F [GeV]	800	900	1000	1100	1200
$\sigma(pp \to X_{5/3}W^-)$ [fb]	0.72	0.38	0.21	0.12	0.07
$\sigma(pp \to Y_{-4/3}W^+)$ [fb]	1.4	0.73	0.40	0.23	0.13



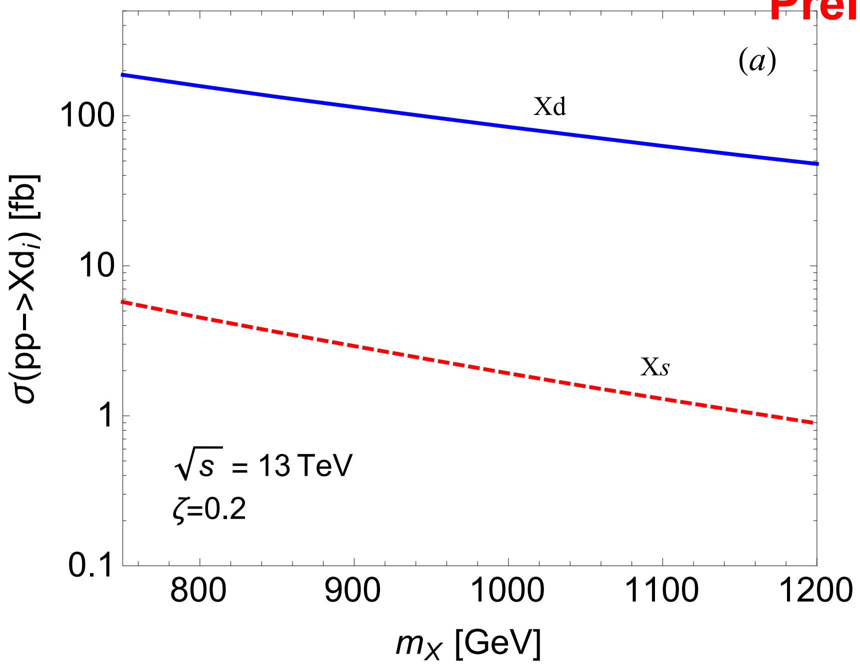
Production of VLTQs at LHC 13 TeV

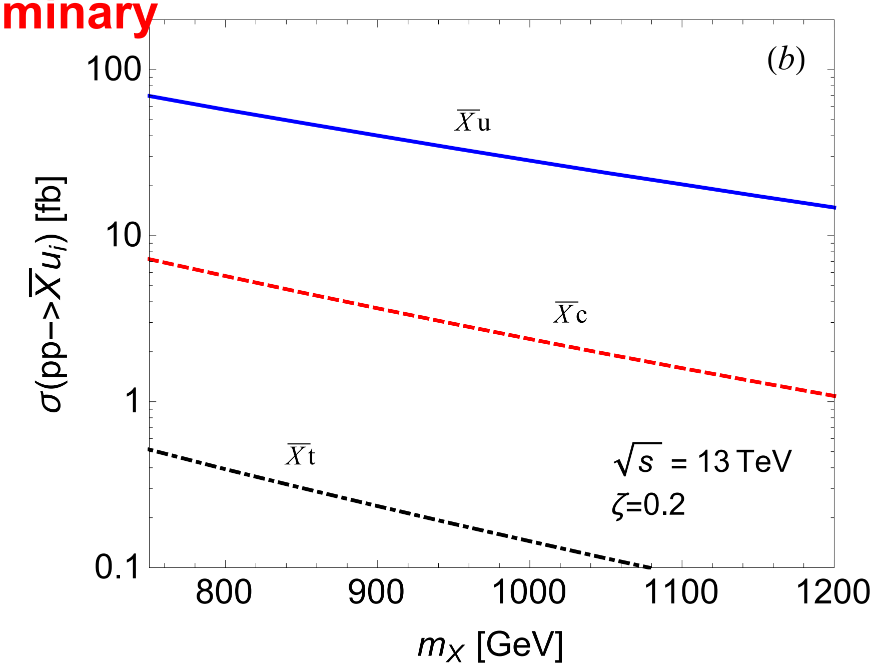
(work in progress)

❖X,Y single production through electroweak process



Preliminary



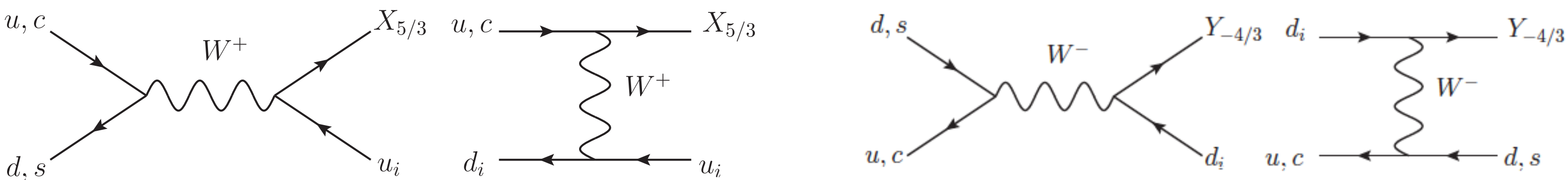


s, c initial states are also important
We find large cross section can be obtained

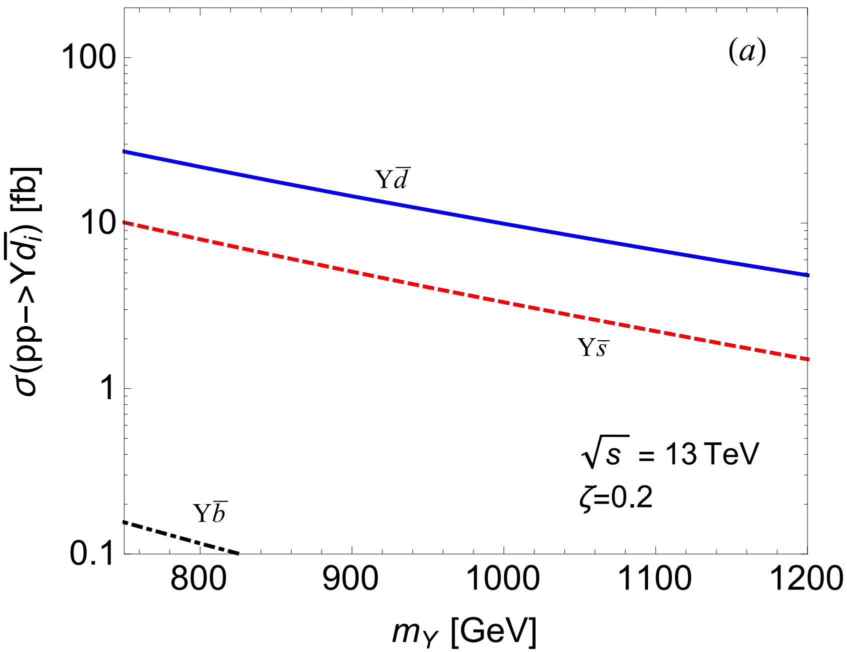
Production of VLTQs at LHC 13 TeV

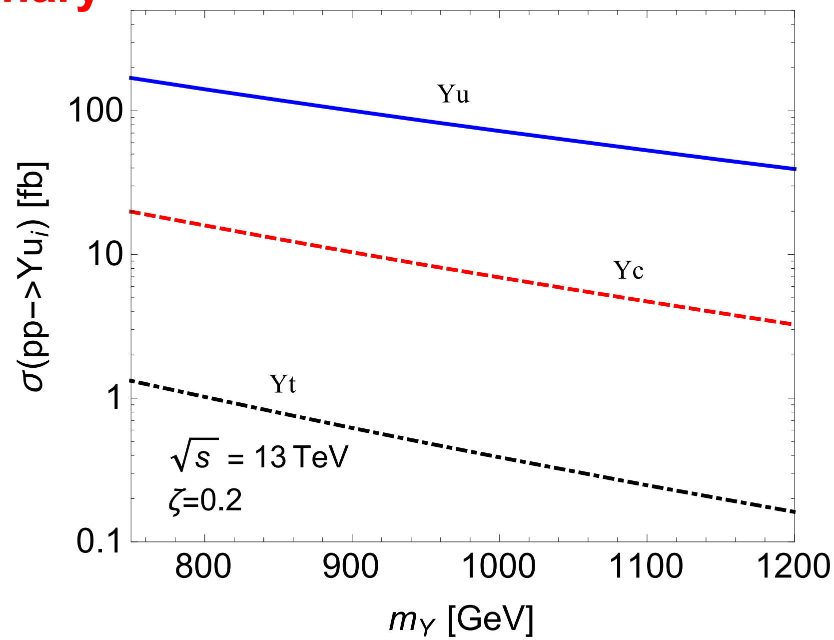
(work in progress)

❖X,Y single production through electroweak process



Preliminary





s, c initial states are also important

We find large cross section can be obtained

Summary and Discussions

- ✧ **Diphoton excess can be explained by singlet scalar + VLTQ**
- ✧ **Production and decay processes from one-loop**
- ✧ **Specific pattern of BRs**
- ✧ **It can be consistent with other experimental constraints**
- ✧ **Width of S is narrow in our model**
- ✧ **The model would be tested by searching for VLTQs**

Thank you !

Loop functions in the partial decay widths

$$A_{1/2}(\tau) = 2\tau[1+(1-\tau)(\sin^{-1}(1/\sqrt{\tau}))^2] \quad (\tau \geq 1)$$

$$A_F = \frac{\alpha}{2\pi s_W c_W} \sum \frac{-4 y_F Q_F}{m_F} (T_F^3 - s_W^2 Q_F)[I_1(\tau,\lambda) - I_2(\tau,\lambda)]$$

$$\tau_i = \frac{4m_{F_i}^2}{m_S^2}, \quad \lambda_i = \frac{4m_{F_i}^2}{m_Z^2}$$

$$\begin{aligned} I_1(a,b) &= \frac{ab}{2(a-b)} + \frac{a^2b^2}{2(a-b)^2}[f(a)^2 - f(b)^2] + \frac{a^2b}{(a-b)^2}[g(a)-g(b)]\,, \\ I_2(a,b) &= -\frac{ab}{2(a-b)}[f(a)^2 - f(b)^2]\,, \\ g(t) &= \sqrt{t-1}\sin^{-1}(1/\sqrt{t})\,. \end{aligned}$$