Probing the ultraviolet completion of the Twin Higgs

Ennio Salvioni

UC Davis

3rd NPKI Workshop

Korea University, Seoul

June 14, 2016

1606.xxxxx *with* **H.-C. Cheng** *and* **Y. Tsai**

+ 1512.02647 *with* **H.-C. Cheng, S. Jung** *and* **Y. Tsai**

… that is to say,

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750 GeV diphotons in Twin Higgs

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Introduction

- **Is the 750 GeV particle related to the stabilization of the weak scale?**

- Given absence of signals of colored top partners, the **Twin Higgs** seems compelling framework to think about this question

see talks by Michael and Chris, this session

- **Non-SUSY UV completions** contain the ingredients needed to explain the signal

  Well-defined setup with given particle content and couplings.

  Include constraints from all aspects of the model

- Goal: quantify the **tuning** needed to explain the diphoton signal

- 750 will be a **'twin quarkonium:'** learn some physics lessons of general applicability

The fraternal Twin Higgs

Craig, Katz, Strassler, Sundrum 2015

Minimal ingredients, motivated by naturalness

- Another Higgs doublet, global symmetry $SU(4) \xrightarrow{f} SU(3)$
- Twin top with Z_2 - symmetric Yukawa
- Twin electroweak gauge bosons with Z_2 - symmetric coupling
- Twin color gauged with $g_s \sim \hat{g}_s$ at high scale $\Lambda_{\rm UV} \lesssim 4\pi f$

Light fermions?

- A full mirror copy of the SM runs into trouble with cosmology (many light dof). Not required by naturalness

➡ **Include only twin 3rd generation**: top, bottom, tau and neutrino

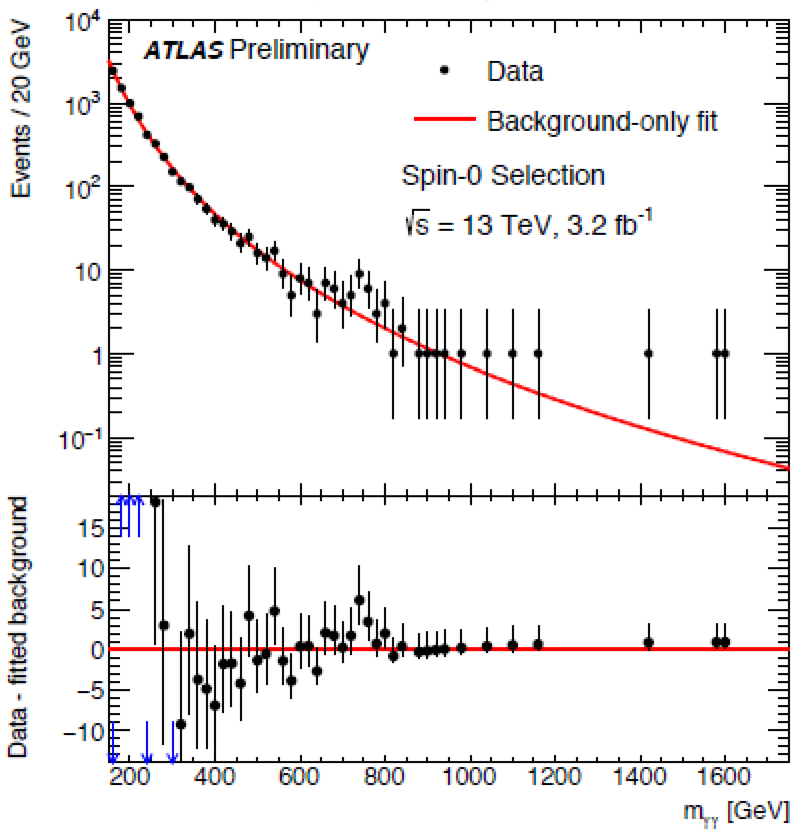
Observation of a SM-like Higgs requires $v_B \gg v_A$

Add small soft Z_2 breaking $\sim \mu^2 H_A^\dagger H_A \quad \rightarrow \quad$ 'irreducible' tuning $\sim \frac{v^2}{f^2}$

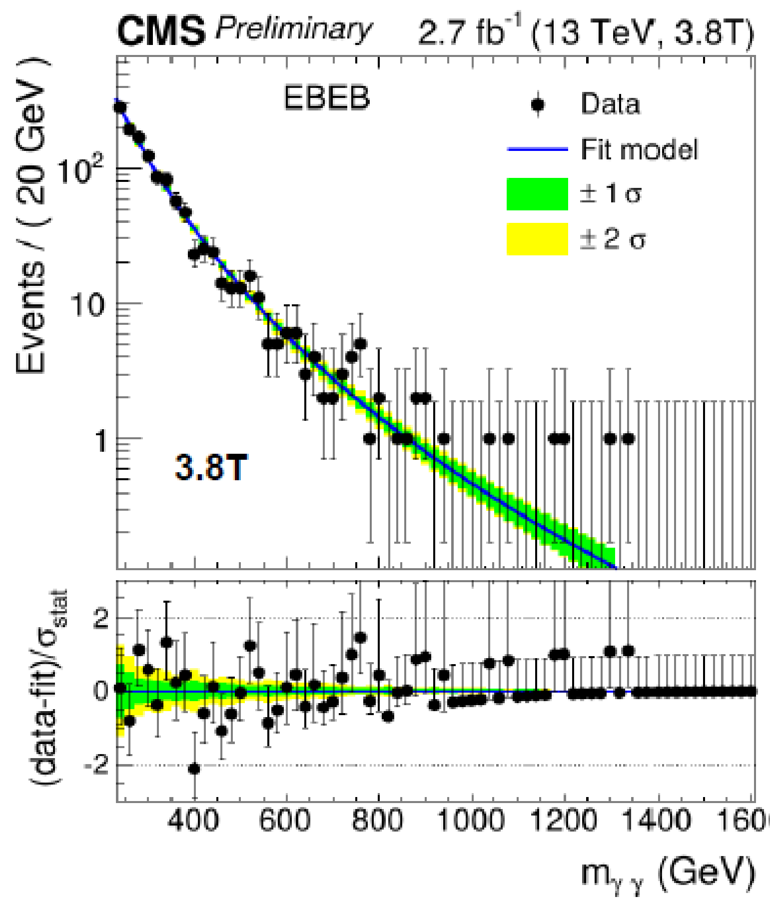
What is this?

SPIN-0 ANALYSIS

background-only fit



2878 events ($m_{\gamma\gamma}$ > 200 GeV)



see talk by Tobi yesterday, and:
Barak, D'Eramo, Elias-Miró, Halkiadakis, Kats, Matskedonskyi, Shadmi, Yu

Diphoton candidates in low-energy theory?

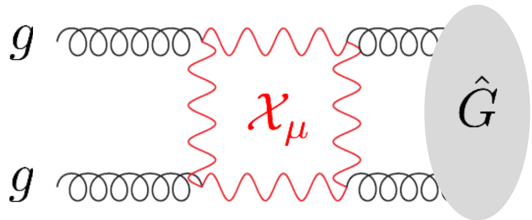
- **Twin Higgs (radial mode)** ?

  Unsuppressed decays to longitudinal gauge bosons/Higgses, hard to make diphoton BR large enough

- **Twin glueball** ?

  Best candidate is 0^{-+} , mass $\sim 10\,\Lambda$ ⇒ $\Lambda \sim 75\ \mathrm{GeV}$

  Production must go through loops of bi-fundamentals of color and twin-color, decay to photons also at loop



  Bifundamentals need to be very light, run into experimental constraints

  Also: lightest glueball is 0^{++} with mass ~ 500 GeV, must hide it

- … ?

UV completing the Twin Higgs

- Low-energy theory is incomplete: quartic couplings from top loops are log-divergent

$$\delta V = \frac{3y_t^4}{8\pi^2} \log \Lambda_{\rm UV} \left(|H_A|^4 + |H_B|^4\right)$$

In the full theory, cutoff must be replaced by physical mass thresholds.

- Proposal already in original Twin Higgs paper: extend the symmetry of top Yukawa to $\underbrace{SU(6)}_{\text{color}} \times \underbrace{SU(4)}_{\text{weak}}$

$$y_t \left(H_A^\dagger \quad H_B^\dagger\right) Q \begin{pmatrix} t_A \\ t_B \end{pmatrix},$$

SM $SU(3)$ twin $SU(3)$

$$Q = \begin{pmatrix} q_A & \tilde{q}_B \\ \tilde{q}_A & q_B \end{pmatrix}$$

SM $SU(2)$

twin $SU(2)$

Chacko, Goh, Harnik 2005

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SM *SU*(3) twin *SU*(3)

SM *SU*(2) twin *SU*(2)

Chacko, Goh, Harnik 2005

- **New fermions charged under both sectors**

They appear in **all** non-SUSY UV completions proposed so far

e.g.: Craig, Knapen and Longhi; Geller and Telem, Barbieri, Greco, Rattazzi and Wulzer; Low, Tesi and Wang

750 GeV as bound state of new fermions

$$Q = \begin{pmatrix} q_A & \tilde{q}_B \\ \tilde{q}_A & q_B \end{pmatrix}$$

Cheng, Jung, Salvioni and Tsai, 2015

- $\tilde{q}_A$ has SM color, mixes with the top quark

$$\Rightarrow \quad \tilde{M}_A \gtrsim \sqrt{2}\, m_t\, f/v \sim 1\ \mathrm{TeV}$$

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For 750 as bound state of colored fermions, see for ex.:
Kats and Strassler; Kamenik and Redi, Ko, Yu and Yuan

750 GeV as bound state of new fermions

$$Q = \begin{pmatrix} q_A & \tilde{q}_B \\ \tilde{q}_A & q_B \end{pmatrix}$$

- $\tilde{q}_B$ can be ~ 375 GeV, contains fermion with twin color and SM el. charge

	$SU(3)$		$SU(2)$		$U(1)$		$U(1)_{\rm em}$	
	A	B	A	B	Y	D	SM	Twin
$\tilde{q}_B = \begin{pmatrix} \xi_u \\ \lambda_d \end{pmatrix}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$	$-1/2$	$2/3$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$	$\begin{pmatrix} 2/3 \\ 2/3 \end{pmatrix}$

twin QCD gives binding

$$\eta_\lambda \to \gamma\gamma$$

Assume $\Lambda \gtrsim 55~\mathrm{GeV}$ to forbid decay of 750 into twin glueballs

➡ m_λ/Λ similar to **charmonium**

750 GeV as bound state of new fermions

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Hidden quarkonium

- The diphoton width of the lightest (pseudoscalar) bound state is

$$\Gamma(\eta_\lambda \to \gamma\gamma) = N_c 4\pi\alpha^2 Q_\lambda^4 \frac{|\psi(0)|^2}{m_\lambda^3} m_\lambda$$

$$\frac{|\psi(0)|^2}{m_\lambda^3} = ?$$

e.g., Kang, Luty 2008

- Semiclassical picture for $m_\lambda \gg \Lambda$:

$$= \frac{\text{hard scattering length}}{\text{string length}} = \frac{1/m_\lambda}{m_\lambda/\Lambda^2} = \frac{\Lambda^2}{m_\lambda^2}$$

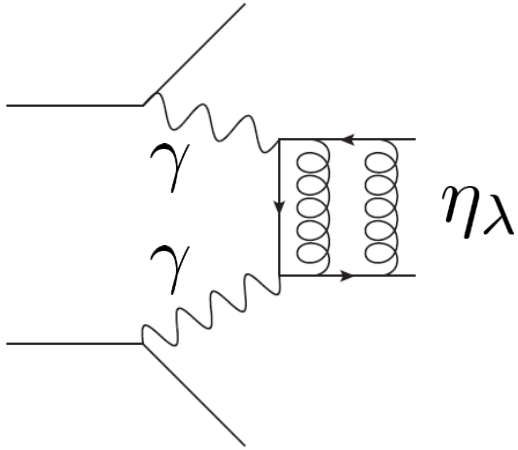
Works within factor ~ 2 for QCD charmonia and bottomonia (e.g. J/ψ , Υ)

750 GeV as pseudoscalar bound state

Two serious issues (generic to *any* bound state of *color-less* fermions)

- **why is diphoton signal so large (~ 5 fb) ?**

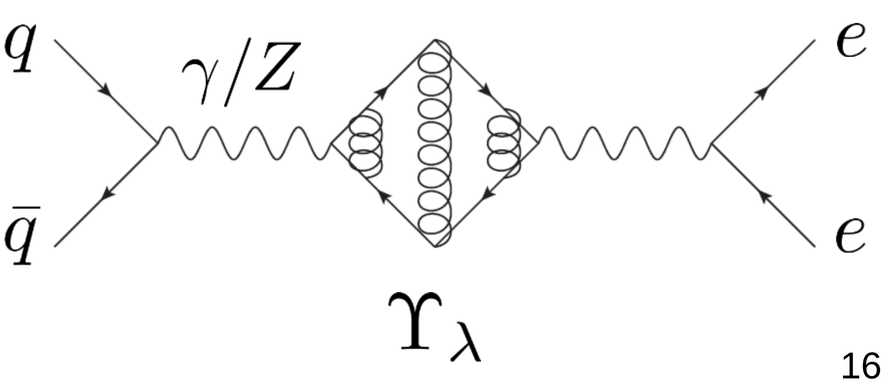
see also Yael's talk, Thursday



~ 1 fb for $Q_\lambda = 1$

e.g. Csaki, Hubisz, Lombardo and Terning, 2016

- **where is the vector bound state ?**



Strong constraint, < 1 fb at 8 TeV

750 GeV diphotons in Twin Higgs

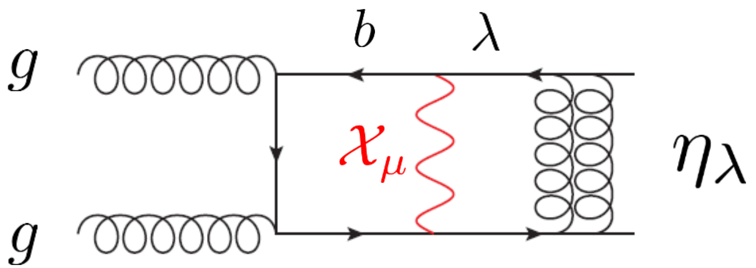
Solution comes from the UV completion

Cheng, Salvioni and Tsai, to appear

$\mathcal{X}_\mu$ off-diagonal gauge boson of strong *SU*(6),

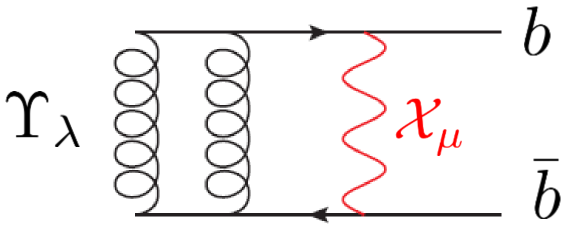
bi-fundamental of color & twin color

✓ Pseudoscalar production via



$\sim \log \frac{m_X^2}{m_b^2}$

✓ Suppressed $\Upsilon_\lambda \to ee$ due to



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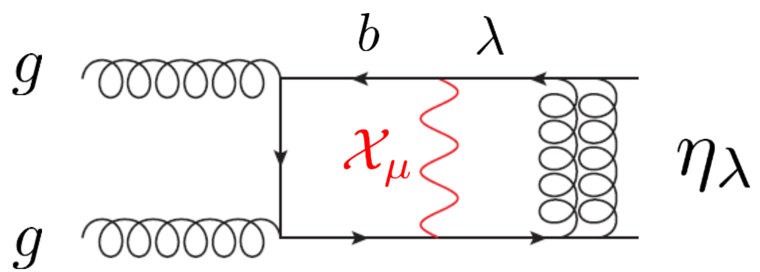
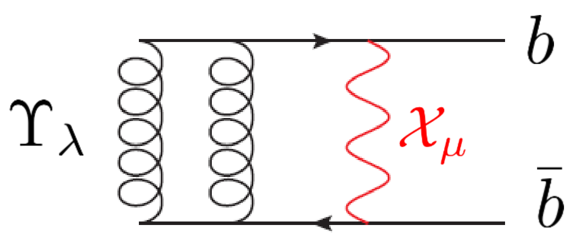


$\sim \log \frac{m_X^2}{m_b^2}$

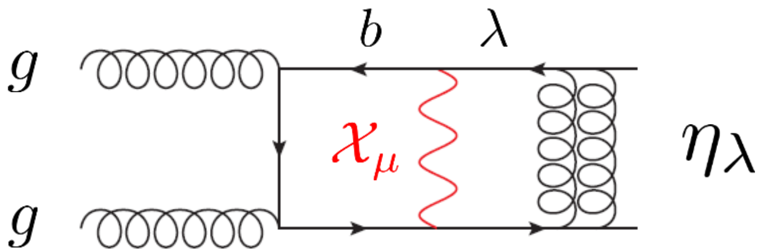
✓ Suppressed $\Upsilon_\lambda \to ee$ due to

(for η_λ need long. $\mathcal{X}$, extra $\frac{1}{m_X^2}$)



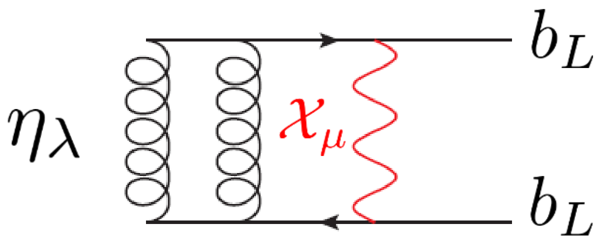
Diphotons from pseudoscalar

13 TeV



$$\sim 58\ \text{fb} \left(\frac{\Lambda}{65\ \text{GeV}}\right)^2 \left(\frac{\alpha_X}{2}\right)^2 \left(\frac{1\ \text{TeV}}{m_X}\right)^8$$

light and strongly coupled χ

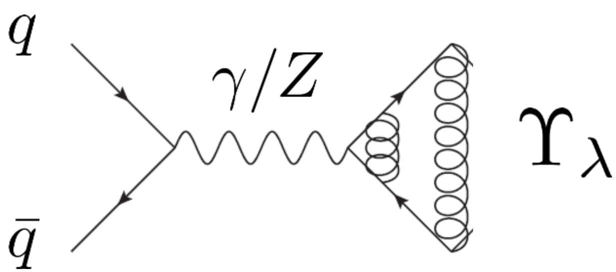


$$\Gamma \sim N_c^2 \frac{\pi \alpha_X^2}{4} \frac{|\psi(0)|^2}{m_\lambda^2} \frac{m_\lambda^8}{m_X^8}$$

mediated by longitudinal χ **strongly suppressed**

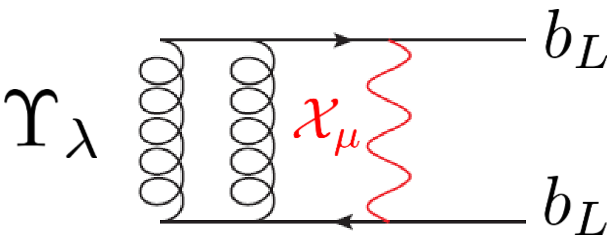
$\mathrm{BR}_{\gamma\gamma} \sim \mathrm{BR}_{bb} \sim 0.2$, diphoton signal ~ 5 fb well reproduced

Vector bound state



$$\sim 110\text{ fb}\left(\frac{\Lambda}{65\text{ GeV}}\right)^2$$

8 TeV



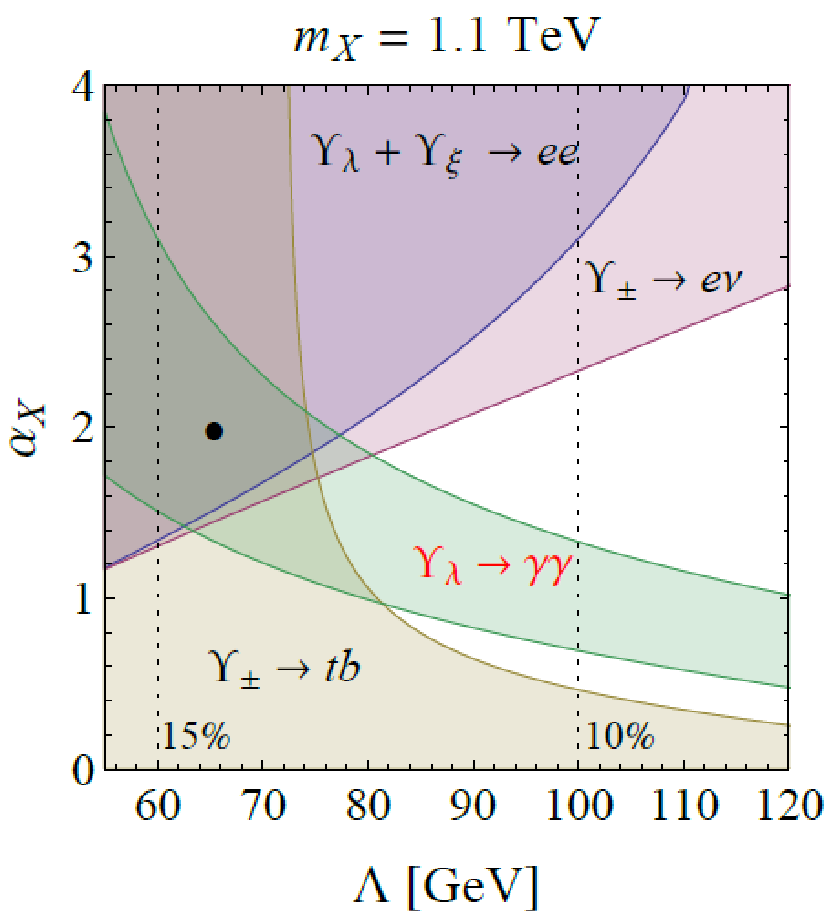
$$\Gamma \sim N_c^2 \frac{\pi\alpha_X^2}{6}\frac{|\psi(0)|^2}{m_\lambda^2}\frac{m_\lambda^4}{m_X^4}$$

mediated by transverse $\mathcal{X}$ **dominant**

$\text{BR}_{e^+e^-} \sim \text{few} \times 10^{-3}$, dilepton rate < 1 fb

Full picture

Cheng, Salvioni and Tsai, to appear

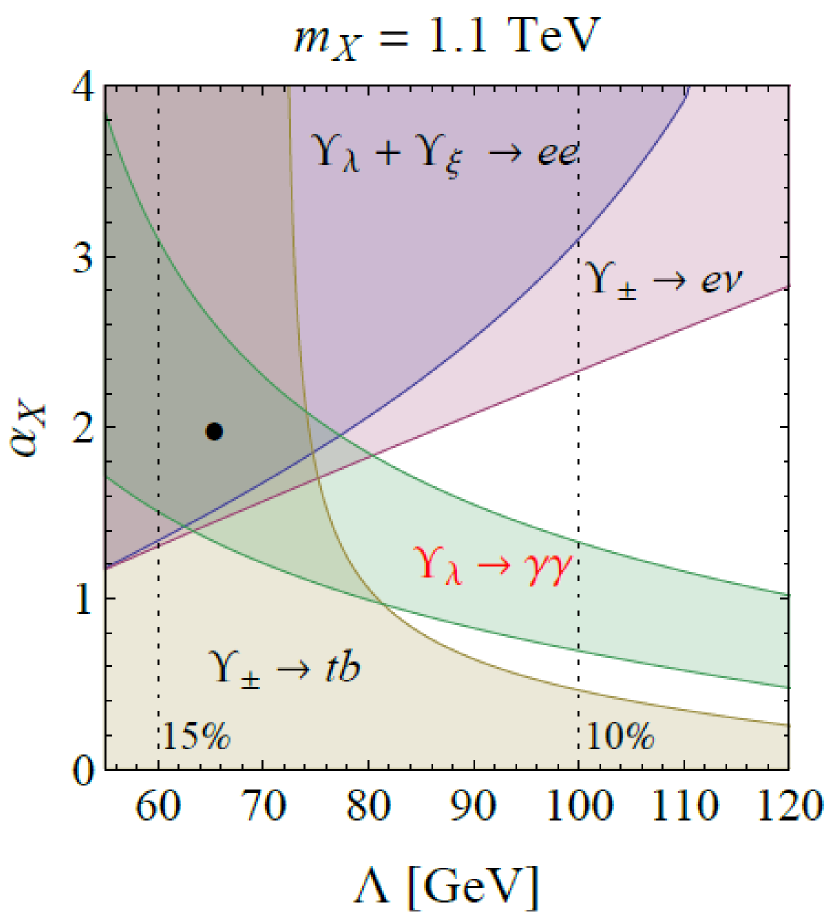


How much tuning? At 2 loops:

- Large $\Lambda \sim 65$ GeV (exact Z_2 gives ~ 5 GeV), **milder than 10%**

Full picture

Cheng, Salvioni and Tsai, to appear



$$\tilde{q}_B = \begin{pmatrix} \xi_u \\ \lambda_d \end{pmatrix} \sim \mathbf{2}_{-1/2}$$

$$m_\lambda - m_\xi \simeq 15 \text{ GeV} \ll \Lambda$$

large η_λ width?

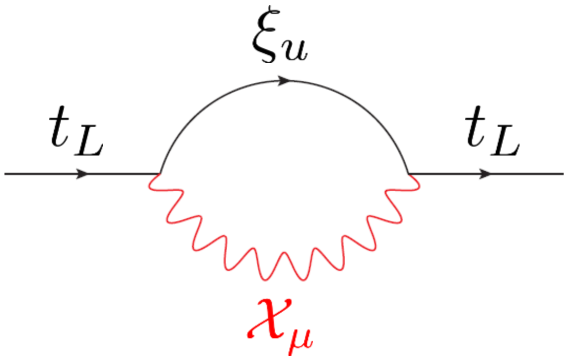
How much tuning? At 2 loops:

- Large $\Lambda \sim 65$ GeV (exact Z_2 gives ~ 5 GeV), **milder than 10%**

Tuning

How much tuning? At 2 loops:

- Mass splitting of $\tilde{q}_B$ and $\tilde{q}_A$:



$$\delta Z_L(\tilde{M}_B)\bar{t}_L \not{p} t_L$$

Same for the twin top, with $\tilde{M}_B \to \tilde{M}_A$

$$\delta m_h^2 \sim \frac{3y_t^2\Lambda_{\rm UV}^2}{4\pi^2}\frac{N_c\alpha_X}{4\pi}\frac{\tilde{M}_B^2-\tilde{M}_A^2}{m_X^2}\log\frac{\Lambda_{\rm UV}^2}{m_X^2}$$

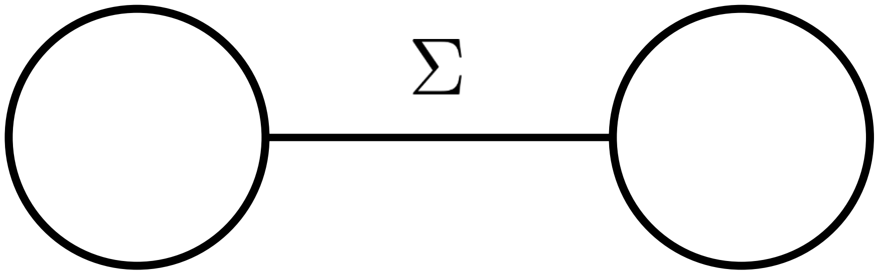
~ few percent

$$(\tilde{M}_B = 375\ \text{GeV}\,,\ \tilde{M}_A \gtrsim 1\ \text{TeV})$$

Two-site picture

$SU(6)[\times SU(4)]$

g_X



$SU(3)^2[\times SU(2)^2]$

$g_s\ ,\hat{g}_s$

$$Q = \begin{pmatrix} q_A & \tilde{q}_B \\ \tilde{q}_A & q_B \end{pmatrix}$$

$b_{R\,A}, b_{R\,B}$

$t_{R\,A}, t_{R\,B}$

- $$|D_\mu \Sigma|^2 \quad \rightarrow \quad m_X^2 = \frac{g_X^2 u^2}{4}\,, \qquad m_G^2 = \frac{\sqrt{g_X^2 + g_s^2}\,u^2}{4}$$

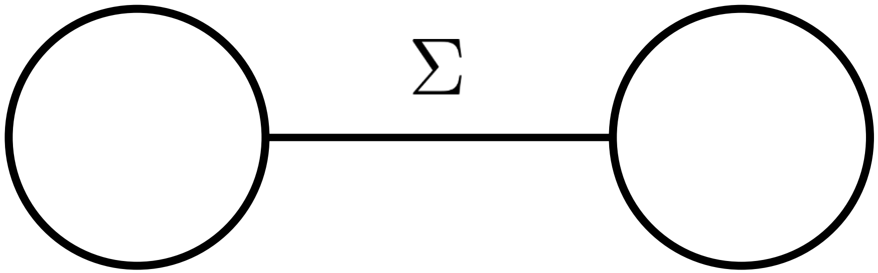
for $g_X \gg g_s$, $m_G \sim m_X$

$$\begin{pmatrix} \mathcal{G} & \mathcal{X}^+ \\ \mathcal{X}^- & \hat{\mathcal{G}} \end{pmatrix}$$

Two-site picture

$SU(6)[\times SU(4)]$

g_X



$SU(3)^2[\times SU(2)^2]$

$g_s \, , \hat{g}_s$

$$Q = \begin{pmatrix} q_A & \tilde{q}_B \\ \tilde{q}_A & q_B \end{pmatrix}$$

$b_{R\,A}, b_{R\,B}$

$t_{R\,A}, t_{R\,B}$

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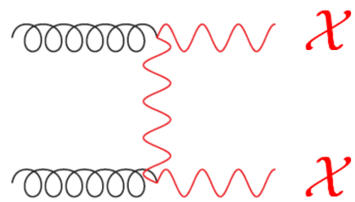
  for $g_X \gg g_s$, $m_G \sim m_X$

- But adding higher dim operators:

$$\Omega = \mathrm{diag}(\mathbf{1}_3, \mathbf{0}_3) \qquad \left|\mathrm{Tr}[\Omega \Sigma^\dagger D_\mu \Sigma]\right|^2 \quad \rightarrow \quad m_G^2 \sim 2\, m_X^2$$

Exotic vector

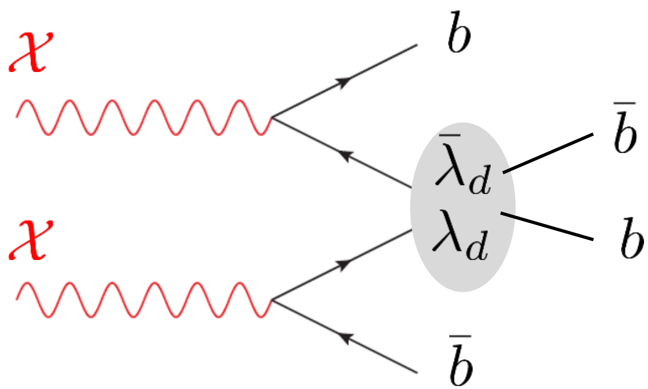
- Pair-produced via QCD



$$\frac{\Gamma_X}{m_X} = \frac{\alpha_X}{4}$$

broad!

- Decays



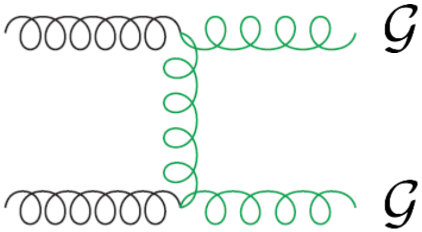
$\Rightarrow$ $4b$

similarly, $\mathcal{X} \to t\xi_u$ gives $4t$, but **constraints OK for** $m_X \sim 1\ \mathrm{TeV}$

- Decay $\mathcal{X} \to t\hat{t}$ gives stop-like signature, but with very heavy (~ 700 GeV) invisible particle. Weak sensitivity

KK gluon

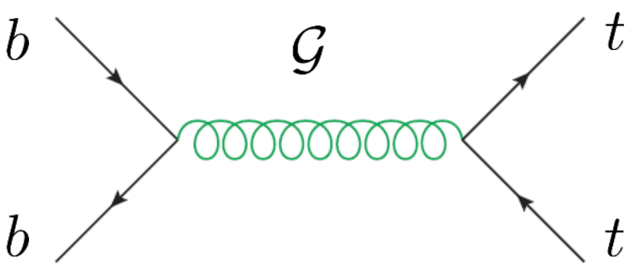
- Couples strongly to top and L bottom
- Pair produced via QCD



ATLAS 1505.04306 + CONF-2016-013; see talk by Aurelio yesterday

4-top search gives $\mathbf{m_G \gtrsim 1.2\ TeV}$

- Also single production in $b\bar{b}$,



If narrow, 13 TeV search for $t\bar{t}$ resonances gives ~ 2.0 TeV

But **broad,** $\frac{\Gamma_G}{m_G} = \frac{\alpha_G}{4} \sim \frac{1}{2}$, actual bound **much weaker**

KK gluon, continued

- Couples strongly to top and L bottom

  generates only LL operators for down sector

$$\mathcal{L}_{\rm eff} = -\frac{g_X^2}{6m_G^2}\bar{b}_L^i\gamma^\mu b_L^i\bar{b}_L^j\gamma_\mu b_L^j$$

- Strongest bound from Kaon mixing,

e.g. Csaki, Falkowski and Weiler 2008

$$\mathcal{H}_{\rm eff} = \frac{g_X^2}{6m_G^2}|V_{td}V_{ts}|^2\bar{d}_L\gamma^\mu s_L\bar{d}_L\gamma_\mu s_L$$

- Assume *CP*-invariance in strong sector, bound from **real part**

$$\frac{m_X}{g_X} > 0.14 \text{ TeV}$$

(Im part $\rightarrow$ 2.1 TeV)

⇒ $m_G < \sqrt{2}m_X \sim 1.6 \text{ TeV}$ **still viable**

Summary

- Attempt to explain 750 GeV signal in Twin Higgs framework
- Focused on non-SUSY UV completions (2-site model)

  Candidate is **'twin quarkonium,'** bound state of color-less fermions

- General issues: (1) small production rate and (2) absence of dilepton signal
- *t* - channel exchange of exotic *SU*(6) vector solves them simultaneously.

  Non-trivial interplay of UV physics

- Well-defined framework allows to quantify **electroweak tuning**:

  few % from Z_2 - breaking in fermion spectrum

- **Predictions:** vector resonances ~ 750 GeV in $b\bar{b}$, $\boldsymbol{t\bar{b}}$, $t\bar{t}$

  \+ **dileptons**, lepton + nu

  Light bifundamental vector and KK gluon, broad. Signals in $t\bar{t}$ and 4 tops

Backup

Exotic quark mixing

- Mass matrix for top and exotic quark

$$-\begin{pmatrix}\overline{u}^A_{3R} & \overline{\tilde{u}}^A_{3R}\end{pmatrix}\begin{pmatrix}\frac{y_t f}{\sqrt{2}} s_h & \frac{y_t f}{\sqrt{2}} c_h \\ 0 & \tilde{M}_A\end{pmatrix}\begin{pmatrix}u^A_{3L} \\ \tilde{u}^A_{3L}\end{pmatrix} + \text{h.c.}$$

- For $\tilde{M}_A = 0$ there is a zero eigenvalue.

  Minimum value consistent with observed top mass:

$$\tilde{M}_A \geq m_t \frac{f}{v}\sqrt{1+\sqrt{1-v^2/f^2}} = \sqrt{2}\, m_t \frac{f}{v} + O(v^2/f^2)\,.$$

$$(f = 1\ \text{TeV} \quad \longrightarrow \quad \tilde{M}_A \gtrsim 1\ \text{TeV})$$

The Twin Higgs

Chacko, Goh, Harnik 2005

- Symmetry breaking pattern

$$SU(4)/SU(3)$$

7 Goldstones

$$H \sim e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix} \quad \begin{matrix} SU(2)_A \\ SU(2)_B \end{matrix}$$

gauged

- 3 Goldstones eaten by '*B*' gauge bosons with mass $\sim g_B f$

  The remaining 4 identified with the SM Higgs doublet

- Quadratic corrections to Higgs potential from gauge loops

$$H \equiv \begin{pmatrix} H_A \\ H_B \end{pmatrix} \qquad \delta V = \frac{9g_A^2}{64\pi^2}\Lambda_{\rm UV}^2 H_A^\dagger H_A + \frac{9g_B^2}{64\pi^2}\Lambda_{\rm UV}^2 H_B^\dagger H_B$$

- $A \overset{Z_2}{\longleftrightarrow} B$ enforces $g_A = g_B$ ➡ $\delta V \sim H^\dagger H$, *SU*(4) invariant

Top quark sector

- Similar cancellation for top loops: Z_2 symmetric Yukawa coupling

$$y_t H_A q_A t_A + y_t H_B q_B t_B$$

'twin top', triplet of $SU(3)_B$

$$\delta V = \frac{3}{8\pi^2}\left[-y_t^2\Lambda_{\rm UV}^2 H^\dagger H + y_t^4 \log\Lambda_{\rm UV}\left(|H_A|^4 + |H_B|^4\right)\right]$$

Top quark sector

- Similar cancellation for top loops: Z_2 symmetric Yukawa coupling

$$y_t H_A q_A t_A + y_t H_B q_B t_B$$

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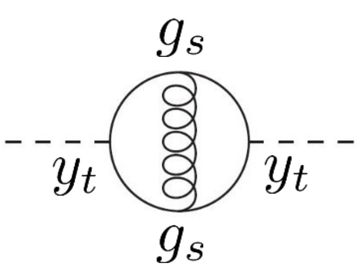
residual log-sensitivity to UV scale

- At this level, $SU(3)_B$ can be a global symmetry. But at 2-loops



$$\delta m_h^2 = \frac{3 y_t^2 g_s^2}{8\pi^4}\Lambda_{\rm UV}^2 \sim (500\ {\rm GeV})^2$$

naturalness suggests to gauge $SU(3)_B$, with $g_s^A \sim g_s^B$ at UV scale

Craig, Katz, Strassler, Sundrum 2015

Exotic quark mass

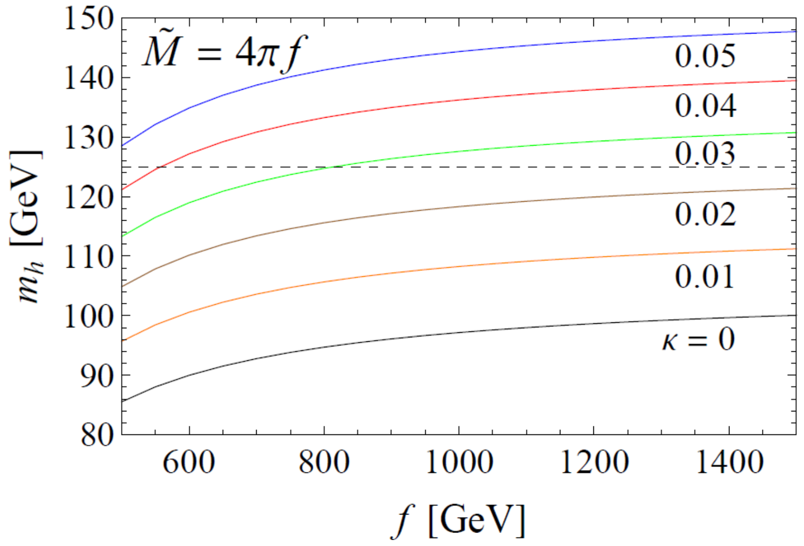
- The mass of the exotic fermions cuts off the divergence in the quartic,

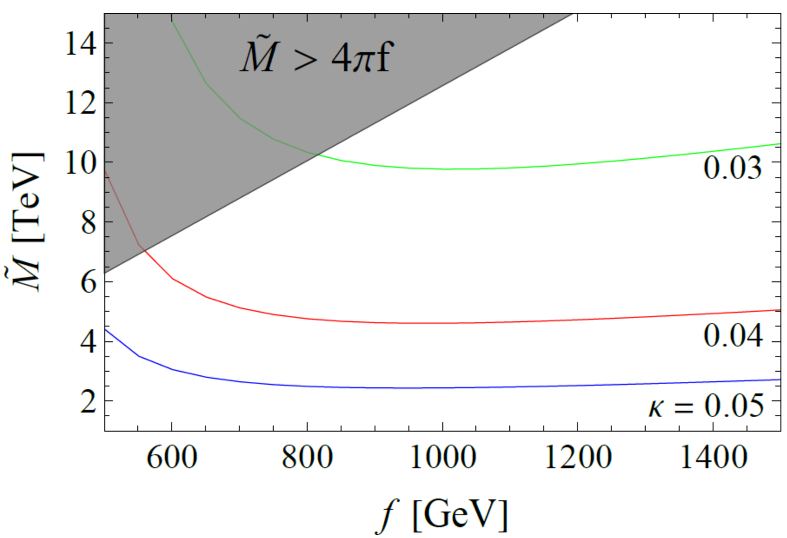
$$\delta V = \frac{3y_t^4}{8\pi^2} \log \tilde{M} \left(|H_A|^4 + |H_B|^4\right)$$

so it is related to the physical Higgs mass. Similar to stops in SUSY

- Exact relation depends on (unknown) extra quartic from UV physics,

$$\delta V = \kappa \left(|H_A|^4 + |H_B|^4\right)$$

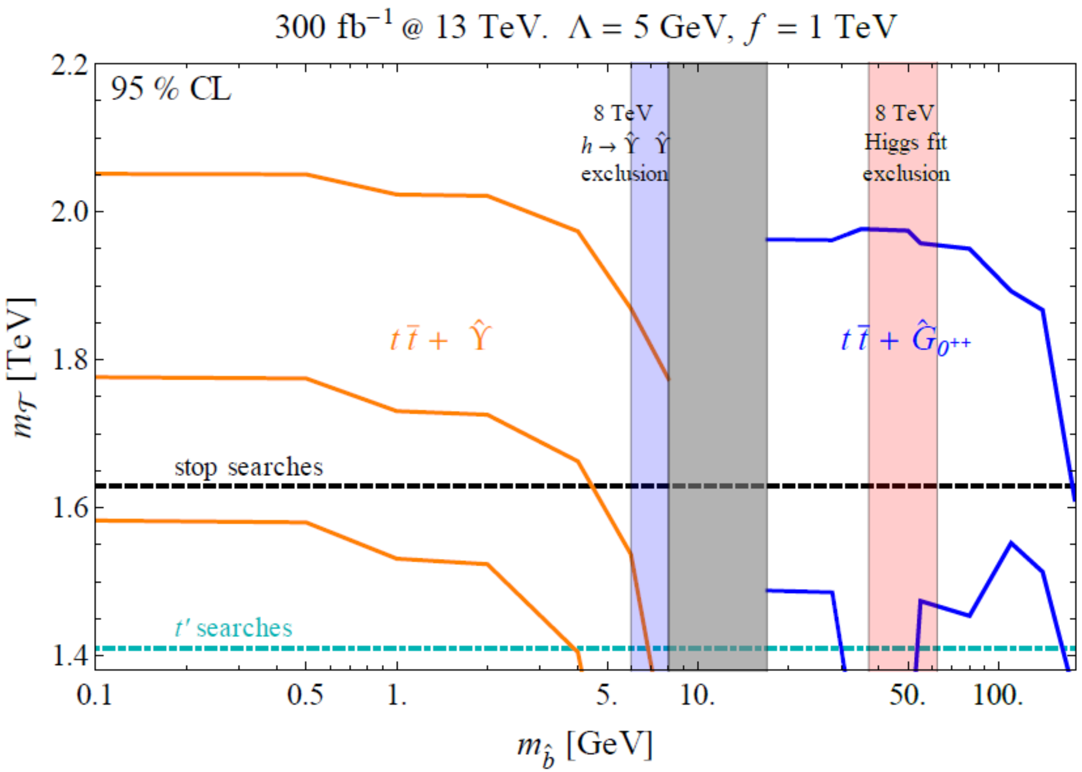




RG-improved 1-loop potential, see **Haber et al. 1996**

$t\bar{t}$ + displaced twin hadron at 13 TeV

Assume background-free ➡ exclude signal at 95% CL if it gives > 3 events



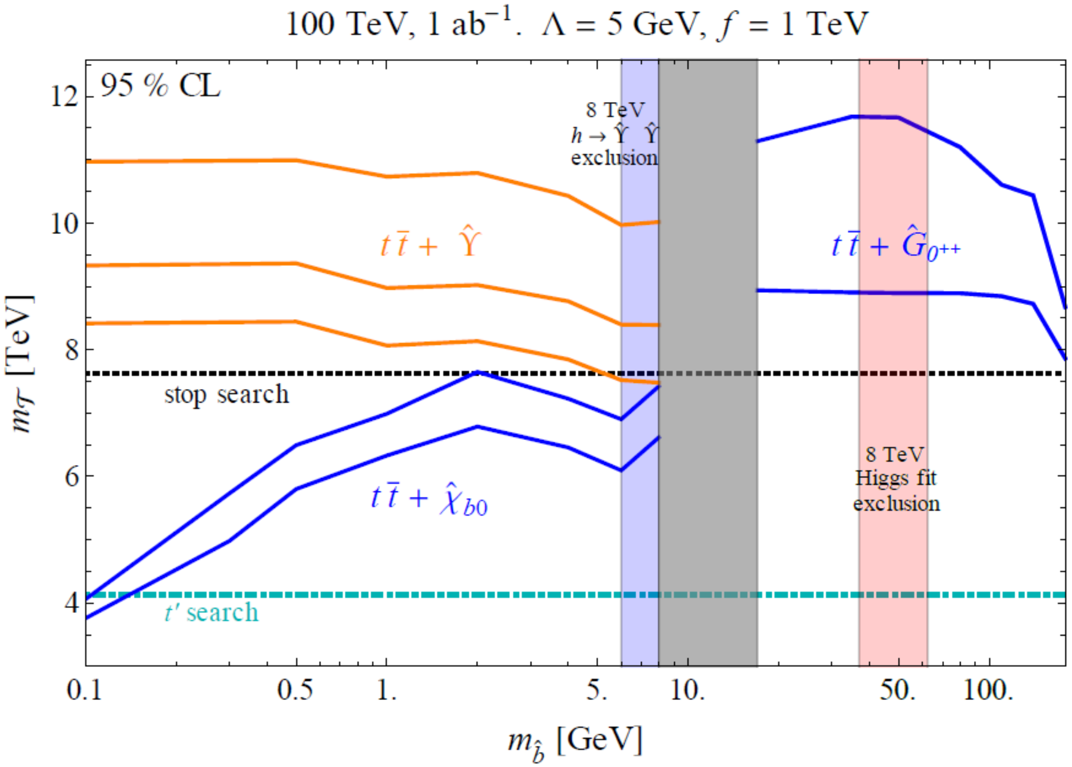
Cheng, Jung, ES, Tsai, 2015

- **Orange** leptonic DV, **blue** hadronic DV
- Different curves represent uncertainties on twin hadron fractions
- Black line shows irreducible bound from stop search

  (assume all twin hadrons leave undetected)

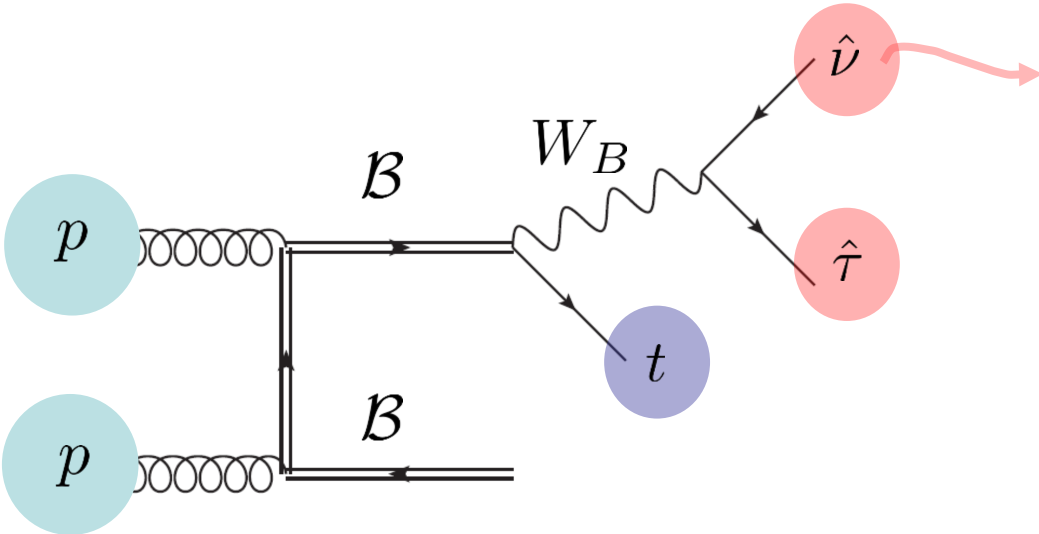
100 TeV

Same simplified modeling of detector as for 13 TeV



- **Orange** leptonic DV, **blue** hadronic DV

Twin lepton signals



So far, assumed twin leptons heavy

However, mass is free parameter from naturalness standpoint

They can mix with the SM neutrinos and behave like **sterile neutrinos**

$$c\tau_{\hat{\ell}} = 10\,\mathrm{cm}\left(\frac{10^{-3}}{\sin\theta_\nu}\right)^2\left(\frac{m_{\hat{\ell}}}{6\ \mathrm{GeV}}\right)^5$$

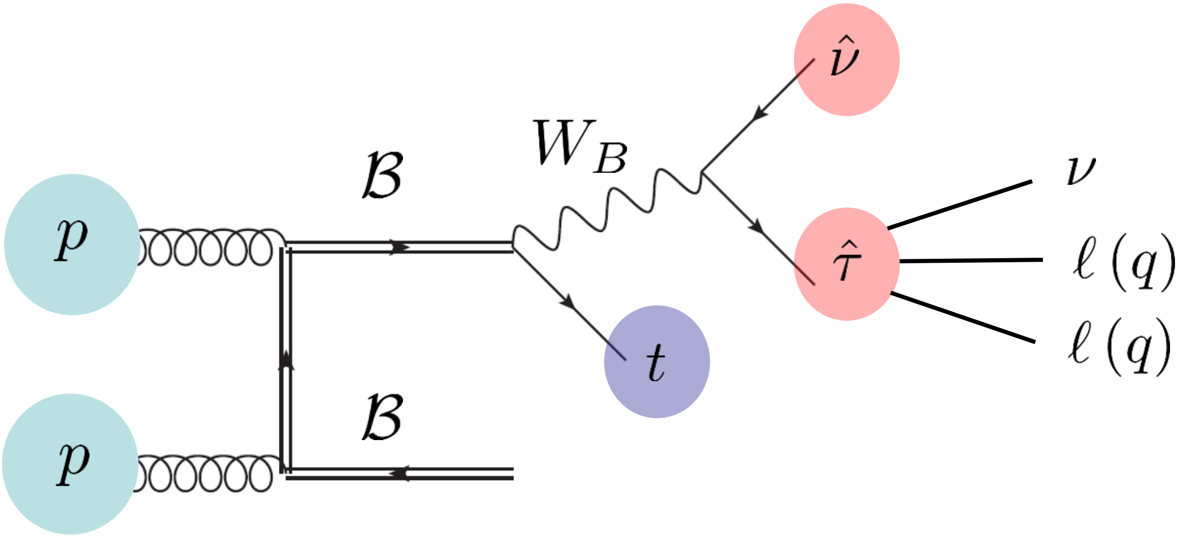
- Decays include $\hat{\ell} \to \nu\ell\ell, \quad \hat{\ell} \to \nu q\bar{q}$

➡ for favorable lifetimes, get **both** leptonic and hadronic DV

- More model-dependent, but gives novel signals

➡ $\text{prompt } t\bar{t} + \text{displaced sterile neutrino}$

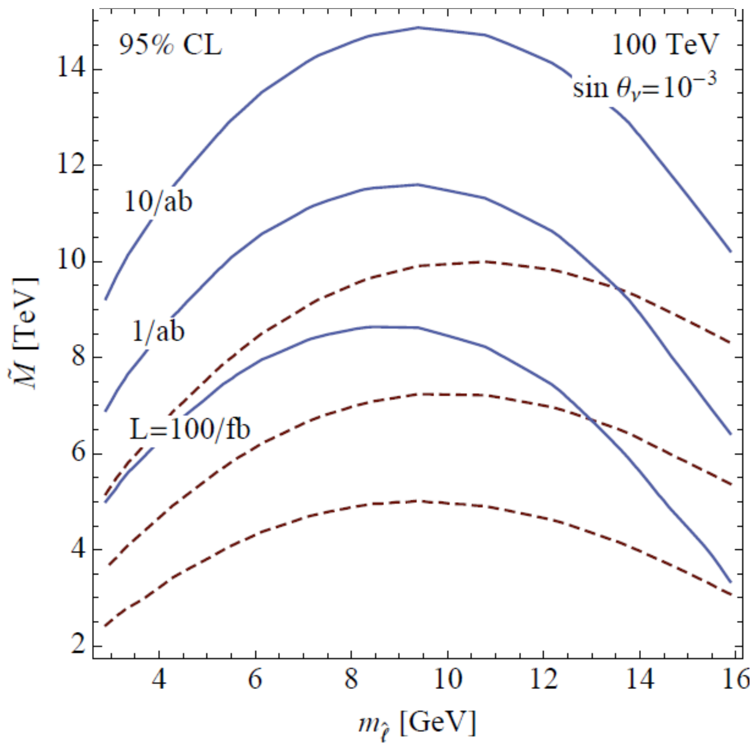
Twin lepton DVs

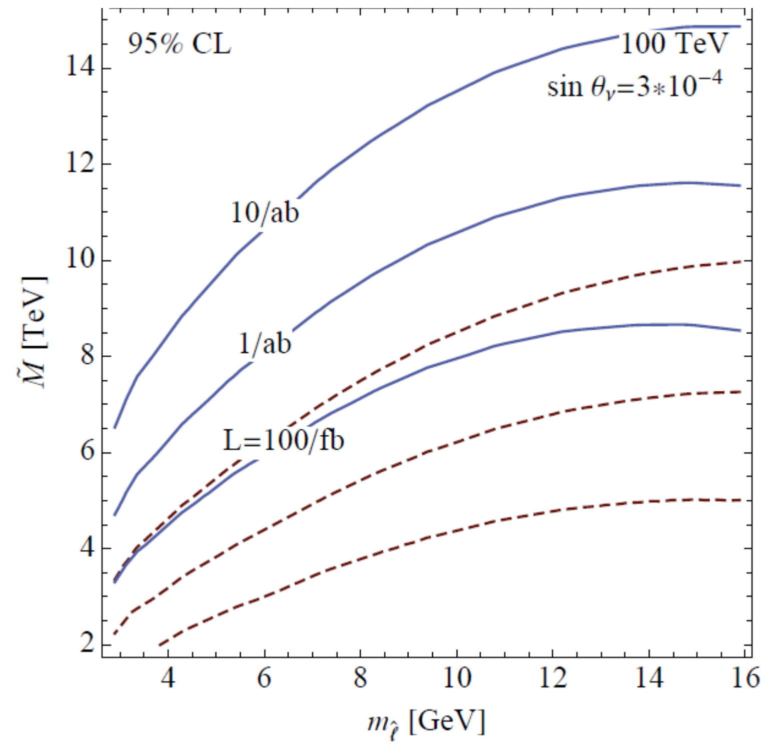


- **Leptonic DV**
  - ID: displaced dilepton search, but large boost of $\hat{\ell}$ gives too small $\Delta R \sim O(0.01)$
  - HCAL + MS: **ATLAS** displaced lepton jet search **1409.0746**
- **Hadronic DV**
  - Again **ATLAS** searches **1504.03634** (ID + MS) and **1501.04020** (HCAL)
  - ID contributes little, due to requirement $d_0 > 10\ \mathrm{mm}$

$t\bar{t}$ + displaced twin lepton at 100 TeV

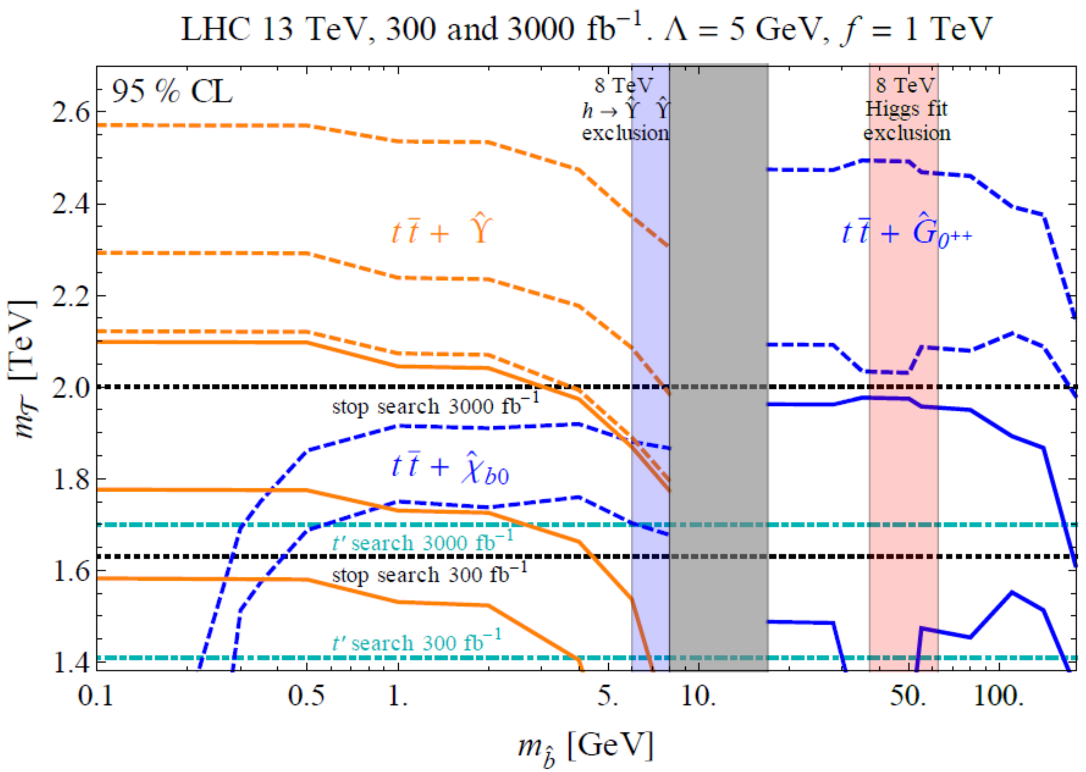
Assume background-free ➡ exclude signal at 95% CL if it gives > 3 events





- Two different assumptions on the neutrino/twin lepton mixing
- **Blue** is hadronic DV, **brown dashed** is leptonic DV

HL-LHC



- Solid curves for 300 fb^{-1}, dashed for 3000 fb^{-1}.
- Blue hadronic DV, orange leptonic DV