Hypercharged Naturalness

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LFC19: Strong dynamics for physics within and beyond the Standard Model at LHC and Future Colliders

In Collaboration with J. Serra, R. Torre and A. Weiler; arxiv: 1905.02203

Outline

Neutral Naturalness

- SUSY or Composite Higgs: top partners that cancel quadratic top contribution to Higgs mass
- SUSY or Composite Higgs: top partners carry color
- no colored particles found at LHC below $\sim$1 TeV
  $\rightarrow$ fine tuning or:
- partner of top quark is not charged under QCD
  $\rightarrow$ Neutral Naturalness

Twin Higgs Mechanism - General Idea

arxiv: 0506256

- Copy of the SM related by $\mathbb{Z}_2$ symmetry: $G_{SM} \overset{\mathbb{Z}_2}{\longleftrightarrow} \tilde{G}_{\tilde{SM}}$
- $V(H, \tilde{H}) =$
  $-m_{\mathcal{H}}(|H|^2 + |\tilde{H}|^2) + \lambda_{\mathcal{H}}(|H|^2 + |\tilde{H}|^2)^2 + \hat{\lambda}(|H|^4 + |\tilde{H}|^4)$
- in limit $\hat{\lambda} \to 0$: $SO(8)$ invariant
- gauging and Yukawas explicitly breaks $SO(8)$ but do not break $\mathbb{Z}_2$

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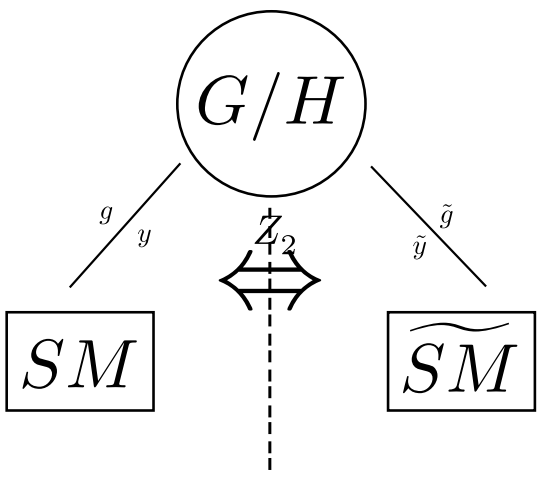
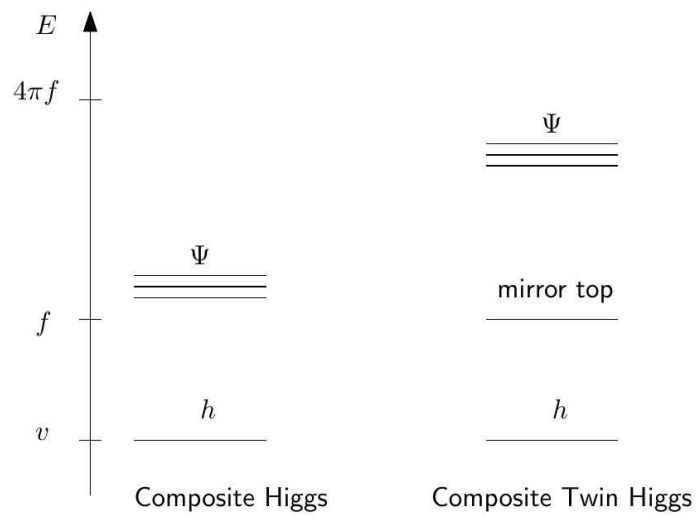
- $V(H, \tilde{H}) =$
  $-m_{\mathcal{H}}(|H|^2 + |\tilde{H}|^2) + \lambda_{\mathcal{H}}(|H|^2 + |\tilde{H}|^2)^2 + \hat{\lambda}(|H|^4 + |\tilde{H}|^4)$
- In limit $\hat{\lambda} \to 0$: $SO(8)$ invariant. SM Higgs is pNGB of $SO(8) \to SO(7)$ by $\langle \tilde{H} \rangle = f/\sqrt{2} \Rightarrow m_h \to 0$.
- Leading (quadratically sensitive) corrections to pNGB Higgs: $\Delta V \propto \Lambda^2(g^2 H^\dagger H + \tilde{g}^2 \tilde{H}^\dagger \tilde{H}) \overset{\mathbb{Z}_2}{=} \Lambda^2 g^2(|H|^2 + |\tilde{H}|^2)$ is again $SO(8)$ symmetric $\Rightarrow$ no mass for pNGB
- Explicit $\mathbb{Z}_2$ breaking necessary in order to have tunable potential $v \ll f$

Composite Twin Higgs: $SO(8)/SO(7)$ coset

arxiv: 1411.2974 and 1501.07803

- Strongly coupled sector with global SO(8) symmetry
- Elementary sector gauges $SU(2)_L \times U(1)_Y \times \tilde{SU}(2)_{\tilde{L}} \times \tilde{U}(1)_{\tilde{Y}}$
- twin fermions to (at least) one generation of SM fermions
- Twin fermions are completely neutral under SM gauge interactions





Is this the minimal model?

The Exceptional Twin Higgs

- Coset: $SO(7)/G_2$
- $SO(7)$ has rank 3 (instead rank 4 of $SO(8)$)
- $SO(7) \subset SU(2)_L \times SU(2)_{\tilde{L}} \times SU(2)_{\hat{R}}$
- Higgs in spinorial rep. 8 of $SO(7)$ and decomposes as $H = (2,1,2)$, $\tilde{H} = (1,2,2)$ under this subgroups

$$\begin{pmatrix} H \\ \tilde{H} \end{pmatrix} = 8 \text{ of } SO(8) \qquad \begin{pmatrix} SO(4) & \\ & SO(4) \end{pmatrix}$$

true minimal embedding with custodial $SU(2)_R$

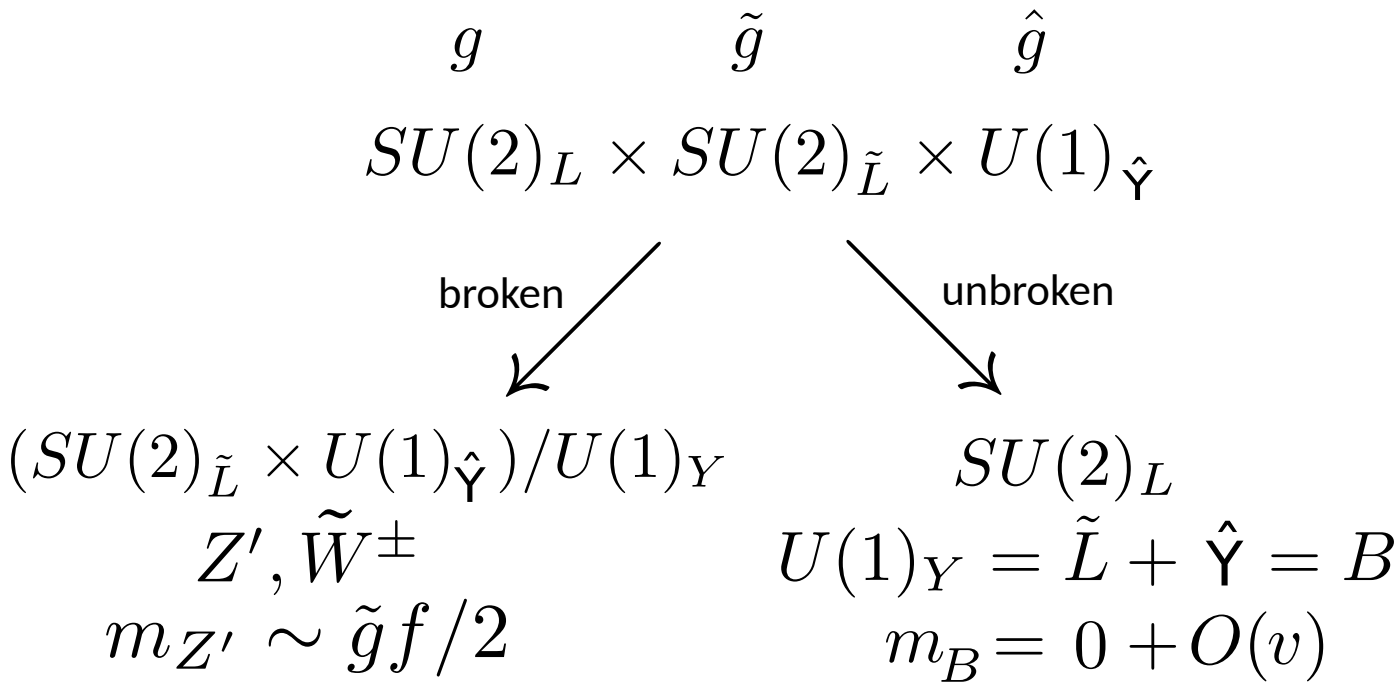
$$\begin{pmatrix} H \\ \tilde{H} \end{pmatrix} = 8 \text{ of } SO(7) \qquad \begin{pmatrix} \boxed{\begin{matrix} SU(2)_L & \\ & SU(2)_{\tilde{L}} \end{matrix}} \end{pmatrix}$$

$SU(2)_{\hat{R}}$

The Exceptional Twin Higgs - $\mathbb{Z}_2$ symmetry

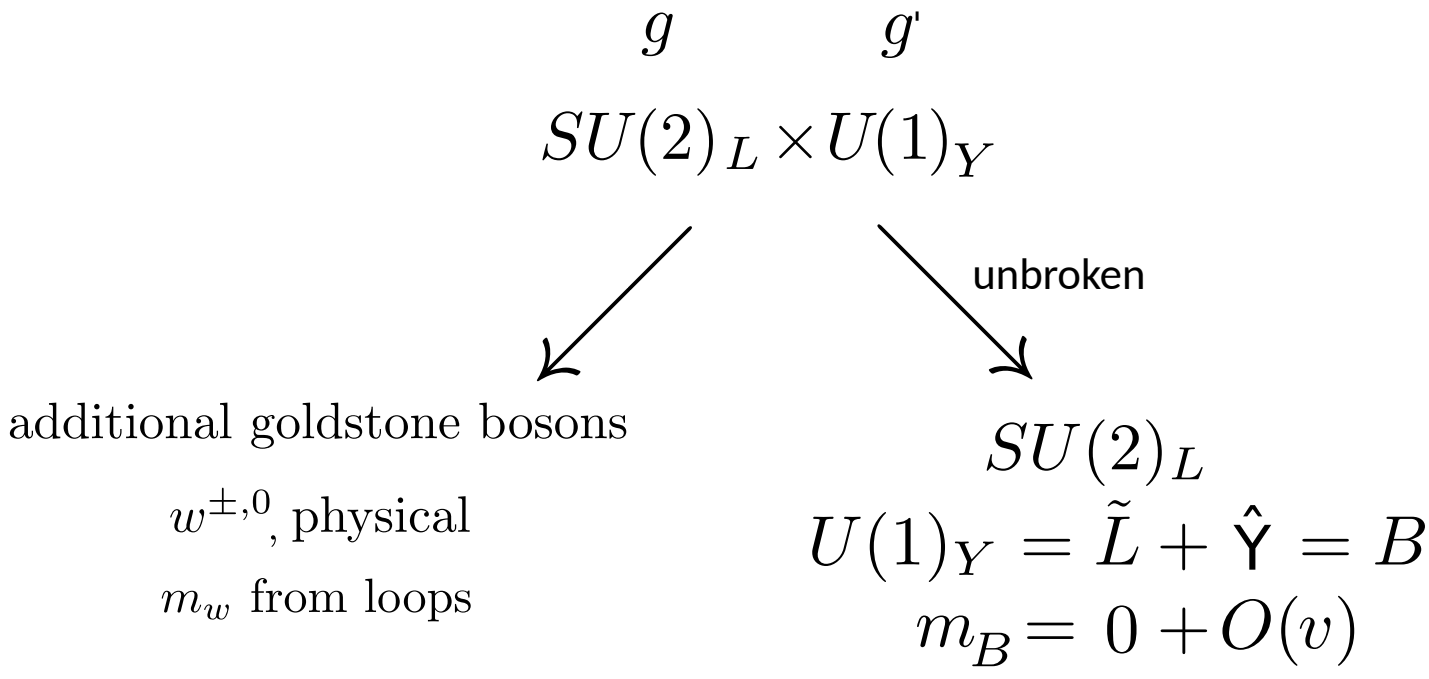
- Strong sector also invariant under $SU(3)_C \times SU(3)_{\tilde{C}} \times \mathbb{Z}_2$
- Extra $U(1)_X \times U(1)_{\tilde{X}}$ to reproduce fermion Hypercharges
- $\mathbb{Z}_2$: $\quad SU(2)_L \leftrightarrow SU(2)_{\tilde{L}} \qquad SU(2)_{\hat{R}} \leftrightarrow SU(2)_{\hat{R}}$
  $SU(3)_C \leftrightarrow SU(3)_{\tilde{C}} \qquad U(1)_X \leftrightarrow U(1)_{\tilde{X}}$
  $H \leftrightarrow \tilde{H}$
- $Q = T_L^3 + T_{\tilde{L}}^3 + T_{\hat{R}}^3 + X + \tilde{X}. \Rightarrow Q_{SM} = Q_{\widetilde{SM}}$
- Custodial $SU(2)_R$: $T_R^i = T_{\tilde{L}}^i + T_{\hat{R}}^i$

The Fraternal Model



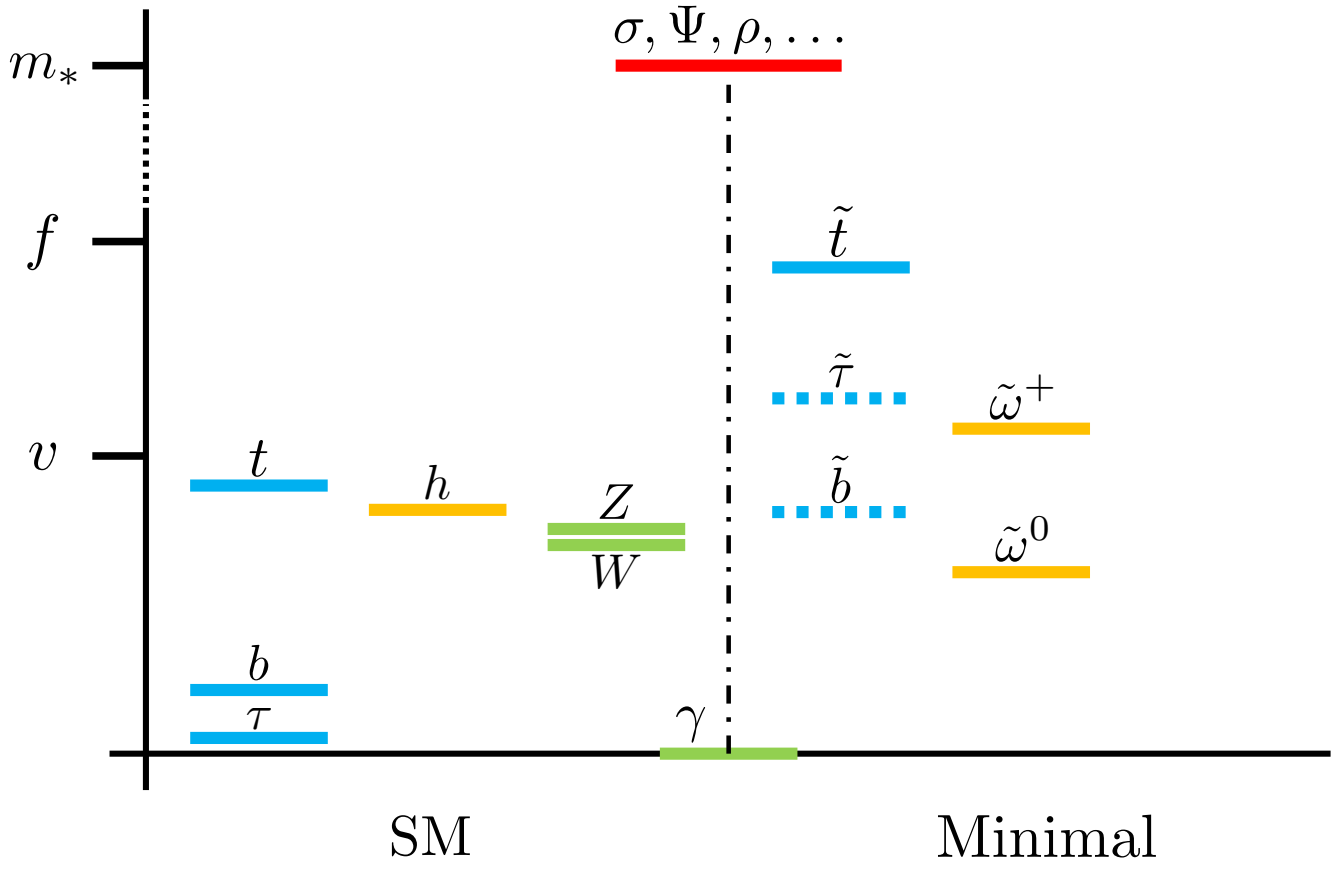
- Fermions: For anomaly cancellation full copy of one SM generation
- bounds on Z' and stable twin lepton disfavor this option

The Minimal Model



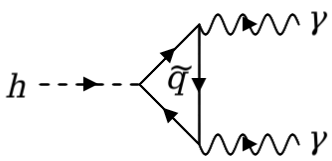
- Only necessary to include the twin top (which is vector-like); other fermions are optional
- only mild tuning $\Delta \sim 15\%$ necessary

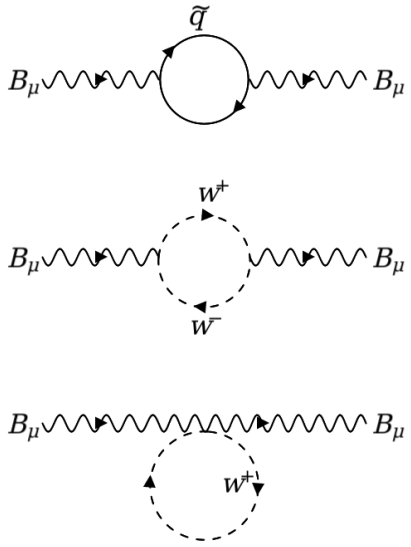
The Minimal Model - particle content



PHENO - Signals of Naturalness from Hypercharged states

- Indirect effects
  - Y parameter
  - running of g'
  - $h \to \gamma\gamma$





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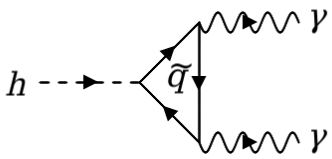
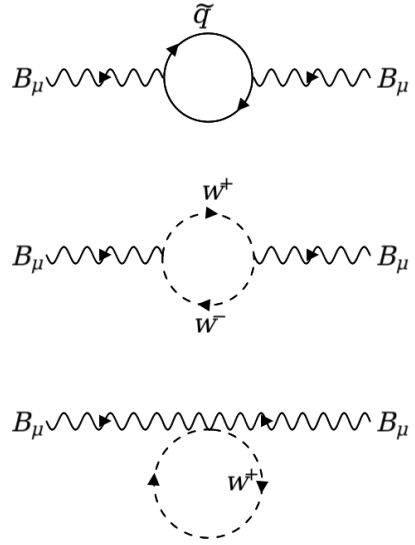
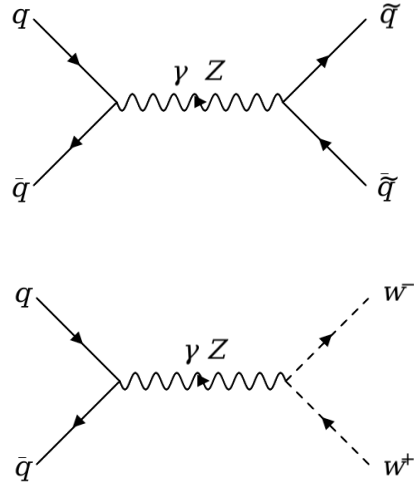
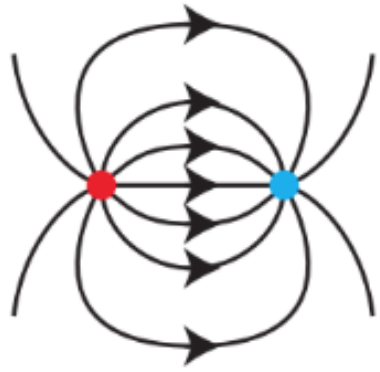




- Direct production
  - $\bar{\tilde{q}}\tilde{q}$ pair production $\Rightarrow$ Quirks!
  - twin glueballs (long lived) $\Rightarrow$ Displaced vertices
  - w^+w^- pair production



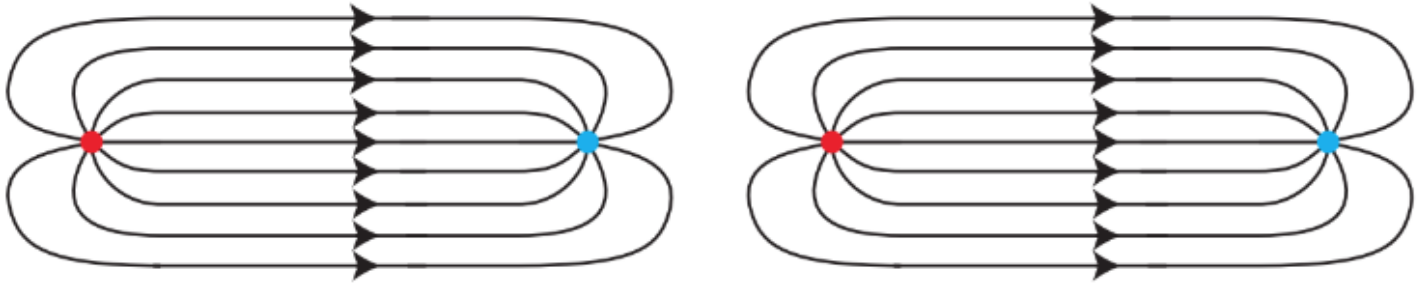
Quirks



- pair production of particles charged under confining group

Quirks

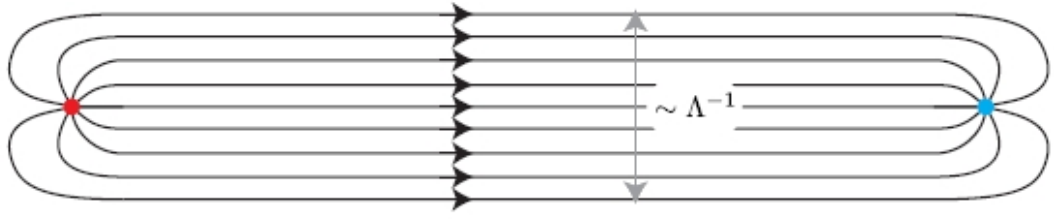
$$m_Q \ll \Lambda$$



- QCD string can break by pair production $\Rightarrow$ Hadronization

Quirks

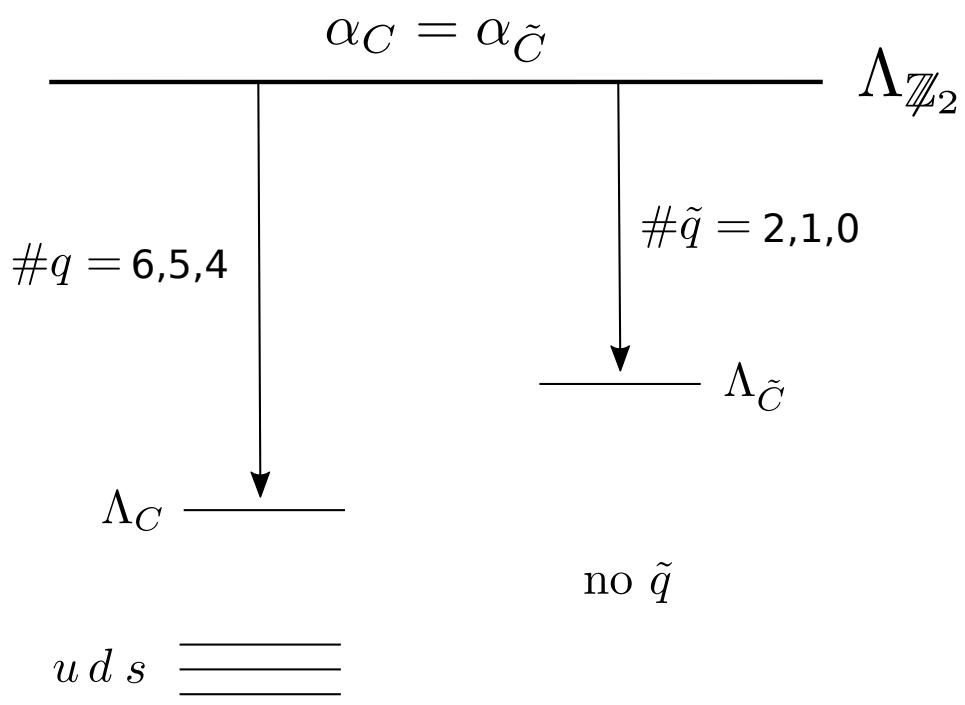
$$m_{\tilde{Q}} \gg \Lambda_{\tilde{C}}$$



- twin QCD string can not break $\Rightarrow$ Quirks

(Okun 1980, Kang, Luty 2008)

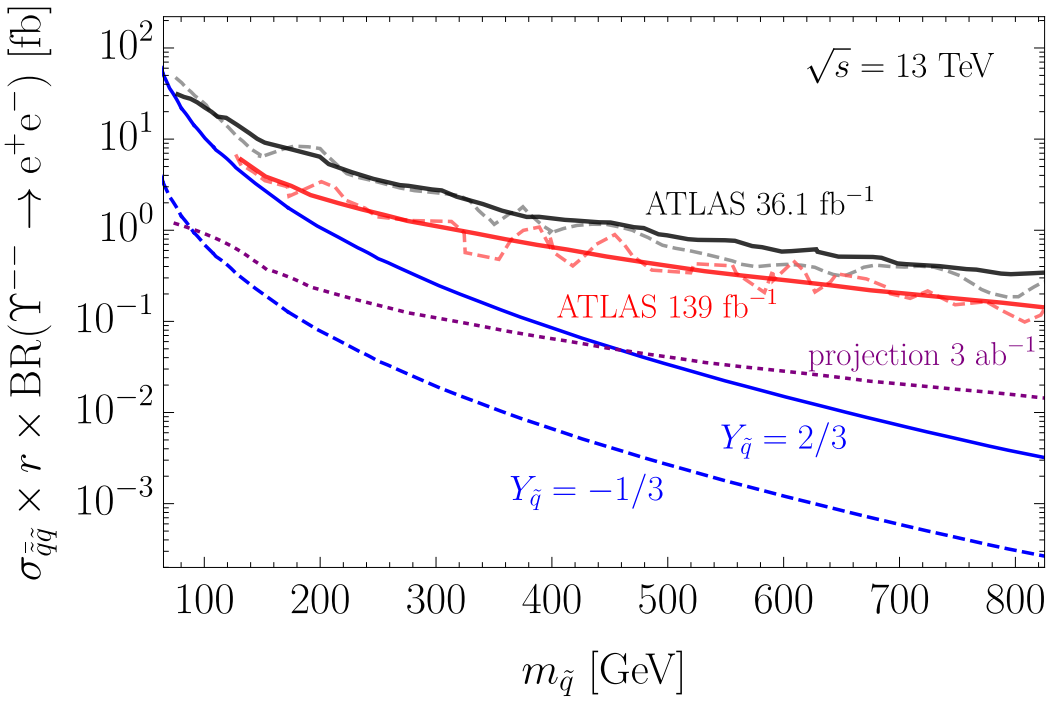
Quirks in our model



- fast deexcitation through photon and twin glueball radiation
  - quirk annihilation strongly suppressed for $l > 0$
- Annihilation from one of the two $l = 0$ ground states: Υ^{--} and η^{-+}

Bound states Υ^{--} and η^{-+}

- decay modes restricted by P,C
- Υ^{--} decay: off-shell γ, Z
  - decay to $l\bar{l}$ pair



- η^{-+} decays to twin glueballs

Twin glueballs

- two production mechanism: η^{-+} decay and higgs decay
- long lived $\Rightarrow$ displaced vertices
- lowest lying glueballs: 0^{++}, 0^{-+}

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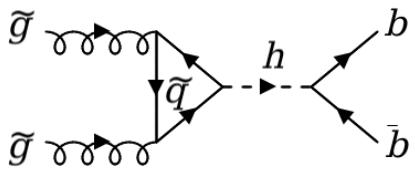

- $c\tau_{0^{++}} \sim (0.4\text{m}) \left(\frac{15\text{GeV}}{m_{0^{++}}}\right)^7 \left(\frac{0.1}{\xi}\right)^2$

Twin glueballs

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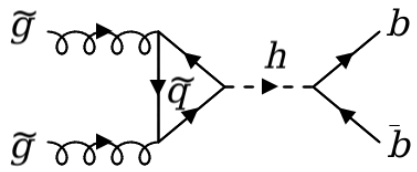
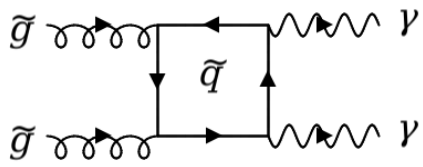
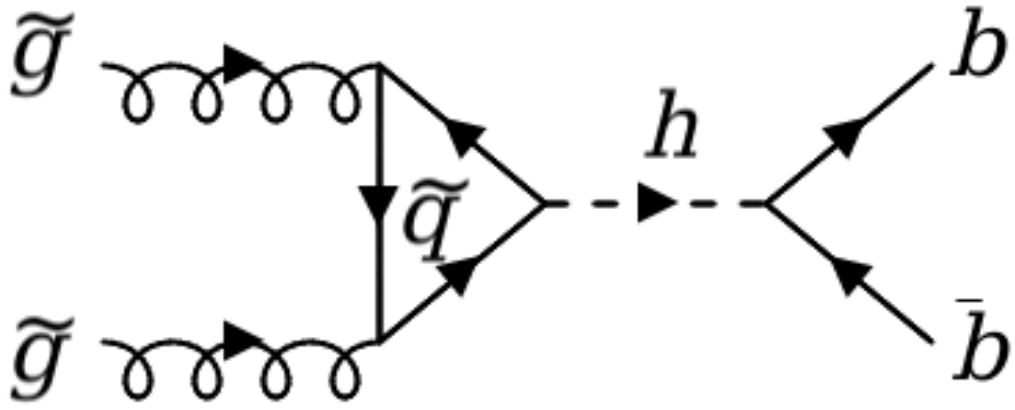


  - $c\tau_{0^{++}} \sim (0.4\text{m}) \left(\frac{15\text{GeV}}{m_{0^{++}}}\right)^7 \left(\frac{0.1}{\xi}\right)^2$
  - 0^{-+} decays predominantly to $\gamma\gamma$, $m_{0^{+-}} \sim 1.5 m_{0^{++}}$



  - $c\tau_{0^{-+}} \sim (55\text{m}) \left(\frac{20\text{GeV}}{m_{0^{++}}}\right)^9 \left(\frac{m_{\tilde{b}}}{150\text{GeV}}\right)^8 \left(\frac{-1/3}{Y_{\tilde{b}}}\right)^4$

Bounds and Projections from $0^{++} \to b\bar{b}$



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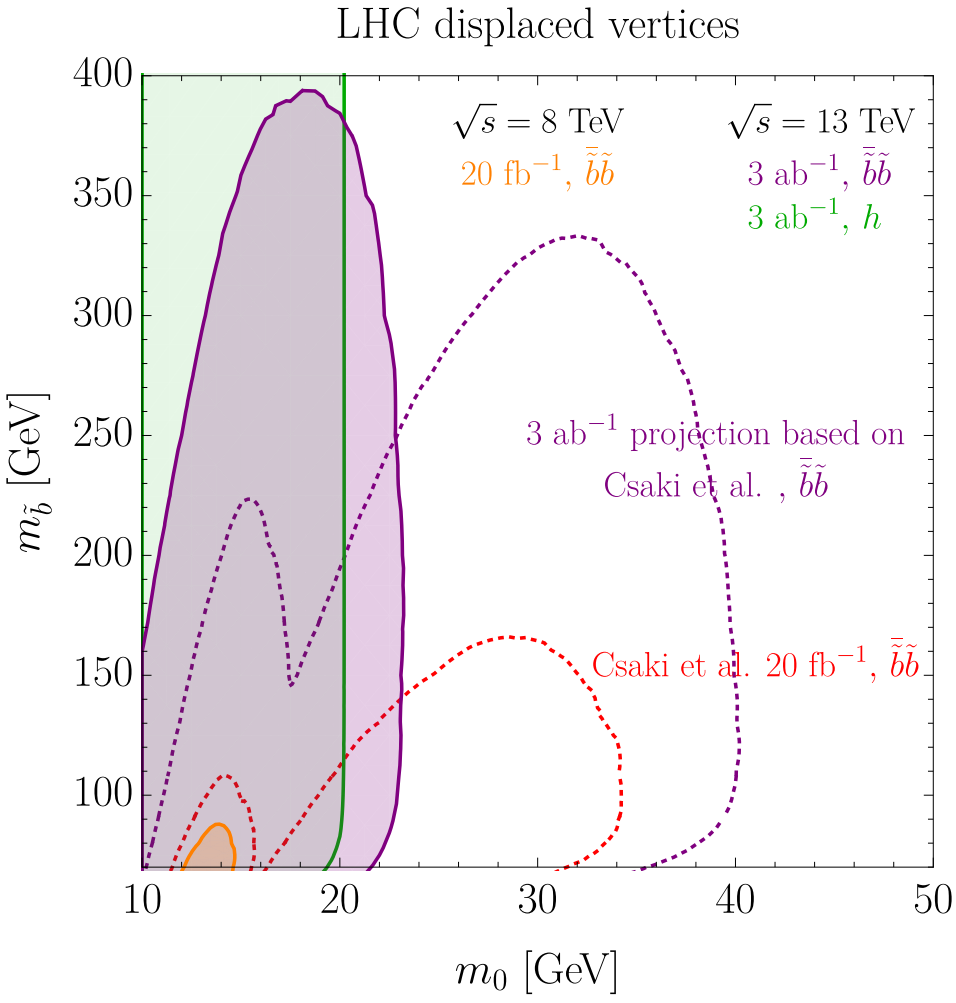
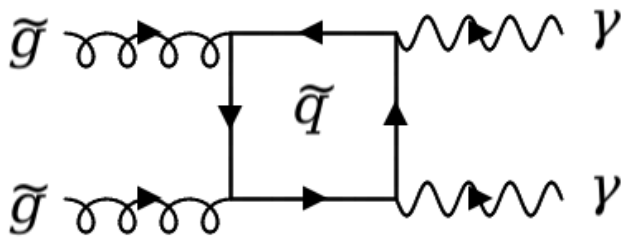
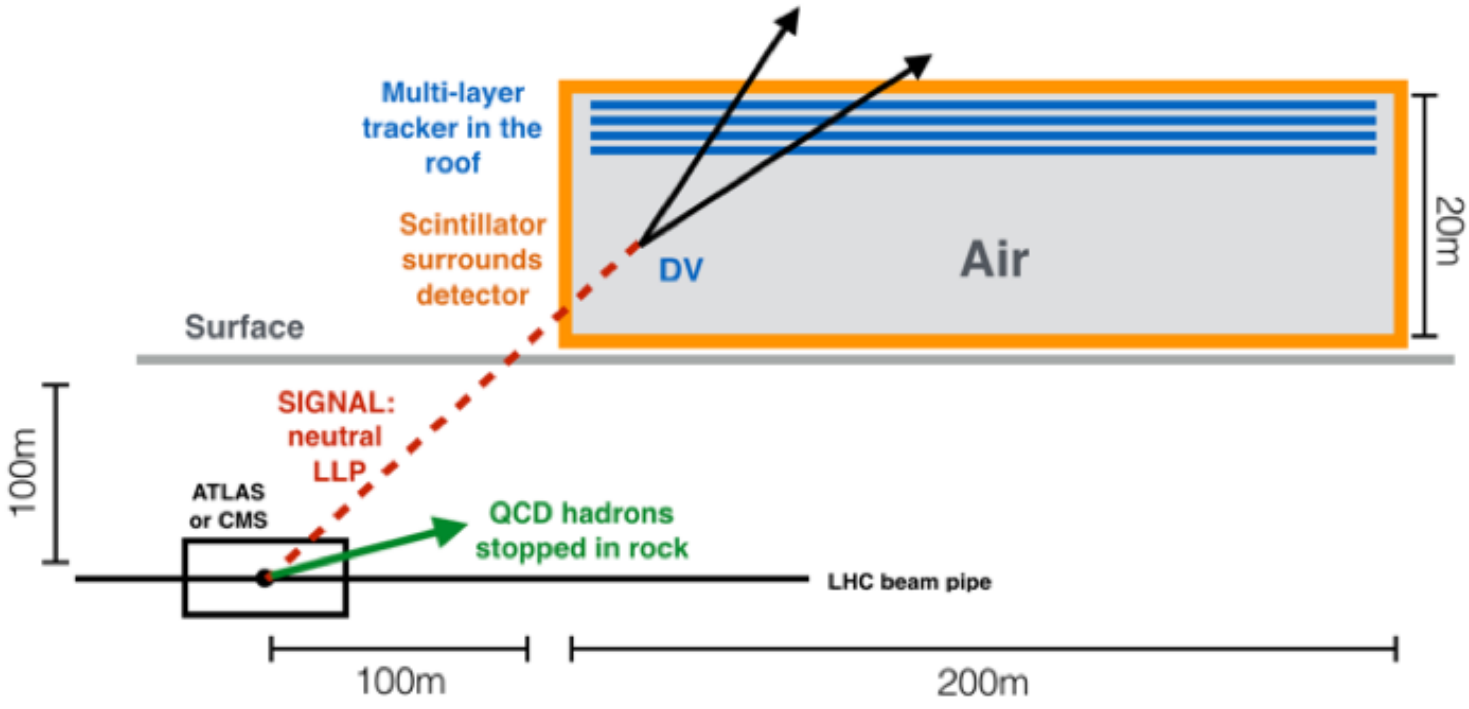


- $m_{0^{++}} \approx 6.9\Lambda_{\tilde{C}}$
- $m_{\tilde{q}} < m_Z/2$ excluded (Z-pole measurements)

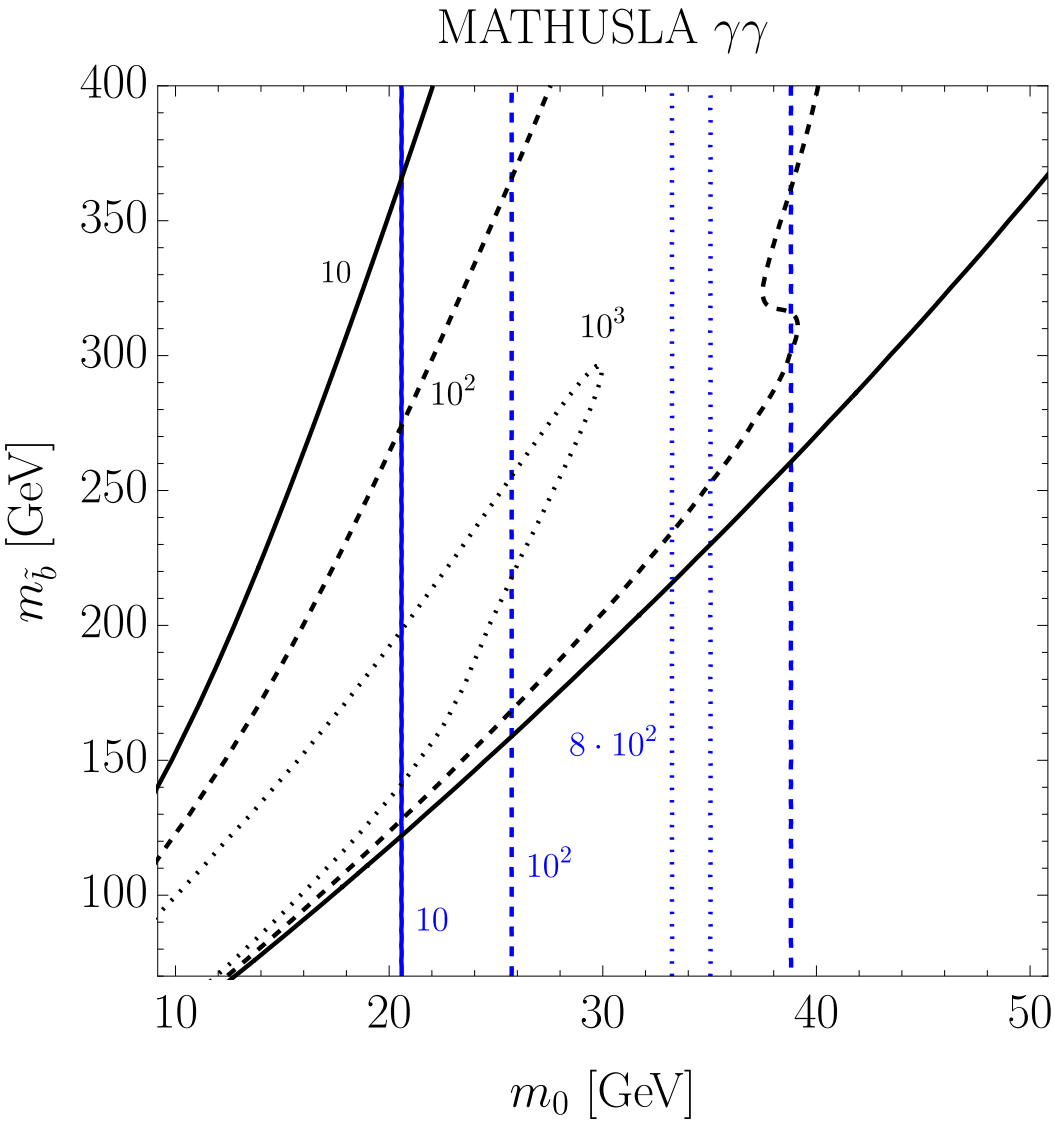
$0^{-+} \to \gamma\gamma$ and the MATHUSLA detector



- MATHUSLA: planned surface detector 100m above ATLAS or CMS; search for LLP



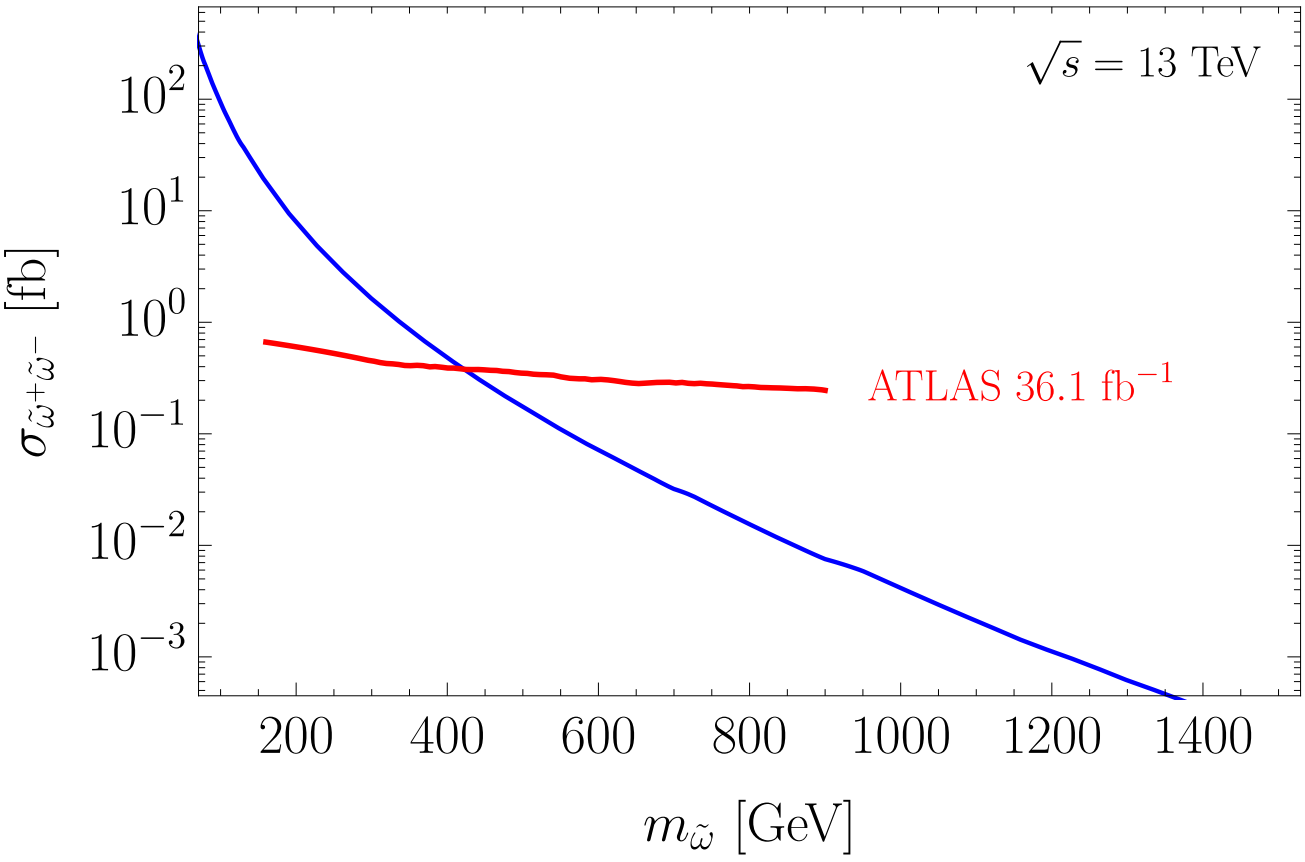
Expected number of diphoton events in the MATHUSLA detector, 13TeV 3ab^{-1}



black: with twin bottom in spectrum; blue: with twin top only

Pair production of charged scalars (13TeV)

- stable on collider scales $\Rightarrow$ long lived charged particles
- pair production through γ, Z
- naive expectation: $m^2_{w^\pm} \approx (550\text{GeV})^2 \left(\frac{\tilde{y}_l}{1}\right)^2 \left(\frac{m_\psi}{4\text{TeV}}\right)^2$



Summary

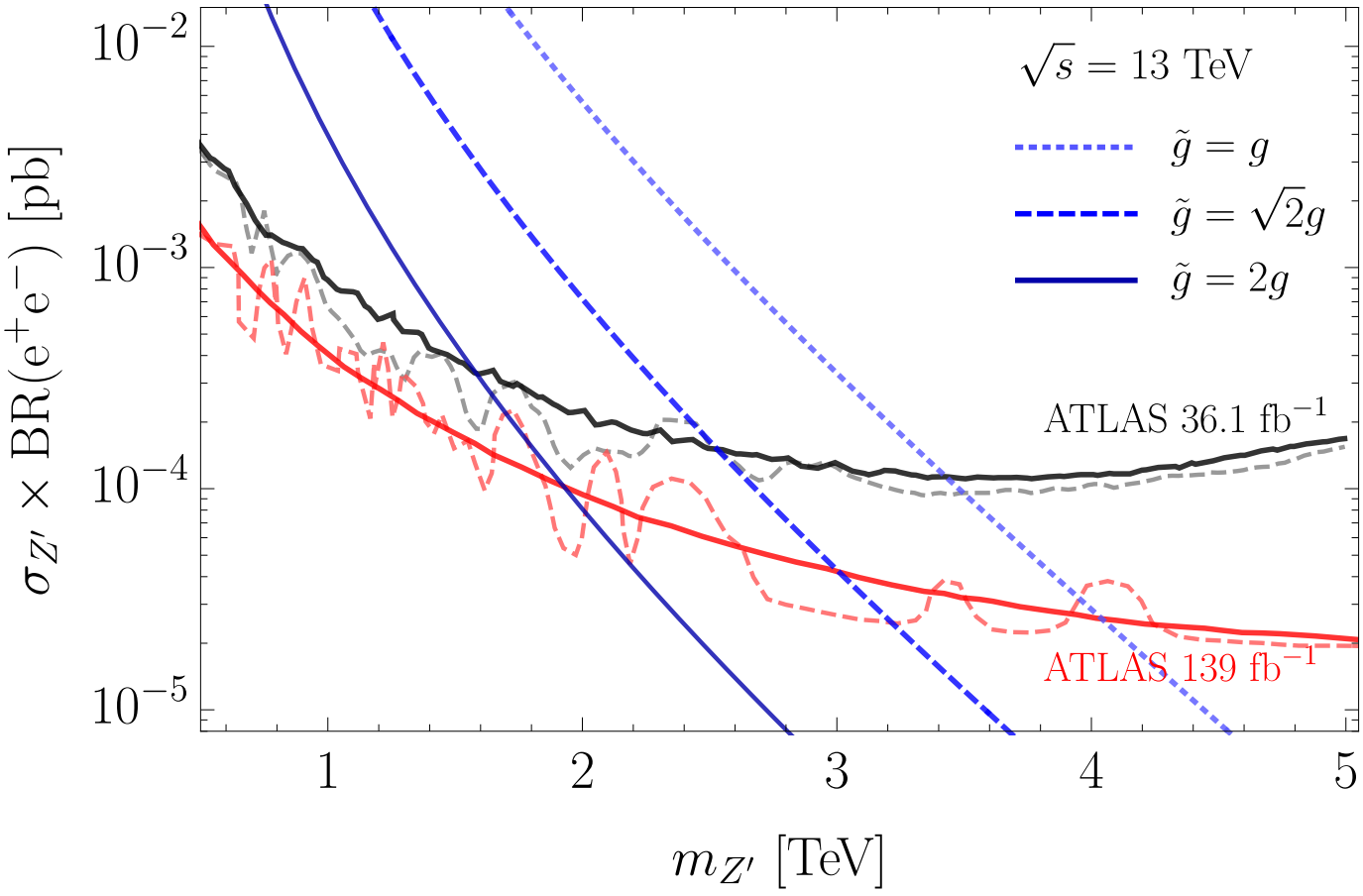
- True minimal symmetry structure required for twin-Higgs with custodial symmetry $\rightarrow$ embedding of $(H, \tilde{H})^T$ as 8 of SO(7)
- Only mild tuning required due to twin-Higgs mechanism
- Exciting new Phenomenology:
  - Alleviation of $h \rightarrow \gamma\gamma$ bound
  - Quirks decaying to dileptons and twin glueballs $\rightarrow$ new production mechanism of twin glueballs
  - twin glueballs can decay displaced to $\bar{b}b$ or $\gamma\gamma$
  - charged (stable) scalars

Thank you!

Backup slides - Indirect effects - Y parameter and running

- $Y_{\tilde{\psi}} = \frac{g'^2}{80\pi^2}\frac{m_W^2}{m_{\tilde{\psi}}^2}\Delta b_Y$ with $\Delta b_Y = \frac{4}{3}N_{\tilde{\psi}}q_{\tilde{\psi}}^2$
- Twin top contribution: $Y_{\tilde{t}} \sim 10^{-5}$.
- $Y_{\tilde{\psi}}$ below LEP sensitivity for all twins with $m_{\tilde{\psi}} \geq 100\text{GeV}$
- lighter fermions Y parameter is no longer adequate
  $\rightarrow$ running of hypercharge gauge coupling
- Accuracy of neutral DY processes too low

Backup slides - fraternal Z'



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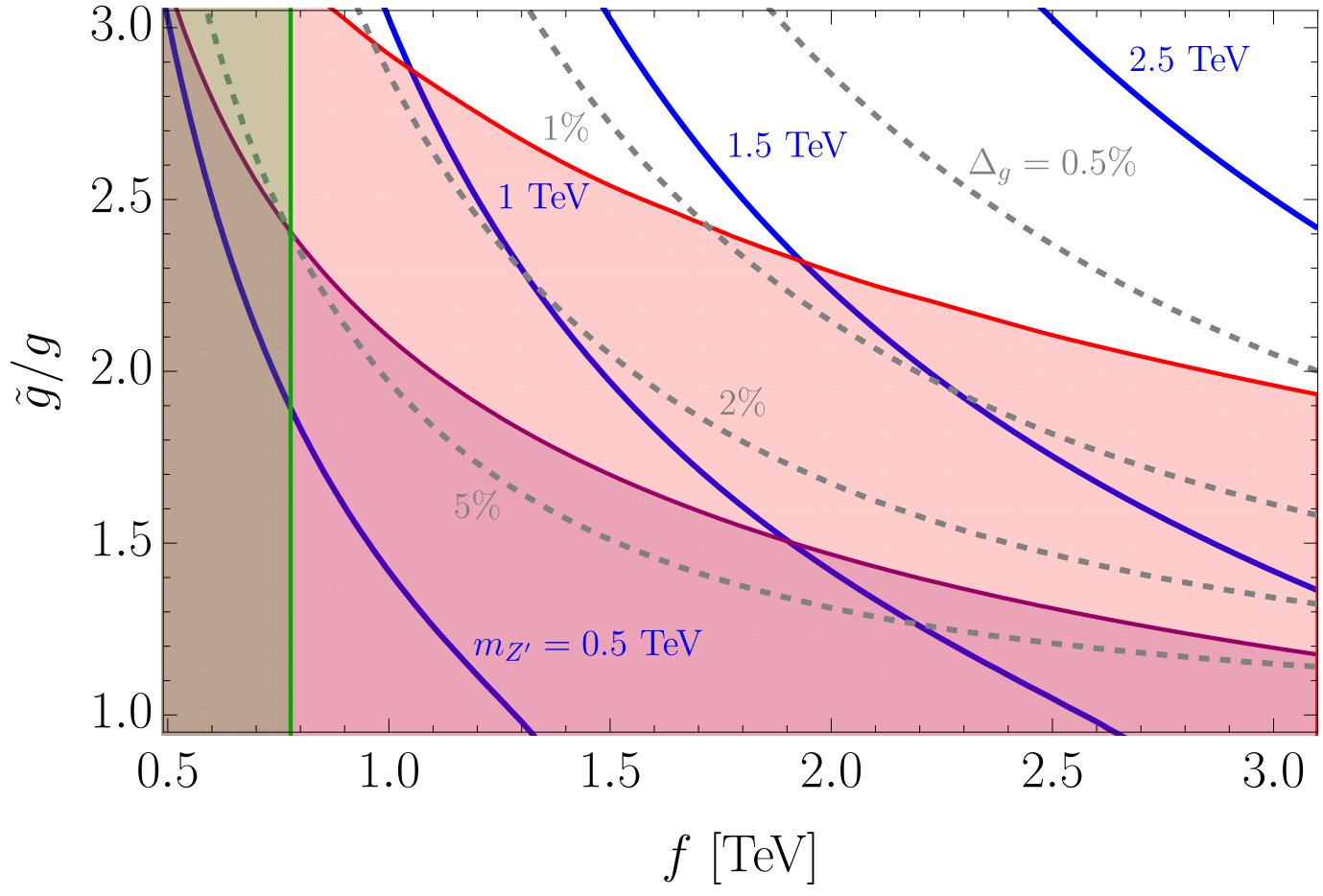
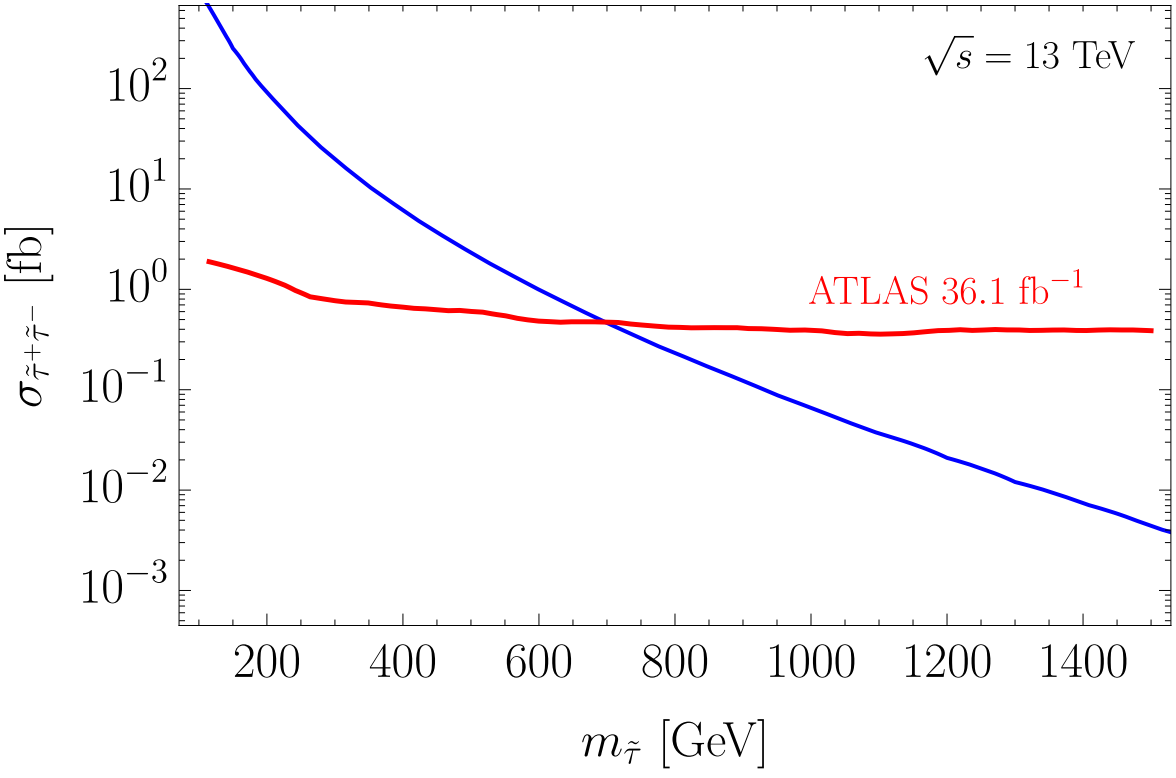


Backup slides - heavy stable twin lepton



- large Yukawa $\rightarrow$ large contribution to Higgs mass
- not guaranteed to be stable $\rightarrow$ model dependent

Backup slides - Potential for the additional pNGB

- $\tilde{w}^{\pm,0}$ are not eaten in Minimal Model
- twin top and bottom not necessarily a doublet under $SU(2)_{\tilde{L}}$. Need not introduce twin bottom $\Rightarrow$ $\tilde{w}^{\pm}$ gets a mass
  - $m^2_{\tilde{w}^{\pm}} \sim c_y \frac{6 m_\psi}{32\pi^2} \tilde{y}_L^2 \approx (550\text{GeV})^2 \left(\frac{\tilde{y}_l}{1}\right)^2 \left(\frac{m_\psi}{4\text{TeV}}\right)^2$
- $\tilde{w}^0$ can get a mass since $U(1)_{\tilde{L}-Z}$ need not be exact any more.
  - One possibility: add a vector like mass for twin top: $m_{\tilde{t}} \bar{\tilde{t}}_R \tilde{t}_L$
  - $m^2_{\tilde{w}^0} \sim (85\text{GeV})^2 \left(\frac{m_{\tilde{t}}}{10\text{GeV}}\right) \left(\frac{750\text{GeV}}{f}\right) \left(\frac{m_*}{5\text{TeV}}\right)^2$