Top-Higgs and Dilatons in light of LHC results

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Limits on SM Higgs

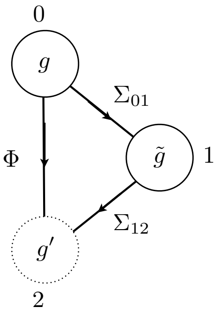
- The ATLAS and CMS collaborations have combined to set strong exclusion limits on the SM Higgs boson.
- Evidence at 125 GeV?
- What do the results mean for other scalars?

Dynamical EWSB: TC2

- Technicolor - Inspired by QCD! Unfortunately, fermion masses an issue! (ETC...)
- TopColor to the rescue!
- Technicolor - most of EWSB, Topcolor takes care of top mass. (TC2).
- Two scales: $f_t < F_T$.

A simple model

- An $SU(2) \times SU(2) \times U(1)$ gauge theory in the "quiver" notation.



- The non-linear sigmas contain the pions: $\Sigma = \exp\left(\frac{2i\vec{\pi}\cdot\vec{\sigma}}{F_T}\right)$.
- The linear sigma Φ contains the top-Higgs.

Deconstructed TC2

- Gauge boson masses from TC side:

$$\mathcal{L}_\Sigma = \frac{F_T^2}{4}\left(\mathrm{Tr}(D_\mu \Sigma_{01}^\dagger D^\mu \Sigma_{01}) + \mathrm{Tr}(D_\mu \Sigma_{12}^\dagger D^\mu \Sigma_{12})\right).$$

- The top-Higgs field can be written as:

$$\Phi = \begin{pmatrix} (f_t + H_t + i\pi_t^0)/\sqrt{2} \\ i\pi_t^- \end{pmatrix},$$

- We parametrize the technicolor and top-color scales as:

$$F_T = \sqrt{2}v \cos\omega; \;\; f_t = v \sin\omega.$$

Role of the top-Higgs field

- Separate top-quark mass from the rest of EWSB.

$$\mathcal{L}_{top} = -\tilde{\lambda}_t \bar{\psi}_{L0} \, \Phi \, t_R + h.c.$$

- Thus, $m_t \approx \tilde{\lambda}_t v \sin\omega$+TC corrections.
- We see that the top-Yukawa in enhanced: $\tilde{\lambda}_t = \lambda_{t,SM} / \sin\omega$.

BC, R.S.Chivukula, H.Logan, A.Martin, and E.H.Simmons, arXiv: 1101.6023.

Particle Content

- SM particles + heavy copies.
- Dimensionful scales: F_T, f_t, and M_D, with $F_T^2 + f_t^2 = v^2$.
- Gauge Spectrum: $M_{\rm light} = g\sqrt{F_T^2 + f_t^2}$; $M_{\rm heavy} \sim \tilde{g} F_T$.
- Fermion Spectrum: $m_{\rm light} = m_{\rm SM}$; $m_{\rm heavy} \sim M_D$.
- A phyical top-Higgs (mass M_{Ht}) (bound state of two tops ∼350 GeV).
- A triplet of uneaten top-pions:

$$\Pi_t^a = -\sin\omega\left(\frac{\pi_0^a + \pi_1^a}{\sqrt{2}}\right) + \cos\omega\,\pi_t^a.$$

Top-Higgs Couplings

- Roughly, the top-Higgs couplings follows the pattern:

$$
\begin{aligned}
H_t, A_{\text{top}} B_{\text{top}} &\sim \frac{SM}{\sin\omega} \\
H_t, A_{\text{techni}} B_{\text{techni}} &\sim SM \times \sin\omega \\
H_t, A_{\text{top}} B_{\text{techni}} &\sim SM
\end{aligned}
$$

- Specifically, we have:

$$
\begin{aligned}
H_t \Pi_t \Pi_t &= \frac{1}{2v \sin\omega} \left[(M_H^2 - 2M_{\Pi_t}^2) \cos 2\omega + M_H^2 \right] \\
H_t \bar{t} t &= \frac{\lambda_{t,SM}}{\sin\omega} \\
H_t W^+ W^- &\sim \frac{g^2}{2} v \sin\omega; \qquad H_t ZZ \sim \frac{g^2}{4\cos^2\theta} v \sin\omega \\
H_t \Pi_t^- W^+ &\sim \frac{g}{2} \cos\omega; \qquad H_t \Pi_t^0 Z \sim -\frac{g}{2\cos\theta} \cos\omega
\end{aligned}
$$

Scaling of the cross-section

- The Higgs at the LHC predominantly is produced via gluon fusion with small VBF contributions.
- The gluon fusion contribution (because of the $H_t gg$ coupling via the top-triangle) is enhanced:

$$\frac{\sigma_{gg}(pp \to H_t)}{\sigma_{gg}(pp \to H_{SM})} = \frac{\Gamma(H_t \to gg)}{\Gamma(H_{SM} \to gg)} \approx \frac{1}{\sin^2 \omega} \ ,$$

while the VBF channel is suppressed:

$$\frac{\sigma_{VBF}(pp \to H_t)}{\sigma_{VBF}(pp \to H_{SM})} = \frac{\Gamma(H_t \to W^+W^-/ZZ)}{\Gamma(H_{SM} \to W^+W^-/ZZ)} \approx \sin^2 \omega \ .$$

Translating the LHC limit

- If all decays of the top-Higgs are kinematically allowed, there emerges a hierarchy of decay widths:

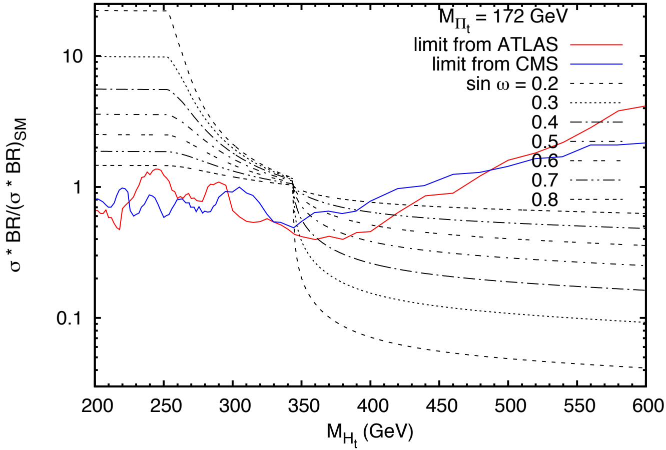
$$\Gamma(H_t \to 2\Pi_t) \gtrsim \Gamma(H_t \to t\bar{t}), \Gamma(H_t \to \Pi_t + W) \gtrsim \Gamma(H_t \to WW).$$

- The ratio we are after is $\frac{\sigma(pp \to H_t \to WW/ZZ)}{\sigma(pp \to H \to WW/ZZ)}$, which can be written as:

$$\frac{\left(\frac{1}{\sin^2\omega}\sigma_{gg}(pp \to H) + \sin^2\omega \cdot \sigma_{VBF}(pp \to H)\right)}{\sigma_{gg}(pp \to H) + \sigma_{VBF}(pp \to H)} \cdot \frac{BR(H_t \to WW)}{BR(H \to WW)} .$$

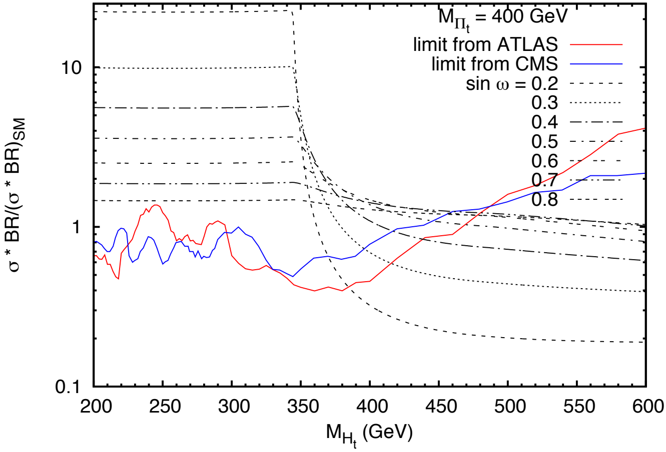
- The ratio of the BR's depends crucially on the mass of the top-pion, if the decay $H_t \to \Pi_t + W/Z$ is kinematically allowed.

$M_{\Pi_t} = m_t$



M_Πt = 172 GeV
limit from ATLAS
limit from CMS
sin ω = 0.2
0.3
0.4
0.5
0.6
0.7
0.8
10
1
0.1
200
250
300
350
400
450
500
550
600
M_Ht (GeV)
σ * BR/(σ * BR)_SM

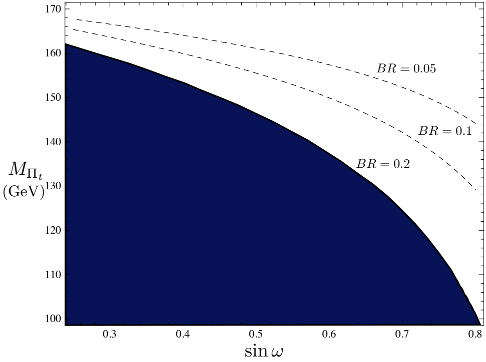
$M_{\Pi_t} > m_t$



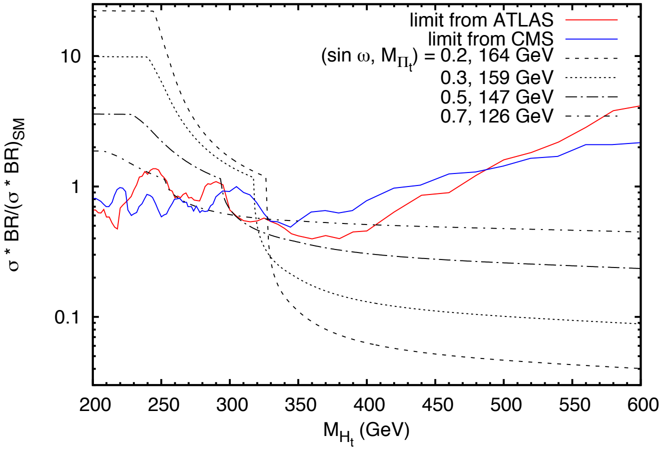
M_{Π_t} = 400 GeV
limit from ATLAS
limit from CMS
sin ω = 0.2
0.3
0.4
0.5
0.6
0.7
0.8
10
1
0.1
200
250
300
350
400
450
500
550
600
M_{H_t} (GeV)
σ * BR/(σ * BR)$_{SM}$

$M_{\Pi_t} < m_t$: Limit on the top-pion mass

- Tevatron has set lower limits on charged higgs based on $\mathrm{BR}(t \to H^+ b) \leq 0.2$. We adapt this to the charged top-pion.

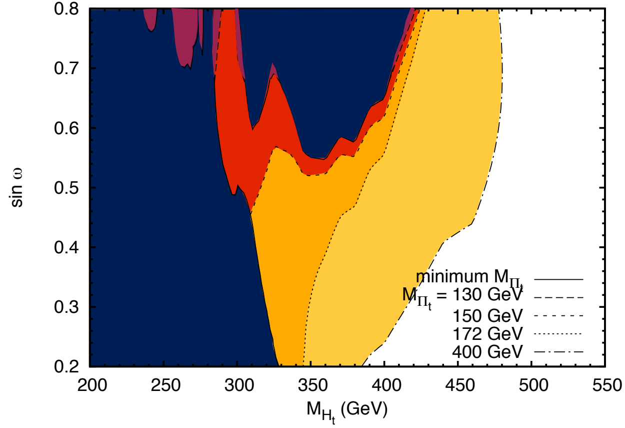


$M_{\Pi_t} < m_t$



limit from ATLAS
limit from CMS
(sin ω, M_{Π_t}) = 0.2, 164 GeV
0.3, 159 GeV
0.5, 147 GeV
0.7, 126 GeV
10
1
0.1
200
250
300
350
400
450
500
550
600
M_{H_t} (GeV)
σ * BR/(σ * BR)$_{SM}$

Putting it all together....



BC, R.S. Chivukula, H. Logan, E.H. Simmons, and A. Martin,
arXiv:1108.4000

So.......

- Strongly interacting models are already heavily constrained by LHC data.
- For $M_{\Pi_t} \geq m_t$, "typical" TC2 parameter space ruled out! Heavy top-Higgs possible.
- Model building avenues still remain!

Higgs or Dilaton?[1]

[1] *W. Goldberger, B. Grinstein, and W. Skiba*, arXiv:0708.1463

Dilaton

- EWSB sector may be coupled to a conformal sector.
- Realizations: Walking TC, or AdS/CFT: RS, XD with BC's etc.
- Low energy theory contains the Goldstone boson of broken scale invariance- the dilaton.

Scale Invariant Lagrangian

- Scale invariant operator: $\mathcal{O} \to e^{\Delta\alpha}\mathcal{O}$, with $\Delta = 4$.
- If $\Delta \neq 4$, use χ as a "compensating" field to make the action scale invariant!

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left|D_\mu U\right|^2 - \frac{1}{4}\left(B_{\mu\nu}\right)^2 - \frac{1}{2}\mathrm{Tr}\left(W_{\mu\nu}\right)^2 - m_i\bar{\psi}_i U\psi_i .$$

- Use our prescription to make this scale invariant:

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left|D_\mu U\right|^2\left(\chi/f\right)^2 - \frac{1}{4}\left(B_{\mu\nu}\right)^2 - \frac{1}{2}\mathrm{Tr}\left(W_{\mu\nu}\right)^2 - m_i\bar{\psi}_i U\psi_i\left(\chi/f\right).$$

Couplings to massive particles

- Paramtrize fluctuations about the vev $\bar{\chi} = \chi - f$ and read off the couplings:

$$\mathcal{L}_{\chi,SM} = \frac{1}{2} m_V^2 V_\mu^2 \left(1 + \frac{2\bar{\chi}}{f} + \frac{\bar{\chi}^2}{f^2}\right) - \left(1 + \frac{\bar{\chi}}{f}\right) m_i \bar{\psi}_i U \psi_i .$$

- Couplings to massive gauge bosons and fermions are rescaled by v/f!

Couplings to massless particles

- Dilatation current, D^μ: $\partial_\mu D^\mu \propto T^\mu_\mu$.
- Direct couplings to massless gauge bosons: QCD (QED) trace anomaly.

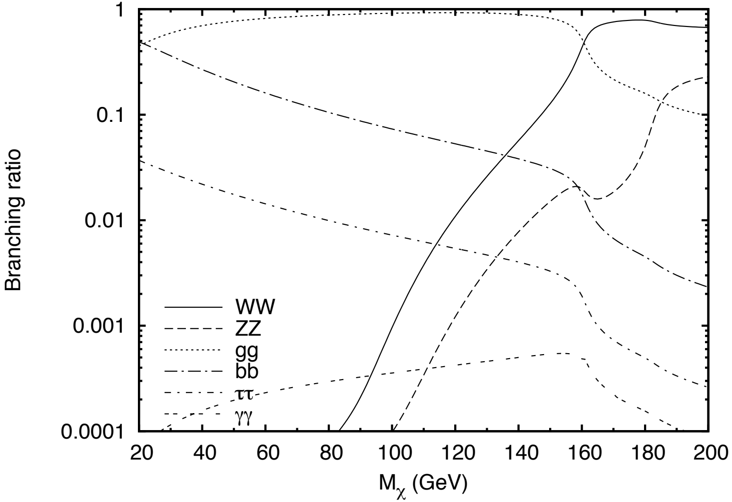
$$\mathcal{L} = \left[\frac{\alpha_{EM}}{8\pi}\left(b_{EM}\right)\left(F_{\mu\nu}\right)^2 + \frac{\alpha_s}{8\pi}\left(b_G\right)\left(G^a_{\mu\nu}\right)^2\right]\frac{\bar{\chi}}{f},$$

where $b_G = 11 - \frac{2}{3}n_F$ and $b_{EM} = -11/3$.

- Indirect (loop-induced) coupling to two gluons just like the SM Higgs.

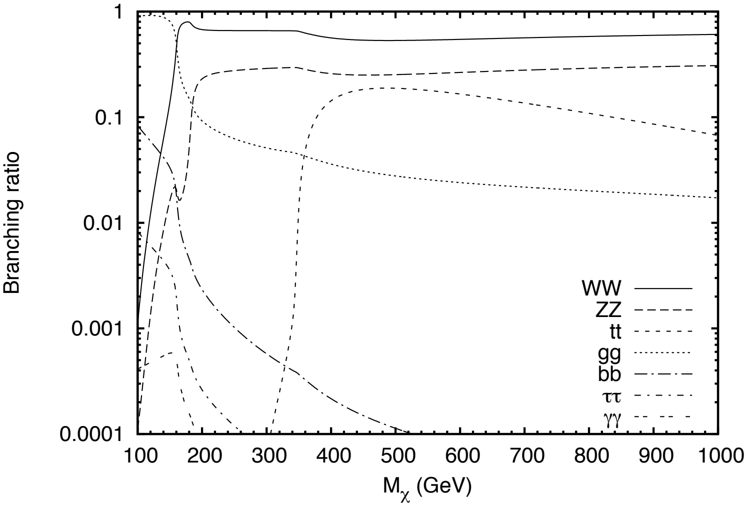
Decays

- Enhanced coupling to gluons!

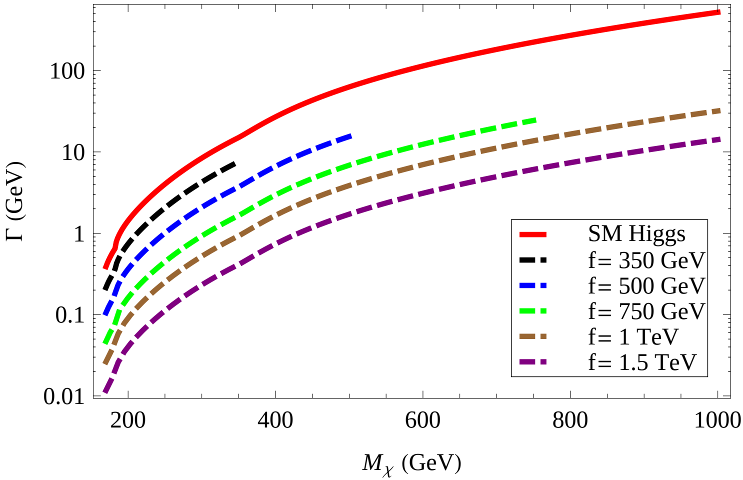


Decays

- Above the *WW* threshold, decays follow the SM Higgs pattern.



- Narrower than the SM Higgs!



Constraints from LEP

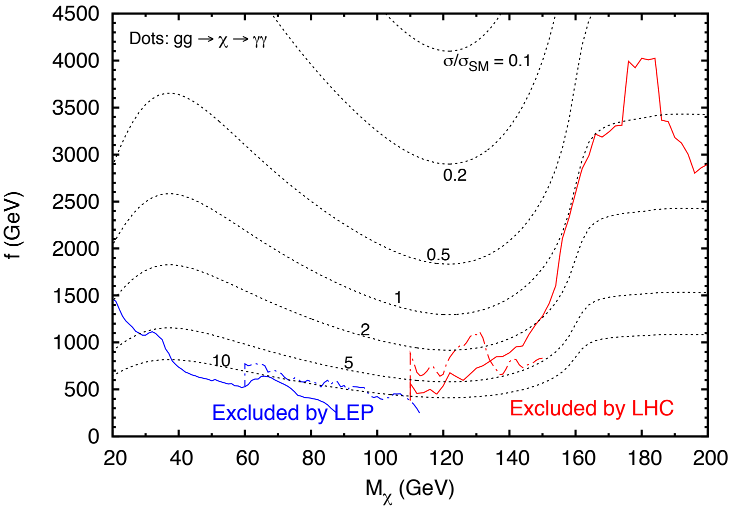
- LEP looked for the Higgs in $e^+e^- \to ZH$ with Higgs decay final states $b\bar{b}$ and $\tau\tau$.
- Results were presented in the parameter space of M_H and ξ^2 , where ξ is a scaling factor on the ZZH production coupling.
- We translate this for the case of the dilaton:

$$\xi^2 = \frac{\sigma(e^+e^- \to Z\chi)}{\sigma(e^+e^- \to ZH_{\rm SM})} \times \frac{{\rm BR}(\chi \to b\bar{b} + \tau\tau)}{{\rm BR}(H_{\rm SM} \to b\bar{b} + \tau\tau)}.$$

- The LEP experiments also performed a flavor-independent search for $e^+e^- \to ZH$ with the Higgs decaying into hadrons. The corresponding ξ^2 is:

$$\xi^2 = \frac{\sigma(e^+e^- \to Z\chi)}{\sigma(e^+e^- \to ZH_{\rm SM})} \times {\rm BR}(\chi \to gg + b\bar{b} + c\bar{c}).$$

LEP limits on Dilaton



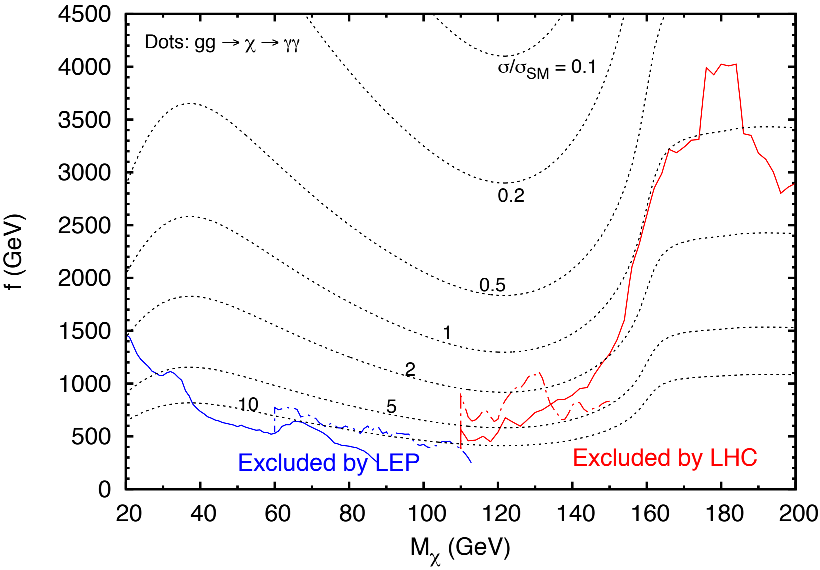
- Enhanced production via gluon fusion mechanism!
- Same search channels as the SM higgs, with modified rates and BRs.

$$\frac{\sigma(pp \to \chi)}{\sigma(pp \to H_{\rm SM})} = \frac{\sigma(gg \to \chi) + \sigma({\rm VBF} \to \chi)}{\sigma(gg \to H_{\rm SM}) + \sigma({\rm VBF} \to H_{\rm SM})}$$
$$= \frac{v^2}{f^2} \frac{R_g \sigma(gg \to H_{\rm SM}) + \sigma({\rm VBF} \to H_{\rm SM})}{\sigma(gg \to H_{\rm SM}) + \sigma({\rm VBF} \to H_{\rm SM})},$$

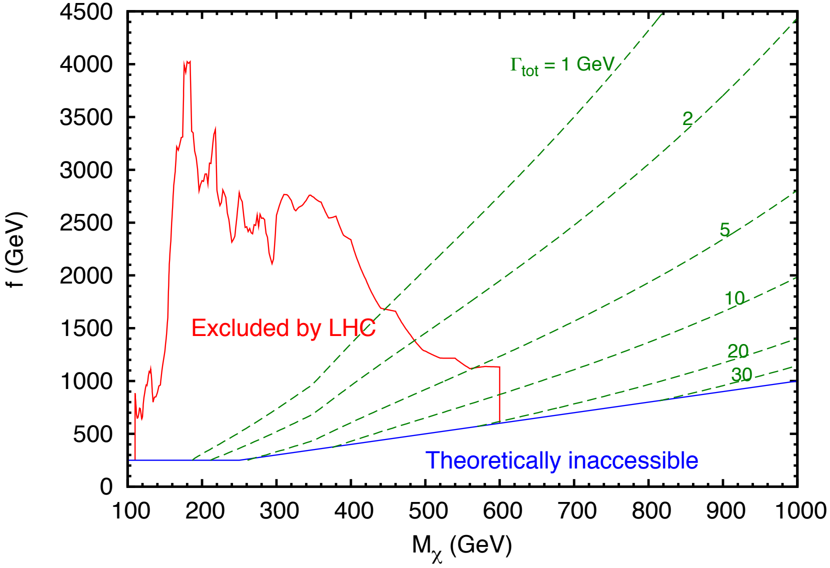
where

$$R_g = \frac{\left|b_G + \frac{1}{2}\sum_i F_{1/2}(\tau_i)\right|^2}{\left|\frac{1}{2}\sum_i F_{1/2}(\tau_i)\right|^2}$$

LHC limits on Dilaton

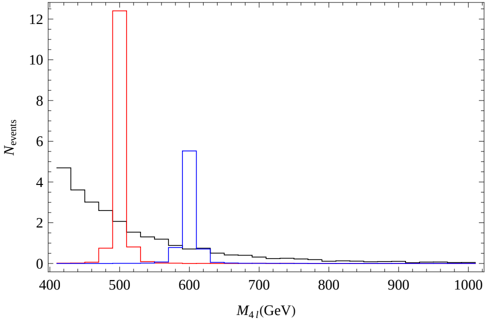


LHC limits on Dilaton

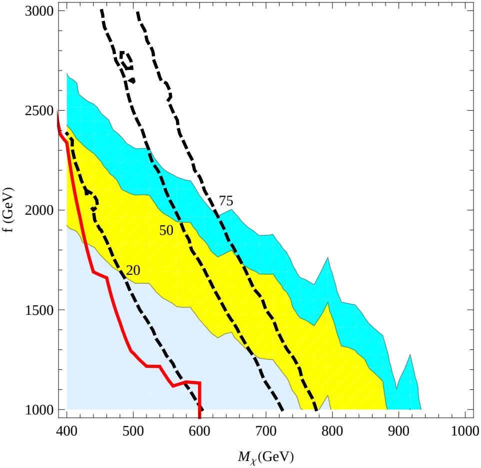


Dilaton at the LHC

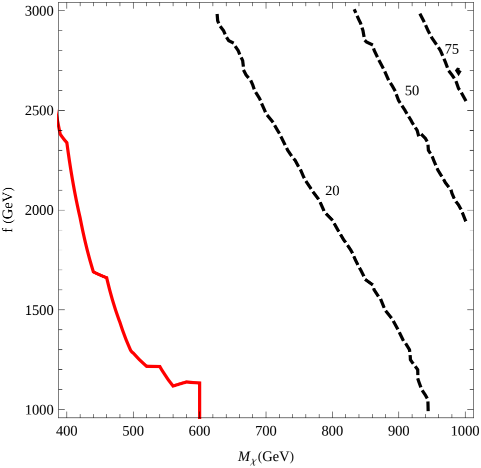
- Search strategy same as SM Higgs: $\chi \to ZZ \to 4\ell$.
- Narrow width - stronger invariant mass cuts possible!
- Require $p_T >$10 GeV, $|\eta| < 2.5$.



@ 7 TeV


3000
2500
2000
1500
1000
f (GeV)
400
500
600
700
800
900
1000
M_χ(GeV)
75
50
20

@ 14 TeV



3000
2500
2000
1500
1000
f (GeV)
400
500
600
700
800
900
1000
M_χ(GeV)
20
50
75

Conclusions

- LHC Higgs exclusion data already placing heavy constraint on models with scalars!
- Light SM Higgs possible - implications for other theories interesting.

TopColor details

$$\mathcal{L}_\mu = \mathcal{L}_{kinetic} + g\left(\bar{\psi}_L \psi_R H + h.c.\right) + Z_H |\partial_\mu H|^2 - M_H^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2,$$

with

$$\begin{aligned} Z_H &= \frac{g^2 N_c}{2(4\pi)} \log(\Lambda^2/\mu^2); \lambda = \frac{2g^4 N_c}{2(4\pi)} \log(\Lambda^2/\mu^2) \\ M_H^2 &= \Lambda^2 - \frac{2g^2 N_c}{(4\pi)^2}(\Lambda^2 - \mu^2) \end{aligned}$$

- Scaling $H \to H/\sqrt{Z_H}$, we find $\tilde{g}^2 = g^2/Z_H, \tilde{m}_H^2 = m_H^2/Z_H$, and $\tilde{\lambda} = \lambda/Z_H^2$.

$$\mathcal{L}_\mu = \mathcal{L}_{kinetic} + \tilde{g}\left(\bar{\psi}_L \psi_R H + h.c.\right) + |\partial_\mu H|^2 - \tilde{m}_H^2 H^\dagger H - \frac{\tilde{\lambda}}{2}(H^\dagger H)^2.$$

- Renormalized quantities: $\tilde{g}^2 = 2\tilde{\lambda}$.