Testing Naturalness at 100 TeV

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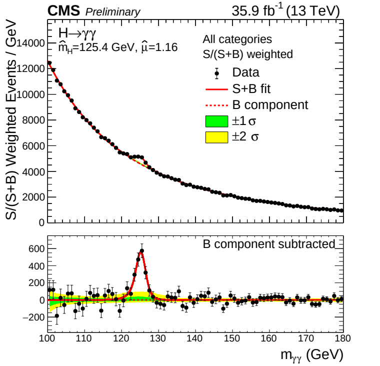
CP3 seminar

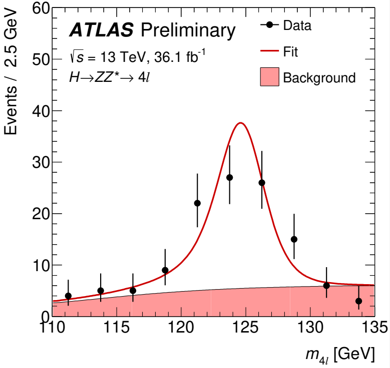
Naturalness

Higgs

$H \to \gamma\gamma$ CMS-PAS-HIG-16-040 2017



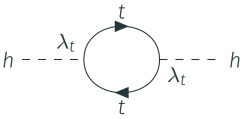
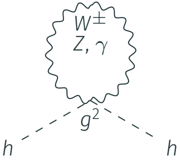
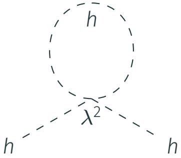
$H \to ZZ^* \to \bar{l}l\bar{l}l$ ATLAS-CONF-2017-046 2017



Hierarchy problem

The total Higgs mass-squared consistent of the tree-level mass-squared parameter and the sum of all loop contributions.

The dominant loop contributions are

Top	SU(2) gauge boson	Higgs
		
$-6\left(\frac{\lambda_t\Lambda}{4\pi}\right)^2$	$\frac{9}{4}\left(\frac{g\Lambda}{4\pi}\right)^2$	$\left(\frac{\lambda\Lambda}{4\pi}\right)^2$

A cut-off scale of $\Lambda \sim 10\,\text{TeV}$ leads to

$$\sim -(2\,\text{TeV})^2 \qquad \sim (700\,\text{GeV})^2 \qquad \sim (500\,\text{GeV})^2$$

For a fine-tuning of 10 %, the top, gauge, and Higgs loops must be cut off at

$$\Lambda_{\text{top}} \lesssim 2\,\text{TeV}\,, \qquad \Lambda_{\text{gauge}} \lesssim 5\,\text{TeV}\,, \qquad \Lambda_{\text{Higgs}} \lesssim 10\,\text{TeV}\,.$$

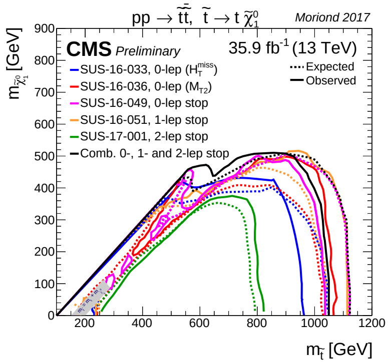
Adding a new symmetry can protect the Higgs mass.

- Supersymmetry leads to scalar top partner
- Little Higgs mechanism leads to fermionic top partner

They couple in such a way to the Higgs that the contribution from the top quark is canceled.

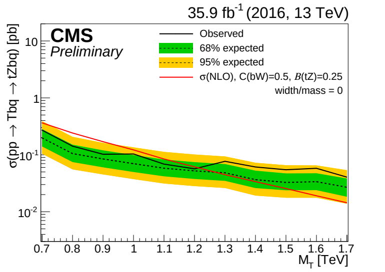
Scalar top partner

CMS Moriond 2017 n.d.



Fermionic top partner

CMS-PAS-B2G-17-007 2017



Higgs as Pseudo Goldstone boson

Nambu Goldstone Theorem

For each spontaneously broken global symmetry generator there is a massless boson in the spectrum.

The Higgs can be seen as part of a Nambu Goldstone boson π with a VEV f.

$$\phi = \phi_0 \exp \frac{i\pi}{f} , \qquad \phi_0 = \begin{pmatrix} 0 \\ f \end{pmatrix} .$$

The simplest little Higgs model breaks a global $\mathrm{SU}(3)$ to $\mathrm{SU}(2)_L$

$$\pi = \begin{pmatrix} \Phi & H \\ H^\dagger & \eta \end{pmatrix} ,$$

H is the $\mathrm{SU}(2)$ Higgs doublet .

Expanded around its VEV the non-linear field ϕ reads

$$\phi = \begin{pmatrix} 0 \\ f \end{pmatrix} + i \begin{pmatrix} H \\ 0 \end{pmatrix} - \frac{1}{2f} \begin{pmatrix} 0 \\ H^\dagger H \end{pmatrix} + \dots ,$$

The Higgs kinetic term and interaction terms are given by

$$f^2 \left|\partial_\mu \phi\right|^2 = \left|\partial_\mu h\right|^2 + \frac{\left|\partial_\mu H\right|^2 H^\dagger H}{f^2} + \dots .$$

Massless NGB

This Higgs field is a massless NGB

$$f^2 \left|\partial_\mu \phi\right|^2 = \left|\partial_\mu h\right|^2 + \frac{\left|\partial_\mu H\right|^2 H^\dagger H}{f^2} + \dots \, .$$

- with non-renormalizable interactions suppressed by a symmetry breaking scale f
- This is an effective theory which becomes strongly coupled at $\Lambda \simeq 4\pi f$

Gauge interactions

Adding gauge interactions via $|D_\mu \phi|^2$ reintroduces the quadratic divergent terms

$$\left(\frac{g\Lambda}{4\pi}\right)^2 H^\dagger H \, .$$

Little Higgs models

[See e.g. Schmaltz, Tucker-Smith 2005]

Collective symmetry breaking [Arkani-Hamed et al. 2002]

If there are two different global symmetries, an exact Goldstone boson remains as long as one symmetry stays unbroken

Two copies of NGBs

$$\phi_{1/2} = \phi_0 \exp \frac{i\pi_{1/2}}{f} \ .$$

The interaction with gauge bosons

$$\mathcal{L} = |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 \ ,$$

lead to quadratically divergent one-loop diagrams

$$\left(\frac{g}{4\pi}\right)^2 \left(\phi_1^\dagger \phi_1 + \phi_2^\dagger \phi_2\right) = \left(\frac{g\Lambda}{4\pi}\right)^2 \left(f^2 + f^2 + \dots\right) \ ,$$

which do not involve the Higgs doublet.

The expansion of the product of both fields

$$\begin{aligned}\phi_1^\dagger \phi_2 &= \begin{pmatrix} 0 & f \end{pmatrix} \exp\left\{ -\frac{2i}{f} \begin{pmatrix} 0 & h \\ h^\dagger & 0 \end{pmatrix} \right\} \begin{pmatrix} 0 \\ f \end{pmatrix} \\ &= f^2 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - 2if \begin{pmatrix} 0 & h \\ h^\dagger & 0 \end{pmatrix} - 2 \begin{pmatrix} h^\dagger h & 0 \\ 0 & h^\dagger h \end{pmatrix} + \dots \\ &= f^2 - 2h^\dagger h + \dots ,\end{aligned}$$

leads to a logarithmically divergent mass-squared for h equal to

$$\left(\frac{g^2}{4\pi}\right)^2 \log\left(\frac{\Lambda^2}{\mu^2}\right) \left|\phi_1^\dagger \phi_2\right|^2 \simeq \left(\frac{g^2}{4\pi}\right)^2 \log\left(\frac{\Lambda^2}{\mu^2}\right) f^2 ,$$

which is $\sim M^2_{\text{weak}}$ for $f \sim$ TeV.

Top sector

The coupling between Higgs fields and a third generation triplet $\mathbf{\Psi}$ is

$$\mathcal{L}_{\text{yuk}} = \lambda_1 \phi_1^\dagger \mathbf{\Psi} t_1^c + \lambda_2 \phi_2^\dagger \mathbf{\Psi} t_2^c \,, \qquad \mathbf{\Psi} = (Q,\, T) \;,$$

where T is a fermionic top-partner.

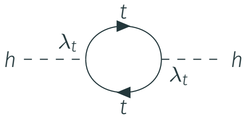
The expansion reads

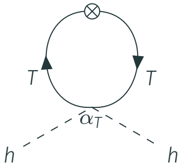
$$\mathcal{L} \sim \frac{\lambda}{\sqrt{2}} \left[fT(t_2^c + t_1^c) + iH^\dagger Q(t_2^c - t_1^c) - \frac{1}{2f} H^\dagger H T (t_2^c + t_1^c) + \dots \right]$$
$$= \lambda H^\dagger Q t^c + \lambda f \left(1 - \frac{1}{2f^2} H^\dagger H \right) T T^c + \dots \;,$$

where

$$T^c = (t_2^c + t_1^c)/\sqrt{2} \,, \qquad t^c = i(t_2^c - t_1^c)/\sqrt{2} \,, \qquad \lambda_1 \equiv \lambda_2 \equiv \lambda/\sqrt{2} \,.$$

The divergent loop contribution cancel each other





Mirror Twin Higgs model

[Burdman et al. 2015]

In mirror twin Higgs models the partner can be neutral under SM charges.

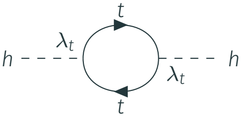
The Higgs H transforms as fundamental under $\mathsf{SU}(4)$ which is gauged into $\mathsf{SU}(2)_{\mathrm{SM}} \times \mathsf{SU}(2)_{\mathrm{twin}}$.

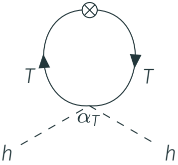
$$H_{\mathsf{SU}(4)} = \begin{pmatrix} H_{\mathrm{SM}} \\ H_{\mathrm{twin}} \end{pmatrix} \, ,$$

The top sector

$$\begin{aligned} \mathcal{L} &= y H_{\mathrm{SM}} Q_{\mathrm{SM}} U^c_{\mathrm{SM}} + y H_{\mathrm{twin}} Q_{\mathrm{twin}} U^c_{\mathrm{twin}} \\ &\to y H Q_{\mathrm{SM}} U^c_{\mathrm{SM}} + y \left(f - \frac{|h|^2}{2f} \right) Q_{\mathrm{twin}} U^c_{\mathrm{twin}} \, , \end{aligned}$$

Also in this case the divergent loop contribution cancel





but here the twin partner T is not charged under the SM gauge group.

Little Higgs models

- The SM Higgs mass is not stabilized against the sizeable loop corrections.
- Little Higgs models relieve the tension.
- The mirror twin-Higgs model provides the same mechanism and evades the strongest bounds from the LHC.

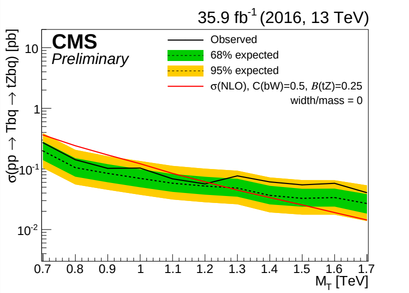
T-parity

T-parity forbids tree-level couplings between little Higgs particles and SM particles.

Simplified model

Guiding questions

- We assume that a top partner of mass m_T has been discovered.
- We want to know which measurement is necessary in order to be sure that the top partner couplings cancel the top quark divergence.
- What will be the reach of a future collider for such a measurement?



Simplified model

We use a simplified Lagrangian describing the couplings between a Higgs doublet H and the third generation quarks q_3 and u_3^c with a vector-like pair (U^c, U) which are singlets under $\mathrm{SU}(2)_w$.

The couplings up to second order in H are

$$\mathcal{L}_U = u_3^c \left(c_0 f U + c_1 H^\dagger q_3 + \frac{c_2}{2f} H^\dagger H U + \dots \right) + U^c \left(\widehat{c}_0 f U + \widehat{c}_1 H^\dagger q_3 + \frac{\widehat{c}_2}{2f} H^\dagger H U + \dots \right) + \text{h.c.}\,.$$

- No additional symmetry is assumed
- The $H^\dagger H$ term can cancel the loop contribution from the linear term
- The parameter $c_{0,1,2}$ describe the couplings of the right handed quark u_3^c
- The parameter $\widehat{c}_{0,1,2}$ describe the couplings of the right handed partner U^c

Mass eigenstates

The rotation into mass eigenstates

top quarks	$t'^c = \dfrac{\widehat{c}_0 u_3^c - c_0 U^c}{c}$,	$t' = q_3$,
top partner	$T'^c = \dfrac{\widehat{c}_0 U^c + c_0 u_3^c}{c}$,	$T' = U$,

and definition of the couplings

Mass	$m_{T'} = fc$,	$c = \sqrt{c_0^2 + \widehat{c}_0^2}$,
Yukawa	$\lambda_{t'} = \dfrac{\widehat{c}_0 c_1 - c_0 \widehat{c}_1}{c}$,	$\lambda_{T'} = \dfrac{c_0 c_1 + \widehat{c}_0 \widehat{c}_1}{c}$,
$H^\dagger H f f^c$	$\alpha_{t'} = \widehat{c}_0 c_2 - c_0 \widehat{c}_2$,	$\alpha_{T'} = c_0 c_2 + \widehat{c}_0 \widehat{c}_2$,

leads to the mass eigenstate Lagrangian

$$\mathcal{L}_{T'} = m_{T'} T'^c T' + \lambda_{t'} H^\dagger t'^c t' + \lambda_{T'} H^\dagger T'^c t' + \frac{\alpha_{t'}}{2 m_{T'}} H^\dagger H t'^c T' + \frac{\alpha_{T'}}{2 m_{T'}} H^\dagger H T'^c T' + \mathcal{O}\left(H^3\right) + \text{h.c.} ,$$

Decoupling of top quark from their partner

Mass eigenstate Lagrangian

$$\mathcal{L}_{T'} = m_{T'} T'^c T' + \lambda_{t'} H^\dagger t'^c t' + \lambda_{T'} H^\dagger T'^c t' + \frac{\alpha_{t'}}{2m_{T'}} H^\dagger H t'^c T' + \frac{\alpha_{T'}}{2m_{T'}} H^\dagger H T'^c T' + \mathcal{O}\left(H^3\right) + \text{h.c.} ,$$

If we want to forbid couplings between top quarks and top partner we have to ensure

$$\lambda_{T'} = \frac{c_0 c_1 + \widehat{c}_0 \widehat{c}_1}{c} \equiv 0 , \qquad \alpha_{t'} = \widehat{c}_0 c_2 - c_0 \widehat{c}_2 \equiv 0 .$$

Examples of models where this is given are

little Higgs with T-parity $\quad c_0 = -\widehat{c}_0 , \quad c_1 = \widehat{c}_1 , \quad c_2 = -\widehat{c}_2 ,$

mirror twin Higgs $\quad c_0 = \widehat{c}_1 = c_2 = 0 .$

Using a vector-like pair (Q^c, Q) of $\mathrm{SU}(2)_w$ doublets (instead of singlets)

$$\mathcal{L}_Q = \left(Q^c c_0 f + u_3^c c_1 H^\dagger + Q^c \frac{c_2}{2f} H^\dagger H + \dots\right) q_3 + \left(Q^c \widehat{c}_0 f + u_3^c \widehat{c}_1 H^\dagger + Q^c \frac{\widehat{c}_2}{2f} H^\dagger H + \dots\right) Q + \text{h.c.}\,.$$

leads to the an identical mass eigenstate Lagrangian with the replacement of

$$T'^c \leftrightarrow T'\,, \qquad t'^c \leftrightarrow t'\,.$$

Various models can be described by these Lagrangians

Model	Coset		SU(2)	c_0	c_1	c_2	$\widehat{c}_0$	$\widehat{c}_1$	$\widehat{c}_2$
Toy model	$\frac{\mathrm{SU}(3)}{\mathrm{SU}(2)}$	Perelstein, Peskin, Pierce 2004	**1**	λ_1	$-\lambda_1$	$-\lambda_1$	λ_2	0	0
Simplest	$\left(\frac{\mathrm{SU}(3)}{\mathrm{SU}(2)}\right)^2$	Kaplan, Schmaltz 2003	**1**	λ	$-\lambda$	$-\lambda$	λ	λ	$-\lambda$
Littlest Higgs	$\frac{\mathrm{SU}(5)}{\mathrm{SO}(5)}$	Arkani-Hamed et al. 2002	**1**	λ_1	$-\sqrt{2}i\lambda_1$	$-2\lambda_1$	λ_2	0	0
Custodial	$\frac{\mathrm{SO}(9)}{\mathrm{SO}(5)\,\mathrm{SO}(4)}$	Chang 2003	**2**	y_1	$\frac{i}{\sqrt{2}}y_1$	$-\frac{1}{2}y_1$	y_2	0	0
T-parity invariant	$\frac{\mathrm{SU}(3)}{\mathrm{SU}(2)}$	Cheng, Low, Wang 2006	**1**	λ	$-\lambda$	$-\lambda$	$-\lambda$	$-\lambda$	λ
T-parity invariant	$\frac{\mathrm{SU}(5)}{\mathrm{SO}(5)}$	Cheng, Low, Wang 2006	**1**	λ	$-\sqrt{2}i\lambda$	-2λ	$-\lambda$	$-\sqrt{2}i\lambda$	2λ
Mirror twin Higgs	$\frac{\mathrm{SU}(4)\,\mathrm{U}(1)}{\mathrm{SU}(3)\,\mathrm{U}(1)}$	Burdman et al. 2015	**1**	0	$i\lambda_t$	0	λ_t	0	$-\lambda_t$

Quadratic divergence

Mass eigenstate Lagrangian

$$\mathcal{L}_{T'} = m_{T'} T'^c T' + \lambda_{t'} H^\dagger t'^c t' + \lambda_{T'} H^\dagger T'^c t' + \frac{\alpha_{t'}}{2m_{T'}} H^\dagger H t'^c T' + \frac{\alpha_{T'}}{2m_{T'}} H^\dagger H T'^c T' + \mathcal{O}\left(H^3\right) + \text{h.c.} \, ,$$

The fermion mass matrix in the basis $(t'^c, \ T'^c)$ and $(t', \ T')$ is

$$\mathcal{M}(H) = \begin{pmatrix} 0 & 0 \\ 0 & m_{T'} \end{pmatrix} + \begin{pmatrix} \lambda_{t'} & 0 \\ \lambda_{T'} & 0 \end{pmatrix} H + \begin{pmatrix} 0 & \alpha_{t'} \\ 0 & \alpha_{T'} \end{pmatrix} \frac{H^\dagger H}{2m_{T'}} + \mathcal{O}\left(H^3\right) \, .$$

Coleman-Weinberg potential

$$V^T_{\text{quad}} = \frac{\Lambda^2}{16\pi^2} \, \mathbf{tr} \, \mathcal{M}^2 \, , \qquad \mathcal{M}^2 = \mathcal{M}(H)^\dagger \mathcal{M}(H) \, ,$$

Absence of quadratically divergent contributions to the Higgs mass for

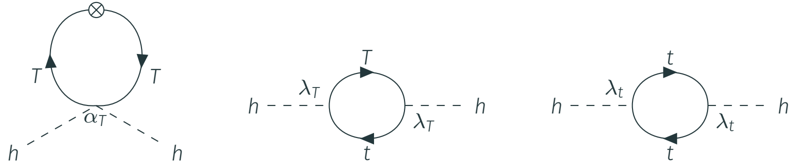
$$\Delta m^2_{\text{quad}} = \frac{1}{2} \left. \frac{\partial^2 V^T_{\text{quad}}}{\partial H^2} \right|_{H=0} \equiv 0 \, ,$$

Naturalness condition

Requiring the coefficients of the $H^\dagger H$ term to vanish leads to the condition

$$\alpha_{T'} = -\left|\lambda_{T'}\right|^2 - \left|\lambda_{t'}\right|^2 \ .$$

which corresponds to a cancellation between



$\alpha_{t'}$ turns out to be unconstrained by this consideration

In terms of the original parameter this condition reads

$$|c_1|^2 + c_0 c_2 = -\left|\widehat{c}_1\right|^2 - \widehat{c}_0 \widehat{c}_2 \ .$$

this holds for example in little and twin Higgs models

Little Higgs	$\lvert c_1\rvert^2 = -c_0 c_2 \ ,$	$\left\lvert\widehat{c}_1\right\rvert^2 = -\widehat{c}_0 \widehat{c}_2 \ ,$
Mirror twin Higgs	$\lvert c_1\rvert^2 = -\hat{c}_0 \hat{c}_2 \ ,$	$c_0 = \hat{c}_1 = c_2 = 0 \ .$

Testing the naturalness relation

Naturalness relation

$$\alpha_{T'} = -|\lambda_{T'}|^2 - |\lambda_{t'}|^2 \ .$$

This can be tested with the knowledge of

- Top Yukawa coupling
- Higgs coupling to a top quark and its partner (can be equal to 0)
- Coupling of a top partner pair to a Higgs pair (large phase space suppression)

It has previously been suggested to test this equation via [Perelstein, Peskin, Pierce 2004]

$$\lambda_{T'} \frac{m_{T'}}{f} = |\lambda_{T'}|^2 + |\lambda_{t'}|^2 \ ,$$

- Measure λ_T with the total decay width: $\Gamma_T = \frac{m_T \lambda_T^2}{16\pi}$
- Measure f in the gauge sector: $M_{Z_H} = \sqrt{\frac{g_L^2 + g_R^2}{2}} f = \frac{\sqrt{2} g}{\sin 2\psi} f$

Downsides

- These measurements are non-trivial
- This naturalness relation is model dependent (e.g. vanishes for $\lambda_{T'} = 0$)

Electroweak symmetry breaking

Expanding the Higgs field around its VEV

$$H = \frac{1}{\sqrt{2}} \left(h^+,\, v + h\right)^T \,, \qquad v = 246\,\text{GeV} \,,$$

and rotating the fermion fields into mass eigenstates

top quarks	$t^c = t'^c \,,$	$t = t' - T' \frac{v}{m_{T'}} \lambda^*_{T'} \,,$
top partner	$T^c = T'^c \,,$	$T = T' + t' \frac{v}{m_{T'}} \lambda_{T'} \,,$

leads to the Lagrangian

$$\mathcal{L}_T = m_T T^c T + \lambda_t v t^c t + \frac{\lambda_t}{\sqrt{2}} h t^c t + \frac{\lambda_T}{\sqrt{2}} h T^c t + \frac{\alpha_t}{4 m_T} h^2 t^c T + \frac{\alpha_T}{4 m_T} h^2 T^c T$$
$$+ \frac{a_t v}{\sqrt{2} m_T} h t^c T + \frac{a_T v}{\sqrt{2} m_T} h T^c T + \mathcal{O}\left(h^3, \frac{v^2}{m_T^2}\right) + \text{h.c.} \,.$$

The couplings m_T, $\lambda_{t,T}$ and $\alpha_{t,T}$ are up to linear order in v/m_T identical to their primed counterparts.

The new VEV induced couplings are

$$a_t = \alpha_{t'} + \lambda^*_{T'} \lambda_{t'} \,, \qquad a_T = \alpha_{T'} + |\lambda_{T'}|^2 \,,$$

Naturalness condition after electroweak symmetry breaking

Lagrangian after electroweak symmetry breaking

$$\mathcal{L}_T = m_T T^c T + \lambda_t v t^c t + \frac{\lambda_t}{\sqrt{2}} h t^c t + \frac{\lambda_T}{\sqrt{2}} h T^c t + \frac{\alpha_t}{4m_T} h^2 t^c T + \frac{\alpha_T}{4m_T} h^2 T^c T + \frac{a_t v}{\sqrt{2} m_T} h t^c T + \frac{a_T v}{\sqrt{2} m_T} h T^c T + \mathcal{O}\left(h^3, \frac{v^2}{m_T^2}\right) + \text{h.c.}\,.$$

The $T^c T h$ coupling together with the naturalness condition

$$a_T = \alpha_{T'} + |\lambda_{T'}|^2 \;, \qquad \alpha_{T'} = -|\lambda_{T'}|^2 - |\lambda_{t'}|^2 \;,$$

leads to the relation

$$a_T = -|\lambda_t|^2 + \mathcal{O}\left(\frac{v^2}{m_T^2}\right) \;,$$

In order to verify the cancellation between the loop contribution of the top quarks and their partners only the measurement of the $T^c T h$ coupling is necessary.

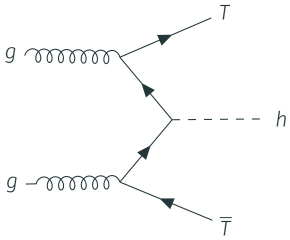
Naturalness parameter

$$\mu = -\frac{\Delta m_H^2|_{\text{NP}}}{\Delta m_H^2|_{\text{SM}}} = -\frac{a_T}{\lambda_t^2} + \mathcal{O}\left(\frac{v^2}{m_T^2}\right) \;, \qquad \mu|_{\text{naturalness}} = 1\,.$$

Collider analysis

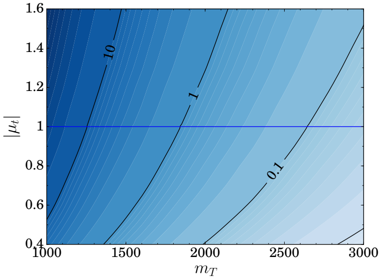
Signal and Background

Process



$pp \to \overline{T}Th \to \bar{t}(Z/h)t(Z/h)h \to \bar{t}jtj\overline{b}b$

Crosssection of TTh in fb at 100 TeV



The horizontal line at $|\mu_t| = 1$ indicates theories with loop cancellation.

Branching Ratio

$$\begin{aligned} \mathrm{BR}(T \to th) &\simeq \mathrm{BR}(T \to tZ) \\ &\simeq \frac{1}{2}\,\mathrm{BR}(T \to Wb) \simeq 25\,\% \,. \end{aligned}$$

Background

We require the Higgs to be unboosted and the decay products of the top partners to be boosted, this ensures that *ttjjjj* is the dominant background. The two leading jets must have $p_T > 400\,\mathrm{GeV}$.

Analysis

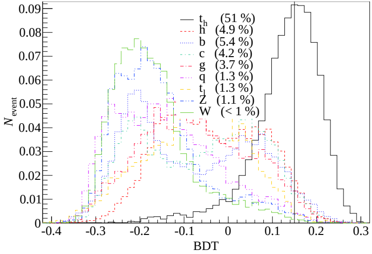
Collider analysis at 100 TeV

- `Madgraph`
- `Delphes`
- `Boosted Collider Analysis (BoCA)`

BoCA https://github.com/BoostedColliderAnalysis/BoCA

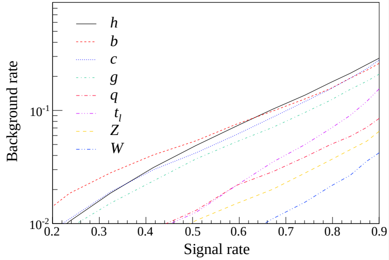
- C++ Analysis software
- uses boosted decision trees for particle reconstruction and background rejection

Hadronic top BDT response

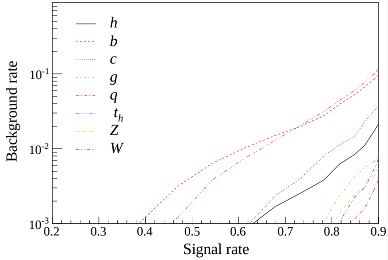


BoCA efficiencies

Hadronic top



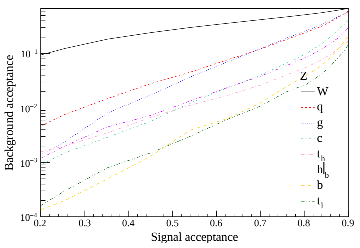
Leptonic top



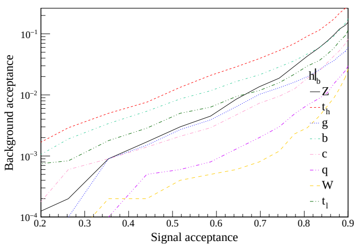
For boosted objects with 1 TeV $< p_T <$ 1.5 TeV at a 100 TeV collider.

BoCA efficiencies

Z-Boson



Higgs



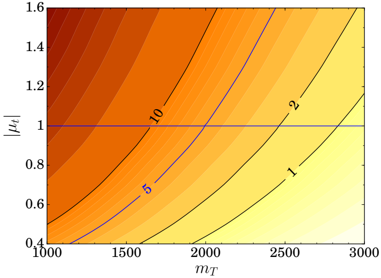
For boosted objects with 1 TeV $< p_T <$ 1.5 TeV at a 100 TeV collider.

Result

Discovery reach and S/B

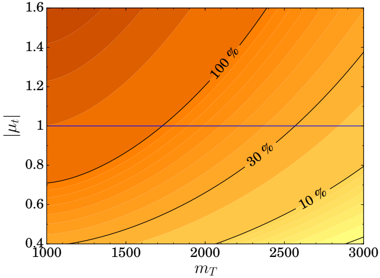
Top partner pair production in association with one Higgs boson

Discovery reach



for a fixed luminosity of $3\,\mathrm{ab}^{-1}$

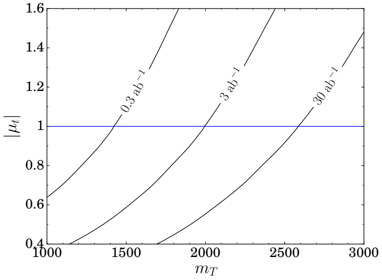
Signal over background



Discovery reach and S/B

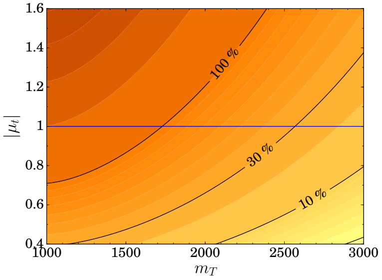
Top partner pair production in association with one Higgs boson

Discovery reach



for luminosities of 0.3, 3, 30 ab^{-1} and a fixed significance of 5

Signal over background



The significance of n observed events is defined via the log-likelihood ratio

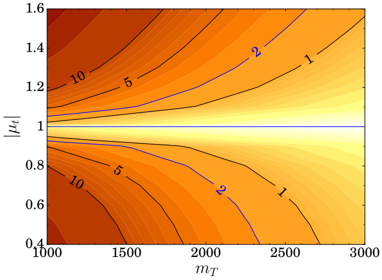
$$Z(x|n) = \sqrt{-2 \ln \frac{L(x|n)}{L(n|n)}} \,, \qquad L(x|n) = \frac{x^n e^{-x}}{n!} \,.$$

where x is the predicted number for the hypothesis which is tested.

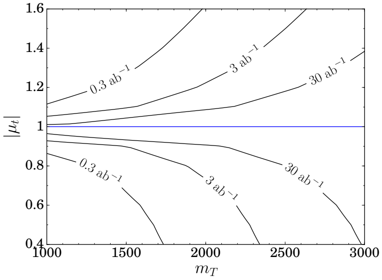
Exclusion limit for unnatural theories

Exclusion limit of unnatural theories with $\mu \neq 1$, against the assumption that the observation at the collider is consistent with the prediction of a natural theory with $\mu = 1$.

Luminosity of 3 ab^{-1}



Significance of 2

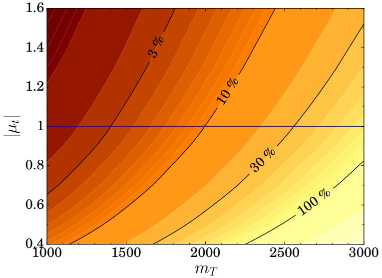


Precision of measuring μ

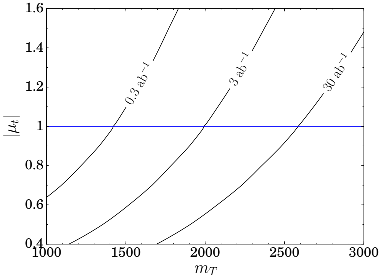
Precision of measuring the naturalness parameter, defined as the uncertainty

$$\delta\mu = \sqrt{\left(-\frac{1}{\lambda_t^2}\delta a_T\right)^2} \,, \qquad \delta a_T = \frac{a_T}{2Z(b|n)} \,.$$

Luminosity of 3 ab^{-1}



Precision of 10 %

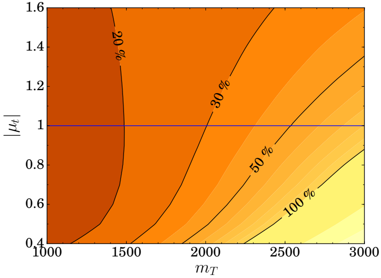


Precision of measuring μ

Precision of measuring the naturalness parameter, defined as the uncertainty

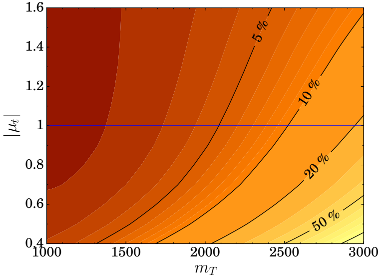
$$\delta\mu = \sqrt{\left(-\frac{1}{\lambda_t^2}\delta a_T\right)^2 + \left(2\frac{a_T}{\lambda_t^3}\delta\lambda_t\right)^2}\,, \qquad \delta a_T = \frac{a_T}{2Z(b|n)}\,.$$

Luminosity of 3 ab^{-1}



$\delta\lambda_t = 10\,\%$

Luminosity of 30 ab^{-}1



$\delta\lambda_t = 1\,\%$

In order to reach a large precision in the naturalness parameter it is crucial to also improve the precision of the top Yukawa coupling.

Conclusion

Conclusion

- We want to distinguish between models with and without cancellation of the quadratic loop divergence in the top sector.
- We have found that after electroweak symmetry breaking generically one simple requirement ensures the cancellation between top quarks and their partner:

$$a_T = -|\lambda_t|^2 + \mathcal{O}\left(\frac{v^2}{m_T^2}\right)$$

- This relation can be tested at a 100 TeV collider up to some TeV.
- This result is easily generalizable to an arbitrary number of top-partners in generic representations.

Thank you