Top-pair as final state and its interplay with the Higgs Physics

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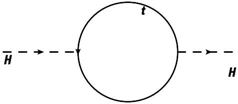
Why $t\bar{t}$ final state?

- Higgs quadratic divergences in the SM is dominated by the top loop



$$\delta m_H^2 \sim \frac{3y_t^2\Lambda^2}{8\pi^2}$$

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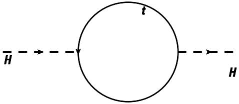


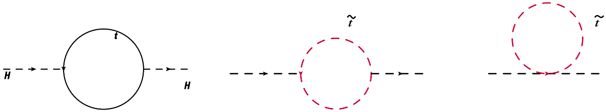
$$\delta m_H^2 \sim \frac{3y_t^2\Lambda^2}{8\pi^2}$$

- New states to regulate quadratic divergence
  - SUSY : superpartners of the SM top quark
  - Composite PNGB higgs: fermionic partners of the top quark
- The same states interact with the Higgs boson, thus they can at one loop modify the Higgs couplings to gluons and photons final state is important
- Generically the states regulating quadratic divergences are appearing as “top-partners”, which decay predominantly to top final state.

Outline

Supersymmetry

Supersymmetry

- Extension of the Poincare symmetry which relates the states with the different statistics. Every bosonic state is accompanied with the correspondent fermionic states and the vice versa.
- 

- Quadratic divergences by the top quarks are cancelled by the loops of the scalar top partners -stops.

$$\delta m_h^2 \sim y_t^2 m_{\tilde{t}}^2 \log \Lambda$$

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$ [fb^{-1}]		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 e,μ + γ	-	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m($\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	m($\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	700 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	420 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	285 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$	1 e,μ + τ	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

Mass scale [TeV] (10^{-1} … 1)

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Searches with $t\bar{t}$ final state

3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222

Natural supersymmetry *(Weiler,Pappucci,Ruderman; Katz,Burst,Sundrum)*

- bottom up spectrum dicated by the naturalness

$$V \sim m_H^2 H^2 + \lambda H^4$$

- measure of the finetuning

$$\Delta \equiv \frac{2\delta m_H^2}{m_H^2}$$

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$$\Delta \equiv \frac{2\delta m_H^2}{m_H^2}$$

- Mass of the higgsinos comes from the superpotential term

$$W \sim \mu H_u H_d$$

  - μ term always contributes to the Higgs mass , it cannot be too heavy$\Rightarrow$

$$\mu \lesssim 200\text{GeV}\left(\frac{m_H}{125}\right)\left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

- **Higgsinos must be light**

Natural supersymmetry *(Weiler,Pappucci,Ruderman; Katz,Burst ,Sundrum)*

- Quadratic corrections to the Higgs mass is cut at the stop mass scale

$$\delta m_{H_u}^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2 \right) \log \frac{\Lambda}{TeV}$$

- **stops must be light**

$$\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} \lesssim 600\text{GeV} \frac{\sin\beta}{\sqrt{1+x_t^2}} \left(\frac{\log \Lambda / TeV}{3} \right)^{-1/2} \left(\frac{m_H}{125} \right) \left(\frac{\Delta^{-1}}{20\%} \right)^{-1/2}$$

Natural supersymmetry *(Weiler,Pappucci,Ruderman; Katz,Burst ,Sundrum)*

- gluino at two loop enters Higgs mass

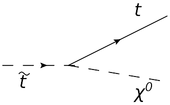
$$\delta m_{H_u}^2 = -\frac{2}{\pi^2} y_t^2 |M_3|^2 \frac{\alpha_s}{\pi} \log^2 \Lambda/\mathrm{TeV}$$

$$M_3 \lesssim 900\mathrm{GeV} \sin\beta \frac{\log \Lambda/\mathrm{TeV}}{3} \left(\frac{m_H}{125}\right) \left(\frac{\Delta^{-1}}{20\%}\right)^{-1/2}$$

- Natural spectrum :3 $\boxed{\textbf{two stops}, \textbf{sbottom}, \textbf{gluino}, \ \textbf{two higgsinos}}$

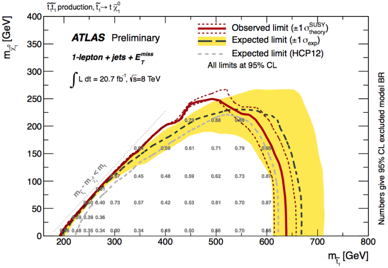
Simplified model: MET $+t\bar{t}$ final state

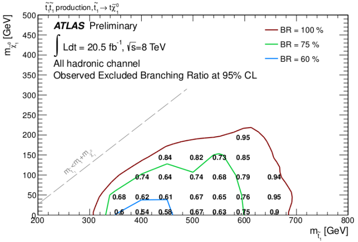
- Simplified models to put bounds on stops



$$pp \rightarrow \tilde{t}\tilde{t} \rightarrow t\bar{t} + E_T^{\text{miss}}$$

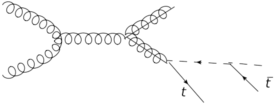
- assuming the pair production of the stops and the subsequent decays into top +neutralinos.





Gluino pair production, four top final state

- Due to the quantum numbers gluino has large QCD pair production

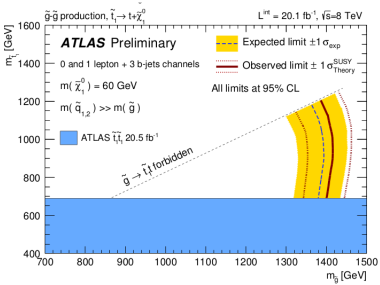


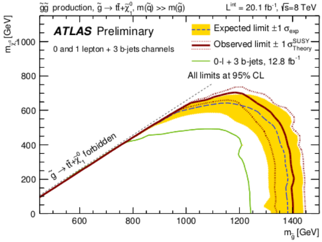
$$pp \to \tilde{g}\tilde{g}$$

$$\tilde{g} \to t\tilde{t}, \quad \tilde{g} \to t\bar{t} + E_T^{miss}$$

- bounds push towards the region of

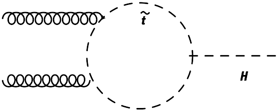
$$\boxed{m_{\tilde{t}} \gtrsim 700 \text{ GeV}, \quad m_{\tilde{g}} \gtrsim 1.4\text{TeV}}$$





One loop effects of the superparnters

- loops of the superpartners can modify the higgs couplings to gluons and photons



- if $\tilde{m}_t \gg m_h$ we can use the LET *(Ellis, Gaillard, Nanopoulos; Shifman,Vainshtein,Voloshin, Zakharov)* to compute the stop loop effects

$$M^2_{\tilde{u}_i} = \begin{pmatrix} \tilde{m}^2_{Q_3} + m_t^2 + \mathcal{O}(g^2 v^2) & m_t X_t \\ m_t X_t & \tilde{m}^2_{u_3} + m_t^2 + \mathcal{O}(g^2 v^2) \end{pmatrix}$$

$\Rightarrow$

$$\frac{hgg^{NP}}{hgg^{SM}} \simeq \frac{1}{4}\left(\frac{m_t^2}{m^2_{\tilde{t}_1}} + \frac{m_t^2}{m^2_{\tilde{t}_2}} - \frac{m_t^2 X_t^2}{m^2_{\tilde{t}_1} m^2_{\tilde{t}_2}}\right)$$

Bounds from the higgs couplings

- Complementary constraints on the stop masses
- Bounds are independent of higgsino/gluino masses
- Advantages : we can test to the compressed region of the spectra $\frac{m_{\tilde{t}} - \mu}{m_{\tilde{t}}} \ll 1$

1401.7601

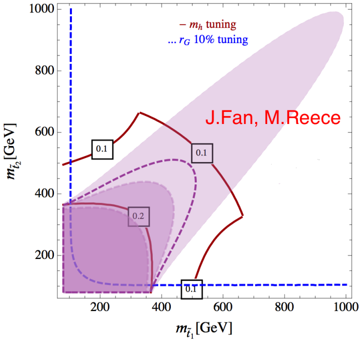


Figure: 99, 95, 68% exclusion contours from the Higgs couplings.

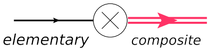
Composite Higgs

Composite pseudo Nambu-Goldstone Higgs

- Models, where Higgs is a composite state give a natural solution to the hierarchy problem
- Higgs can be made naturally light if it is Pseudo Nambu Goldstone Boson(PNGB) (*Georgi, Kaplan*)
- This scenario is realized in the warped extra dimensional models *Randall,Sundrum* with gauge-higgs unification, the Higgs boson arises as the 5th component of the 5D gauge field
- The minimal construction with consistent with the constraints from the $\Delta\rho$ parameter is realized in $SO(5) \to SO(4)$(*Contino, Agashe, Pomarol*)

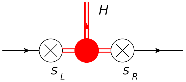
Fermions: partial compositeness *(Kaplan)*

- SM fermions mix only linearly with composite fermions



$\Delta\mathcal{L} = \lambda \bar{q} O$

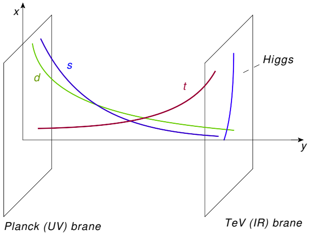
- Fermion mass generation



mixing at the low scale

$s_{L,R} \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{\gamma_{L,R}}, \quad m \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{\gamma_L+\gamma_R}$

- 5D-Randall-Sundrum picture

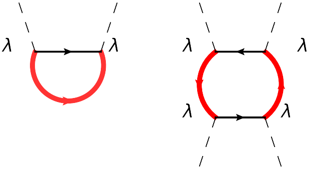


$s_{L,R} \Leftrightarrow f(\text{IR brane})$

Top must mix strongly with the composite sector$\Leftrightarrow$ top must localized near the tev brane $\Leftrightarrow$ large interaction (λ_t) with the new resonances

Higgs potential

Mixing with the SM fields violates the PNGB symmetry- Higgs potential is generated.



- $V(h) = \alpha \sin^2 \frac{h}{f} + \beta \sin^4 \frac{h}{f}$,
  $\xi = \sin^2 \frac{\langle h \rangle}{f} = -\frac{\alpha}{2\beta}$

$$\alpha^t_{L,R} \sim \frac{N_c}{16\pi^2}(\lambda^t_{L,R})^2 M_*^2, \;\; \beta \sim \frac{N_c}{16\pi^2}(\lambda^t_L \lambda^t_R)^2$$

Quadratic divergences are cut at the scale of the fermionic top partners M_*

$$\text{F.T.} \sim \frac{-2\beta\,\xi}{\alpha^t_{L,R}} \sim \frac{\min\left[(\lambda^t_R)^2, (\lambda^t_L)^2\right] v^2}{M_*^2 f^2}$$

Fermionic top partners M_* must be light.

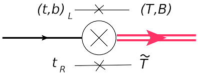
Top quark in Composite Higgs models

- Top quark is mixes strongly with the composite sector, its coplings are the most sensitive probe of the new physics.
- The Higgs potential is generated by the top quark and top quark mixing parameters are strongly constrained by the Higgs mass
- $v \ll f$ **and the light Higgs prefer light fermionic top partners** *(Agashe et al;Pomarol et al;Panico et al;Marzocca et al; Redi et al;)*

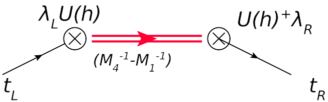
MCHM 5 model

- Minimal model based on the $SO(5)/SO(4)$ coset where composite fermions appear as a multiplet of **5**
- SM mass generation

$$\mathbf{5}: \quad \mathcal{Q} = \frac{1}{\sqrt{2}} \begin{pmatrix} T_{2/3} & \mathbf{X_{5/3}} \\ B_{-1/3} & T'_{2/3} \end{pmatrix} \oplus \tilde{\mathbf{T}}_{\mathbf{2/3}}$$



$$\Delta\mathcal{L} \qquad = \lambda_L^t \bar{q}_L P_q U(\pi) \mathcal{Q} + \lambda_R^T \bar{t}_R P_t U(\pi) \mathcal{Q} + M_1 \bar{\mathcal{Q}}_1 \mathcal{Q}_1 + M_4 \bar{\mathcal{Q}}_4 \mathcal{Q}_4$$



$$\Rightarrow \quad m_t \sim \frac{\lambda_L^t \lambda_R^t v}{f M_*}$$

Properties of top partners

$$\mathbf{5}: \quad \mathcal{Q} = \frac{1}{\sqrt{2}} \begin{pmatrix} T_{2/3} & \mathbf{X_{5/3}} \\ B_{-1/3} & T'_{2/3} \end{pmatrix} \oplus \tilde{\mathbf{T}}_{\mathbf{2/3}}$$

field	production	decay
$X_{5/3}$	QCD, association with top	$Br(X \to tW) = 100\%$
$T'_{2/3}$	QCD, association with top	$Br(T'_{2/3} \to Zt, ht) \sim 50\%$
$T_{2/3}$	QCD, association with top	$Br(T_{2/3} \to Zt, ht) \sim 50\%$
$B_{-1/3}$	QCD, association with top	$Br(B \to Wt) \sim 100\%$
$\tilde{T}$	QCD, association with t & b	$Br(\tilde{T} \to Zt, ht) \sim \frac{1}{2} Br(Wb) \sim 25\%$

(*De Simone,Matsedonskyi,Rattazzi,Wulzer*) the typical spectra

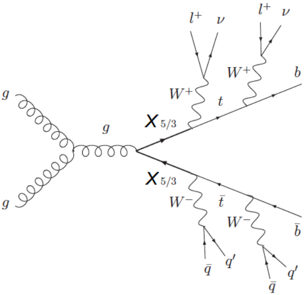
$$M_{X_{5/3}} \lesssim M_{T'_{2/3}} \lesssim M_{T_{2/3}} \lesssim M_{B_{-1/3}}$$

$X_{5/3}$ **is the lightest field, and from the charge conservation** $Br(X \to tW) = 100\%$

Bounds on 5/3 field

- top parners are charged under QCD SU(3)
- are pair produced

$$pp \to XX, \quad X \to tW$$



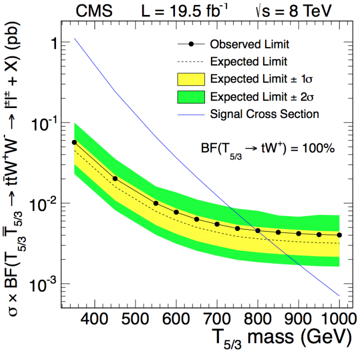


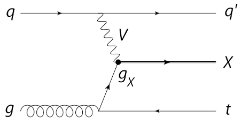
Figure: *CMS-B2G-12-012*

$m_{5/3} \gtrsim 800$ **GeV**

Bounds on the 5/3 field

- single production of top partners can be very important

  (De Simone,Matsedonskyi,Rattazzi,Wulzer)
- are pair produced



- $\sim g_X \chi^{\dagger}_{5/3} W^{-} t$

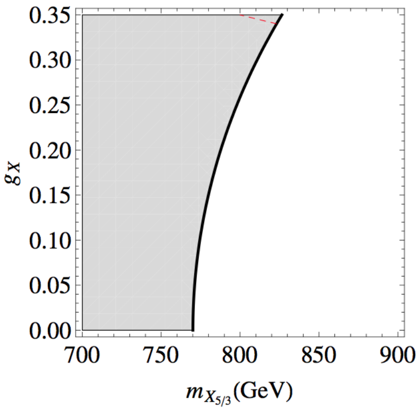


Figure: recast of CMS-PAS-B2G-12-012 A.A. M.Son, M. Salvarezza,M.Spannowsky

$m_{5/3} \gtrsim 800$ **GeV**

Charge 2/3 partners production at LHC

- Pair production due to the QCD
- Three decay modes are open by charge conjugation $T \to tz$, $T \to bW$, $T \to th$

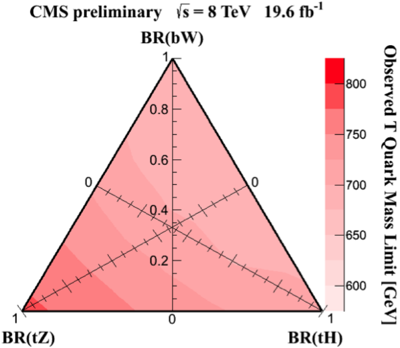


Figure: *CMS PAS B2G-12-015*

$m_{2/3} \gtrsim 600 - 800$ **GeV**

Charge 8/3 fields

- More exotic models based on the **14** multiplet, under $SO(5)/SU(2)_L \times SU(2)_R$

$$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + \mathbf{1}$$

  $(\mathbf{3},\mathbf{3})$ contains charge 8/3 fields

- $$pp \to X_{8/3}\bar{X}_{8/3},$$
  $$X_{8/3} \to tW^+W^+$$
  $$\boxed{M_{8/3} \gtrsim 940 \ GeV}$$

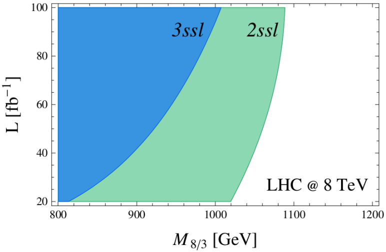
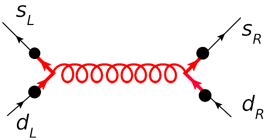


Figure: Expected exclusion constraints, *(Matsedonskyi, Riva,Vantalon)*

Vector resonances

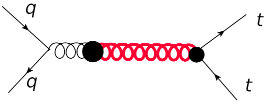
- Models based on the partial compositeness necessary contain color octet vector resonance -ρ- composite/KK gluon
- Flavor bounds are strong $M_{KK} \gtrsim 15$ TeV *(Csaki et al;Agashe et al...)*



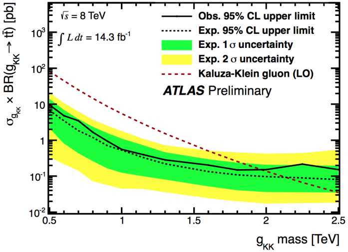
- Looks hopeless for the LHC, however the bound appears in the "anarchic models" accepting some mild tuning...

Vector resonances

- ρ interacts with the light quarks with the strength $g_x \rho \bar{q} q$, $\quad g_x \sim \frac{g_{QCD}^2}{g_*}$ (analog of the photon rho mixing)

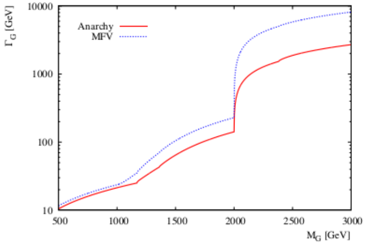


- $t\bar{t}$ is the main decay channel, if the decays into top partners are kinematically not allowed

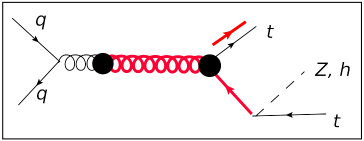


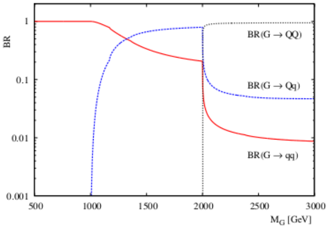
Vector resonances

1205.2378



- If the decay to two top partners becomes open ρ becomes very wide, narrow resonance techniques are not applicable any more...



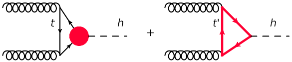


Higgs physics in the composite models

- How loop of the composite resonances affect hgg, $h\gamma\gamma$?

Higgs physics in the composite models

- How loop of the composite resonances affect $hgg, h\gamma\gamma$?
- Higgs LET+linear mixing between elementary and composite fermions leads to the (1110.5646)

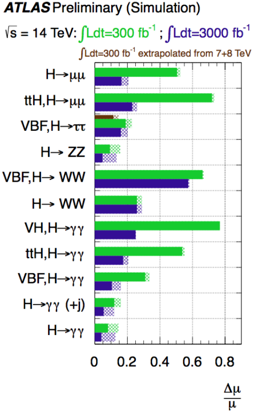


$$F(\tfrac{v}{f}), \quad F(\tfrac{v}{f})_{f\to\infty} \to \frac{1}{v}$$

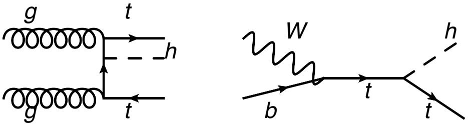
The modification of the top loop due to the different Yukawa coupling is canceled exactly against the loop of new resonances.

- The lightest charge 5/3 fields do not contribute to the single Higgs production
- We still have modification of the top Yukawa coupling, is important to have an independent measurement of the Yukawa coupling

Prospects for high luminosity LHC: direct measurement of the *tth* coupling

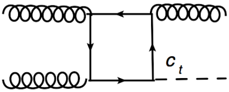


- $\sim 20\%$ uncerainty on the signal rate $\Rightarrow \sim 10\%$ uncertainty on the top Yukawa coupling
- Maltoni, Rainwater, Willenbrock; S. Biswas, E. Gabrielli and B. Mele; S. Biswas, E. Gabrielli, F. Margaroli and B. Mele ; Curtin, Galloway, Wacker; Farina, Grojean, Maltoni, Salvioni, Thamm; Craig, Park, Shelton; Onyisi, Kehoe, Rodriguez , Ilchenko; Agrawal, Bandyopadhyay, Das...



Accessing the Yukawa couplings

Indirect: Higgs production at high p_t
(1308.4771, 1309.5273, 1312.3317, 1405.4295, 1406.6338)



- LET at high p_T are not applicable any more → we can differentiate the contributions of the top quark loop and new physics.
- $c_t = 1^{+0.29}_{-0.24}$ at 95% CL *from arXiv:1405.4295 Schlaffer et al.*

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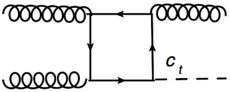

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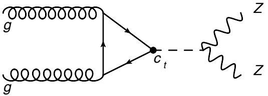
Similar effect in the off-shell Higgs production *(1405.0285, 1406.1757, 1406.6338)*



- $c_t = 1 \pm 0.25$ with 14 TeV 3 ab^{-1} with the simple counting analysis

Outlook

- Many motivated New Physics models which address the naturalness problem lead ot the $\bar{t}t$ final state: Natural SUSY , Composite Higgs.
- Higgs quadratic divergences is usually cured by the "top-partners" which predominantly decay to the $t\bar{t}$ final state.
- New states interact with the Higgs boson leading to the modifications of its coupling.
- Indirect searches are often complementary to the direct searches.