# Constraining BSM with 4 tops 

[L. Darmé, B. Fuks and MDG, 1805.10835]

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## Overview

- BSM models with four tops
- ... Dirac gaugino models
- Recasting CMS $35.9 \mathrm{fb}^{-1}$ search
- Prospects for HL-LHC


## Four top signature in SM

Four-top production in SM dominated by QCD,

but also Higgs associated production:


## Four top signature in BSM models

Many BSM models predict a four-top signature. Essentially from decay of two heavy particles:

- Scalar/vector
- Singlet/octet under SU(3)
but also associated production:

E.g.
- Singlet scalars produced from decay of heavier state (e.g. in 750 GeV models)
- Composite (Higgs/top) models $\rightarrow$ all contain octet resonance, usually predicted to be lightest heavy state (like $\rho$ meson of QCD)
- $\leftrightarrow$ KK gluon in Randall-Sundrum
- Colour octet scalars ubiquitous in Seiberg dual theories
- ... required in Dirac gaugino models/N $=2$ SUSY


## Dirac gauginos

- In SUSY, we add a gaugino for every gauge group.
- But when we break SUSY it needs to get a mass.
- In the MSSM we take Majorana mass:

$$
\mathcal{L} \supset-\frac{1}{2} M_{\lambda} \lambda \lambda
$$

- BUT: this isn't the only choice!
- One very interesting alternative is to take Dirac masses instead (or as well). This was the original option proposed by Fayet in '78!
- To allow Dirac masses for the gauginos, must add chiral adjoint field for each group:

$$
\boldsymbol{\Sigma}=\Sigma+\sqrt{2} \theta^{\alpha}(\chi)_{\alpha}+(\theta \theta) \mathrm{F}_{\Sigma}+\ldots \rightarrow \mathcal{L} \supset-\mathrm{m}_{\mathrm{D}} \chi \lambda
$$

- $\rightarrow$ Adjoint superfields will contain fermions to partner gauginos, but scalars too.
- So add S (singlet), T (triplet), O (octet) - each are initially complex scalars, so two real scalars.

| Superfield | Scalars, $\mathrm{R}=0$ | Fermions, $\mathrm{R}=-1$ | $\left(\mathrm{SU}(3), \mathrm{SU}(2), \mathrm{U}(1)_{\mathrm{Y}}\right)$ |
| :---: | :---: | :---: | :---: |
| $\mathbf{0}$ | $\mathrm{O}^{\mathrm{a}}=\frac{1}{\sqrt{2}}\left(\mathrm{O}_{1}^{\mathrm{a}}+\mathfrak{i O _ { 2 } ^ { a } )}\right.$ | $\chi_{\mathrm{O}}^{\mathrm{a}}$ | $(\mathbf{8 , 1}, 0)$ |
| $\mathbf{T}$ | $\mathrm{T}^{0}=\frac{1}{\sqrt{2}}\left(\mathrm{~T}_{\mathrm{P}}^{0}+\mathfrak{i} T_{M}^{0}\right), \mathrm{T}^{ \pm}$ | $\tilde{W}^{\prime 0}, \tilde{W}^{\prime \pm}$ | $(\mathbf{1 , 3}, 0)$ |
| $\mathbf{S}$ | $\mathrm{S}=\frac{1}{\sqrt{2}}\left(\mathrm{~S}_{\mathrm{R}}+\mathfrak{i} \mathrm{S}_{\mathrm{I}}\right)$ | $\tilde{\mathrm{B}}^{\prime 0}$ | $(\mathbf{1 , 1}, 0)$ |

## Motivation for Dirac gauginos

The study of Dirac gaugino masses is an ongoing large research project with many motivations:

- Dirac gauginos allow to relax LHC search bounds as production of squarks is suppressed since no chirality flip is possible. Gluino production is enhanced a little relative to MSSM, but this is greatly suppressed when $m_{\tilde{q}_{1,2}}>\mathrm{m}_{\tilde{\mathfrak{g}}}$.
- They typically suppress processes such as $B \rightarrow s \gamma$ and $\Delta F=2$.
- They allow for increased naturalness: supersoft masses do not lead to large corrections to stop mass.
- They allow new Higgs couplings, permitting increased Higgs mass $\rightarrow$ compatibility with e.g. light stops.
- There would have been/could soon be clear signals from accompanying adjoint scalars if light (this would have been a surprise)
- If gauginos are found at the LHC, we will have to determine whether they are Majorana or Dirac in nature, and this is very difficult to do directly: maybe only possible at ILC
- (Pseudo-) Dirac dark matter candidate?


## Supersafeness

E.g. from recasting done in [Chalons, MDG, Reyes-Gonzalez, Kraml, Williamson, 1812.09293]:


Typical scenarios have heavy gluinos $\rightarrow$ this is natural because of "supersoftness"

## Supersoft operator

- Mass term comes from the operator

$$
\int d^{2} \theta 2 \sqrt{2} m_{D} \theta^{\alpha} \operatorname{tr}\left(W_{\alpha}^{a} \Sigma^{a}\right) \supset-m_{D}\left(\lambda^{a} \chi^{a}\right)+\sqrt{2} m_{D} \Sigma^{a} D^{a}
$$

- It doesn't enter RGEs of other masses/lead to large corrections to squark masses
- $\rightarrow$ it is naturally large compared to other soft terms $\rightarrow$ gauginos can be heavy.
- Adjoint scalar masses and B-type masses are modified:

$$
\begin{aligned}
\mathcal{L} \supset & \frac{1}{2} D_{a}^{2}+\sqrt{2}\left(m_{D} O_{a}+\bar{m}_{D} \bar{O}_{a}\right) D_{a}-m_{O}^{2}|O|^{2}-\frac{1}{2}\left(B_{O} O^{2}+c . c .\right) \\
\stackrel{m_{D}}{ } \xrightarrow{\text { real }} & -\left(m_{O}^{2}+4 m_{D}^{2}+B_{O}\right) \frac{1}{4}\left(O^{a}+\bar{O}^{a}\right)^{2}-\left(m_{O}^{2}-B_{O}\right) \frac{1}{4}\left(O^{a}-\bar{O}^{a}\right)^{2} \\
& -\sqrt{2} g\left(O^{a}+\overline{\mathrm{O}}^{a}\right) \sum_{q} \tilde{q}^{*} T^{a} \tilde{q}
\end{aligned}
$$

- Typically $\mathrm{B}_{\mathrm{O}}$ is large, so $\mathrm{m}_{\mathrm{O}}^{2}-\mathrm{B}_{\mathrm{O}}$ can be small $\rightarrow$ pseudoscalar typically light!
- Also gives a coupling to squarks $\rightarrow$ but only for the CP-even singlet/triplet/sgluon!


## Sgluon tree couplings

The octet scalars - sgluons - have the usual gauge couplings and so can be produced in pairs at tree level:
(a)

(b)



## Tree level decays

They have trilinear couplings with the squarks and gauginos

$$
\begin{aligned}
\mathcal{L}_{\text {Dirac }} & =-\int d^{2} \theta \frac{m_{D}}{4 \sqrt{2} f^{2}} \bar{D}^{2} D^{\alpha}\left(X^{\dagger} X\right) W_{\alpha}^{a} O^{a} \supset \sqrt{2} m_{D}\left(O^{a}+O^{a *}\right) D_{c}^{a}, \\
& \rightarrow-2 g_{s} m_{D} T_{x y}^{a} \sum_{\tilde{q}_{L}, \tilde{q}_{R}}\left(\tilde{q}_{L x i}^{*} \tilde{q}_{L y i}-\tilde{u}_{R x i}^{*} \tilde{u}_{R y i}-\tilde{d}_{R x i}^{*} \tilde{d}_{R y i}\right)\left(\cos \left(\frac{\phi_{O}}{2}\right) O_{1}^{a}+\sin \left(\frac{\phi_{O}}{2}\right) O_{2}^{a}\right) \\
\mathcal{L}_{G a u g e} & \supset i f{ }^{a b c} \bar{O}^{b} \lambda^{a} x^{c}+\text { h.c. } .
\end{aligned}
$$

These lead to rapid decays if the squarks or gluinos are ligher than half the octet mass $\rightarrow$ but this would mean rather heavy octets anyway.

## Octet loop couplings

More interestingly, the above generate couplings at one loop with the quarks and gluons, which provide the conventional decay modes:

(b)


Won't talk about single production ... but it is not very large.

## Loop couplings

- The widths to quarks and gluons are parametrised by
$\mathcal{L} \supset g_{8} d_{a b c} O_{1}^{a} G_{\mu \nu}^{b} G^{\mu v c}+\tilde{g}_{8} d_{a b c} O_{2}^{a} G_{\mu \nu}^{b} \tilde{G}^{\mu v c}+c_{1 \bar{t} t} \bar{t} O_{1} t+c_{2 \bar{t} t} i \bar{t} O_{2} \gamma_{5} t$,
- The widths to gluons are given by

$$
\Gamma\left(\mathrm{O}_{1} \rightarrow \mathrm{gg}\right)=\frac{5 \alpha_{\mathrm{s}}^{3}}{192 \pi^{2}} \frac{\mathrm{~m}_{\mathrm{D} 3}^{2}}{\mathrm{M}_{\mathrm{O}_{1}}} \cos ^{2}\left(\frac{\phi_{\mathrm{O}}}{2}\right)\left|\lambda_{\mathrm{g}_{1}}\right|^{2}, \quad \Gamma\left(\mathrm{O}_{2} \rightarrow \mathrm{gg}\right)=\frac{5 \alpha_{\mathrm{s}}^{3}}{192 \pi^{2}} \frac{\mathrm{~m}_{\mathrm{D} 3}^{2}}{M_{\mathrm{O}_{2}}} \sin ^{2}\left(\frac{\phi_{\mathrm{O}}}{2}\right)\left|\lambda_{\mathrm{g}_{2}}\right|^{2} .
$$

- Pseudoscalars do not decay to gluons - they only decay to tops $\rightarrow$ four top events (as suggested in e.g. 1501.07580), provide interesting constraints.
- Surprisingly, scalars can still be light, but we don't necessarily expect them to be.


## Rough four-top limits on sgluons

For squarks $\sim$ TeV and gluinos of 2.5 (top) $3,3.5$ (bottom) TeV , rough limits on scalar sgluons from four-top events in 2016 were:


RHS: limit of $\sigma<140 \mathrm{fb}$ for four-top events. For scalars constraint depends on squark/gluino mass, and may vanish.

For pseudoscalars, this gives $\mathrm{m}_{\mathrm{O}_{2}} \gtrsim 880 \mathrm{GeV} \rightarrow$ much more interesting. CMS-TOP-17-009 improved the limit to $\sim 30 \mathrm{fb}^{-1}$. Do these limits better with full recasting and the more recent data ...

## Recast

Recast analysis of CMS-TOP-17-009 using FeynRules, NLOCT to generate and NLO UFO for MADGRAPH5_aMC@NLO, analysed with MadAnalysis 5. Generated $\mathcal{O}\left(10^{6}\right)$ events (b/c tiny $\sigma$ ). Validated against total number of events/bin, $\mathrm{H}_{\mathrm{T}}, \mathrm{N}_{\mathrm{jets}}, \mathrm{b}$-jets, $\mathrm{p}_{\mathrm{T}}^{\text {miss }}$. Analysis now publically available in PAD.


## New limits

Obtain limits on octet production, c.f. NLO cross-section:


We find $\mathrm{m}_{\mathrm{O}}>1060 \mathrm{GeV}$ at $95 \%$ confidence.

Can we do better? the search is not optimised for octets, but for SM 4t signal:



## Njets

## Number of jets is less skewed:



## Projections for HL and HE LHC

We also looked at projections for the HL/HE LHC:



These are terrible! They are certainly too naive (done by simple rescalings), but octet signal is swamped by growth in background.
$\rightarrow$ need a new search strategy!

## Conclusions

- Sgluons are ubiquitous in BSM models
- Relatively light pseudoscalar sgluons are natural "predictions" of Dirac gaugino models and decay (mostly) to tops
- We have placed bounds using current data, will improve these with latest searches
- ... but to make a large improvement could develop a new seach.


## BACKUP




