

# Deriving LHC constraints on the minimal Dirac gaugino model

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Based on work in collaboration with Guillaume Chalons, Mark Goodsell, Sabine Kraml and Humberto Reyes-González (arXiv:1812.09293; to appear in JHEP)

Imperial College, London, 3<sup>rd</sup> April 2019



# Motivation

- SUSY searches at the LHC: large focus on (simplified) **MSSM** scenarios.
- Naturalness and contracting MSSM parameter space → **non-minimal scenarios**



Minimal Dirac gaugino supersymmetric standard model (**MDGSSM**)

- Increased naturalness (**supersoft operators**) (Fox, Nelson, Weiner: ArXiv:0206096)
- Enhanced tree-level Higgs mass
- Allow for R-symmetry → simpler SUSY breaking (Fayet, 1978)
- $\mathcal{N} = 2$  SUSY (Antoniadis, Benakli, Delgado, Quiros: ArXiv:0610265),  
(Ellis, Quevillon, Sanz: arXiv:1607.05541), (Benakli, Goodsell, SW: arXiv:1801.08849)
- etc.

# MSSM + Dirac gauginos

- Add  $\mathcal{N} = 1$  chiral multiplets **S** (singlet), **T** ( $SU(2)$  triplet), **O** ( $SU(3)$  octet) in the adjoint representation of the corresponding gauge groups.
- **Majorana** gauginos (one Weyl fermion)  $\rightarrow$  **Dirac** gauginos (Weyl fermion + **new** adjoint chiral fermion)
  - $\mathcal{L} \supset -\frac{1}{2}M_i\lambda_i\lambda_i + h.c. \quad \rightarrow \quad \mathcal{L} \supset -m_{iD}\chi_i\lambda_i + h.c.$
  - MDGSSM allows for both - we choose  $M_i = 0$ .
- New Higgs **superpotential** couplings:

$$W_{\text{Higgs}} = \mu \mathbf{H}_u \cdot \mathbf{H}_d + \lambda_S \mathbf{S} \mathbf{H}_u \cdot \mathbf{H}_d + 2\lambda_T \mathbf{H}_d \cdot \mathbf{T} \mathbf{H}_u.$$

- Higgs mass boost:

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{v^2}{2}(\lambda_S^2 + \lambda_T^2) \sin^2 2\beta.$$

# Additional particle content

Superfield	Scalars	Fermions	Vectors	$(SU(3), SU(2), U(1)_Y)$	
<b>Matter Sector</b>					
MSSM chiral superfields					
(S)quarks	$\mathbf{Q}_i$	$\tilde{\mathbf{Q}}_i = (\tilde{u}_{i,L}, \tilde{d}_{i,L})$	$(u_L, d_L)$	-	$(\mathbf{3}, \mathbf{2}, 1/6)$
	$\mathbf{u}_i^c$	$\tilde{u}_{i,R}^c$	$u_{i,R}^c$	-	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$
	$\mathbf{d}_i^c$	$\tilde{d}_{i,R}^c$	$d_{i,R}^c$	-	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
(S)leptons	$\mathbf{L}_i$	$(\tilde{\nu}_{i,L}, \tilde{e}_{i,L})$	$(\nu_{i,L}, e_{i,L})$	-	$(\mathbf{1}, \mathbf{2}, -1/2)$
	$\mathbf{e}_i^c$	$\tilde{e}_{i,R}^c$	$e_{i,R}^c$	-	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs/ Higgsinos	$\mathbf{H}_u$	$(H_u^+, H_u^0)$	$(\tilde{H}_u^+, \tilde{H}_u^0)$	-	$(\mathbf{1}, \mathbf{2}, 1/2)$
	$\mathbf{H}_d$	$(H_d^0, H_d^-)$	$(\tilde{H}_d^0, \tilde{H}_d^-)$	-	$(\mathbf{1}, \mathbf{2}, -1/2)$
<b>Gauge Sector</b>					
MSSM gauge superfields					
Gluons/gluinos	$\mathbf{W}_{3,\alpha}$	-	$\tilde{g}_\alpha$	$G_\mu$	$(\mathbf{8}, \mathbf{1}, 0)$
W/ Winos	$\mathbf{W}_{2,\alpha}$	-	$\tilde{W}^0, \tilde{W}^\pm$	$W_\mu^\pm, W_\mu^0$	$(\mathbf{1}, \mathbf{3}, 0)$
B/ Binors	$\mathbf{W}_{Y,\alpha}$	-	$\tilde{B}$	$B_\mu$	$(\mathbf{1}, \mathbf{1}, 0)$
Dirac gaugino adjoint chiral superfields					
Adjoint-octet	$\mathbf{O}_g$	$O_g$	$\tilde{g}'$	-	$(\mathbf{8}, \mathbf{1}, 0)$
Adjoint-triplet	$\mathbf{T}$	$\{T^0, T^\pm\}$	$\{\tilde{W}'^\pm, \tilde{W}'^0\}$	-	$(\mathbf{1}, \mathbf{3}, 0)$
Adjoint-singlet	$\mathbf{S}$	$S$	$\tilde{B}'$	-	$(\mathbf{1}, \mathbf{1}, 0)$

What is the impact of this new particle content on squark and gluino mass limits?

# Glino and squark production

Why would we expect different limits than in the MSSM?

- Glino production

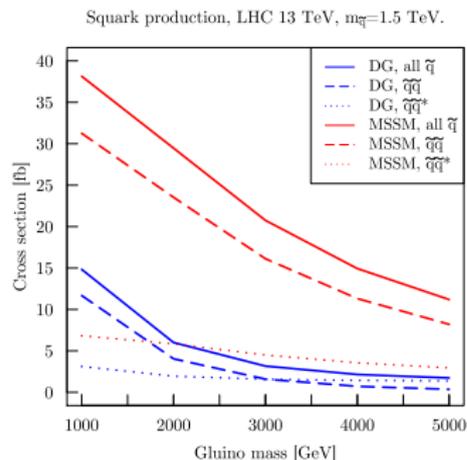
- Cross-section of Dirac gauginos **enhanced** relative to Majorana gauginos (more gluino d.o.f)

- Squark production

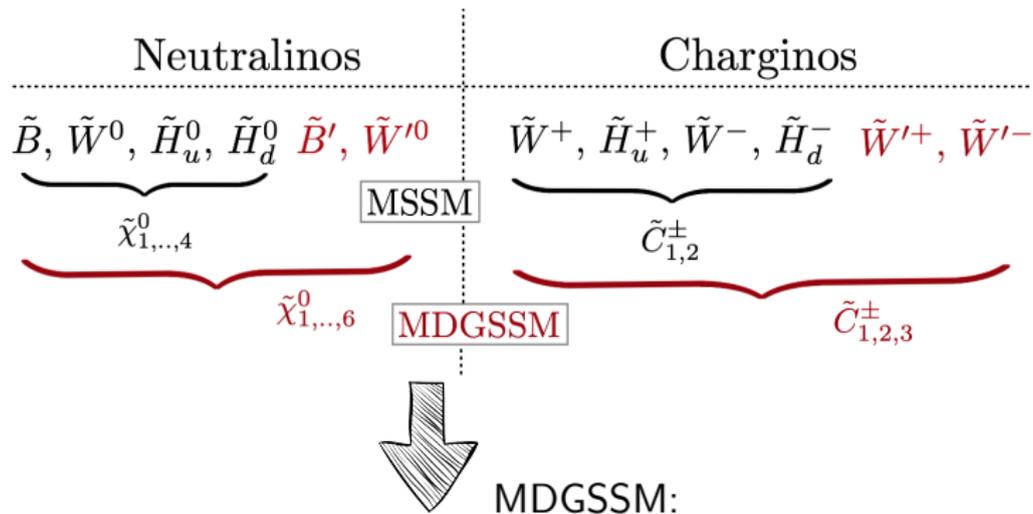
- Squark production strongly **suppressed** in DG case (final states with same chirality squarks forbidden)

- Glino-squark production

- Cross-sections as in MSSM.



# New electroweak scale particles (electroweakinos)

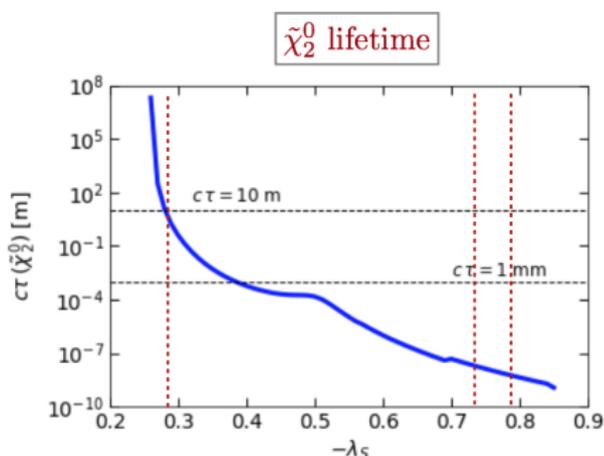
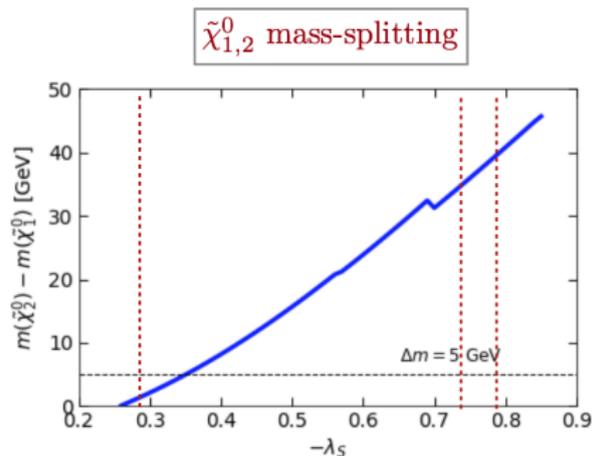


MDGSSM:

- 2 bino-, 2 wino- and 2 higgsino-like neutralinos
- 2 wino- and 1 higgsino-like charginos
- In our benchmarks, we use:  $m_{\text{winos}} > m_{\text{higgsinos}} > m_{\text{binos}}$

# Benchmark scenarios: choice motivation

- **Fix** electroweakino spectrum + **scan** over squark and gluino masses
- Among benchmarks: vary  $m_{\tilde{t}}, m_{\tilde{b}}, \lambda_S, \lambda_T$
- $\lambda_S$  drives bino mass splitting
  - Small  $\tilde{\chi}_{1,2}^0$  mass-splitting  $\leftrightarrow$  long-lived  $\tilde{\chi}_2^0$
  - 3 scenarios with large  $\tilde{\chi}_{1,2}^0$  mass-splitting (using  $\lambda_S = -0.74, \lambda_S = -0.79$ )
  - 1 scenario with small  $\tilde{\chi}_{1,2}^0$  mass-splitting ( $\lambda_S = -0.27$ )



# Benchmark scenarios: values

Parameters					Masses				
	DG1	DG2	DG3	DG4		DG1	DG2	DG3	DG4
$m_{1D}$	200	200	200	200	$\tilde{\chi}_1^0$	201.35	182.1	181.8	182.4
$m_{2D}$	500	500	500	1175	$\tilde{\chi}_2^0$	201.72	218.0	216.6	213.2
$\mu$	400	400	400	400	$\tilde{\chi}_3^0$	403	400	396	408
$\tan \beta$	2	2	2	2	$\tilde{\chi}_4^0$	419	445	441	437
$-\lambda_S$	0.27	0.74	0.74	0.79	$\tilde{\chi}_5^0$	537	536	535	1226
$\sqrt{2} \lambda_T$	0.14	0.14	0.14	-0.26	$\tilde{\chi}_6^0$	548	548	546	1227
$m_{\tilde{Q}_3}^2$	1.25e7	6.5e6	2.26e6	8.26e6	$\tilde{\chi}_{1\pm}$	400	395	391	398
$m_{\tilde{Q}_1}^2$	6.25e6	6.25e6	6.25e6	6.25e6	$\tilde{\chi}_{2\pm}$	536	536	534	1224
$m_{3D}$	1750	1750	1750	1750	$\tilde{\chi}_{3\pm}$	549	548	547	1229
					$\tilde{t}_1$	3604	2607	1590	2894
					$\tilde{t}_2$	3613	2637	1613	2927
					$h_1$	124.0	125.0	125.3	125.2

- $m_{1D}, m_{2D}, \mu, \tan \beta, \lambda_S, \lambda_T, m_{\tilde{Q}_3}^2 = m_{\tilde{U}_3}^2 = m_{\tilde{D}_3}^2$  fixed.
- $m_{3D}$  and  $m_{\tilde{Q}_1}^2 = m_{\tilde{U}_1}^2 = m_{\tilde{Q}_1}^2$  varied.

# Numerical analysis

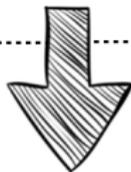
- Mass spectrum + decays



MADGRAPH



- (LO) cross-sections



- Simplified model limits

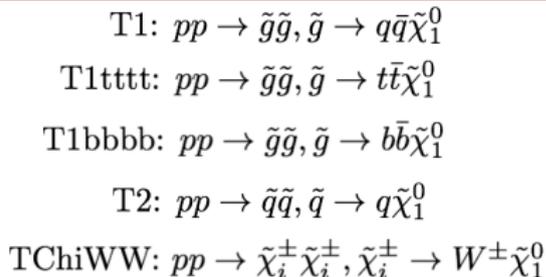
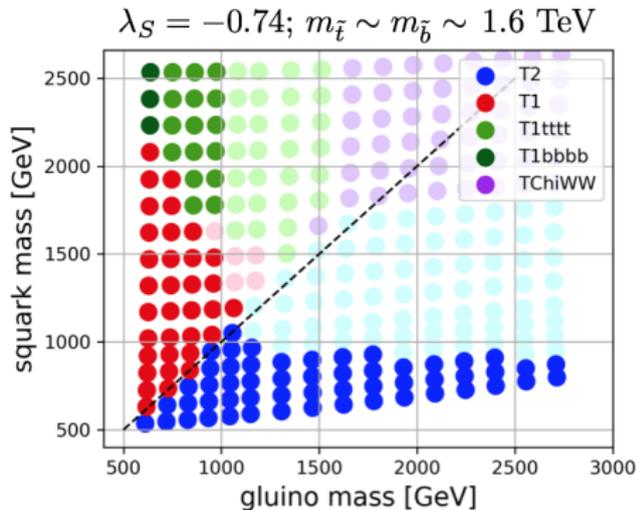
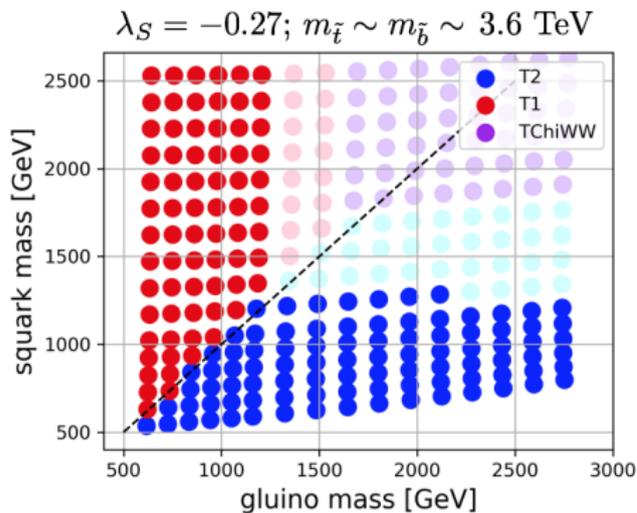
See Wolfgang Waltenberger's slides from earlier today!

**MAD**  
Analysis 5



- MC simulation
- Recasting

# SModels exclusion



Decays via non-SMS topology  
 $\rightarrow$  reduced T1, T2, T1tttt, T1bbbb  
 cross-sections

Search for squarks and gluinos in final states with jets and missing  $p_T$  using  $36 \text{ fb}^{-1}$  of  $\sqrt{s} = 13 \text{ TeV}$   $pp$  collision data with the ATLAS detector.

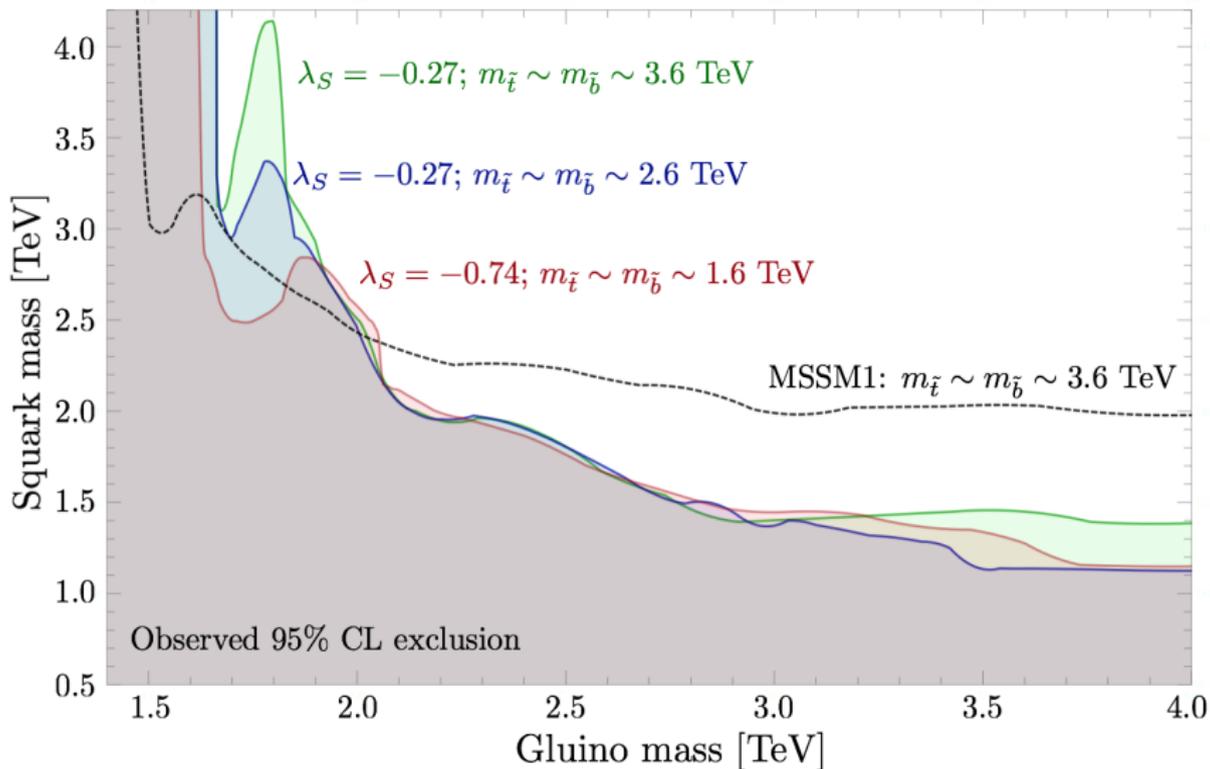
- Meff-based search
  - Effective mass:  $M_{\text{eff}} = p_{T_{j_1}} + p_{T_{j_2}} + E_T^{\text{miss}}$
  - $M_{\text{eff}} \in [1000, 2600] \text{ GeV}$
  - $N_j \in [2, 6]$
- Lepton veto
- MET > 250 GeV
- $p_T$  of all reconstructed jets > 50 GeV

ATLAS analyses, 13 TeV

Analysis	Short Description	Implemented by	Code	Validation note	Version
<a href="#">ATLAS-SUSY-2015-06</a>	Multijet + missing transverse momentum	S. Banerjee, B. Fuks, B. Zaldivar	<a href="#">Inspire</a>	<a href="#">PDF</a>	v1.3/Delphes3
<a href="#">ATLAS-SUSY-2016-07</a>	Multijet + missing transverse momentum (36.1 fb-1)	G. Chalons, H. Reyes-Gonzalez	<a href="#">Inspire</a>	<a href="#">PDF</a> <a href="#">Pythia files</a>	v1.7/Delphes3
<a href="#">ATLAS-EXOT-2015-03</a>	Monojet (3.2 fb-1)	D. Sengupta	<a href="#">Inspire</a>	<a href="#">PDF</a>	v1.3/Delphes3
<a href="#">ATLAS-EXOT-2016-25</a>	Mono-Higgs (36.1 fb-1)	S. Jeon, Y. Kang, G. Lee, C. Yu	<a href="#">Inspire</a>	<a href="#">PDF</a>	v1.6/Delphes3
<a href="#">ATLAS-EXOT-2016-27</a>	Monojet (36.2 fb-1)	D. Sengupta	<a href="#">Inspire</a>	<a href="#">PDF</a>	v1.6/Delphes3
<a href="#">ATLAS-EXOT-2016-32</a>	Monophoton (36.1 fb-1)	S. Baek, T.H. Jung	<a href="#">Inspire</a>	<a href="#">PDF</a>	v1.6/Delphes3
<a href="#">ATLAS-CONF-2016-086</a>	b-pair + missing transverse momentum	B. Fuks & M. Zumbihl	<a href="#">Inspire</a>	<a href="#">PDF</a>	v1.6/Delphes3

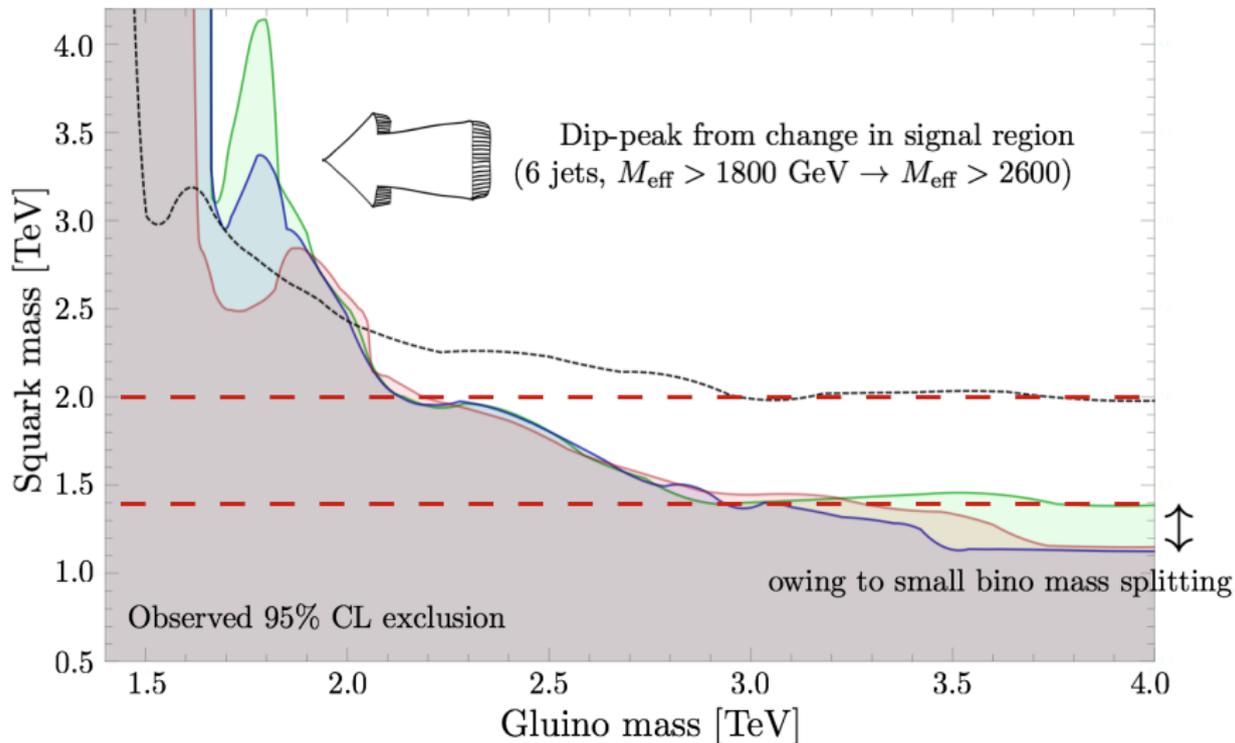
<http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase>

# Recast: exclusion plane plots - light wino scenarios



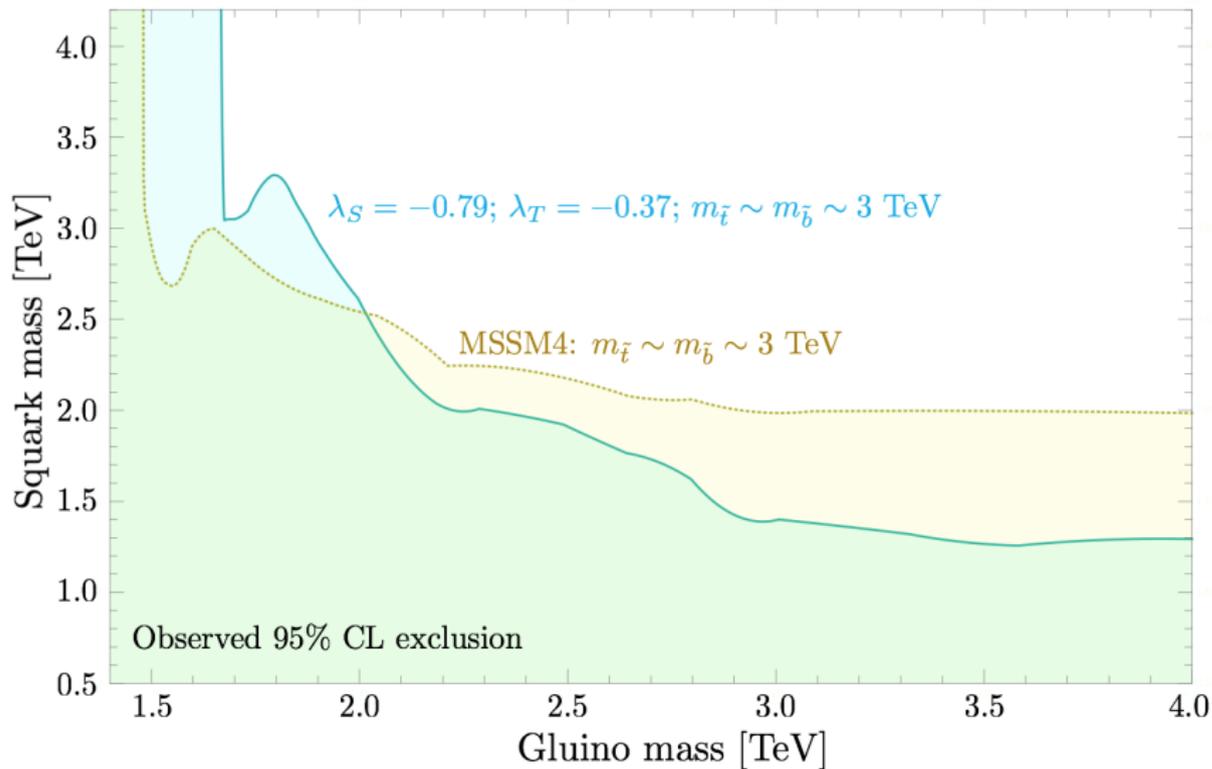
Note: MSSM  $\leftrightarrow$  MDGSSM scenario mass equivalency:  $M_1 \leftrightarrow m_{1D}$ ,  $M_2 \leftrightarrow m_{2D}$

# Recast: exclusion plane plots - light wino scenarios



Note: leading order cross-sections

# Recast: exclusion plane plots - heavy wino scenarios



# Reproducibility

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December 19, 2018

**Dirac gaugino benchmark points from arXiv:1812.09293**

Chalons, Guillaume; Goodsell, Mark D.; Kraml, Sabine; Reyes-Gonzalez, Humberto; Williamson, Sophie L.

**Benchmark points, in SUSY Les Houches Accord (SLHA) format**, from the paper "LHC limits on gluinos and squarks in the minimal Dirac gaugino model", arXiv:1812.09293, for 2 TeV gluino and 2.6 TeV squark masses.

We also provide the **UFO** and **SPheno models** (exported from SARAH), and the benchmark points. For usage in SPheno, expand DiracGauginos\_SPheno.zip to directory and compile with

```
make Model=DiracGauginos
```

This produces the library `./Lib/LibSPhenoDiracGauginos.a` and the executable (Tested with SPheno-4.0.3)

Note that compared to the version exported from SARAH, we have changed the ordering of the squarks, so that, for instance, PDG 1000006 is always the lightest.

The two additional scripts provided serve to add the QNUMBERS blocks and compile files. This is necessary for event generation with MadGraph5 / Pythia.

Preview

1 Benchmark-SLHA-files.zip

Dataset Open Access

88 views 65 downloads

See more details...

Zenodo: 2585685

Zenodo: 2581296

**(Re)interpretation of LHC results for BSM studies**

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Search (Re)interpretation of LHC results for BSM studies

March 6, 2019 (v1) Dataset Open Access View

**Data for Figs. 5 and 9 of arXiv:1812.09293**

Chalons, Guillaume; Goodsell, Mark D.; Kraml, Sabine; Reyes-Gonzalez, Humberto; Williamson, Sophie L.;

MadGraph5 parameter cards (i.e. SLHA files) and MadAnalysis5 CLs summaries for the scan points used to define the 95% CL exclusion contours in the gluino vs. squark mass plane, for scenarios DG1, DG2, DG3 and MSSM1 presented in Figure 5 as well as scenarios DG4 and MSSM4 presented in Figure 9

Uploaded on March 7, 2019

December 19, 2018 (v3) Dataset Open Access View

**Dirac gaugino benchmark points from arXiv:1812.09293**

Chalons, Guillaume; Goodsell, Mark D.; Kraml, Sabine; Reyes-Gonzalez, Humberto; Williamson, Sophie L.;

Benchmark points, in SUSY Les Houches Accord (SLHA) format, from the paper "LHC limits on gluinos and squarks in the minimal Dirac gaugino model", arXiv:1812.09293, for 2 TeV gluino and 2.6 TeV squark masses. We also provide the UFO and SPheno models (exported from SARAH), and the SP

Uploaded on March 1, 2019

# Conclusions

- LHC limits on **Dirac gaugino models** differ from the MSSM owing to
  - Supressed squark production
  - Enhanced gluino production
  - Larger electroweakino spectrum
- **SModels** provides fast but weak constraints
- Stronger constraints generated by **recasting**
  - Weaker limits on heavy gluinos (Dirac gluinos can be naturally heavy)
  - Weaker limits on light squarks
- Data provided on **Zenodo** for reproducibility :-)
- **Outlook**: study of electroweakinos and of a light  $\tilde{\chi}_2^0$  in LLP searches.

THANK YOU FOR LISTENING!

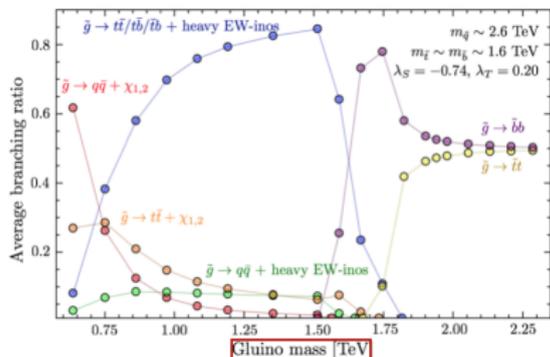


Figure 1: My mother advised me that people would find my slides less boring if I included a picture of my dog. So just in case she's right (and she always is) .....

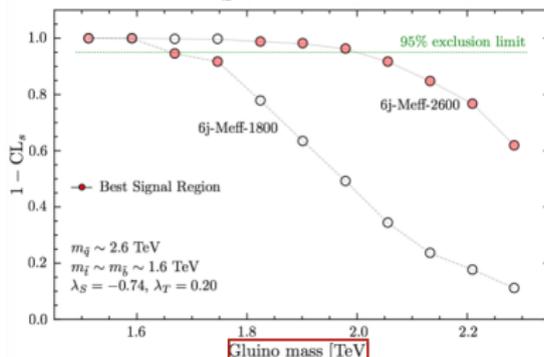


# Backup: Gluino mass constraints

Branching ratio of gluino decays

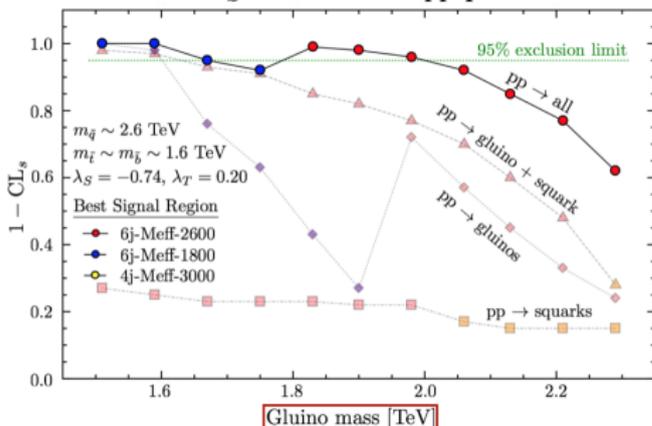


$1 - \text{CL}_S$  values in 2 BSRs



$1 - \text{CL}_S$  values for all  $pp$  processes

DG3 benchmark



# Backup: 1 – $CL_5$ exclusion limits for DG4 with k-factors

