Color-octet scalars in Dirac gaugino models with broken *R* symmetry

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DIRAC GAUGINOS: A REVIEW

- In *e.g.* MSSM, $\tilde{g} = \tilde{g}_{\mathrm{M}} \longleftrightarrow g$ is Majorana:

$$\mathcal{L}_{\mathrm{Maj}} \supset -\frac{1}{2} M_3 (\lambda_3^a \lambda_3^a + \mathrm{H.c.}) \equiv -M_3\, \tilde{g}_{\mathrm{M}}^a \tilde{g}_{\mathrm{M}}^a$$

- **Supersoft operators** [1] offer a different approach:

$$\mathcal{L}_{\mathrm{Dirac}} \supset \frac{\kappa_3}{\Lambda} \int \mathrm{d}^2\theta\, \mathcal{W}'^{\alpha} \mathcal{W}_{3\alpha}^a \mathcal{O}^a + \mathrm{H.c.}$$

  - ☐ $\mathcal{W}'$ = field-strength superfield of hidden $\mathrm{U}(1)'$ sector
  - ☐ $\mathcal{O}^a = \varphi_3^a + \theta^\alpha \psi_{3\alpha}^a + \cdots =$ new $\mathrm{SU}(3)_{\mathrm{c}}$ adjoint (**octet**) superfield

- If $\mathcal{L}_{\mathrm{Maj}} = 0$, then $\tilde{g} = \tilde{g}_{\mathrm{D}}$ is Dirac:

$$\mathcal{L}_{\mathrm{Dirac}} \supset -m_3 (\lambda_3^a \psi_3^a + \mathrm{H.c.}) \equiv -m_3\, \bar{\tilde{g}}_{\mathrm{D}}^a \tilde{g}_{\mathrm{D}}^a$$

Why Dirac gauginos?

- MSSM is increasingly constrained by LHC:
  - ☐ $\tilde{t}_{1,2}$ excluded in simple scenarios below 1 – 1.2 TeV [2]
  - ☐ $\tilde{g}$ excluded below 2 – 2.2 TeV
- Experimental reality motivates non-minimal realizations
- Models with Dirac gauginos offer alternative phenomenology and can be less constrained [3, 4]
  - ☐ **Supersafeness**: squark pair production suppressed due to vanishing of some amplitudes (*e.g.* $q_\mathrm{L} q_\mathrm{L} \to \tilde{q}_\mathrm{L} \tilde{q}_\mathrm{L}$ via t-channel $\tilde{g}_\mathrm{D}$)
  - ☐ **Supersoftness**: D-term SUSY breaking generates finite corrections to squark and slepton masses (minimal UV sensitivity):

$$e.g. \quad \delta m_{\tilde{q}}^2 \propto \alpha_3 m_3$$

  - ☐ Natural loop-induced hierarchy between squark and gluino masses

R SYMMETRY AND COLOR-OCTET SCALARS

- $\mathcal{L}_{\mathrm{Maj}}$ is forbidden by an ***R*** **symmetry** under which *e.g.*

$$\mathcal{W}_3 \to \mathrm{e}^{\mathrm{i}R}\mathcal{W}_3 \implies g \to g \quad \text{and} \quad \lambda_3 \to \mathrm{e}^{\mathrm{i}R}\lambda_3$$

- Typically SM bosons have $R = 0$, but Higgs R charge varies
- Supersoft operators — hence Dirac gaugino masses — allowed if

$$\mathcal{O} \to \mathcal{O} \implies \varphi_3 \to \varphi_3 \quad \text{and} \quad \psi_3 \to \mathrm{e}^{-\mathrm{i}R}\,\psi_3$$

- New color-octet fermion ψ_3 brings along **color-octet scalar**(s)

$$\varphi_3^a \equiv^* \frac{1}{\sqrt{2}}(O^a + \mathrm{i}o^a)$$

*Assuming no CPV s.t. $O =$ scalar, $o =$ pseudoscalar

R SYMMETRY AND COLOR-OCTET SCALARS

- **Sgluons** O, o studied frequently in models with Dirac gluino/unbroken R symmetry (see imminent talk by M.J.S.!)
- Many interesting operators respect gauge symmetry but break R:
  - R-breaking superpotential

$$W_{\not{R}} \supset \mu_3 \,\mathrm{tr}\, \mathcal{O}\mathcal{O} + \varrho_{SO}\, \mathcal{S}\, \mathrm{tr}\, \mathcal{O}\mathcal{O} + \frac{1}{3}\varrho_O \,\mathrm{tr}\, \mathcal{O}\mathcal{O}\mathcal{O}$$

  - R-breaking softly supersymmetry-breaking operators

$$-\mathcal{L}_{\mathrm{soft}} \supset M_3(\mathrm{tr}\, \lambda_3\lambda_3 + \mathrm{H.c.}) + 2M_O^2 \,\mathrm{tr}\, \varphi_3^\dagger \varphi_3 + B_O^2(\mathrm{tr}\, \varphi_3\varphi_3 + \mathrm{H.c.})$$

- Some of these (μ_3, ϱ_O, M_3) give Majorana masses to λ_3, ψ_3
- Others (ϱ_{SO}, ϱ_O) generate new interactions for color-octet scalars
- Goal: study models with “mildly” explicitly broken R symmetry

BROKEN R: GLUINOS AND SQUARKS

- Majorana gluino masses split $\tilde{g}_{\mathrm{D}}$ into two (Majorana) $\tilde{g}_1, \tilde{g}_2$:

$$-\mathcal{L} \supset \operatorname{tr} \Psi_{\tilde{g}}^{\intercal} M_{\tilde{g}} \Psi_{\tilde{g}} + \text{H.c.}, \quad \Psi_{\tilde{g}} = \begin{pmatrix} \psi_3 \\ \lambda_3 \end{pmatrix} \;\; \& \;\; M_{\tilde{g}} = \begin{pmatrix} M_3' & m_3 \\ m_3 & M_3 \end{pmatrix}$$

  - ☐ Recall: $m_3 =$ Dirac mass, $M_3 =$ soft-breaking λ_3 mass
  - ☐ Upper-diagonal element $M_3' = \mu_3 + \varrho_{SO} v_S/\sqrt{2}$ contains multiple contributions to $\mathcal{L} \propto \operatorname{tr} \psi_3 \psi_3$

- Lightest squarks $\tilde{t}_{\mathrm{L/R}}$ mix/split → $\tilde{t}_{1,2}$:

$$-\mathcal{L} \supset \Phi_{\tilde{t}}^{\dagger} M_{\tilde{t}}^2 \Phi_{\tilde{t}}, \quad \Phi_{\tilde{t}} = \begin{pmatrix} \tilde{t}_{\mathrm{L}} \\ \tilde{t}_{\mathrm{R}} \end{pmatrix} \;\; \& \;\; M_{\tilde{t}}^2 = \begin{pmatrix} m_{\mathrm{LL}}^2 & m_{\mathrm{LR}}^2 \\ m_{\mathrm{LR}}^2 & m_{\mathrm{RR}}^2 \end{pmatrix}$$

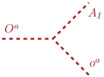
  - ☐ Diagonal elements $\propto v_S, v_T$, off-diagonals $\propto \mu, v_S, v_T, a_u$

Broken R: new adjoint interactions

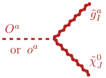
- Sgluons in R-symmetric models interact @ TL with $g, \tilde{g}_{\mathrm{D}}, \tilde{q}_{\mathrm{L,R}}$
- $\tilde{g}_{\mathrm{D}} \to \tilde{g}_1, \tilde{g}_2$ and $\tilde{t}_{\mathrm{L,R}} \to \tilde{t}_{1,2}$ interactions are affected by R breaking per previous slide
- Entirely new interactions arise with other adjoints → Higgs bosons H, A and neutralinos $\tilde{\chi}^0$:

$\varrho_O \,\mathrm{tr}\, \mathcal{O}\mathcal{O}\mathcal{O} \;\to$

$\varrho_{ST}\, \mathcal{S} \,\mathrm{tr}\, \mathcal{T}\mathcal{T} + \varrho_{SO}\, \mathcal{S} \,\mathrm{tr}\, \mathcal{O}\mathcal{O} \;\to$



$\varrho_{SO}\, \mathcal{S} \,\mathrm{tr}\, \mathcal{O}\mathcal{O} \;\to$



  - Some of these vertices modify loop couplings to colored SM particles
  - Decay widths, branching fractions, and single production are affected
- Aside: new operators modify minimal TL sgluon masses

HOW MUCH R BREAKING?

- Variety of scenarios considered in literature in IR and UV
- We are interested in models "not too far" from **Dirac limit**
- In this limit *e.g.*

$$M_{\tilde{g}} \to \begin{pmatrix} 0 & m_3 \\ m_3 & 0 \end{pmatrix} \implies \frac{1}{\sqrt{2}}(\tilde{g}_1 - \mathrm{i}\tilde{g}_2) = \tilde{g}_{\mathrm{D}}$$

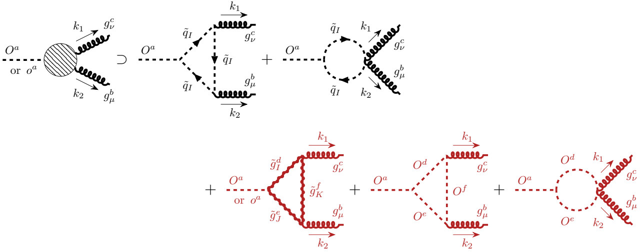
  - Natural to restrict Majorana masses $\sim m_3 \times \mathcal{O}(0.1)$
  - But with high number of *a priori* unrelated sources, how to quantify extent of R breaking in model at large?

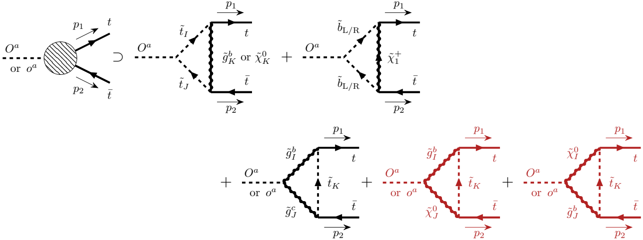
- Adopt (very) simple global measure of R breaking: $\not{R}$

$$\varrho_{SO} = \varrho_O = \not{R} \quad \text{and} \quad \delta_3 \equiv m_3^{-1}(\mu_3^2 + M_3^2)^{1/2} = \not{R}$$

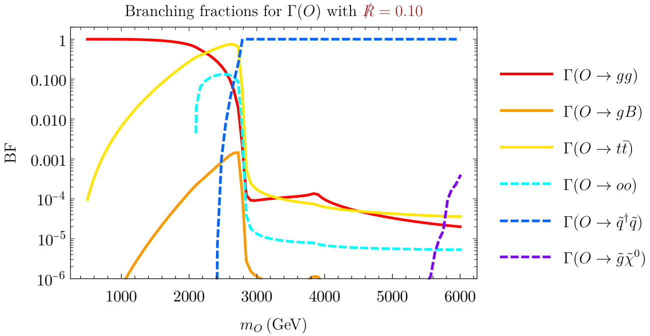
- Set three benchmarks with $\not{R} = 0.10$, $\not{R} = 0.25$, $\not{R} = 0.50$

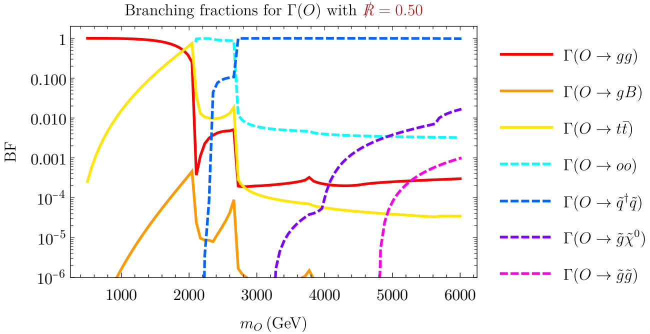
Decays to colored SM particles





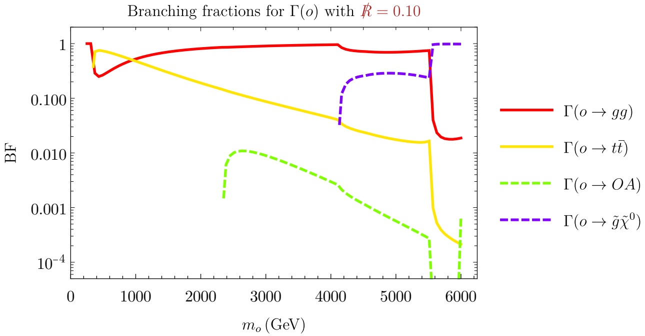
SCALAR BRANCHING FRACTIONS

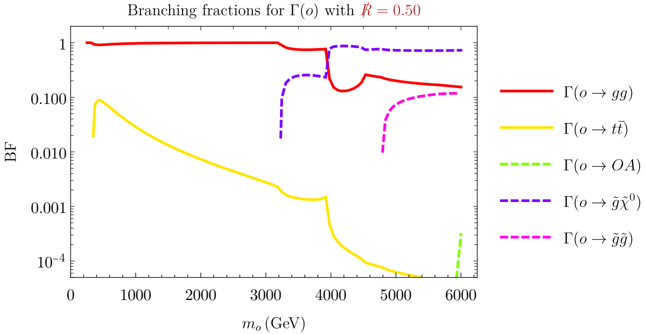

Branching fractions for $\Gamma(O)$ with $\not{R} = 0.10$


Branching fractions for $\Gamma(O)$ with $\not{R} = 0.50$

- $\Gamma(O \to oo)$ kills SM decay channels and even $\tilde{t}^\dagger\tilde{t}$ below threshold
- Decays involving $\tilde{\chi}^0$ become significant for very heavy O

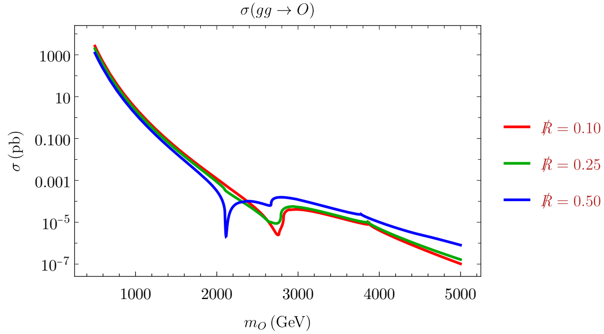
PSEUDOSCALAR BRANCHING FRACTIONS

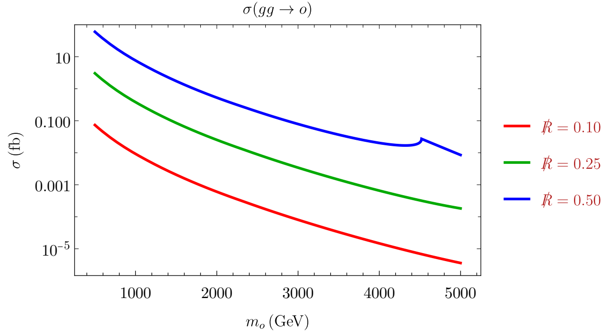




- $\Gamma(o \to gg) = 0$ in Dirac limit but grows quickly with $\not{R}$
- Gluino decays eventually dominate (for both sgluons)

Single sgluon production



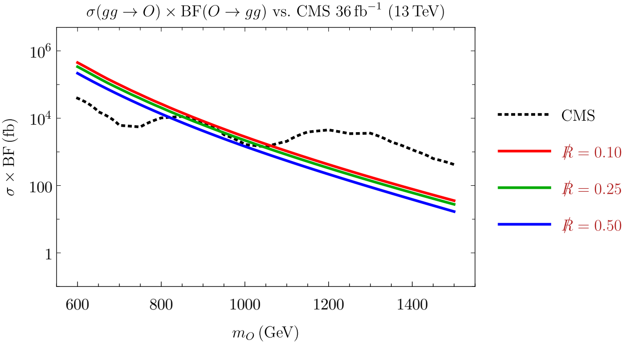


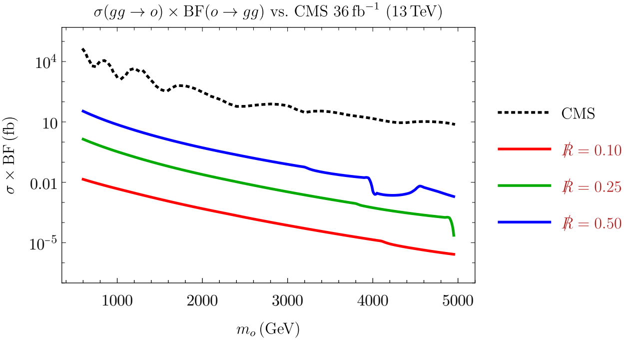
- Interference in $\mathcal{M}(O \to gg)$ at $\tilde{t}_{1,2}$, $\tilde{b}_{\mathrm{L,R}}$ thresholds
- Considerable increases in o production with growing $\not R$

SURVEYING LHC CONSTRAINTS

- Good handful of existing LHC searches for color-octet scalars:
  - ATLAS [5] — four flavorless jets — 7 TeV, $4.6\,\mathrm{fb}^{-1}$
  - ATLAS [6] — four top quarks ($t\bar{t}t\bar{t}$) — 8 TeV, $20.3\,\mathrm{fb}^{-1}$
  - ATLAS [7] — four flavorless jets — 13 TeV, $36.7\,\mathrm{fb}^{-1}$
  - CMS [8] — dijet resonances — 13 TeV, $36\,\mathrm{fb}^{-1}$
- These constrain color-octet scalars in simplified models — how do bounds apply to our models?
- We perform (very) simple reinterpretation of each search in our benchmarks to estimate existing constraints
  - Both sgluons satisfy narrow-width approximation: *e.g.* $\sigma(pp \to O \to gg) \approx \sigma(pp \to O) \times \mathrm{BF}(O \to gg)$
  - Existing searches model correct kinematics, so we take efficiencies at face value
- Will sgluon pair production remain most constrained?

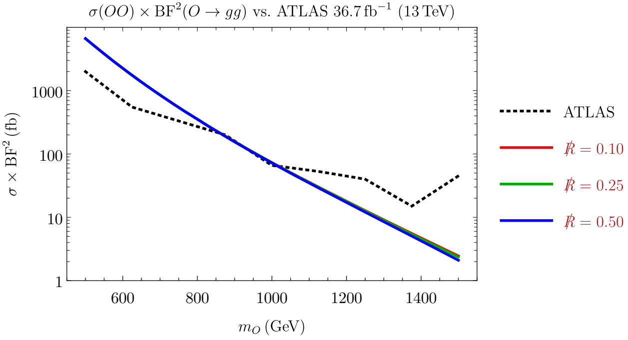
CONSTRAINTS FROM SINGLE PRODUCTION

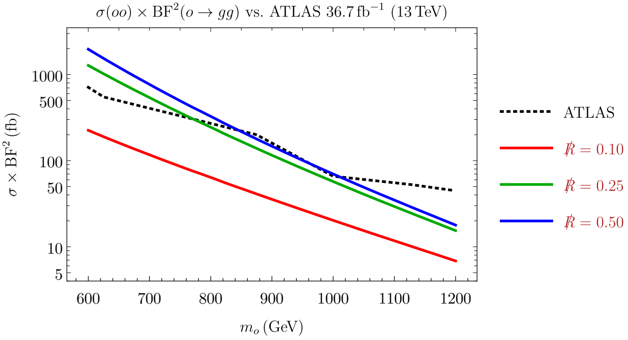




- Huge boost to $\sigma(pp \to O)$ allows CMS to rule out $m_O \lesssim 1\,\mathrm{TeV}$
- Not quite enough for the pseudoscalar

CONSTRAINTS FROM PAIR PRODUCTION





- 13 TeV ATLAS searches competitive with 13 TeV CMS search
- Not shown: both particles ruled out in all cases below ≈ 300 GeV

LHC CONSTRAINTS: A SUMMARY

	Benchmark	Lower bounds (GeV)		Limiting high-mass search		
		Low	High	$2j_{13}^{\text{CMS}}$	$t\bar{t}t\bar{t}_8^{\text{ATLAS}}$	$4j_{13}^{\text{ATLAS}}$
Scalar O	$\not R = 0.10$	290	1050	✓		
	$\not R = 0.25$	290	1030	✓		
	$\not R = 0.50$	290	1010			✓
Pseudo o	$\not R = 0.10$	290	820		✓	
	$\not R = 0.25$	290	770			✓
	$\not R = 0.50$	290	1018			✓

OUTLOOK

- Catalog of gauge-invariant color-octet scalar interactions in models with (pseudo-)Dirac gauginos is complete
- Explicit R symmetry breaking generates observable changes in sgluon phenomenology
- More investigation of scalar sector ($\mathrm{SU}(2)_{\mathrm{L}}$ and $\mathrm{U}(1)_Y$ adjoints) probably warranted
- New (spring 2021) measurements of $\sigma(pp \to t\bar{t}t\bar{t})$ [9, 10]!
  Work complete for R-symmetric and R-broken sgluons...

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Thank you for your attention

I am happy to answer questions if we have time

Bibliography (1)

[1] P. J. Fox, A. E. Nelson, and N. Weiner, J. High Energy Phys. **08**, 035.

[2] G. Aad *et al.* (ATLAS), ATLAS **TWiki**, SUSY March Summary Plot Update (2021).

[3] E. Dudas, M. Goodsell, L. Heurtier, and P. Tziveloglou, Nucl. Phys. B **884**, 632 (2014).

[4] P. Diessner, W. Kotlarski, S. Liebschner, and D. Stöckinger, J. High Energy Phys. **2017** (142).

[5] G. Aad *et al.* (ATLAS), Eur. Phys. J. C **73**, 2263 (2013).

[6] G. Aad *et al.* (ATLAS), J. High Energy Phys. **2015** (105).

[7] M. Aaboud *et al.* (ATLAS), Eur. Phys. J. C **78**, 250 (2018).

BIBLIOGRAPHY (2)

[8] A. M. Sirunyan *et al.* (CMS), J. High Energy Phys. **2018** (130).

[9] M. Aaboud *et al.* (ATLAS), Eur. Phys. J. C **80** (2020).

[10] G. Aad *et al.* (ATLAS), *ATLAS-CONF-2021-013*, Tech. Rep. (2021).

[11] N. Aghanim *et al.*, Astronomy & Astrophysics **641**, A6 (2020).

[12] G. Aad *et al.* (ATLAS), *ATLAS-CONF-2020-027*, Tech. Rep. (2020).

[13] P. A. Zyla *et al.* (Particle Data Group), Progress of Theoretical and Experimental Physics **2020** (2020).

Bonus material

CHOICES AND CONSTRAINTS

- Interested in viable scenarios with TeV $\tilde{t}_{1,2}$, multi-TeV $\tilde{g}_{1,2}$
- Natural for Dirac bino/wino masses m_1, m_2 to be heavy, so we choose Higgsino (N)LSP $\tilde{\chi}^0_{1,2}$
  - ☐ $\tilde{\chi}^0_1$ can be DM candidate: ensure $\Omega_{\tilde{\chi}} h^2 \leq 0.12$ via freeze-out [11]
- Require $\approx 125\,\text{GeV}$ scalar composed primarily of H_u and/or H_d
  - ☐ Convenient to decouple other H, A to respect Higgs data [12]
  - ☐ Respect $\delta\rho \propto (v_T/v)^2 \sim \mathcal{O}(10^{-4})$ by keeping $v_T \lesssim 2.5\,\text{GeV}$ [13]
- Phenomenological approach to sgluon masses: fix one while varying the other from ∼weak scale to TeV scale
- Answers must agree with known results in Dirac limit! Analytic results verified, numerical results checked for all benchmarks ✓

Benchmarks

		Benchmark 1	Benchmark 2	Benchmark 3
		$\not{R} = 0.10$	$\not{R} = 0.25$	$\not{R} = 0.50$
QCD	$m_{\tilde{t}_1}$	1383.3	1318.2	1166.3
	$m_{\tilde{t}_2}$	1446.0	1475.6	1495.2
	$m_{\tilde{b}_\mathrm{L}}$	1411.2	1394.7	1334.4
	$m_{\tilde{b}_\mathrm{R}}$	1939.1	1927.8	1886.4
	$m_{\tilde{g}_1}$	3286.3	2962.2	2396.2
	$m_{\tilde{g}_2}$	3695.1	4004.0	4515.4
Electroweakinos	$m_{\tilde{\chi}^0_1}$	844.29	841.36	832.77
	$m_{\tilde{\chi}^0_2}$	848.23	851.10	856.61
	$m_{\tilde{\chi}^0_3}$	2262.4	1964.3	1554.7
	$m_{\tilde{\chi}^0_4}$	2298.1	2004.8	1592.4
	$m_{\tilde{\chi}^0_5}$	2507.0	2812.2	3221.8
	$m_{\tilde{\chi}^0_6}$	2523.8	2815.9	3245.3
	$m_{\tilde{\chi}^\pm_1}$	847.06	848.21	850.87
	$m_{\tilde{\chi}^\pm_2}$	2298.0	2004.5	1591.8
	$m_{\tilde{\chi}^\pm_3}$	2523.8	2816.0	3222.0
Higgs bosons	m_{H_1}	125.00	124.90	130.50
	m_{H_2}	5231.3	5272.2	5334.5
	m_{H_3}	5534.7	5531.3	5527.4
	m_{A_2}	1950.4	2064.4	2220.8
	m_{A_3}	5536.7	5533.6	5530.6
	$\Omega_{\tilde{\chi}} h^2$	0.0779	0.0788	0.0751