# $t\bar{t}t\bar{t}$ signatures through the lens of color-octet scalars

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# ATLAS-CONF-2020-013: $\sigma(pp \to t\bar{t}t\bar{t})$

- SM production of four top quarks is rare —

$$\sigma_{\mathrm{SM}}(pp \to t\bar{t}t\bar{t}) = (12.0 \pm 2.4)\,\mathrm{fb} \quad \text{at} \quad \sqrt{s} = 13\,\mathrm{TeV}$$

- ATLAS-CONF-2020-013 [1]:
  search for $t\bar{t}t\bar{t}$ production in multilepton final states
  - $4.2\sigma$ over background: closer than ever to $5\sigma$ discovery
  - Signal strength $\mu = 2.0^{+0.8}_{-0.6}$, cross section $\sigma(pp \to t\bar{t}t\bar{t}) = 24^{+7}_{-6}\,\mathrm{fb}$
  - $1.7\sigma$ over SM prediction
- ATLAS-CONF-2021-013 [2]: search in lepton(s) + jets final states
  improves $4.2\sigma \to 4.7\sigma$ (null), $1.7\sigma \to 2.0\sigma$ (SM)
- New physics hiding in these results?
  Multiple SUSY scenarios feature resonances decaying to $t\bar{t}$

# ATLAS-CONF-2020-002: many jets + $E_{\mathrm{T}}^{\mathrm{miss}}$

- Meanwhile, the search for physics beyond SM — particularly SUSY — continues
- ATLAS-CONF-2020-002 [3]:
  search for new phenomena in final states with 8–12 jets and significant missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$)
  - 8 signal regions (SRs) optimized for various bSM scenarios
  - Constrains *e.g.* model with pair-produced $\tilde{g} \to t\bar{t} + \tilde{\chi}_1^0$ ($E_{\mathrm{T}}^{\mathrm{miss}}$)
  - No excess over SM background reported
- Ever-improving multijet analysis enhances bSM probing power
- CONF-2020-013 ($t\bar{t}t\bar{t}$) sees excess while CONF-2020-002 ($t\bar{t}t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$) does not — what models can accommodate both?
- Maybe color-octet scalars in models with **Dirac gauginos**

# 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** [4] 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:

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

# $R$ SYMMETRY AND COLOR-OCTET SCALARS

- $\mathcal{L}_{\text{Maj}}$ 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

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

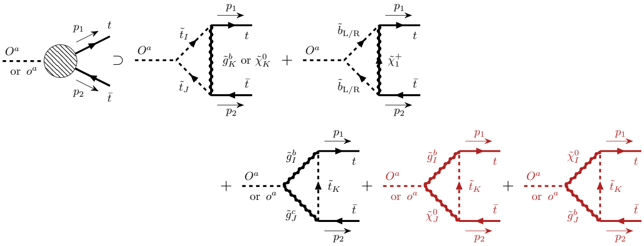
- New color-octet fermion $\psi_3$ brings along **color-octet scalar**(s)

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

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

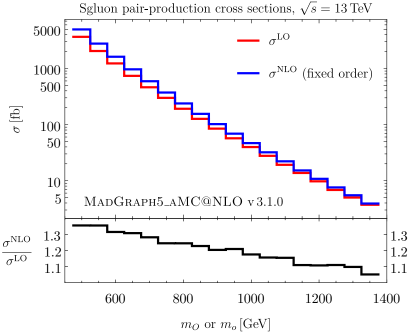
# Sgluon interactions with SM particles

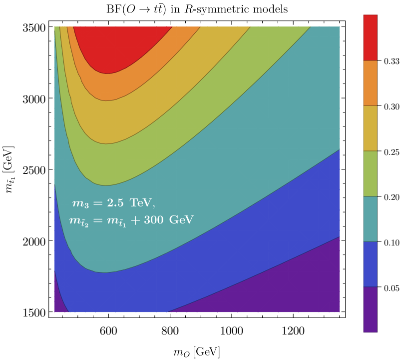
- **Sgluons** $O$, $o$ enjoy loop couplings to quarks and gluons [5]




- Available decay channels and partial widths can be modified by $R$ symmetry breaking, which splits Dirac gluino + introduces novel interactions [6]
  - Generally diminishes branching fractions to $t\bar{t}$!

# Cross sections & branching fractions




- $\sigma(pp \to OO \,\text{or}\, oo) \in [1\,\text{fb}, 1\,\text{pb}]$ with modest $K$ factors
- $\mathrm{BF}(O \to t\bar{t}) \lesssim 0.30$ in natural $R$-symmetric models

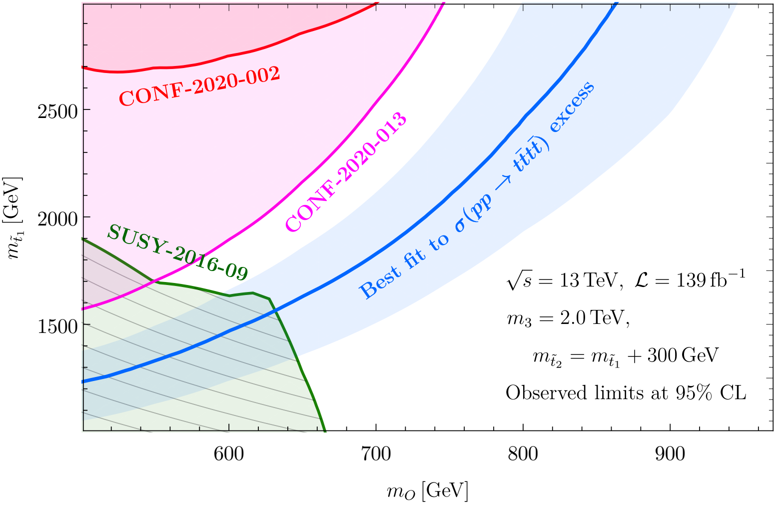
# Results: best fit, limits, and discovery

- Recall: ATLAS-CONF-2020-013 finds

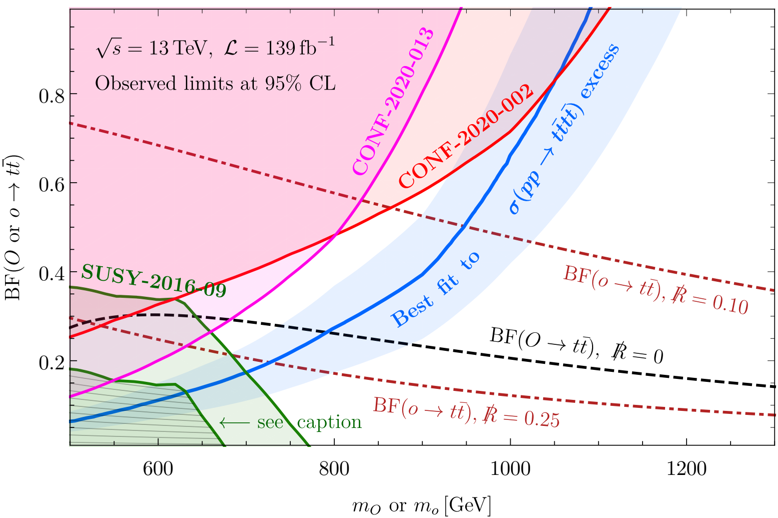
$$\mu = 2.0^{+0.8}_{-0.6} \quad \text{and} \quad N_{\text{obs}}(t\bar{t}t\bar{t}) = 60 \quad \implies \quad \sim 30 \text{ event excess}$$

- We use MadAnalysis 5 to compute best fit to $t\bar{t}t\bar{t}$ excess + exclusion limits at 95% CL for sgluon pair-production model
- Results provided in natural $R$-symmetric (Dirac gaugino) + generic BF($O$ or $o \to t\bar{t}$) parameter spaces
- Analysis extrapolated to planned HL-LHC luminosity $\mathcal{L} = 3\,\text{ab}^{-1}$
  - Future 95% CL limits estimated with luminosity-scaled background yield errors in case no excess is found
  - Also estimate $5\sigma$ discovery potential $\mathcal{S} = s_{\text{HL-LHC}}/\sqrt{b_{\text{HL-LHC}}}$
- Multiple scenarios can be discovered or excluded in future

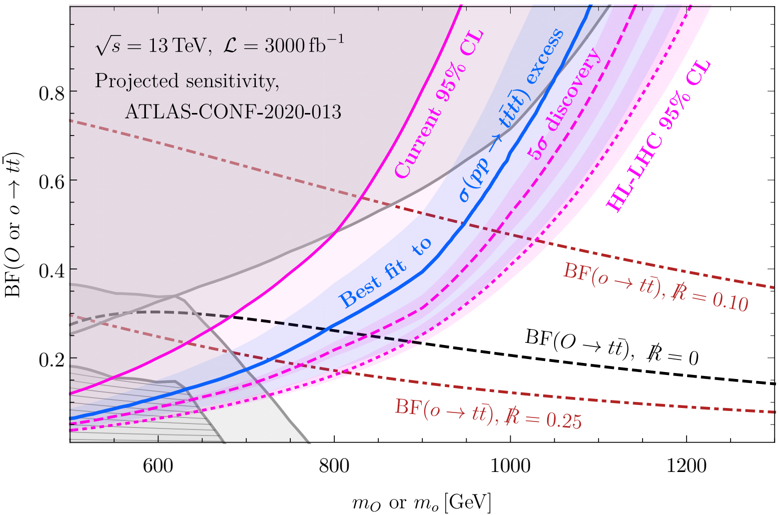
# Results in natural DG parameter space



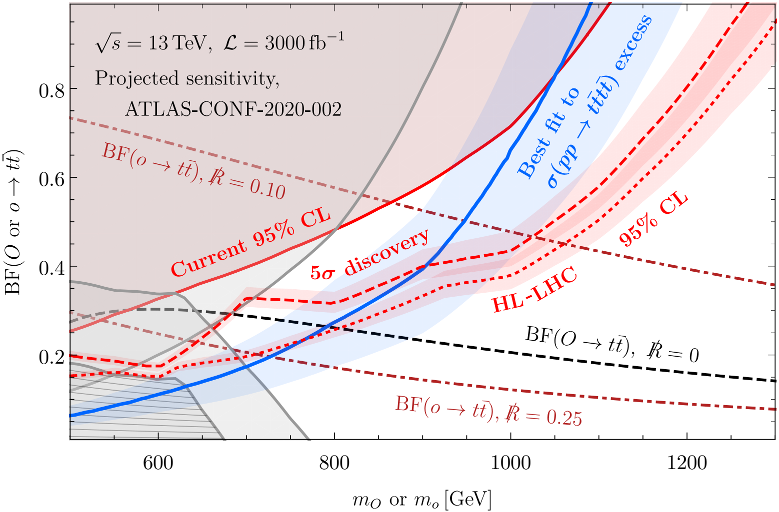
# Results in generic parameter space



# HL-LHC projections: $\sigma(pp \to t\bar{t}t\bar{t})$



# HL-LHC projections: jets + $E_T^{miss}$



# Outlook

- We have found complementary constraints on color-octet scalars from ATLAS searches for $t\bar{t}t\bar{t}$ production and events with $t\bar{t}t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$
- $R$-symmetric (Dirac gaugino) scenarios and models with broken $R$ symmetry both currently viable
- At HL-LHC, these searches provide complementary discovery channels for TeV-scale color-octet scalars decaying to top quarks — or can rule them out
- Future hypothesis discrimination or discovery without a $t\bar{t}t\bar{t}$ signal may depend on other channels, including $g\gamma/gZ$

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*Thank you for your attention*

I am happy to answer questions if we have time

# Bibliography (1)


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

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

[3] G. Aad *et al.* (ATLAS), J. High Energy Phys. **2020** (10).

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

[5] T. Plehn and T. M. P. Tait, J. Phys. G **36**, 10.1088/0954-3899/36/7/075001 (2009).

[6] L. M. Carpenter and T. Murphy, J. High Energy Phys. **05** (079).

[7] E. Conte, B. Fuks, and G. Serret, Comput. Phys. Commun. **184**, 222–256 (2013).

# Bonus material

# Reinterpreting ATLAS-CONF-2020-013

- Both searches recast for application to color-octet scalar models using MadAnalysis 5 framework [7]
- ATLAS-CONF-2020-013 defines one inclusive SR with stringent preselection criteria:
  - 1 SS lepton pair **or** $\geq 3$ leptons with no charge requirement
  - SS $e$ pairs: $m_{ee} > 15\,\text{GeV}$ and $\notin [81, 101]\,\text{GeV}$
  - OSSF lepton pairs: $m_{\ell\ell} \notin [81, 101]\,\text{GeV}$
  - $\geq 6$ jets **and** $\geq 2$ $b$-tagged anti-$k_t$ jets with $R = 0.4$
  - Total scalar transverse momentum

$$H_{\text{T}} \equiv \sum_i \left[ p_{\text{T}i}^{\text{jet}} + p_{\text{T}i}^{\text{lepton}} \right] \geq 500\,\text{GeV}$$

- We apply cuts to SM signal + leading backgrounds to validate reimplementation at $\mathcal{O}(10)\%$ level

# CONF-2020-013 RECAST VALIDATION

- We simulate $5 \times 10^4$ events for signal and three leading backgrounds for SM without $t\bar{t}t\bar{t}$

| | ATLAS yield | MadAnalysis 5 yield | Error [%] |
|---|---|---|---|
| $t\bar{t}W$ + jets | $102 \pm 26$ | 90.3 | $-11.5$ |
| $t\bar{t}Z$ + jets | $48 \pm 9$ | 37.7 | $-21.5$ |
| $t\bar{t}H$ + jets | $38 \pm 9$ | 21.1 | $-44.5$ |
| $t\bar{t}t\bar{t}$ [SM] | $30 \pm 8$ | 32.6 | $+8.76$ |

- We achieve errors of $\mathcal{O}(10)\%$
- Lepton cuts are most stringent
- Largest errors likely statistical for smaller backgrounds

# Reinterpreting ATLAS-CONF-2020-002

- Eight non-overlapping SRs with multiple ways to control SM multijet background
  - 0 leptons in any SR
  - 8–12 $R = 0.4$ jets with $p_{\mathrm{T}} \geq 50\,\mathrm{GeV}$ + 1–2 $b$ jets in some SRs
  - Missing transverse energy significance $\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}}) > 5.0$
  - Cumulative mass of reclustered fat ($R = 1.0$) jets

$$M_{\mathrm{J}}^{\Sigma} \equiv \sum_i m_i^{\mathrm{jet},R=1.0} \geq 340\,\mathrm{GeV} \text{ or } 500\,\mathrm{GeV}$$

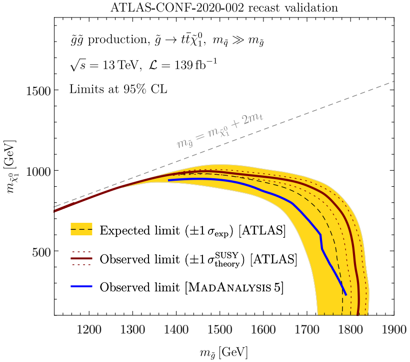
- ATLAS performs single-bin and multi-bin subanalyses — we reimplement single-bin
- We apply cuts to gluino pair-production benchmark model and directly compare to ATLAS results, again achieving $\mathcal{O}(10)\%$ error

# CONF-2020-002 recast validation

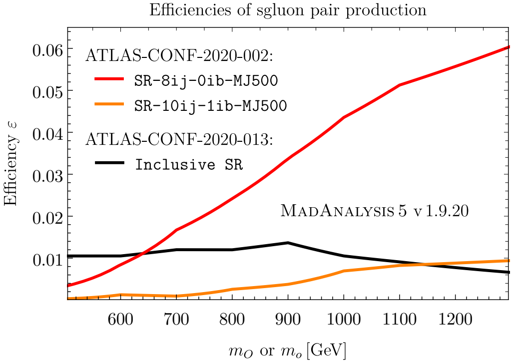
- ATLAS offers constraints on benchmark "SUSY" model with

$$pp \to \tilde{g}\tilde{g} \quad \text{followed by} \quad \tilde{g} \to t\bar{t} + \tilde{\chi}_1^0 \quad \text{via off-shell } \tilde{q}$$

- We simulate $10^4$ events for variety of $m_{\tilde{g}}$ and $m_{\tilde{\chi}_1^0}$



# MA5 SGLUON EFFICIENCIES




- Efficiencies statistically concurrent for scalar and pseudoscalar
- CONF-2020-002 more efficient for heavier sgluons decaying to increasingly boosted $t\bar{t}$