Color-octet scalars and $t\bar{t}t\bar{t}$ production at LHC Runs 2 & 3: A theorist's projections

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

$$\sigma_{\mathrm{SM}}(pp \to t\bar{t}t\bar{t}) = (12.0 \pm 2.4)\,\mathrm{fb} \quad (\sqrt{s} = 13\,\mathrm{TeV},\ \mathrm{NLO})\ [1]$$

- ATLAS-CONF-2020-013 $\longrightarrow$ ATLAS-TOPQ-2018-05 [2]: search for $t\bar{t}t\bar{t}$ production in multilepton final states
  - 4.2σ [obs] over background: closer than ever to 5σ discovery
  - Signal strength $\mu = 2.0^{+0.8}_{-0.6}$, $\sigma(pp \to t\bar{t}t\bar{t}) = 24^{+7}_{-6}\,\mathrm{fb}$
  - 1.7σ over SM prediction
- Recent: ATLAS-TOPQ-2021-08 [3] in same final states
  - Discovery! 6.1σ [obs] over background
  - Results held steady: $\sigma(pp \to t\bar{t}t\bar{t}) = 22.5^{+6.6}_{-5.5}\,\mathrm{fb}$, 1.8σ over SM
- On the other hand... CMS-TOP-18-003 [4]
  - $\sigma(pp \to t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2}\,\mathrm{fb}$ agrees with SM within $<1\sigma$
- So is there new physics or not? Unclear, but possible
  Many scenarios feature exotic 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 [5]:
  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, $\tilde{g} = \tilde{g}_{\rm M} \longleftrightarrow g$ is Majorana:

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

- **Supersoft operators** [6] offer a different approach:

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

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

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

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

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

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

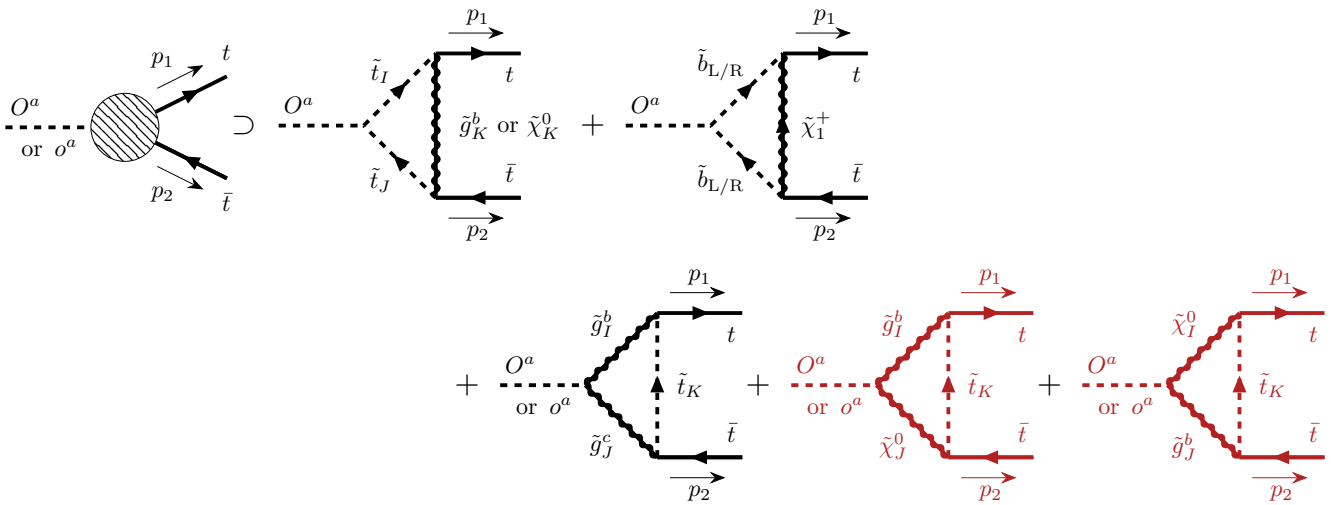
- New color-octet fermion ψ_3 brings along **color-octet scalar**(s)

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

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

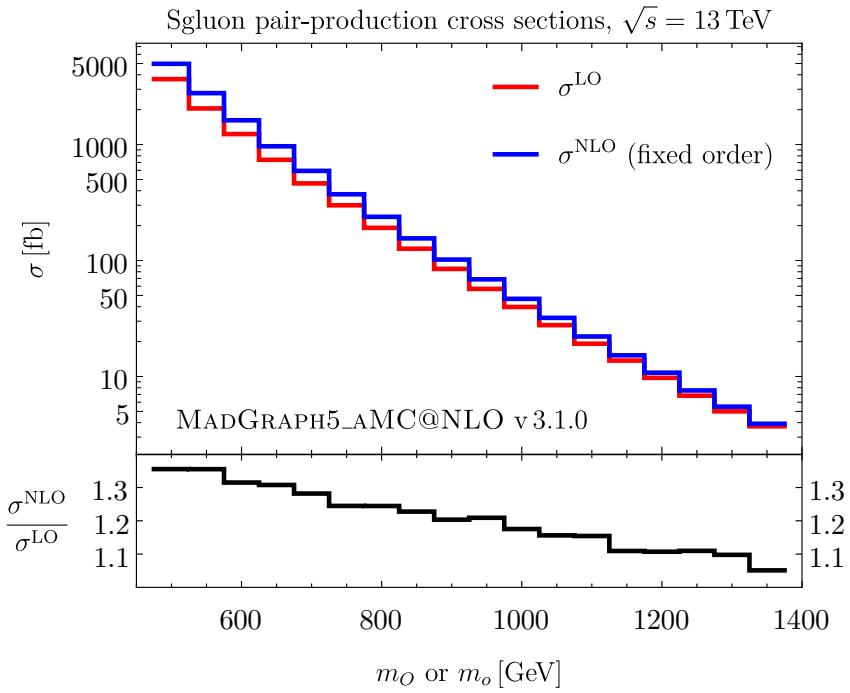
Sgluon interactions with SM particles

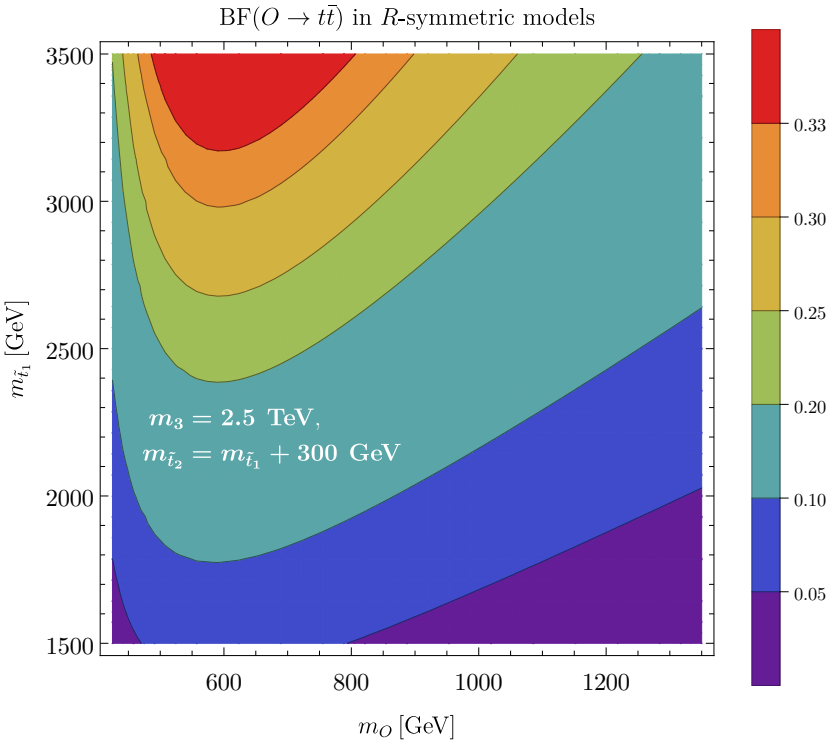
- **Sgluons** O, o enjoy loop couplings to quarks and gluons [7]



- Available decay channels and partial widths can be modified by R symmetry breaking, which splits Dirac gluino + introduces novel interactions [8]
  - 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
- $\text{BF}(O \to t\bar{t}) \lesssim 0.30$ in natural R-symmetric models

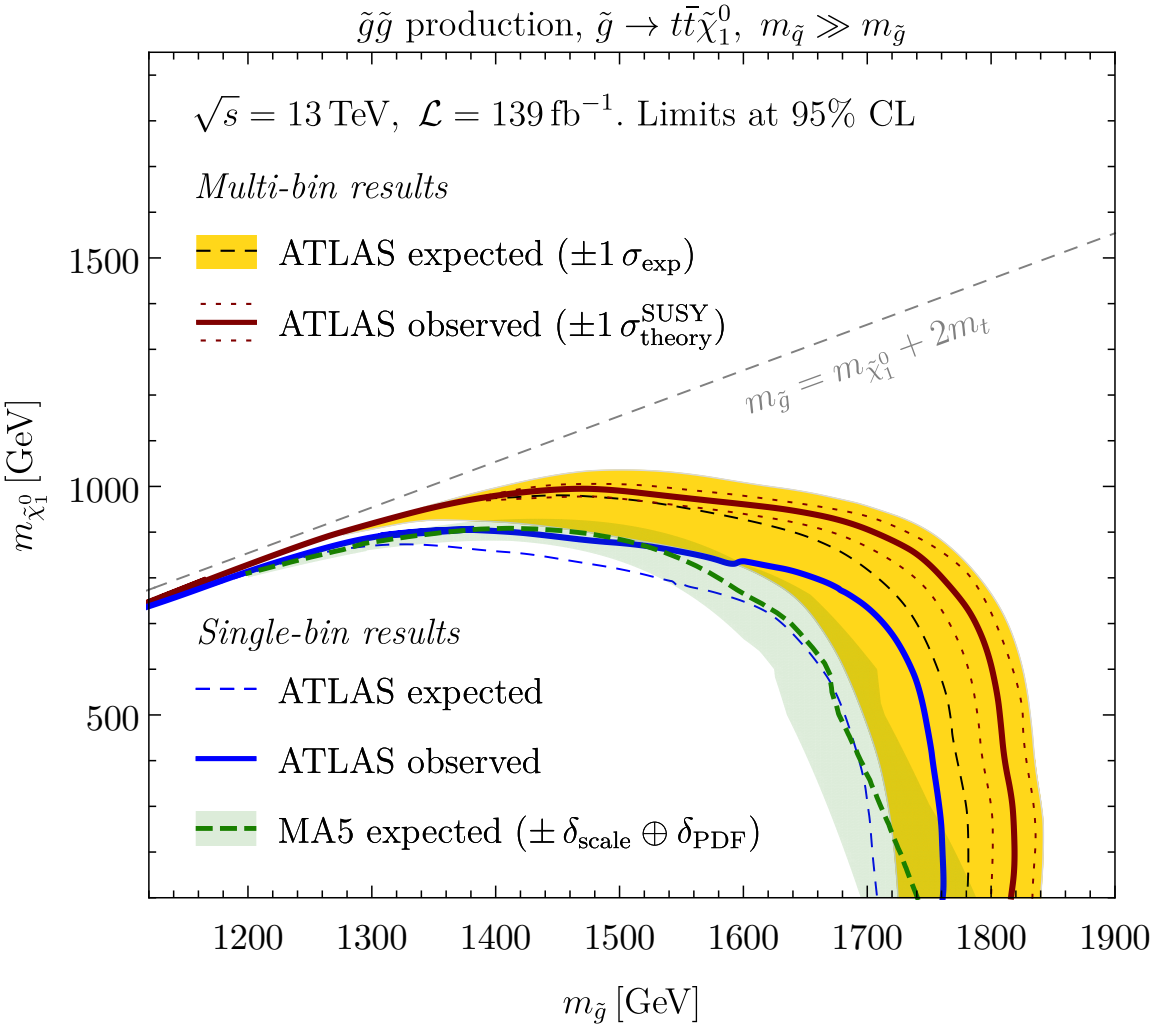
Results: best fit, limits, and discovery

- Recall: ATLAS-CONF-2020-013 finds

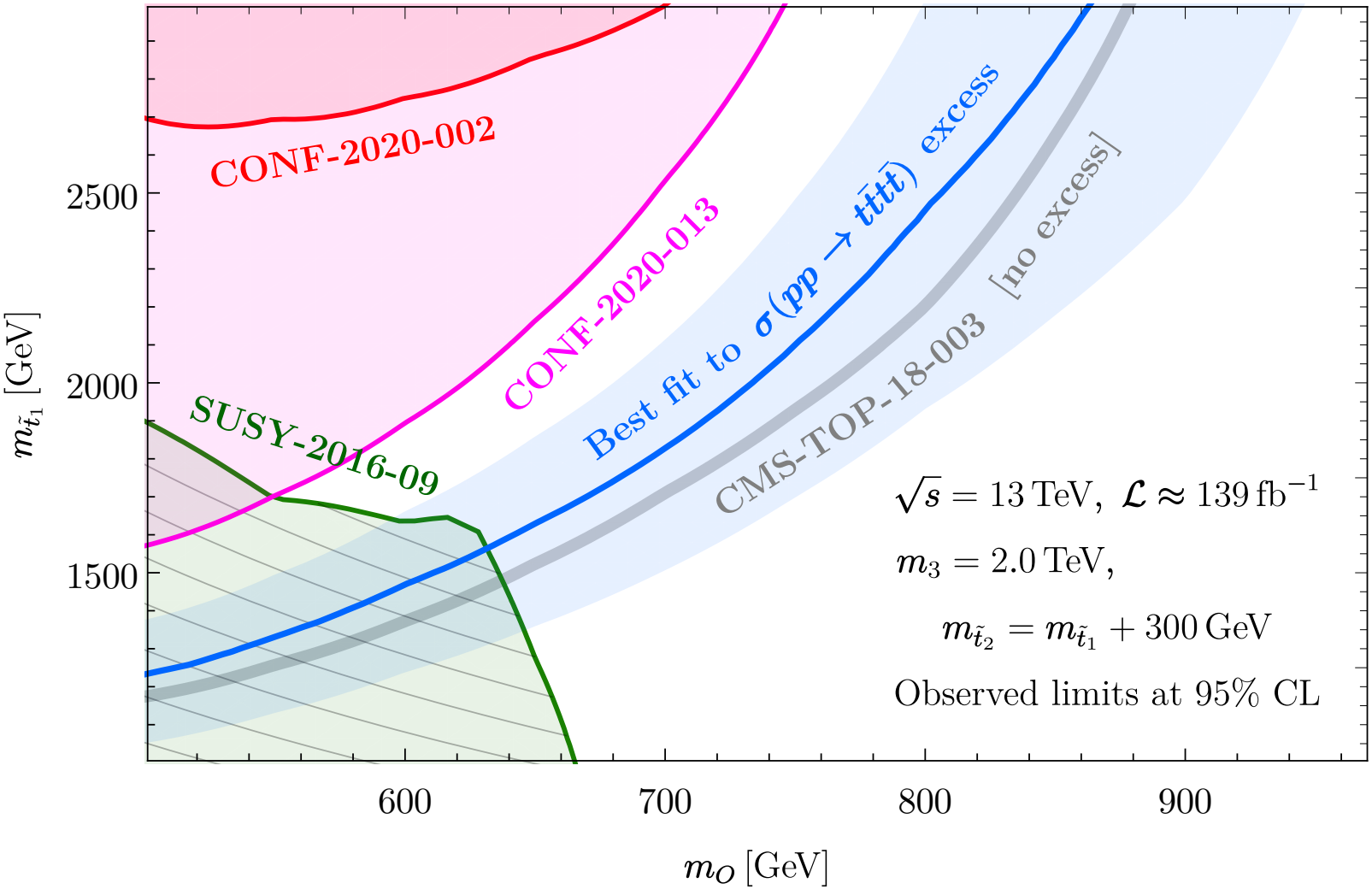
$$\mu = 2.0^{+0.8}_{-0.6} \quad \text{and} \quad N_{\text{obs}}(t\bar{t}t\bar{t}) = 60 \quad \Longrightarrow \quad \sim 30 \text{ event excess}$$

- 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 5σ discovery potential $\mathcal{S} = s_{\text{HL-LHC}}/\sqrt{b_{\text{HL-LHC}}}$
- Multiple scenarios can be discovered or excluded in future

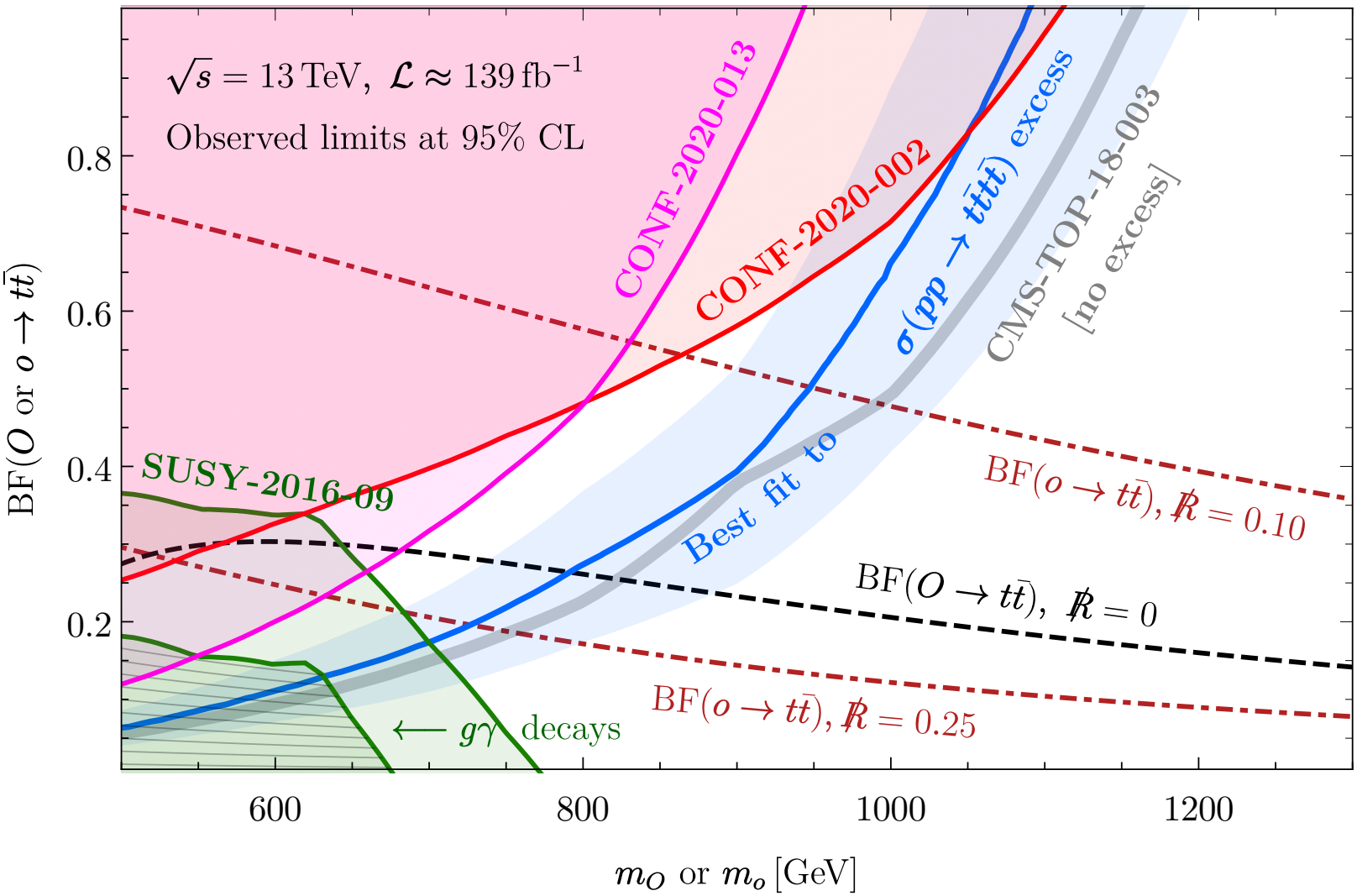
ATLAS-CONF-2020-002 RECAST



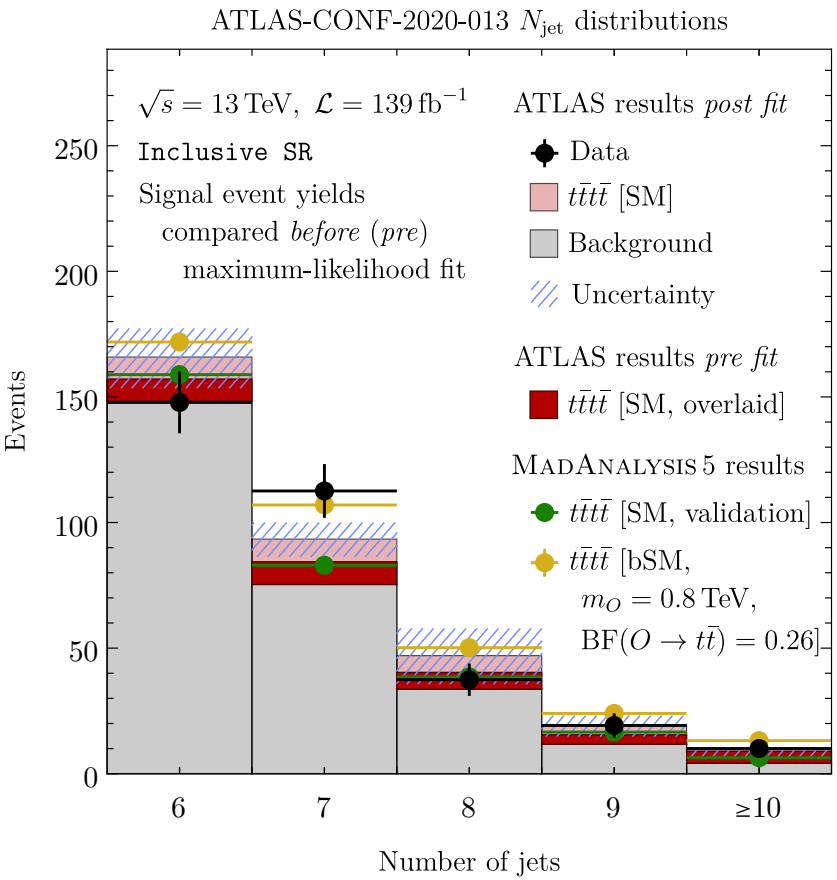
Results in natural DG parameter space

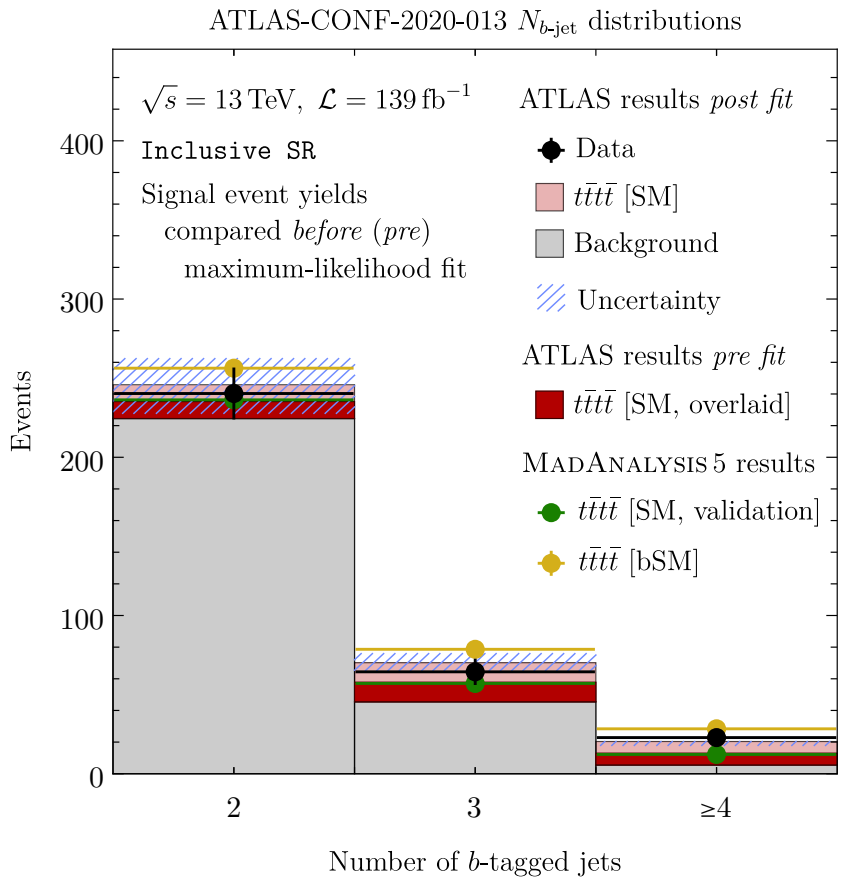


Results in generic parameter space

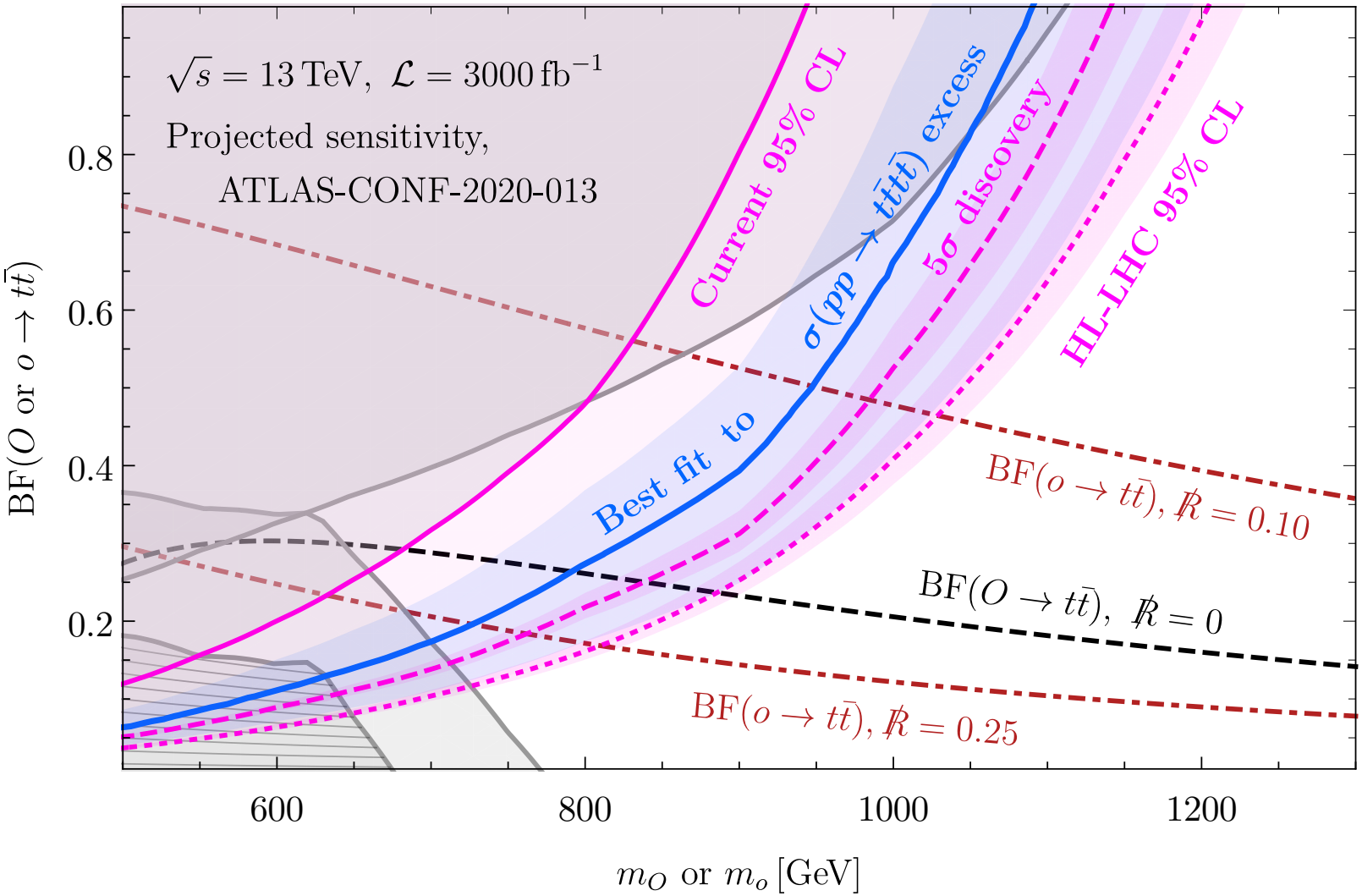


Can we fit the signal shape?

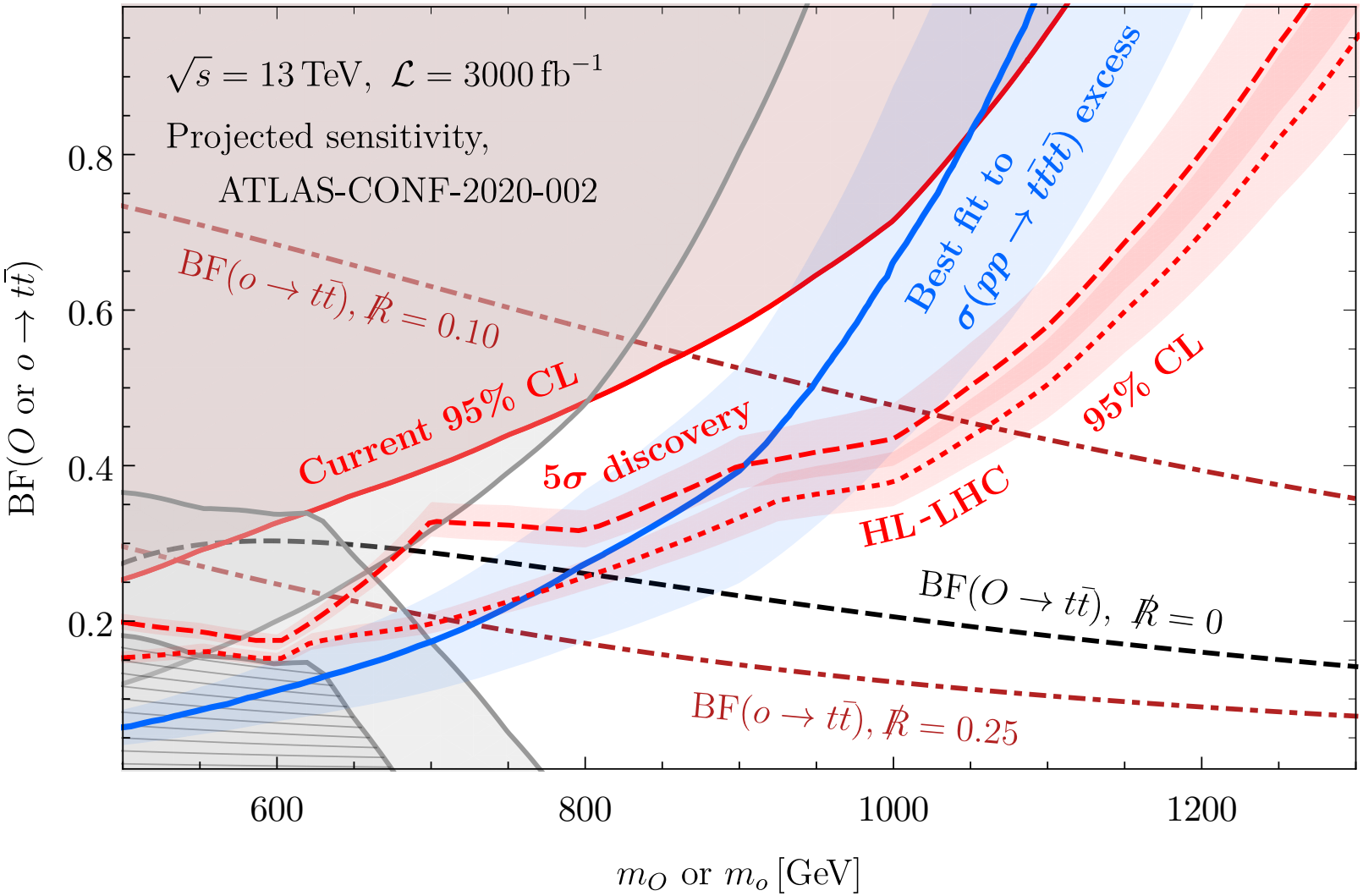




HL-LHC PROJECTIONS: $\sigma(pp \to t\bar{t}t\bar{t})$



HL-LHC PROJECTIONS: jets + $E_{\mathrm{T}}^{\mathrm{miss}}$



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] R. Frederix *et al.*, J. High Energy Phys. **02**, 031.

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

[3] G. Aad *et al.* (ATLAS), 2303.15061 (2023).

[4] A. M. Sirunyan *et al.* (CMS), Eur. Phys. J. C **80**, 75 (2020), arXiv:1908.06463 [hep-ex] .

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

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

[7] T. Plehn and T. M. P. Tait, J. Phys. G **36** (2009).

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

[9] 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 [9]
- ATLAS-CONF-2020-013 defines one inclusive SR with stringent preselection criteria:
  - 1 SS lepton pair **or** ≥ 3 leptons with no charge requirement
  - SS e pairs: $m_{ee} > 15\,\text{GeV}$ and $\notin [81, 101]\,\text{GeV}$
  - OSSF lepton pairs: $m_{\ell\ell} \notin [81, 101]\,\text{GeV}$
  - ≥ 6 jets **and** ≥ 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 5×10^4 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 ± 26	90.3	-11.5
$t\bar{t}Z$ + jets	48 ± 9	37.7	-21.5
$t\bar{t}H$ + jets	38 ± 9	40.2	$+5.73$
$t\bar{t}t\bar{t}$ [SM]	30 ± 8	28.4	-5.48

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

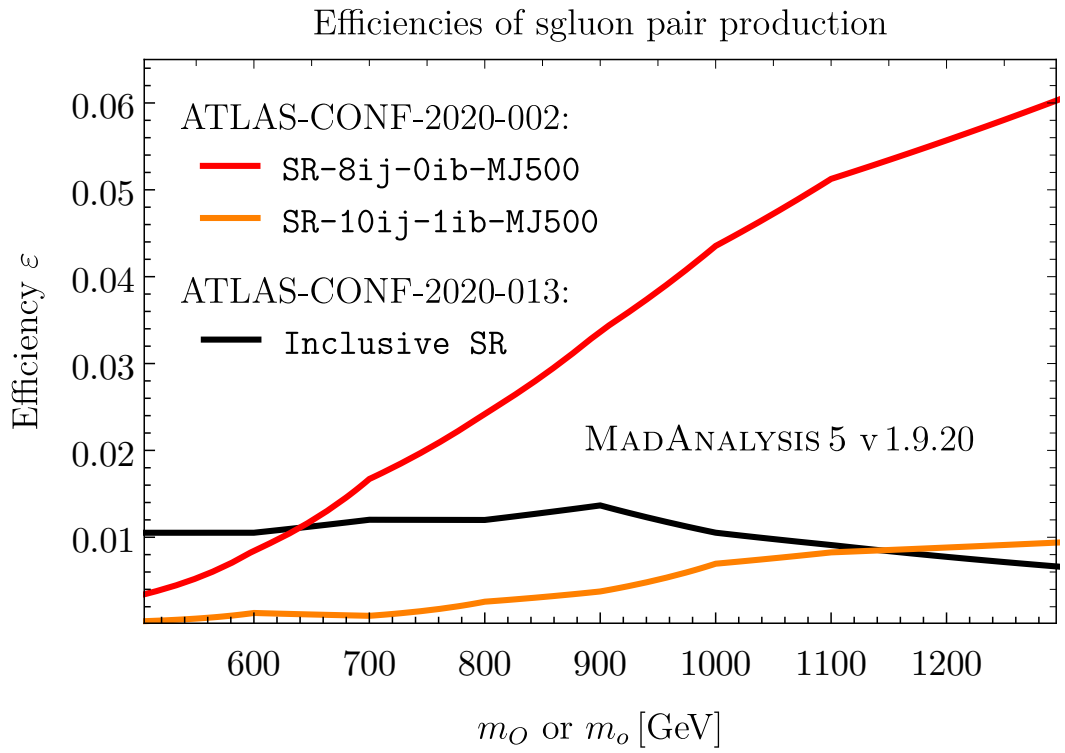
Reinterpreting ATLAS-CONF-2020-002

- 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

MA5 SGLUON EFFICIENCIES



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