Top-philic scalar dark matter in a composite theory

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Top LHC France

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In this talk

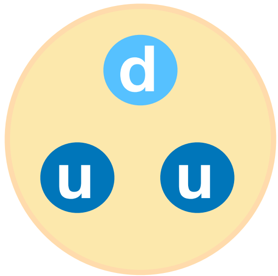
- Including a heavy scalar resonance coupled to the top sector using an effective model
- Include ingredients usually present including a dimension-five operator
- Examine at experiment to derive constraints (and find large parts testable at current and future experiment)

Cornell, A.S., Deandrea, A., Flacke, T., Fuks, B. and Mason, L. Contact interactions and top-philic scalar dark matter. *J. High Energ. Phys.* **2021,** 26 (2021). https://doi.org/10.1007/JHEP07(2021)026

Background

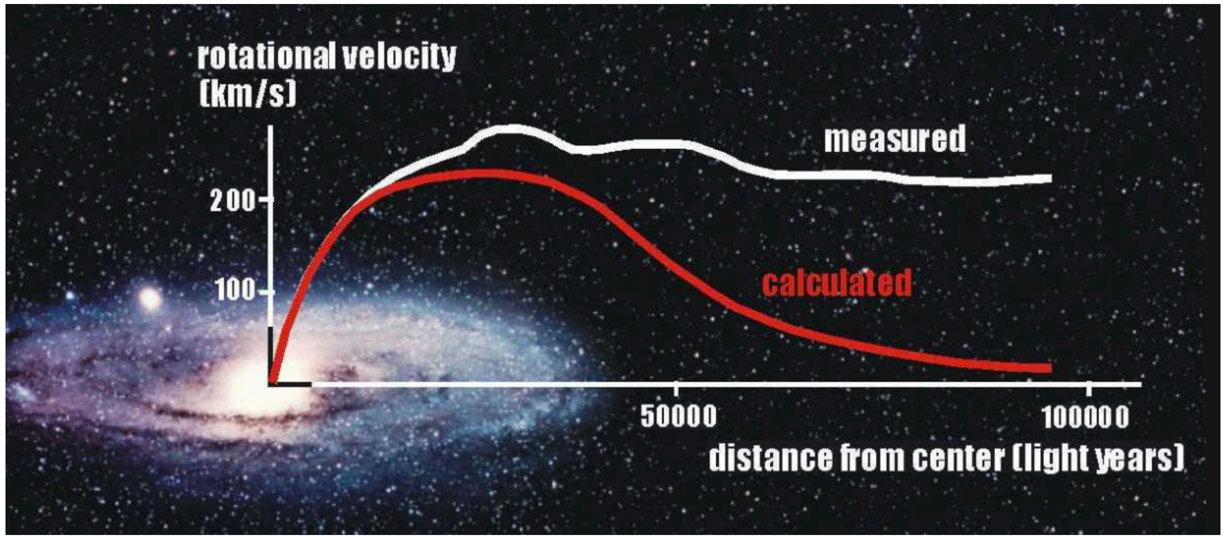
Composite Higgs models:

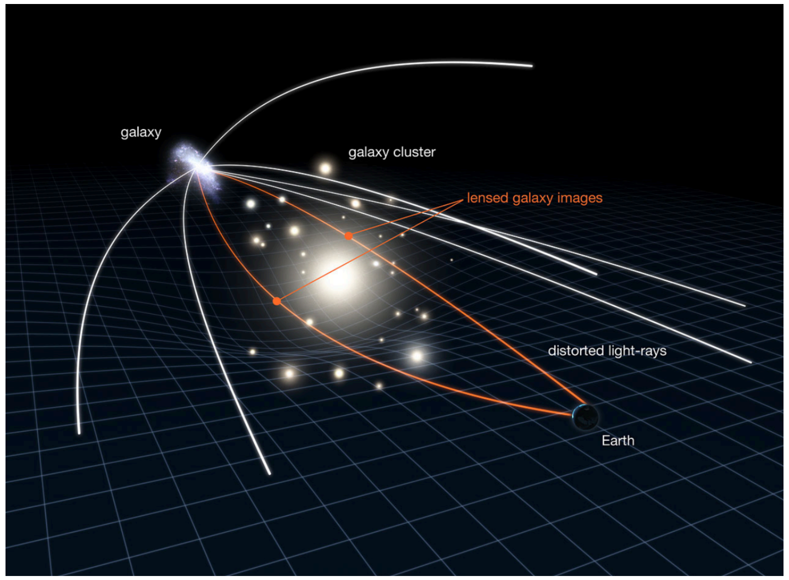
- High scale fundamental gauge dynamics + new strong sector
- Higgs is a bound state of fermions (but not the ones we already know)
- Higgs accompanied by light states generated by same dynamics
- First signs of compositeness?
- Compositeness at current and next generation of colliders?
- Address apparent hierarchy in fundamental scales and.. dark matter?



Dark matter: relic density

- The universe is ~25% dark matter, ~70% dark energy, ~5% ordinary baryonic matter
- Observed DM density, or **relic density**, is a constant
- Cold non-baryonic candidates strongly constrained by $\Omega_{DM}h^2 = 0.1186 \pm 0.0020$ (~ annihilation cross section SS > xx)

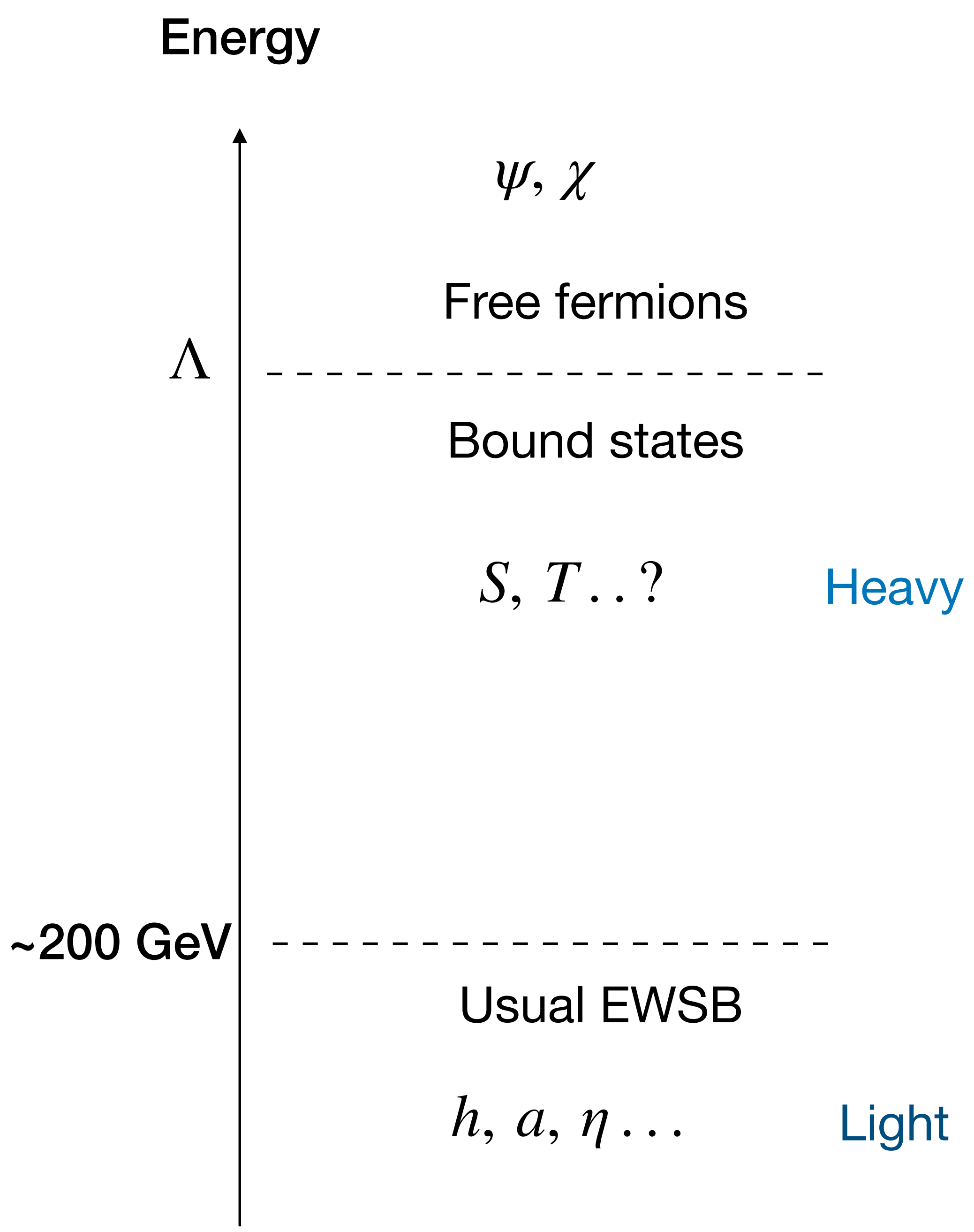




Dark matter and composite Higgs models

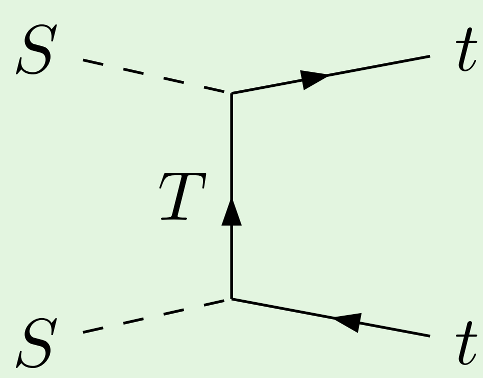
- Dark matter appears often in composite Higgs models as a pNGB
- Instead, imagine it as a heavy bound state

Recall:



Our setup

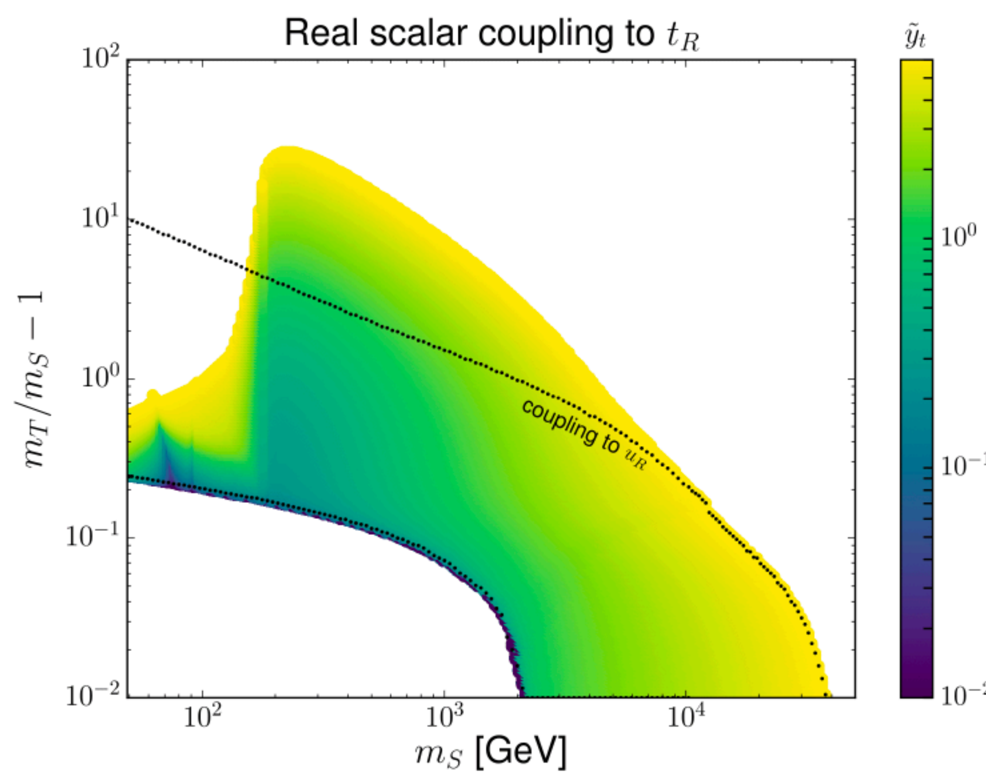
- $SS \to t\bar{t}$ annihilation dominates
- Heavy fermonic mediator, $m_S < m_T$



- Could S, T emerge as heavy resonances in a CH model?
- $200 \text{ GeV} \lesssim m_S \lesssim 3 \text{ TeV}$

Extension of 1804.05068 (Colucci, Fuks, Giacchino, Lopez Honorez, Tytgat, Vandecasteele)

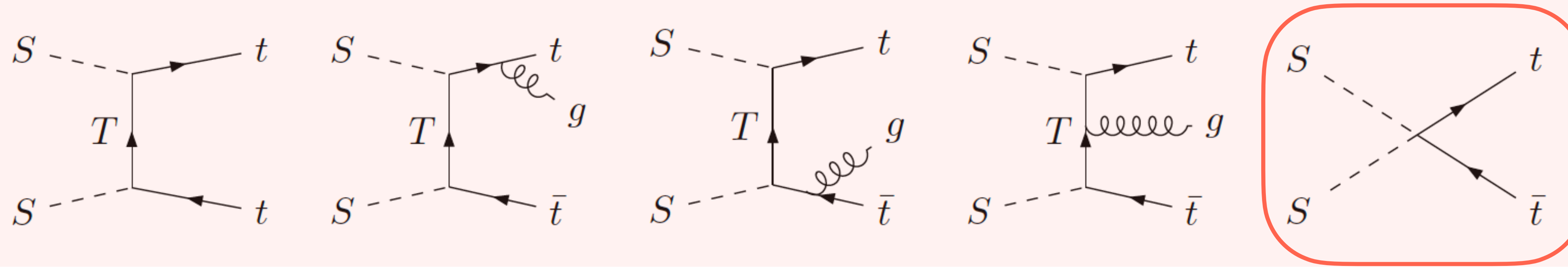
- Featuring S, T both heavy, NLO is NB

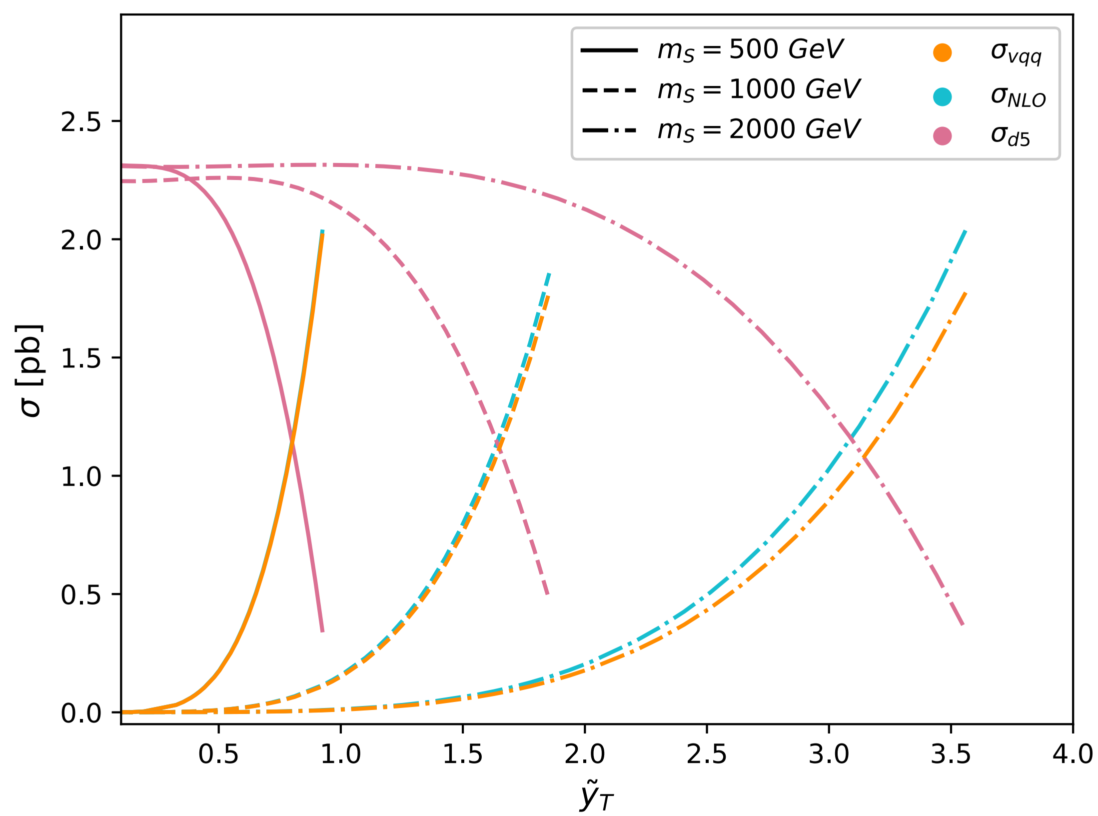


$$\sigma v_{t\bar{t}}|_{\text{NLO}} \approx \begin{cases} \sigma v_{t\bar{t}} & m_S < 300\,\text{GeV}, \\ \sigma v_{t\bar{t}g}|_{m_t=0} + \sigma v_{t\bar{t}} & m_S > 300\,\text{GeV}. \end{cases}$$

Our setup

$$\mathcal{L} = i\bar{T}\not{D}T - m_T\bar{T}T + \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{1}{2}m_S^2 S^2 + [\tilde{y}_t S\bar{T}P_R t + h.c.] + \frac{1}{2}\lambda S^2\phi^\dagger\phi + \frac{C}{\Lambda}SSt\bar{t}$$





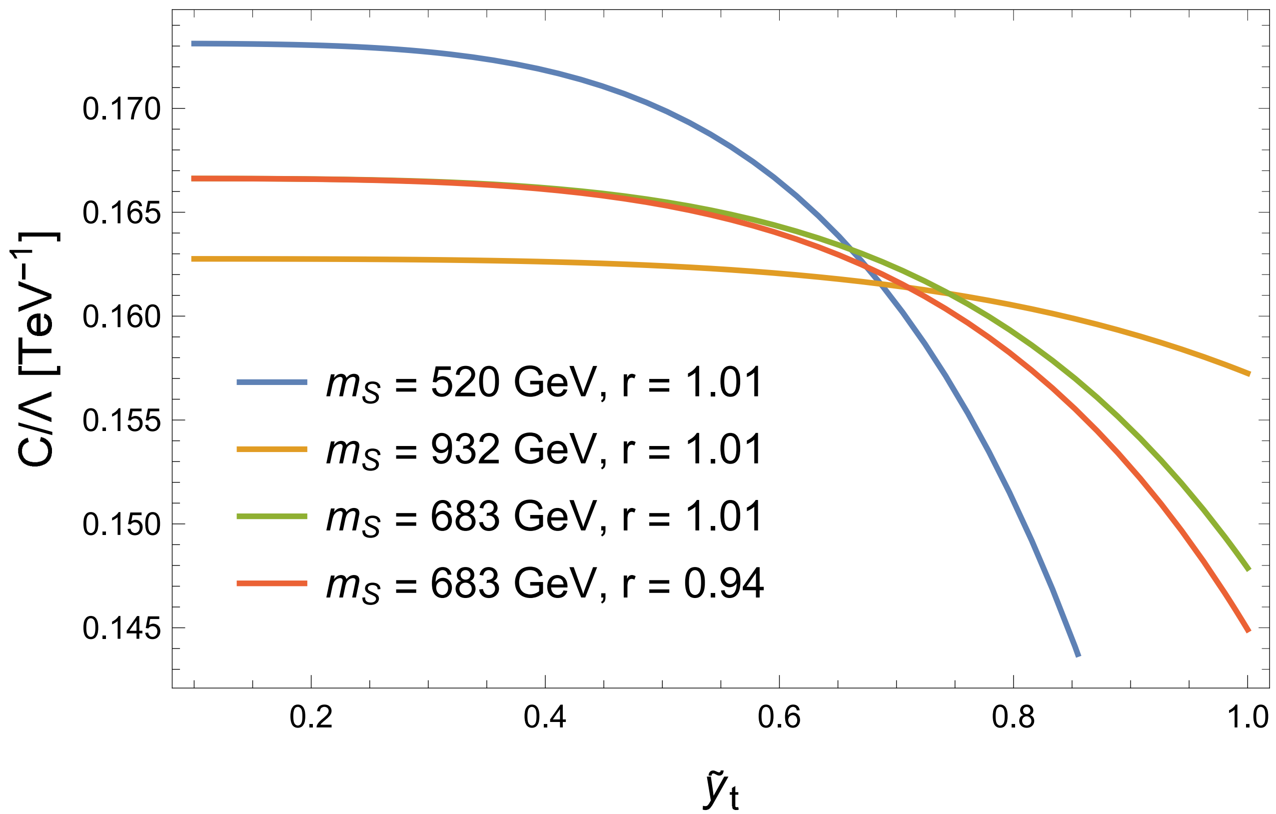
- Addition of generic dim-5 operator with $\mathcal{O}(1)$ Wilson coefficient
- Contact term competes with Yukawa term in annihilation
- Modification of the relic density

Parameter interplay

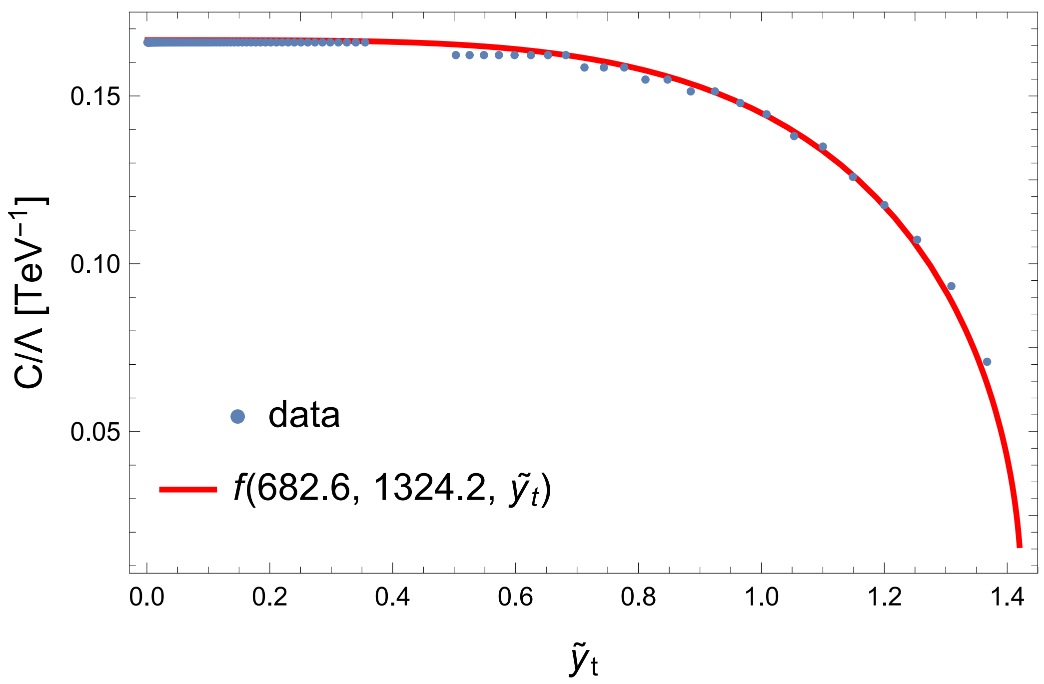
$$\langle \sigma v \rangle = \langle \sigma v \rangle_{NLO} + \langle \sigma v \rangle_{SStt}$$

$$\frac{C}{\Lambda} \approx f(m_S, m_T, \tilde{y}_t) = \frac{1}{\sqrt{A(m_S)}} \sqrt{b' - B(m_S, m_T)\left(\tilde{y}_t - \alpha\left[\beta\gamma^{\frac{m_S}{\Lambda}}\right]^r\right)^4}$$

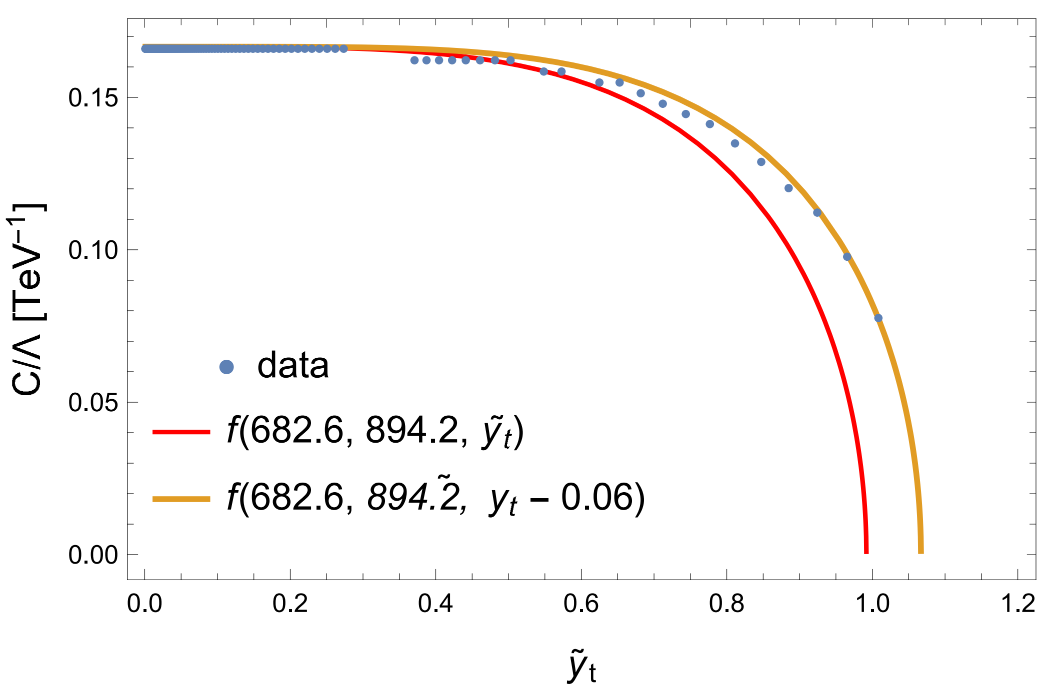
See 2104.12795 for more on fit

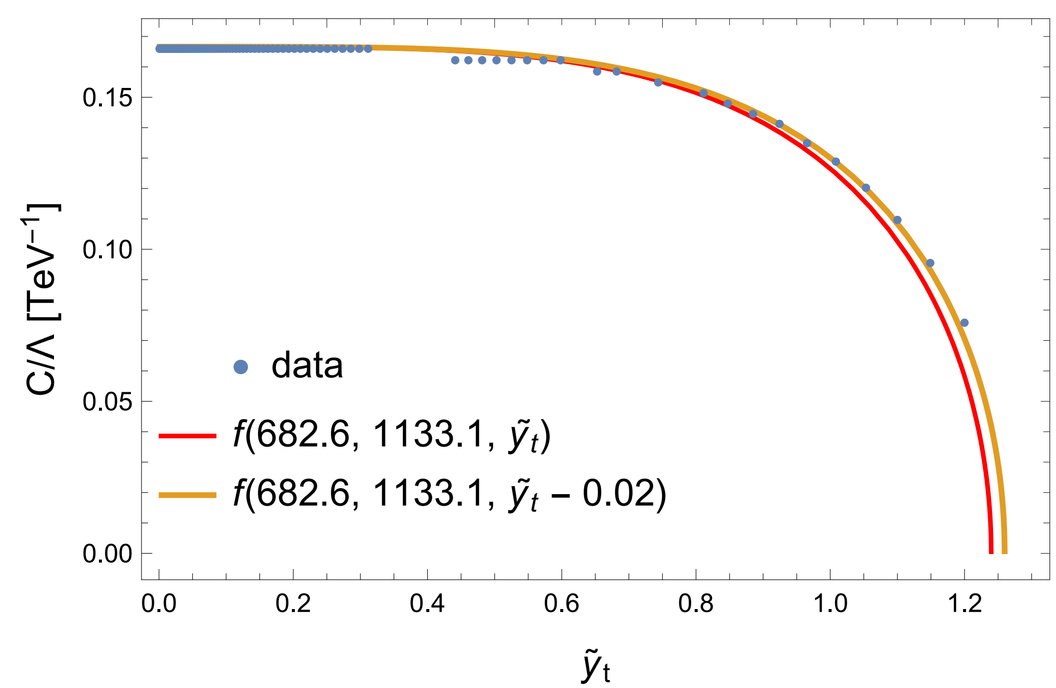


Coannihilations



- Define $r = m_T/m_S - 1$
- When S and T get close in mass, the coannihilations of T with S are no longer negligible ($r \lesssim 0.8$)

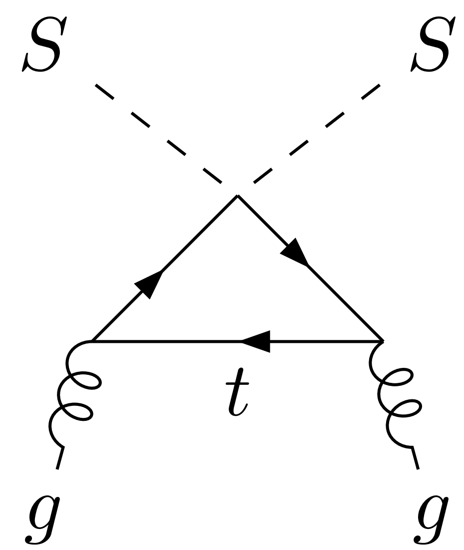


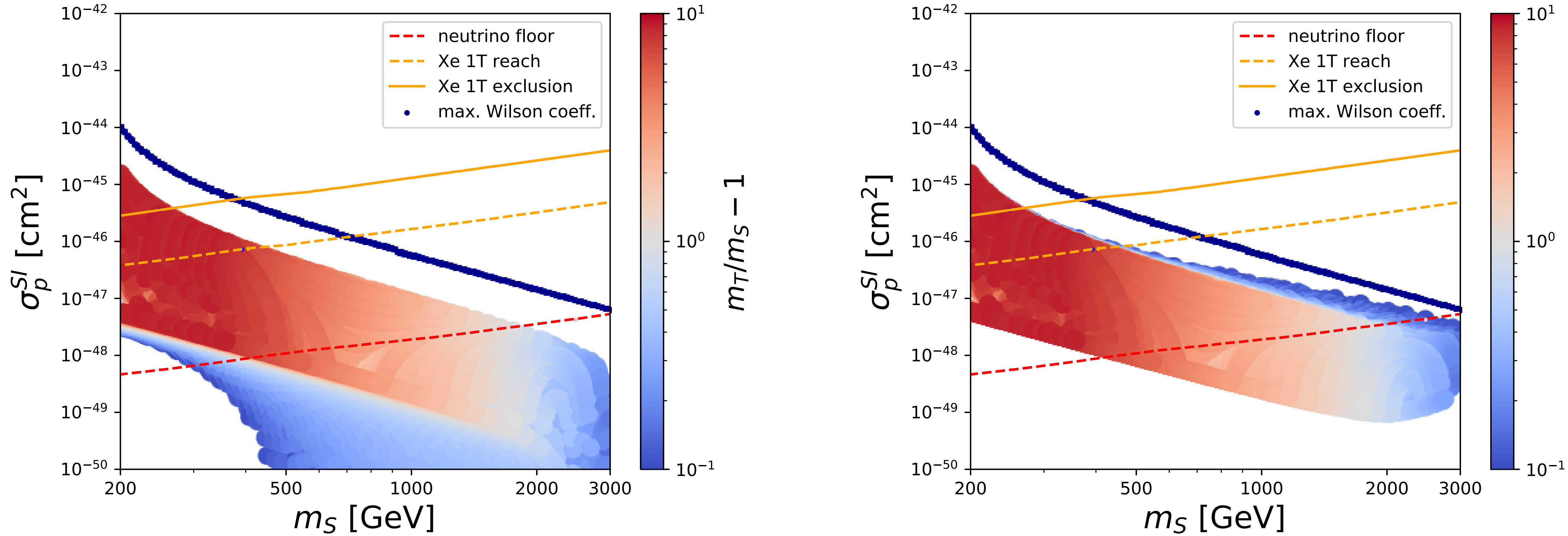


Direct detection

- Scattering off atomic nuclei: DM gluon interactions
- (top quark absent from nucleus!)

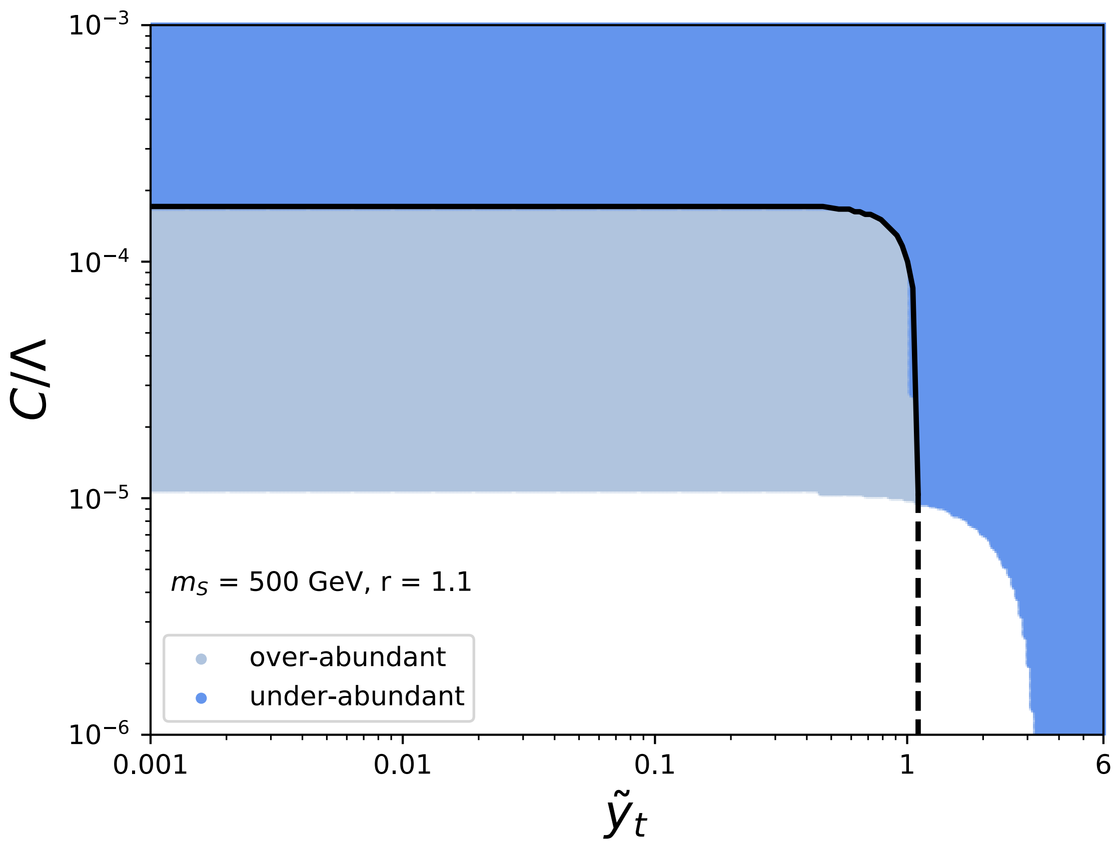
$$\mathscr{L} = C_S^g \mathcal{O}_S^g = C_S^g \frac{\alpha_s}{\pi} S^2 G^{\mu\nu} G_{\mu\nu}$$

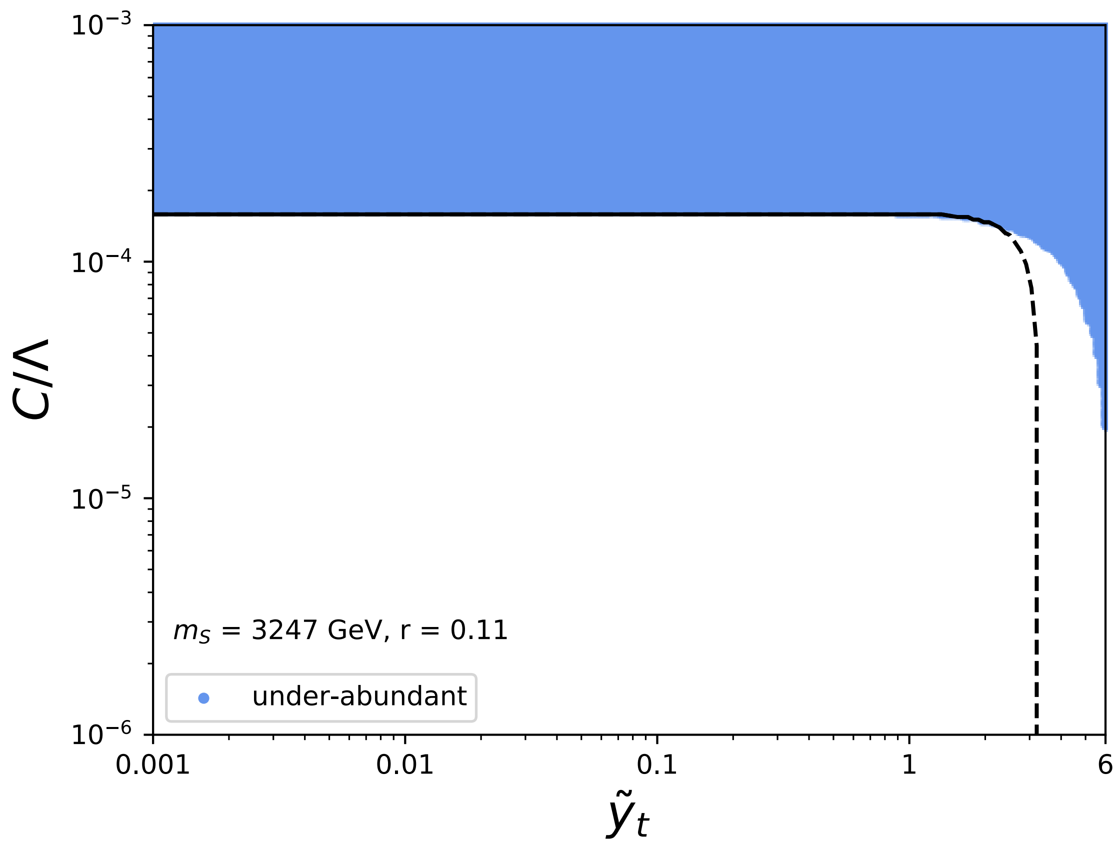




Direct detection

- Identify over/under-abundant areas of parameter space



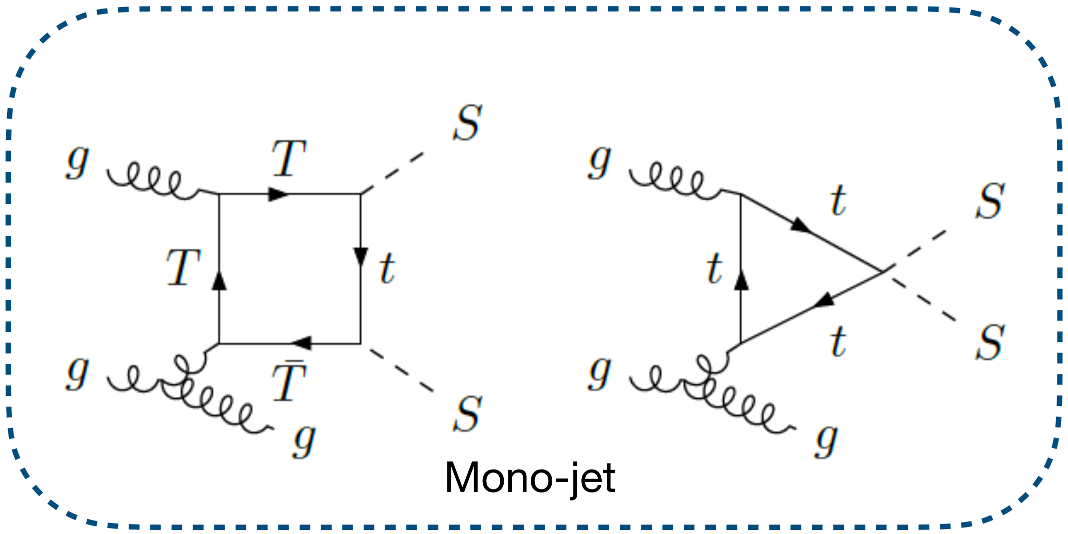


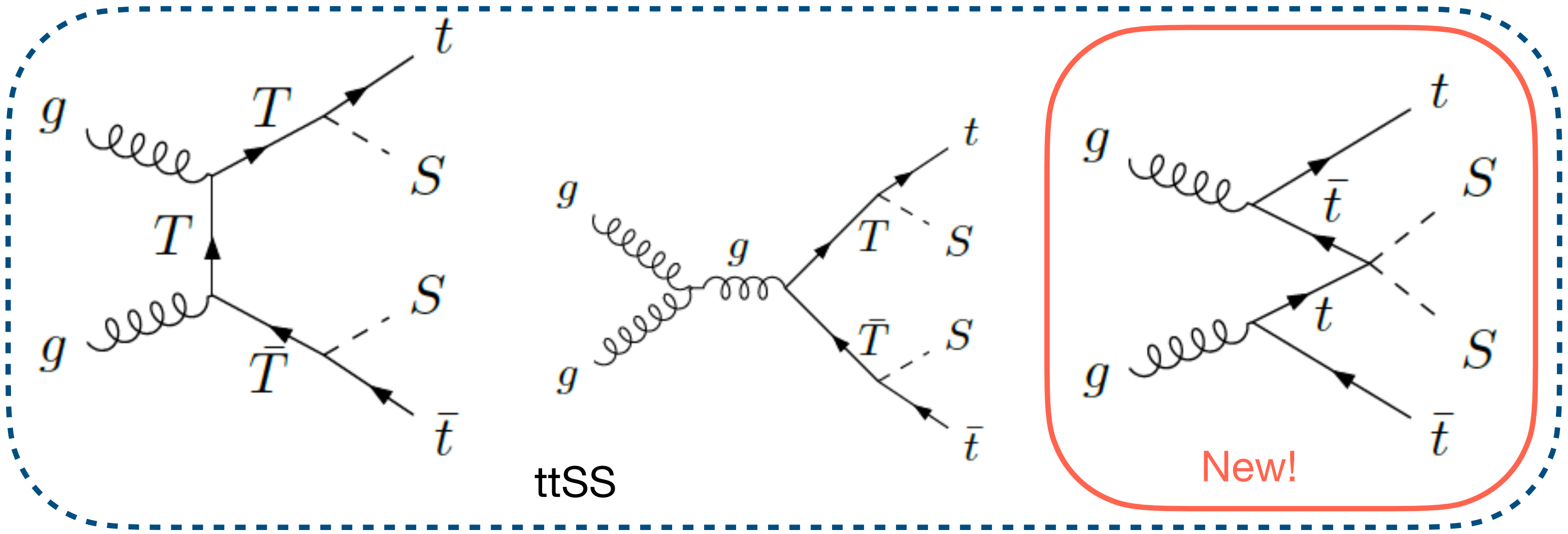
- Also indirect detection.. see paper

Collider: $pp \to t\bar{t}SS$

Recasting previous ATLAS and CMS analyses using MadAnalysis5

Collider signatures $(pp \to t\bar{t} + \not{E}_T)$ can be probed using existing DM searches focusing on the mono-jet / multi-jet / ttbar + MET signatures

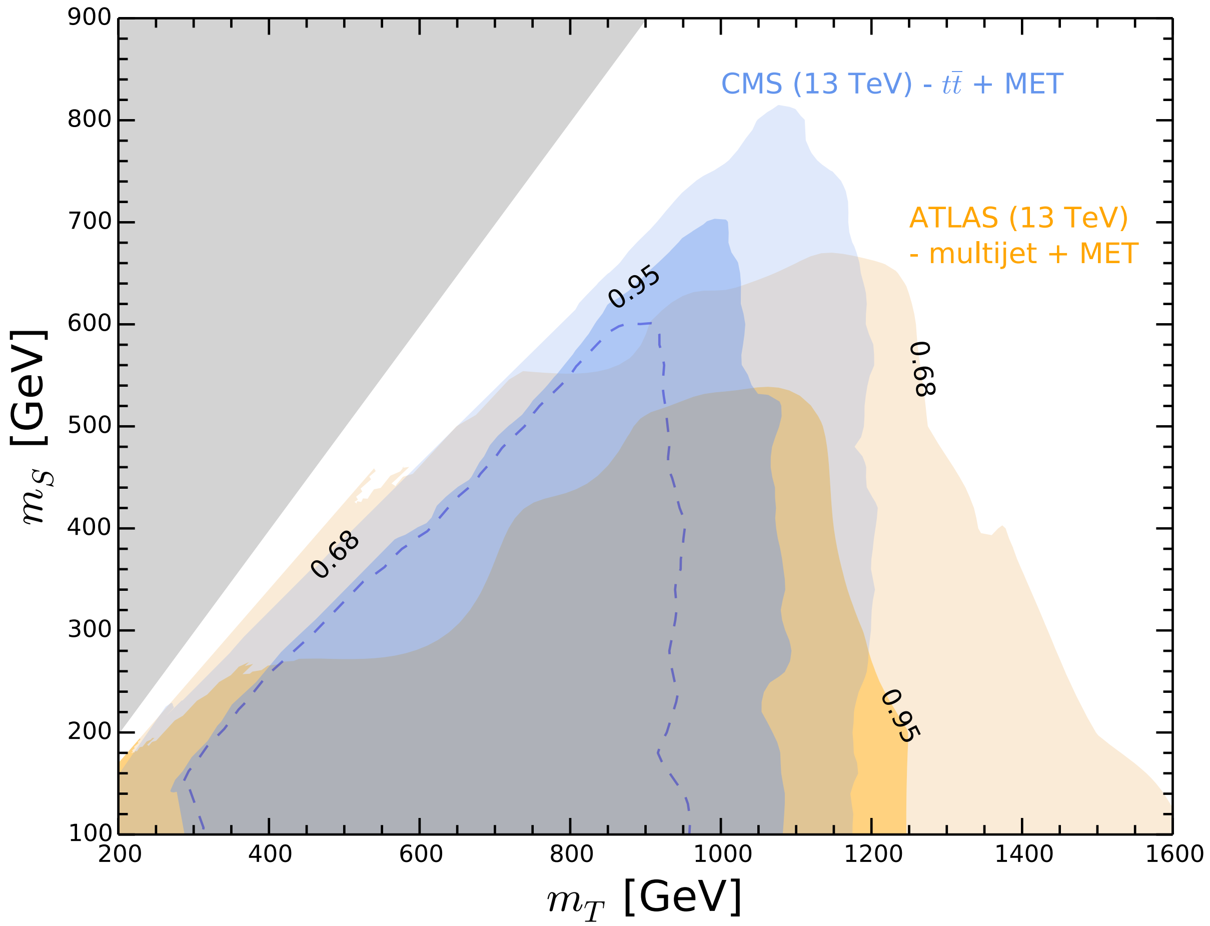


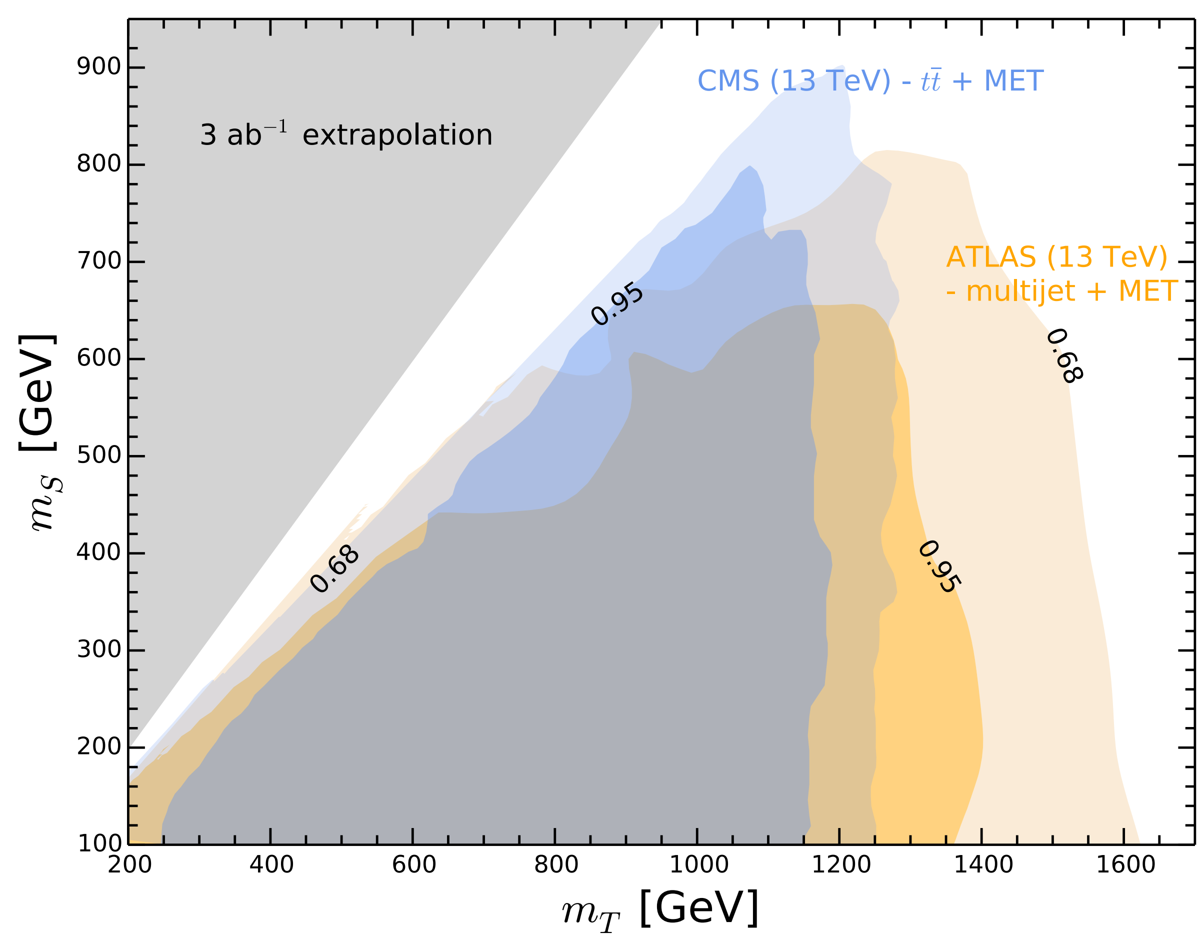


$$\sigma_{t\bar{t}SS}(M_T, M_S) = \sigma^0_{t\bar{t}SS}(M_T, M_S) + \frac{C}{\Lambda}\hat{\sigma}^{\rm int}_{t\bar{t}SS}(M_T, M_S) + \frac{C^2}{\Lambda^2}\hat{\sigma}^{\rm dim5}_{t\bar{t}SS}(M_S)$$

Collider: Madanalysis5 recasting

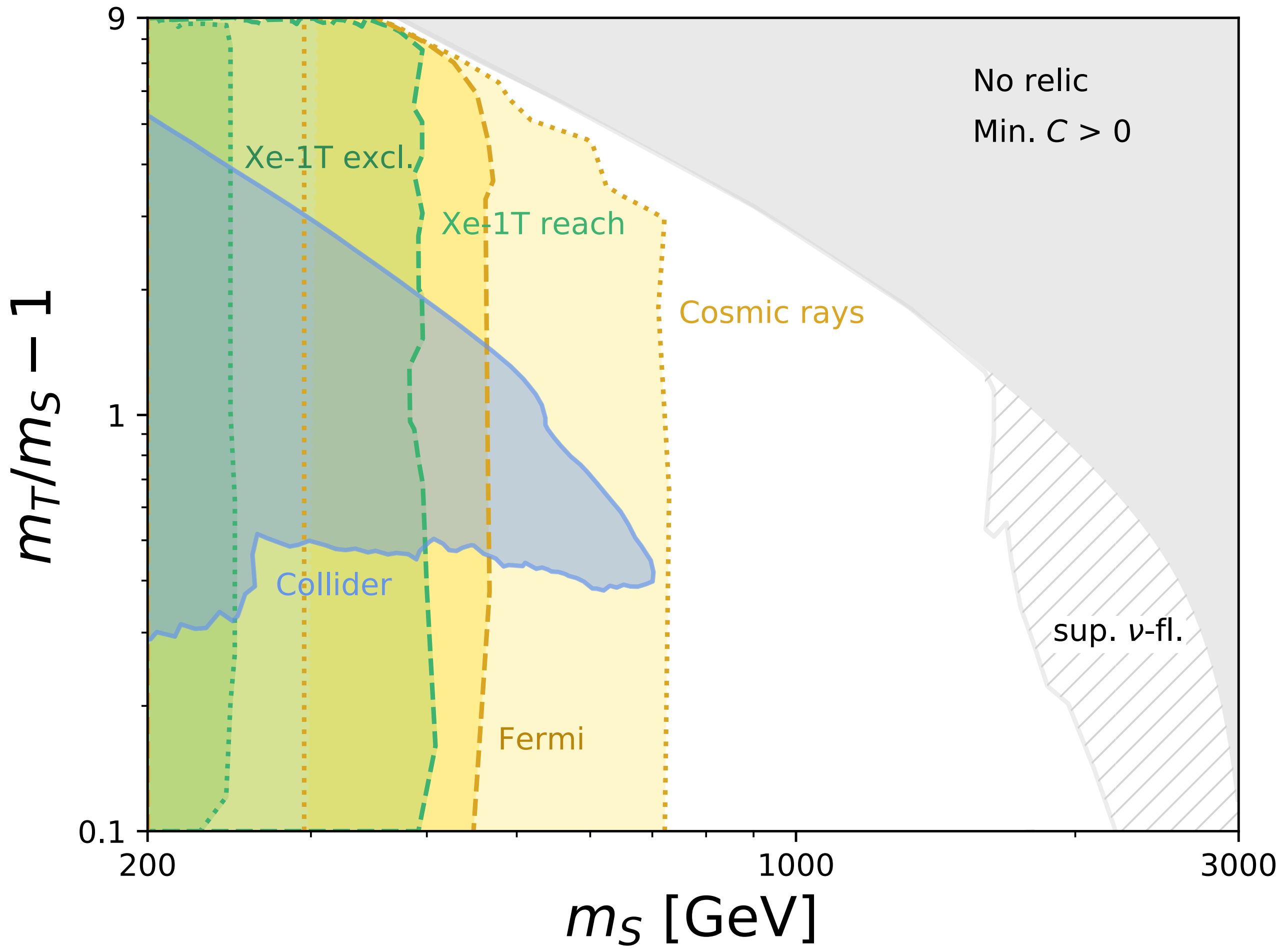
- Multi-jet: ATLAS_CONF_2019_040 (≥ 2 hard jets + $\overrightarrow{p}_T^{\text{miss}}$, 139 fb^{-1})
- ttbar + MET: CMS_SUS_17_001 ($\ell^+\ell^- + \overrightarrow{p}_T^{\text{miss}}$, 35.9 fb^{-1})
- Additional operator yields no significant modification



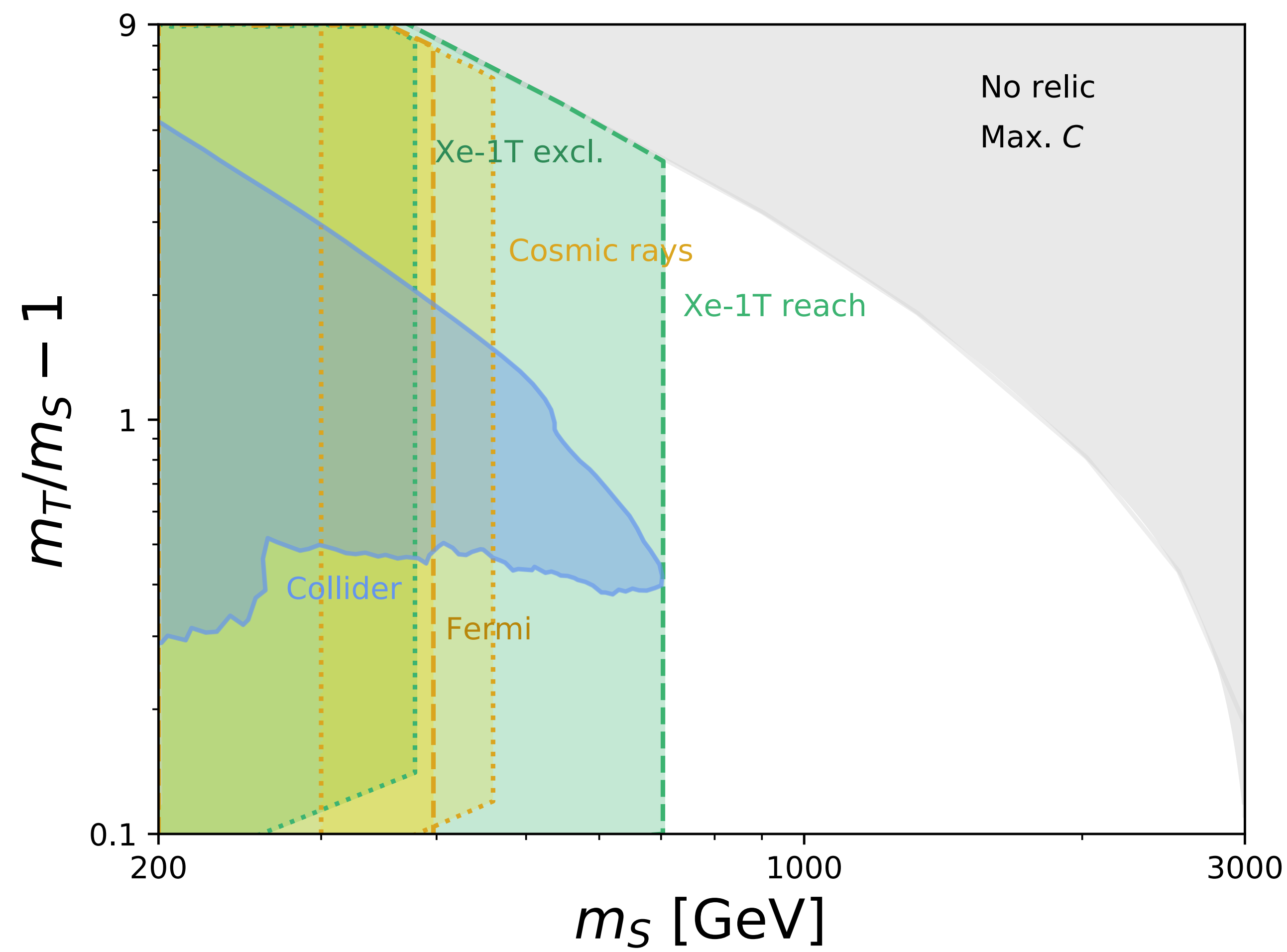


Re scaling: see 1910.11418 (Araz, Frank, Fuks)

Exclusions



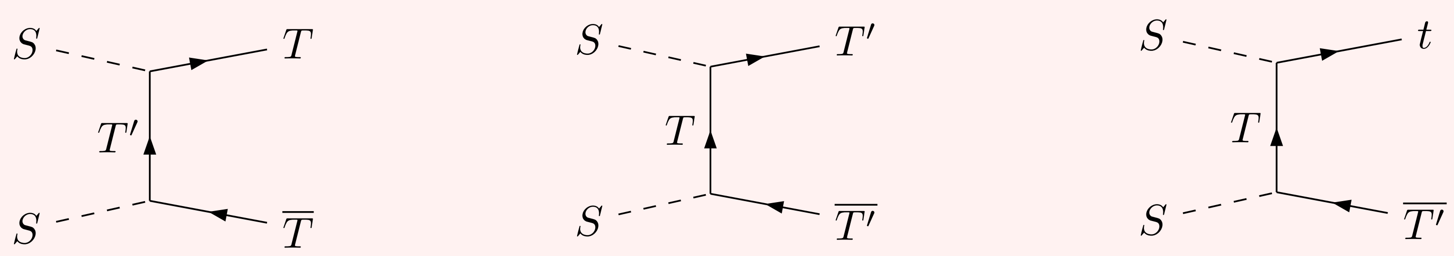
- Complementarity of collider constraints with astrophysical ones (more affected by the contact term)

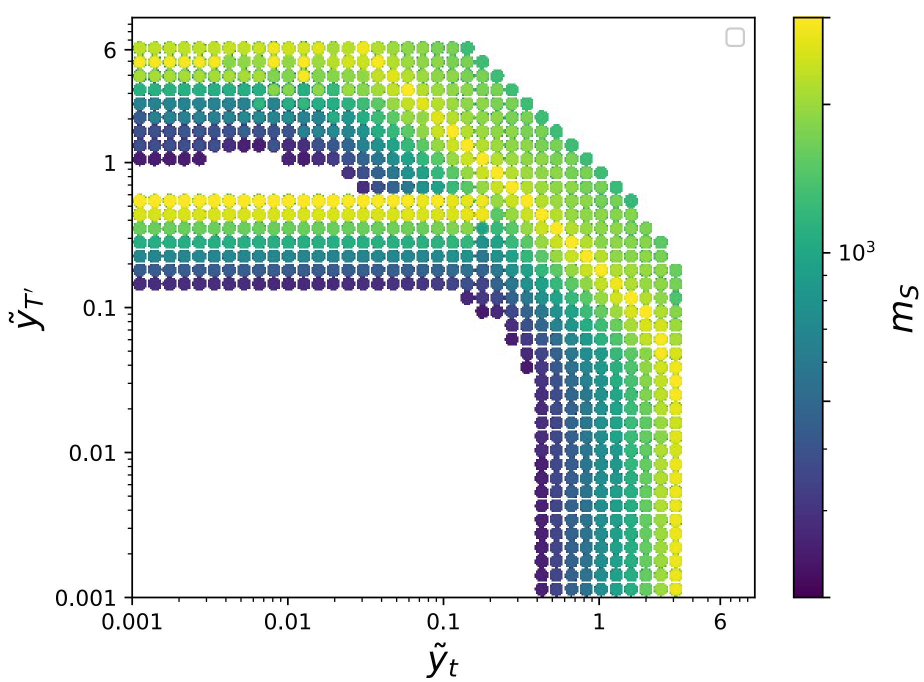


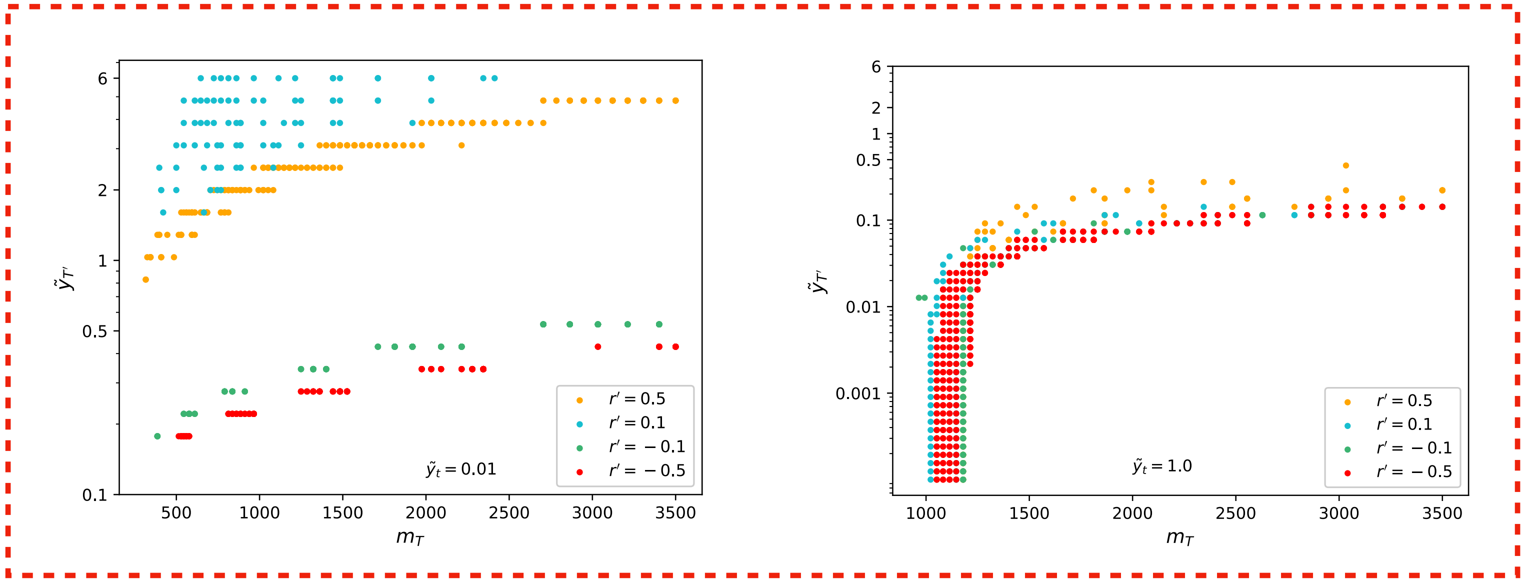
- LHC bounds due to extrapolation to full Run-2
- Larger luminosities hold even more potential
- Wilson coefficient dep. on underlying theory, but collider immune

Adding an additional heavy fermion

- How to make contact with a fundamental model?
- Top partner T' : standard inclusion within a composite model



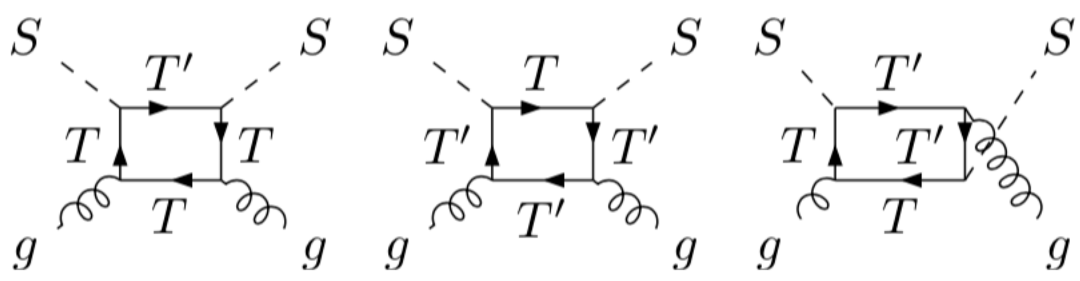




A top partner

- TP contributes to SS annihilations only when $2m_S \geq m_{T'} + m_t$

- Direct detection prospects



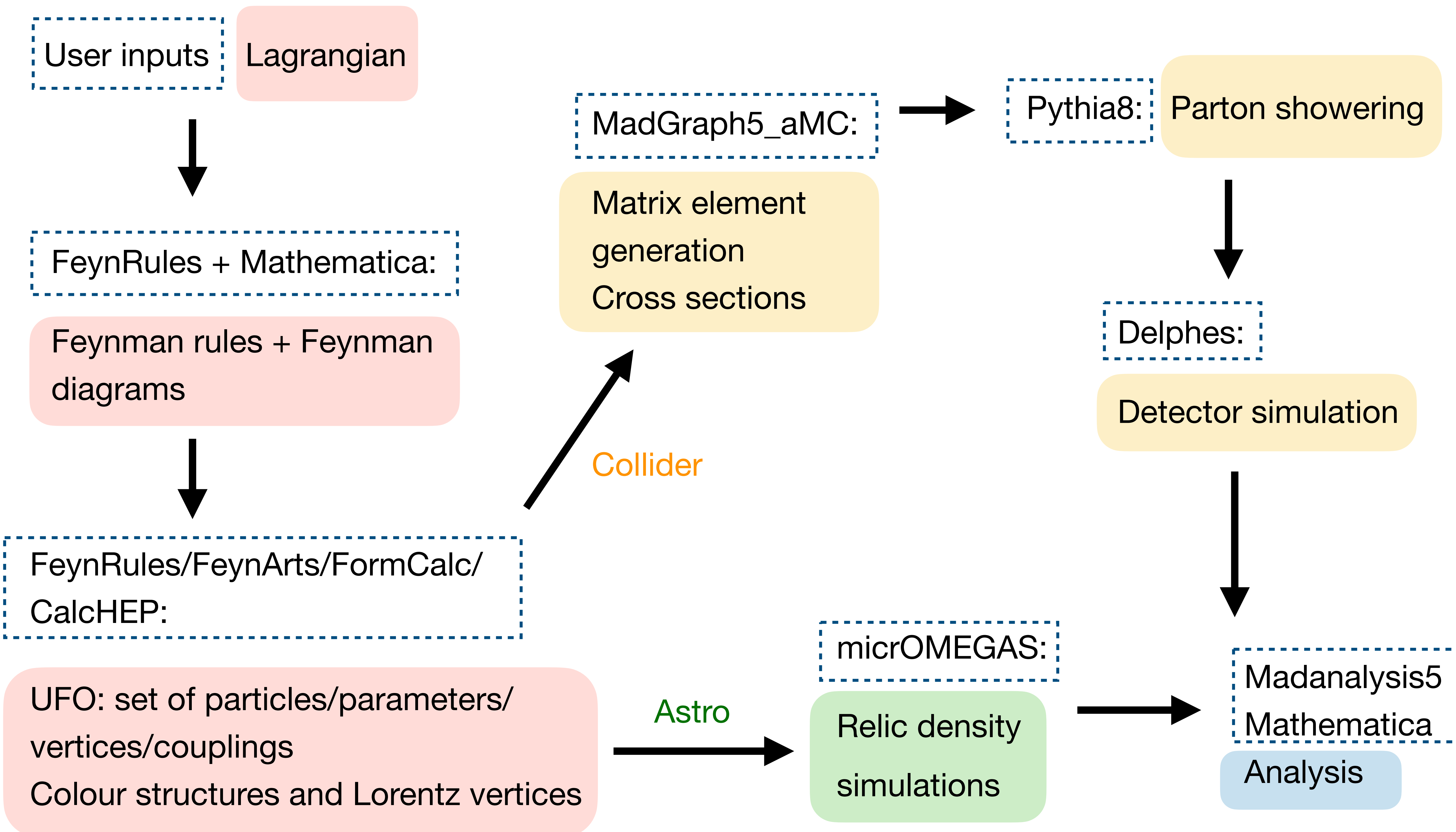
- Collider constraints: current bounds on top partner sit at $1.3\ \mathrm{TeV}$, not expected to be modified here (recall collider bounds)

- We will rely only on direct detection modification of bounds

- Currently being extended!

THANK YOU

Simulation ecosystem



Just for completeness..

$$A(m_S) = \frac{\Lambda^2 \langle \sigma v \rangle_{SStt}}{C^2} = \frac{N_c}{4\pi}\left(1 - \frac{m_t^2}{m_S^2}\right)^{3/2},$$

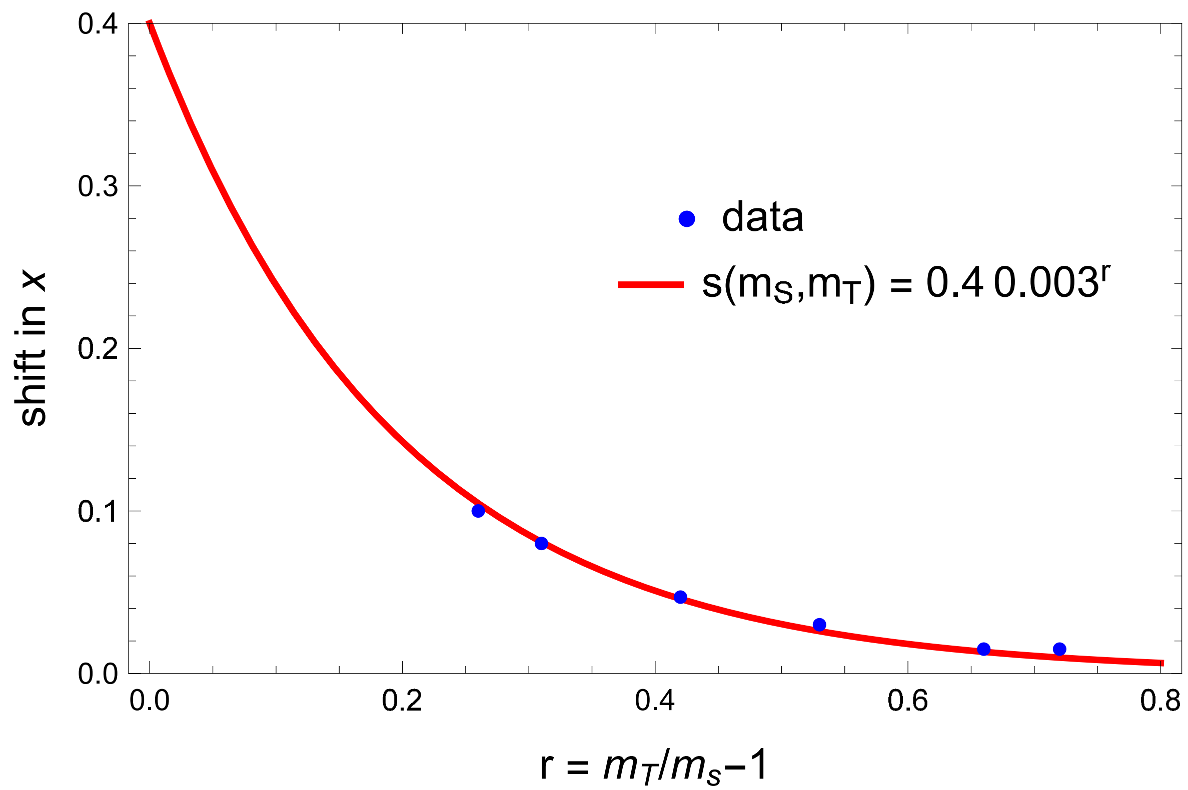
$$\begin{aligned}
B(m_S, m_T) &= \frac{\sigma v_{q\bar{q}} + \sigma v_{VIB}^{(0)}}{\tilde{y}_t^4} \\
&= \frac{N_c}{4\pi m_S^2}\Bigg(\frac{m_t^2 (m_S^2 - m_t^2)^{3/2}}{m_S (m_S^2 + m_T^2 - m_t^2)^2} \\
&+ \frac{\alpha_S C_F}{2\pi}\Bigg[\left((r+1)^2 + 1\right)\left(\frac{\pi^2}{6} - \log^2 \frac{1+(r+1)^2}{2(r+1)^2} - 2\mathrm{Li}_2\left(\frac{1+(r+1)^2}{2(r+1)^2}\right)\right) \\
&+ \frac{4(r+1)^2 + 3}{(r+1)^2 + 1} + \frac{4(r+1)^2 - 3(r+1)^2 - 1}{2(r+1)^2} \log \frac{(r+1)^2 - 1}{(r+1)^2 + 1}\Bigg]\Bigg),
\end{aligned}$$

$$b'(x_F, g_*(x_F)) = \left(7.19 \times 10^{-10}\ \mathrm{GeV}^{-2}\right) \frac{x_F}{\sqrt{g_*(x_F)}}.$$

Coannihilations

- The Boltzmann equation is generalised to a set of coupled equations

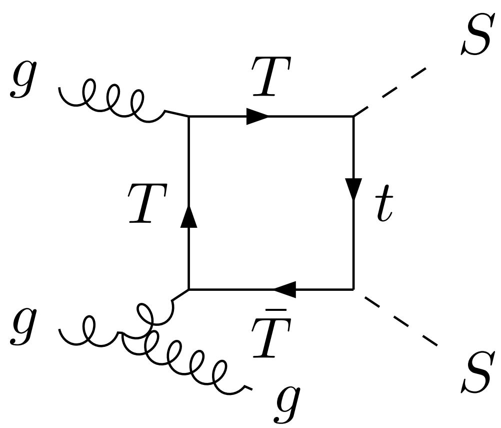
$$\sigma_{eff}(x) = \sigma_{SS} + \sigma_{ST} \frac{g_S g_T}{g_{eff}^2} \left(\frac{m_T}{m_S}\right)^{3/2} \exp\left[-x\ r\right]$$

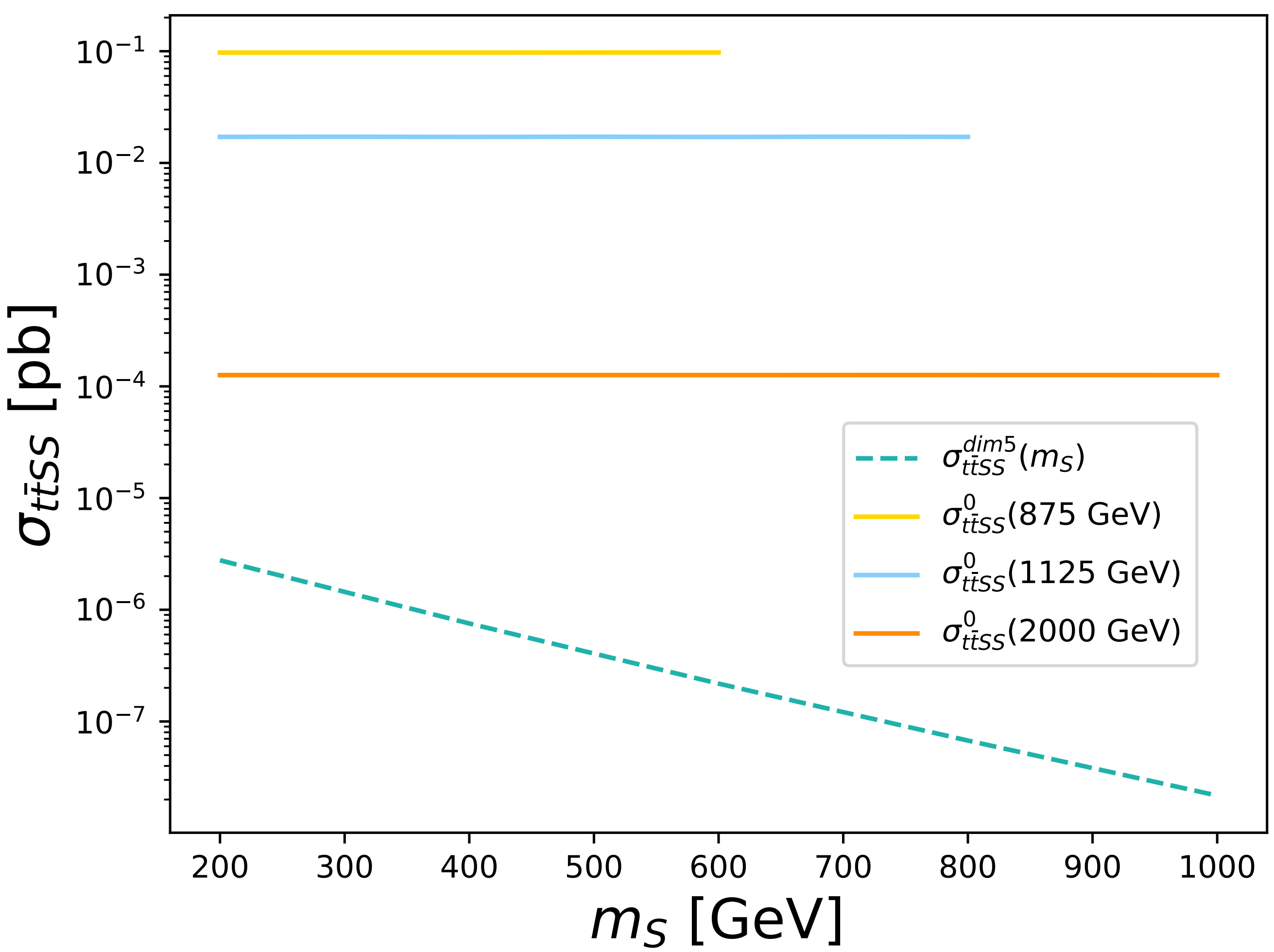


$$\frac{C}{\Lambda} \approx f(m_S, m_T, \tilde{y}_t) = \frac{1}{\sqrt{A(m_S)}} \sqrt{b' - B(m_S, m_T)\left(\tilde{y}_t - \alpha\left[\beta\gamma^{\frac{m_S}{\Lambda}}\right]^r\right)^4}$$

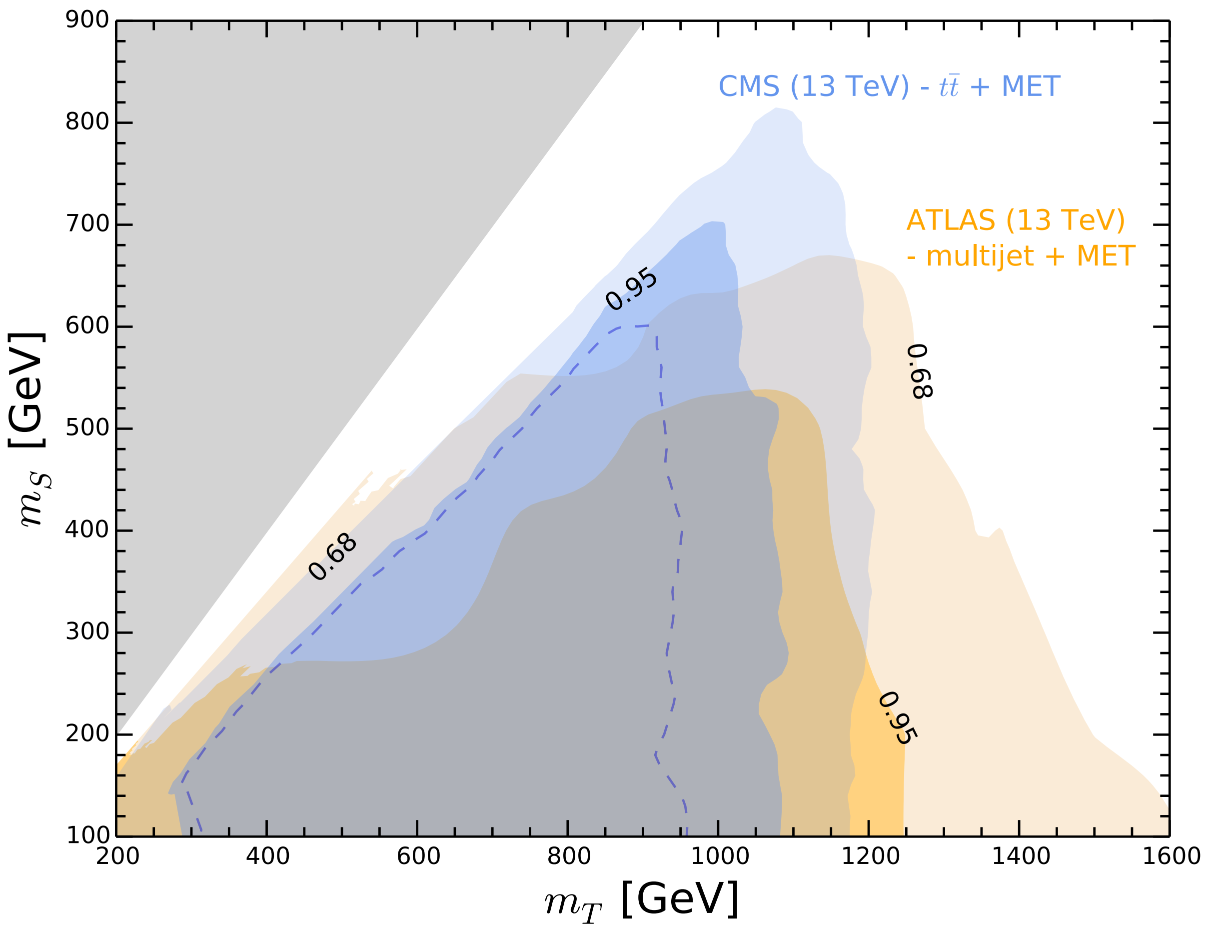
Collider: Madanalysis5 recasting

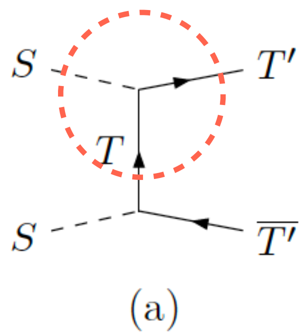
- Mono-jet: ATLAS_EXOT_2016_27 (energetic jet and large missing momentum, 36.1 fb^{-1})
- Shown previously to have minimal contribution.





Collider bounds





m_T	m_S	Bounds modified for
$m_T \sim 1.0$ TeV	$500 < m_S < 700$ GeV	1.5 TeV $< m_{T'} <$ 1.7 TeV
$m_T \sim 1.15$ TeV	200 GeV $< m_S <$ 500 GeV	$1.35 < m_{T'} < 1.65$ TeV
$m_T \sim 1.25$ TeV	$m_S \sim 100$ GeV	$m_{T'} > 1.35$ TeV

Table 5.2 Modification of the bounds in the relevant mass cases.