imagine the impossible

Heavy Quark(s) Flavored Scalar Dark Matter

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based on arXiv: 1606.00072 and in preparation

Outline

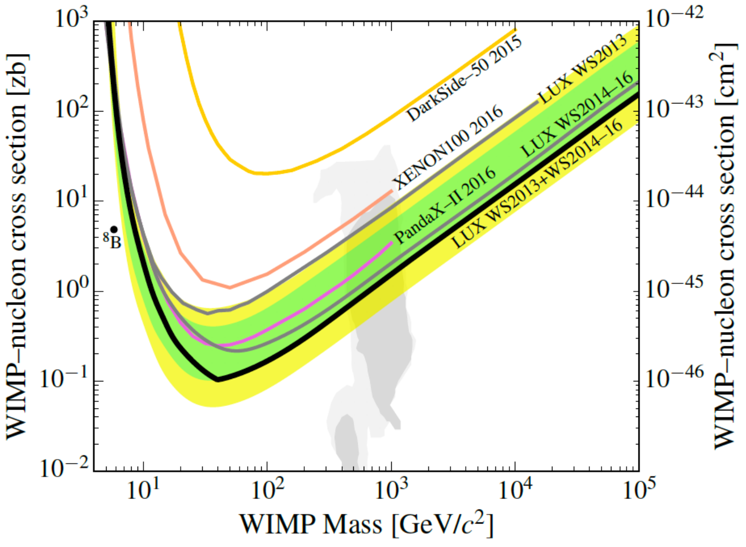
- Motivation: Why heavy quark flavored DM?
- Model description
- Properties: what's special?
    - Thermal relic density
    - Direct/Indirect detection
    - Collider search
- Summary

Why Flavored DM?

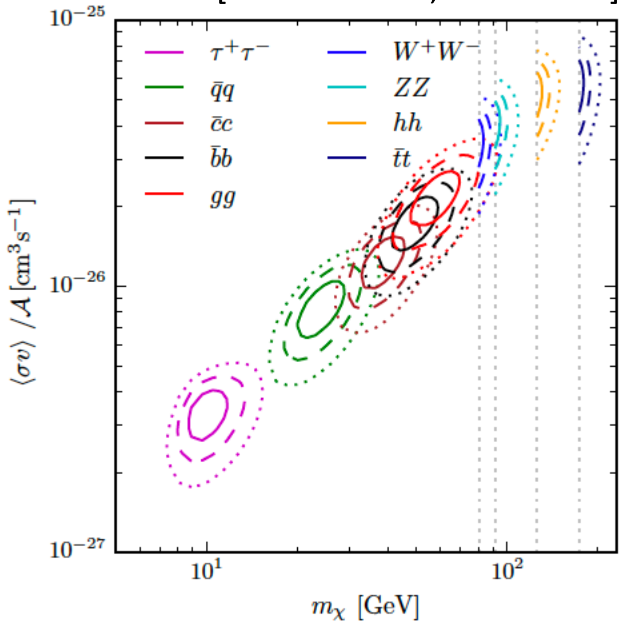
- No confirmed DD signal yet
  - small/vanishing ***direct*** coupling of DM to u/d quarks
- Favored channels when fitting astro- anomalies
  - $b\bar{b}, \tau\tau$ are favored, up to astro- uncertainties

    [see Hooper et al]
- Theoretical model building [see Agrawal, Kilic et al]
  - flavor symmetry in dark sector, MFV…

[LUX, 1608.07648]



[F. Calore et al, 1411.4647]



If: small/vanishing ***direct*** coupling of DM to u/d

- causes
  - DM is heavy quarks/lepton-philic
  - …
- loop diagrams can still generate DM couplings to u/d/gluon

- one can start from effective operators, then specify details
  - DM/mediator spin, real/complex…

Mediators inside EFT

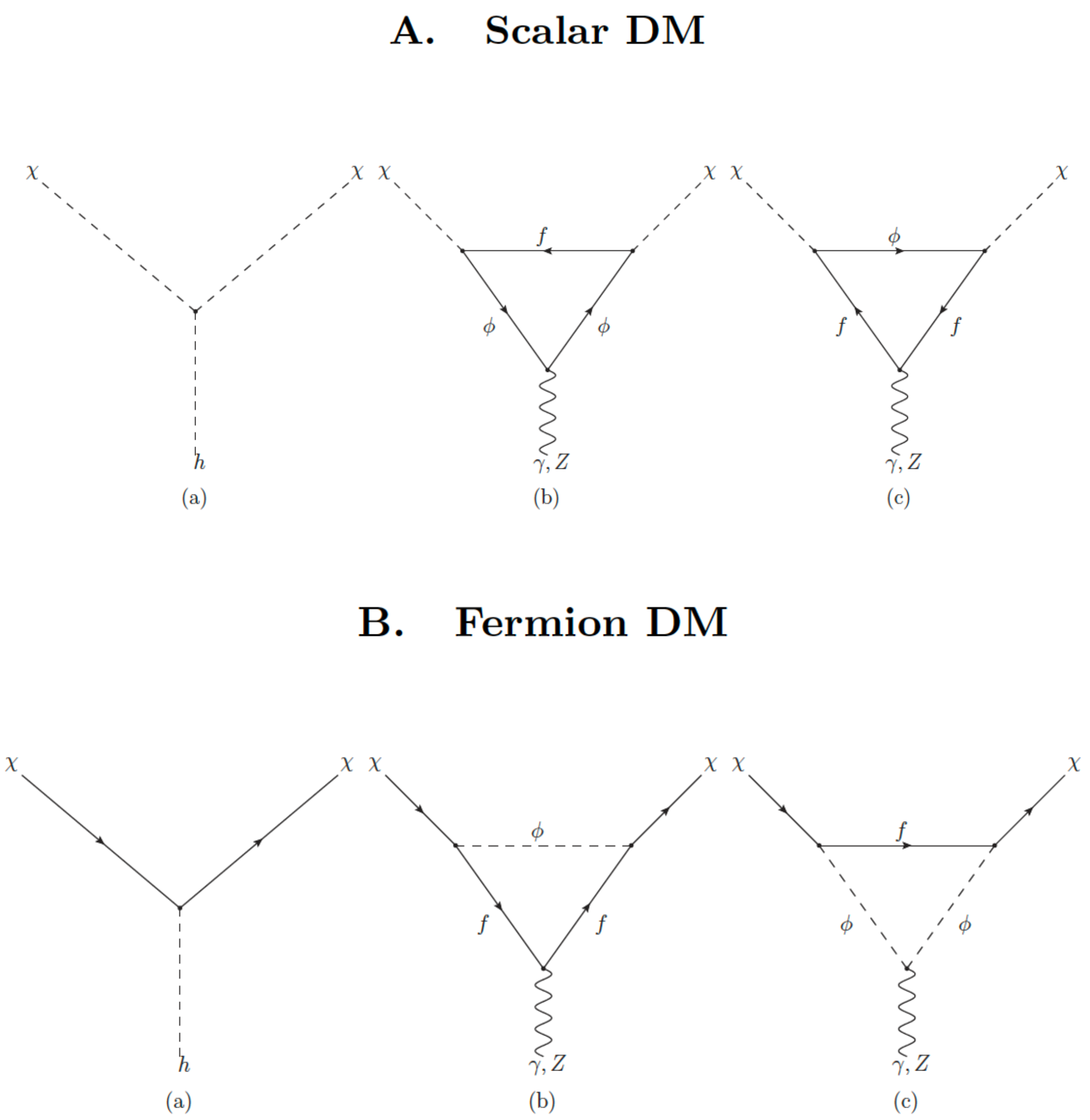
- Complex Scalar
- Dirac/Majorana Fermion

$$\mathcal{L}_{\text{charge radius}} = \begin{cases} 2b_\chi\, \partial_\mu \chi^* \partial_\nu \chi\, F^{\mu\nu} & \text{(complex scalar DM)} \\ b_\chi\, \bar{\chi}\gamma_\nu \chi\, \partial_\mu F^{\mu\nu} & \text{(Dirac fermion DM)} \end{cases}$$

$$\mathcal{L}_{\text{magnetic moment}} = \frac{\mu_\chi}{2} \bar{\chi}^* \sigma_{\mu\nu} \chi F^{\mu\nu} \text{ (Dirac fermion DM)}$$

$$L_{\text{anapole moment}} = \bar{\chi}\gamma_5\gamma_\mu\chi\, \partial_\nu F^{\mu\nu} \text{ (Majorana Fermion DM)}$$

[Markus Luty et al, 1402.7358]



[Can Kilic et al, 1410.3030]

Mediators inside EFT

- Vector DM, more complex gauge structures are needed
  - we do not address here, see e.g. Hisano et al 1012.5455
- ***Real scalar*** DM: simplest case, also simplest BSM model

First step: Top Flavored

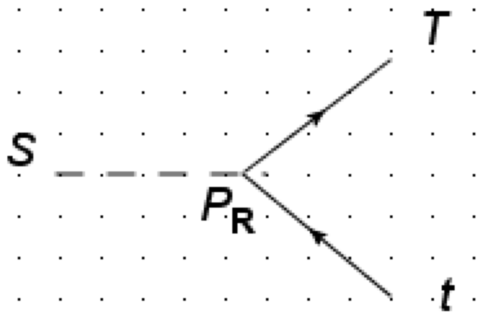
Why Top quark for Real scalar DM?

- Real Scalar DM: both s/p-wave are ***chirally*** suppressed
- wide mass range below $t\bar{t}$ threshold: $m_S < m_t$
  - co-annihilation, constrained mass spectrum
  - sensitive regions in many DD results, e.g. ~30 GeV for LUX
- if Higgs portal is negligible
  - is it possible to detect the loop suppressed DD rate in future?
- no $q\bar{q}$ fusion in direct DM pair production at collider
- …

Existing Top-flavored DM studies

- Most on Complex scalar, Dirac/Majorana DM
  - Kilic, C., Klimek, M. D., & Yu, J.-H. (2015). Signatures of Top Flavored Dark Matter. http://doi.org/10.1103/PhysRevD.91.054036
  - Arina, C., Backović, M., Conte, E., Fuks, B., Guo, J., Heisig, J., … Vryonidou, E. (2016). A comprehensive approach to dark matter studies: exploration of simplified top-philic models. http://arxiv.org/abs/1605.09242
  - Gomez, M. A., Jackson, C. B., & Shaughnessy, G. (2014). Dark Matter on Top. http://doi.org/10.1088/1475-7516/2014/12/025
  - Kumar, A., & Tulin, S. (2013). Top-flavored dark matter and the forward-backward asymmetry. http://doi.org/10.1103/PhysRevD.87.095006
  - Blanke, M., & Kast, S. (2017). Top-Flavoured Dark Matter in Dark Minimal Flavour Violation. http://arxiv.org/abs/1702.08457
  - …
- We focus on real scalar DM which has simpler interaction forms. However, special attention is needed, e.g. in RGE effects in the direct detection.

Model: Top-flavored Real Scalar DM



- DM: real scalar S
  - SM singlet, couple only to t_R
- Vector-like (VL) fermion T
  - (T, t_R) same quantum number
  - no chiral anomaly

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_S + \mathcal{L}_T + \mathcal{L}_Y + \mathcal{L}_G$$

$$\mathcal{L}_Y = -(y_{ST} S \bar{T} t_R + h.c.)$$

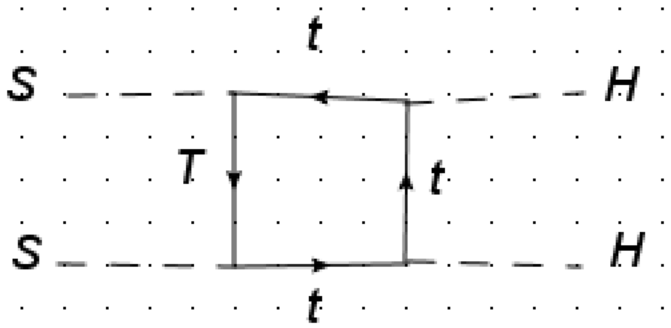
$$\mathcal{L}_G = C_{Sg}(y_{ST}, m_S, m_T) \frac{\alpha_s}{\pi} S^2 G^{\mu\nu} G_{\mu\nu}$$

$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2$$

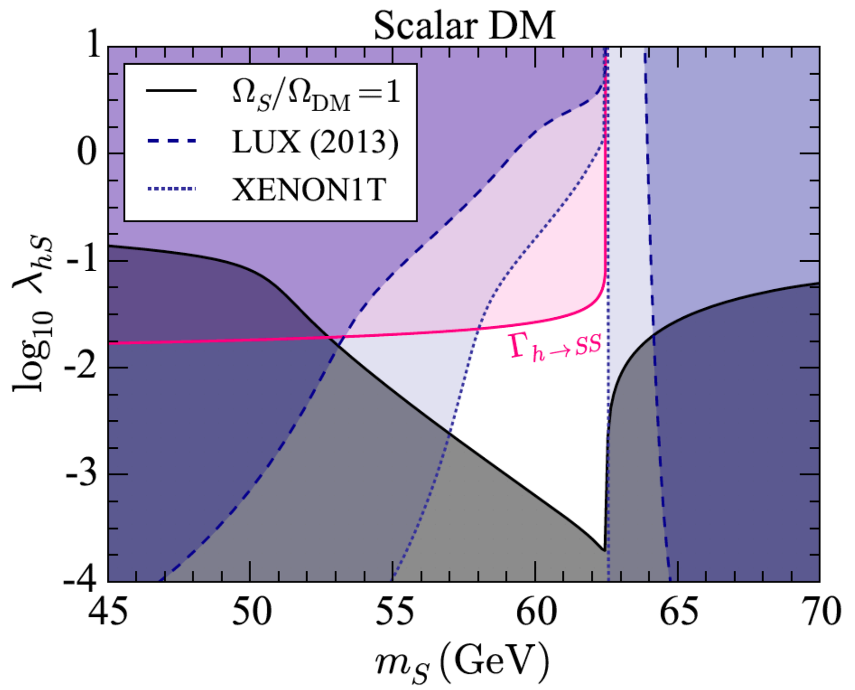
$$\mathcal{L}_T = \bar{T}(i\not{D} - m_T)T$$

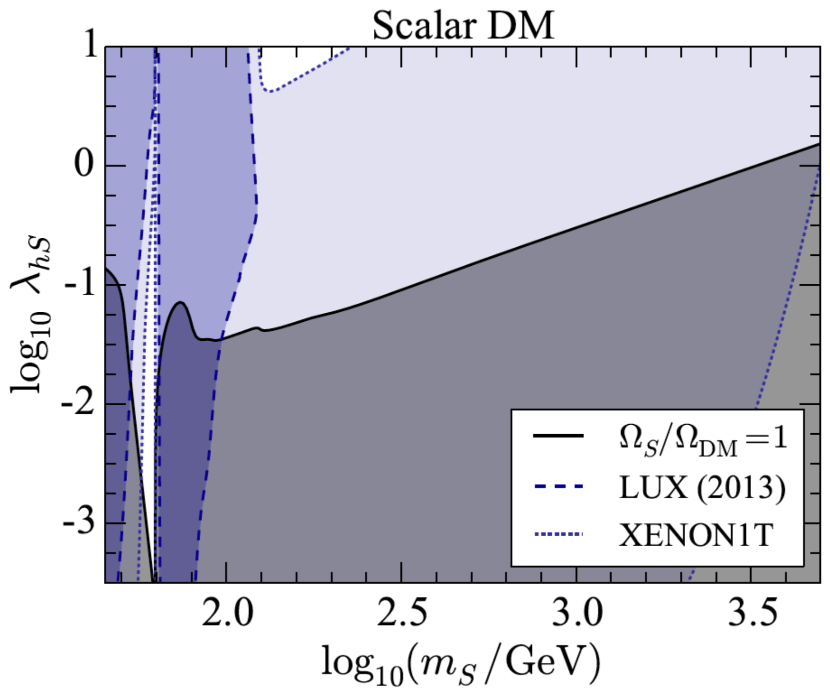
Higgs portal

- also generated via loop in our model
- strongly constrained by current experiments
- We set $\lambda_{SH}^{ren.}(\mu_{EFT} = m_Z) = 0$ in this work

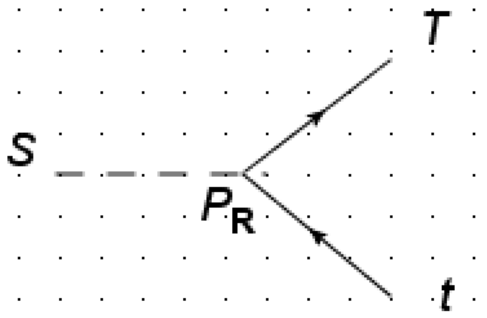


[1512.06458, Beniwal *et al*]





Model: Top-flavored Real Scalar DM



- DM: real scalar S
  - SM singlet, couple only to t_R
- Vector-like (VL) fermion T
  - (T, t_R) same quantum number
  - no chiral anomaly
- Z_2 parity to stabilize DM: S, T are odd
  - no mass mixing $(S, H), (T, t)$
  - $Br\left(T \to St^{(*)}\right) = 100\%$
  - LHC searches for VL (T, B) do not apply

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_S + \mathcal{L}_T + \mathcal{L}_Y + \mathcal{L}_G$$

$$\mathcal{L}_Y = -(y_{ST} S \bar{T} t_R + h.c.)$$

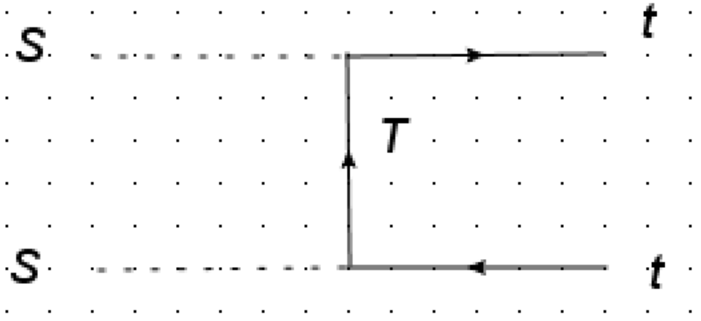
$$\mathcal{L}_G = C_{Sg}(y_{ST}, m_S, m_T) \frac{\alpha_s}{\pi} S^2 G^{\mu\nu} G_{\mu\nu}$$

$$\mathcal{L}_S = \frac{1}{2}\left(\partial_\mu S\right)^2 - \frac{1}{2} m_S^2 S^2$$

$$\mathcal{L}_T = \bar{T}(i\not{D} - m_T)T$$

Thermal Relic

$$r_S = \frac{m_S}{m_{top}}, \quad r_T = \frac{m_T}{m_S}$$

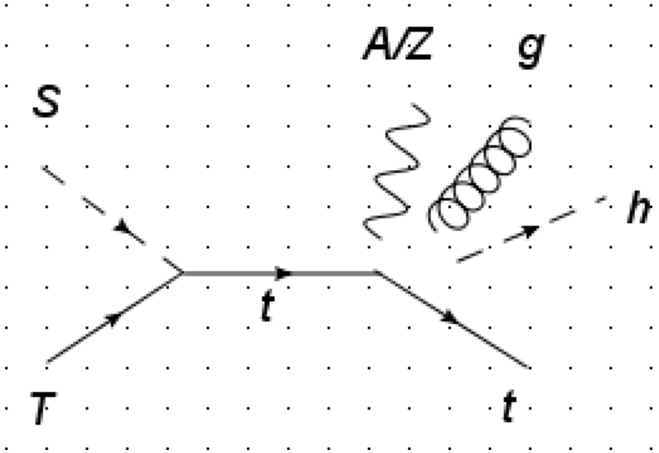


$$\sigma v(SS \to t\bar{t})_s = [y_3{}^4]\frac{3}{4\pi m_t{}^2}\frac{(r_S{}^2-1)^{3/2}}{r_S{}^3(r_S{}^2(r_T{}^2+1)-1)^2}$$

$$\sigma v(SS \to t\bar{t})_p = [y_3{}^4]\frac{1}{32\pi m_t{}^2}\frac{\sqrt{r_S{}^2-1}}{r_S{}^3(r_S{}^2(r_T{}^2+1)-1)^4} \times(-16r_S{}^6(2r_T{}^2+1)+r_S{}^4(r_T{}^2+1)(9r_T{}^2+41)-2r_S{}^2(9r_T{}^2+17)+9)$$

$$\sigma v(ST \to gt)_s = [y_3{}^2 g_s{}^2]\frac{1}{6\pi m_t{}^2}\frac{r_S{}^2(r_T+1)^2-1}{r_S{}^4 r_T(r_T+1)^5}$$

$$\sigma v(ST \to gt)_p = [y_3{}^2 g_s{}^2]\frac{1}{36\pi m_t{}^2}\frac{1}{r_S{}^4 r_T(r_T+1)^7(r_S r_T+r_S-1)(r_S r_T+r_S+1)} \times(r_S{}^4(r_T(16r_T-13)-1)(r_T+1)^4 -2r_S{}^2(4(r_T-3)r_T-1)(r_T+1)^2+r_T(8r_T-11)-1)$$

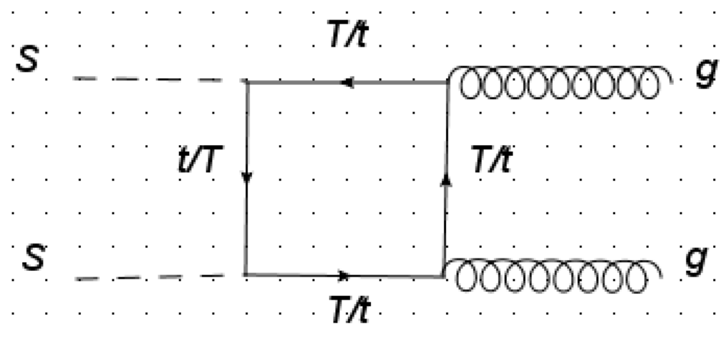


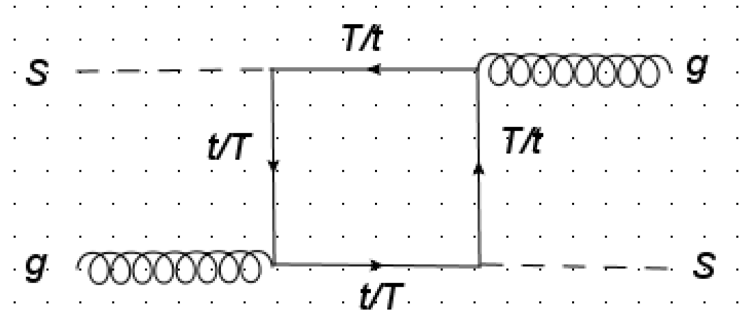
Thermal Relic

- $C_{Sg} \propto y_{ST}^{2} \times f_{loop}(m_S, m_T, m_t)$
- $\langle \sigma v \rangle_{gg} \propto y_{ST}^{4}$
  - can be sizable when $y_{ST} \sim \mathcal{O}(10)$

$$\sigma v(SS \to gg)_s = \frac{64}{\pi}\left(\frac{\alpha_S}{\pi} C_{SSgg}\right)^2 m_S^2$$

$$\sigma v(SS \to gg)_p = \frac{16}{\pi}\left(\frac{\alpha_S}{\pi} C_{SSgg}\right)^2 m_S^2$$





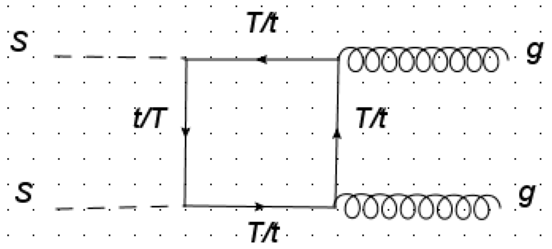
[arXiv: 1502.02244, J. Hisano *et al*]

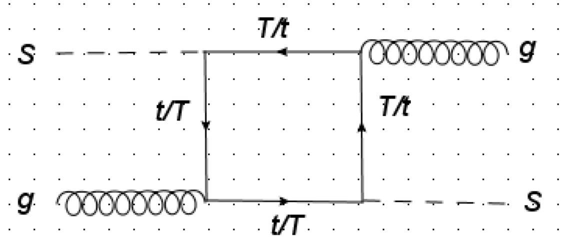
Thermal Relic: C_{Sg}

[Hisano et al, 1502.02244]

$$\mathcal{L} = S\overline{\psi}(a_Q + b_Q\gamma^5)Q + h.c. \qquad a_Q = b_Q = \frac{y_3}{2}$$

$$C_S^g|_Q = \frac{1}{4}\sum_{i=a,b,c}\left[(a_Q^2+b_Q^2)f_+^{(i)}(M;m_Q,m_{\psi_Q}) + (a_Q^2-b_Q^2)f_-^{(i)}(M;m_Q,m_{\psi_Q})\right]$$





$$f_+^{(a)}(M;m_1,m_2) \equiv -\frac{m_1^2m_2^4(M^2+m_1^2-m_2^2)}{\Delta^2}L - \frac{(-M^2+m_1^2+2m_2^2)\Delta+6m_1^2m_2^2(M^2-m_1^2+m_2^2)}{6\Delta^2},$$

$$f_-^{(a)}(M;m_1,m_2) \equiv \frac{m_1m_2^3\{\Delta+m_1^2(M^2-m_1^2+m_2^2)\}}{\Delta^2}L - \frac{m_2\{(-2M^2+m_1^2+2m_2^2)\Delta-6m_1^2m_2^2(M^2+m_1^2-m_2^2)\}}{6m_1\Delta^2},$$

$$f_+^{(b)}(M;m_1,m_2) \equiv f_+^{(a)}(M;m_2,m_1),$$

$$f_-^{(b)}(M;m_1,m_2) \equiv f_-^{(a)}(M;m_2,m_1),$$

$$f_+^{(c)}(M;m_1,m_2) \equiv \frac{-M^2+m_1^2+m_2^2}{2\Delta} - \frac{m_1^2m_2^2}{\Delta}L,$$

$$f_-^{(c)}(M;m_1,m_2) \equiv \frac{2m_1m_2}{\Delta} - \frac{m_1m_2(-M^2+m_1^2+m_2^2)}{\Delta}L,$$

$$\Delta(M;m_1,m_2) \equiv M^4 - 2M^2(m_1^2+m_2^2) + (m_2^2-m_1^2)^2,$$

$$L(M;m_1,m_2) \equiv \begin{cases} \frac{1}{\sqrt{|\Delta|}}\ln\left(\frac{m_1^2+m_2^2-M^2+\sqrt{|\Delta|}}{m_1^2+m_2^2-M^2-\sqrt{|\Delta|}}\right) & (\Delta>0) \\ \frac{2}{\sqrt{|\Delta|}}\arctan\left(\frac{\sqrt{|\Delta|}}{m_1^2+m_2^2-M^2}\right) & (\Delta<0) \end{cases}$$

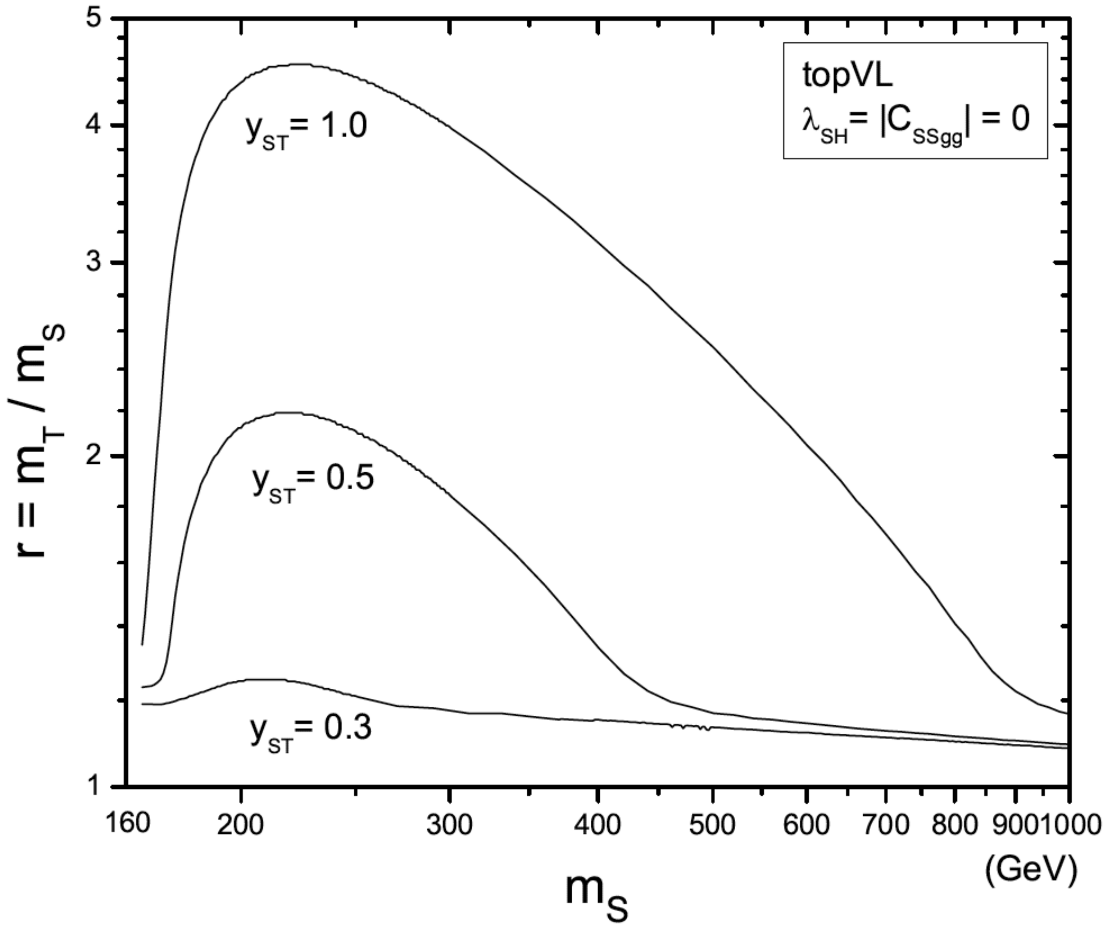
Thermal Relic

$$\sigma v(SS \to t\bar{t})_s = [y_3{}^4]\frac{3}{4\pi m_t{}^2}\frac{(r_S{}^2-1)^{3/2}}{r_S{}^3(r_S{}^2(r_T{}^2+1)-1)^2}$$

$$\sigma v(SS \to t\bar{t})_p = [y_3{}^4]\frac{1}{32\pi m_t{}^2}\frac{\sqrt{r_S{}^2-1}}{r_S{}^3(r_S{}^2(r_T{}^2+1)-1)^4}$$
$$\times(-16r_S{}^6(2r_T{}^2+1)+r_S{}^4(r_T{}^2+1)(9r_T{}^2+41)-2r_S{}^2(9r_T{}^2+17)+9)$$

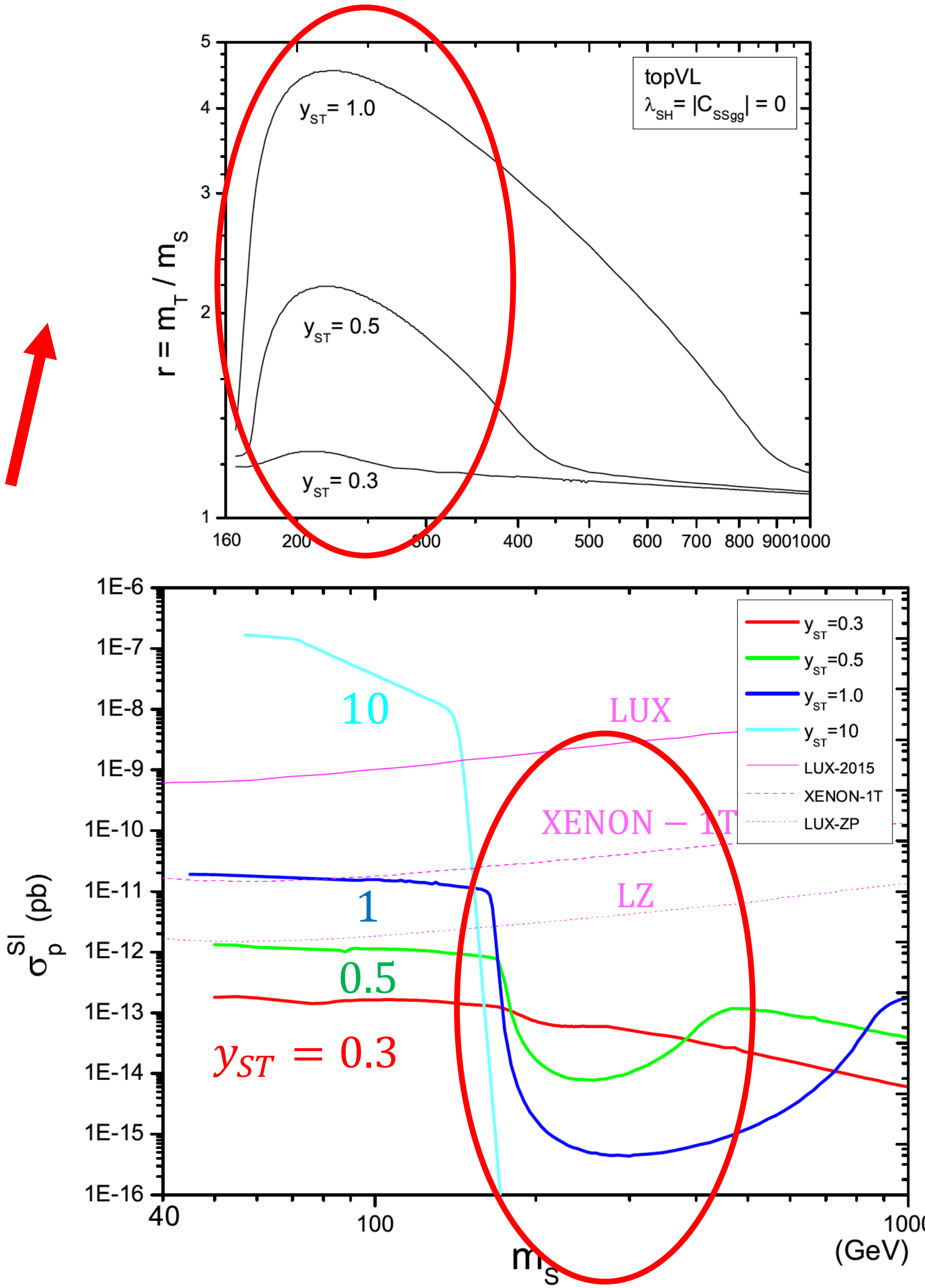
$$r_S = \frac{m_S}{m_{top}}, \quad r_T = \frac{m_T}{m_S}$$

- mass spectrum $\{m_S, r_T = \frac{m_T}{m_S}\}$
- when $SS \to t\bar{t}$ is open, $r_S > 1$
  - relaxed r_T
  - larger y_{ST}, even larger r_T



Direct detection

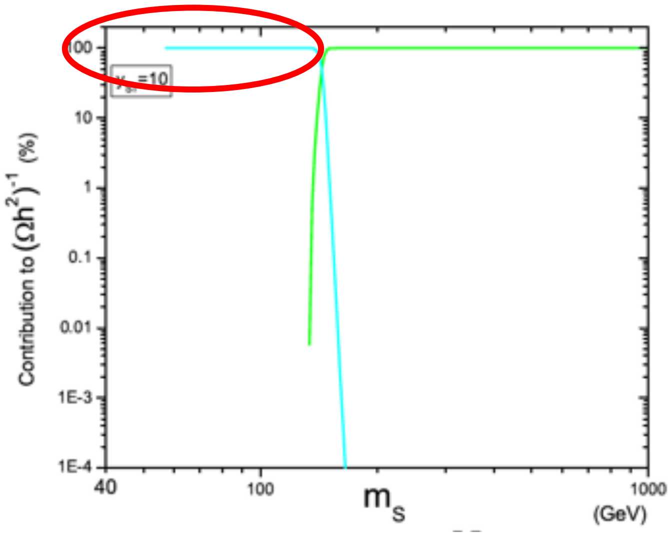
- for $m_S > m_t$, where $SS \to t\bar{t}$ and $r_T = \frac{m_T}{m_S}$
  - generally heavier m_T
  - suppressed C_{Sg} and σ_{SI}

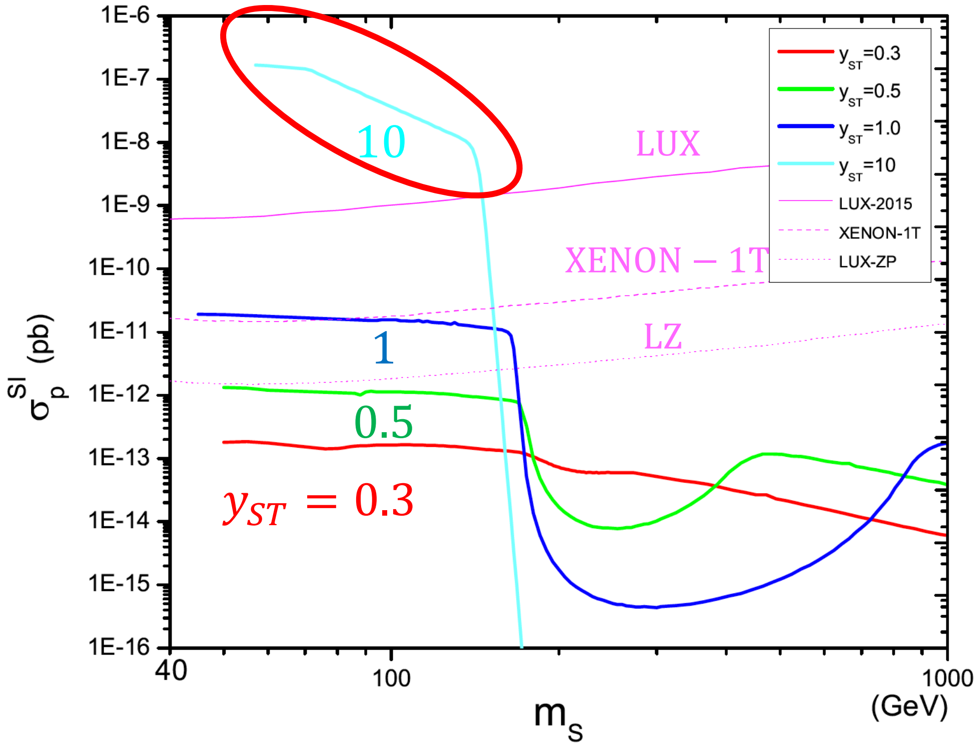


Direct detection

- $C_{Sg} \propto y_{ST}^2 \times f_{loop}(m_S, m_T, m_t)$
- for $m_S < m_t$,large $y_{ST} \sim O(10)$
  - $SS \to gg$ dominate in light m_S
  - σ_{SI} locked by canonical $\langle \sigma v \rangle \sim 1\,pb \cdot c$
  - excluded by LUX-2015
- $y_{ST} > 0.5$
  - light $m_S < m_t$ can be tested at LZ

$y_{ST} = 10$

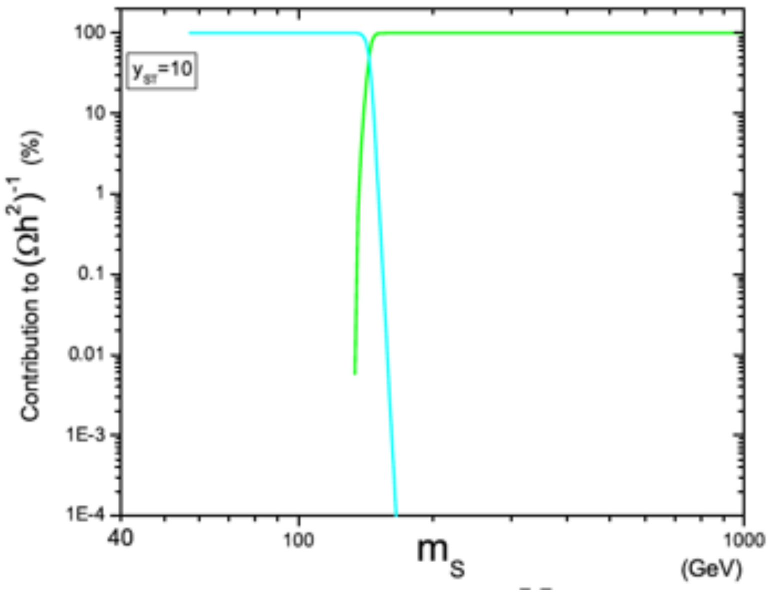




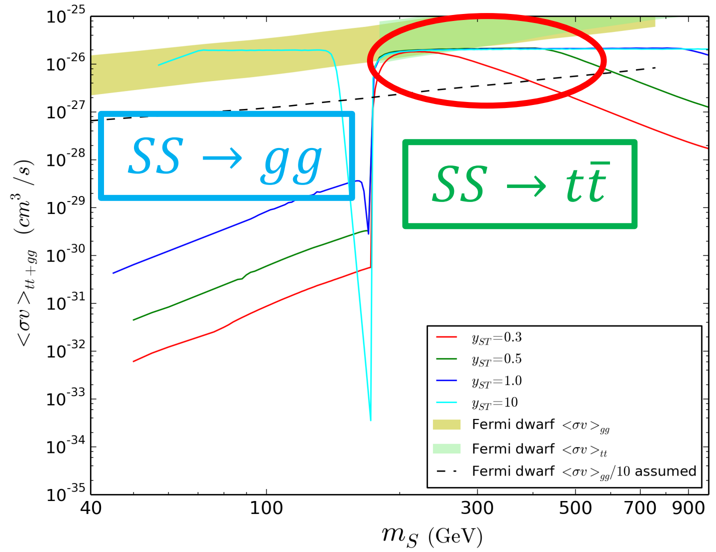
Indirect detection (γ-ray)

- current bounds are about to be able to constrain
- sensitivities ×10 can cover wide regions in $m_S > m_t$
  - complementary to DD

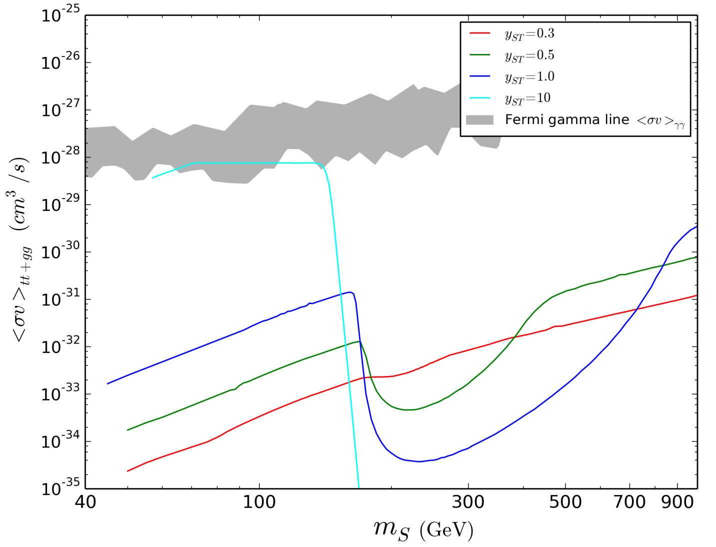
$y_{ST} = 10$



Dwarf **continuous** γ-spectrum

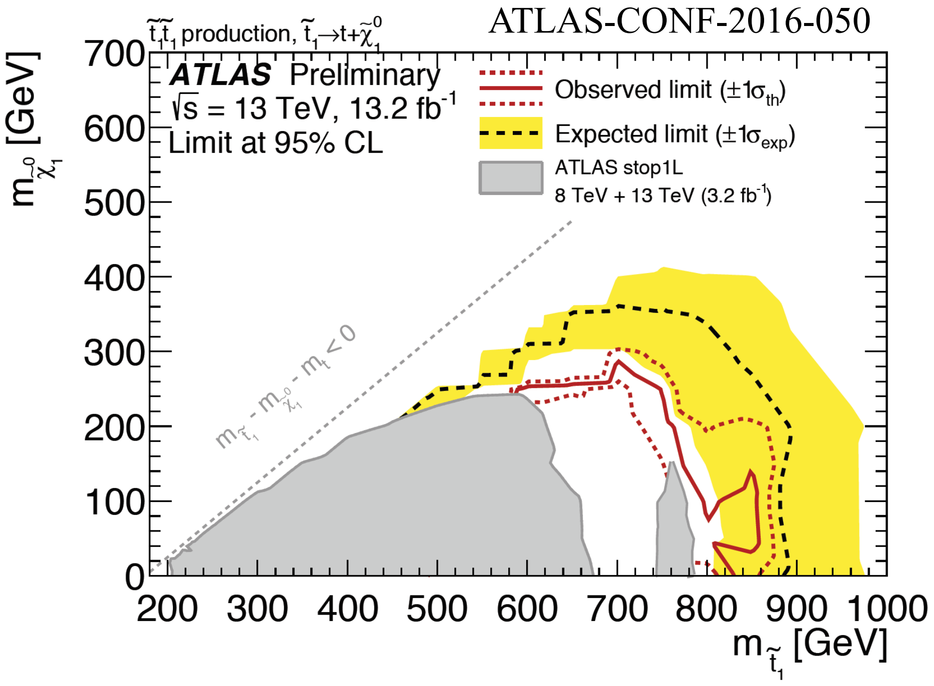


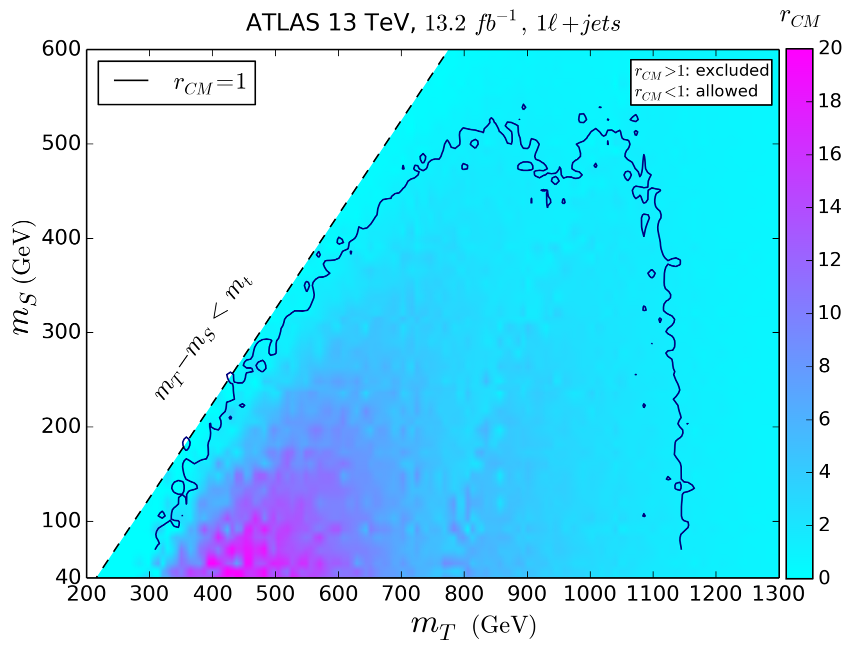
Galactic Center **line** γ-spectrum



Collider search (ATLAS 13.2 fb^{-1} @ 13 TeV)

- $pp \to T\bar{T} \to t\bar{t} + MET$
  - exclude m_T from **300** (650)-**1150** (1100) GeV for $m_S = 40$ (400) GeV
  - SUSY stop $\tilde{t}$ search: **200** - **850** GeV (smaller production cross section)

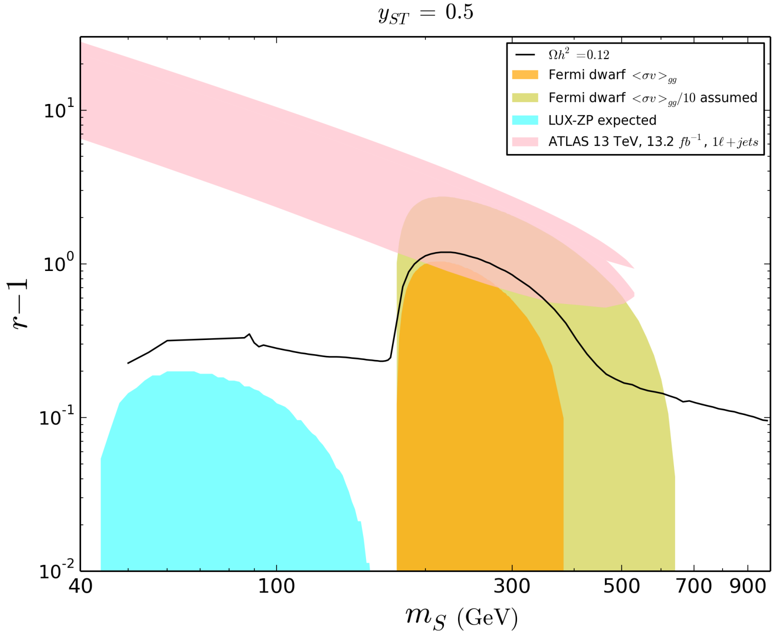




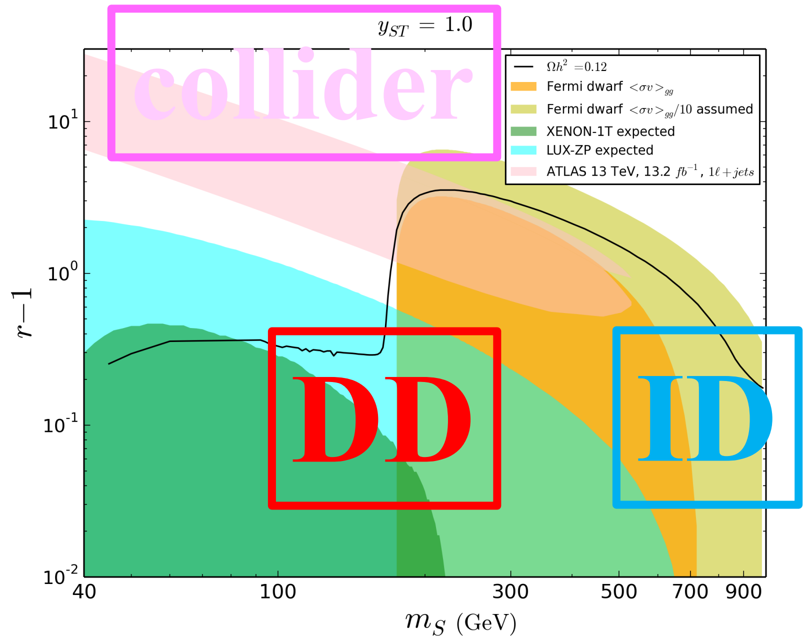
Summary for Top-flavored Scalar DM

- perturbative $y_{ST} > 0.5$: just about to be tested in future
- complementarity between **DD**/**ID** for $m_S < (>) m_t$
- collider signals are also promising

$y_{ST} = 0.5$



$y_{ST} = 1$



Top+Charm Flavored

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_S + \mathcal{L}_T + \boldsymbol{\mathcal{L}_Y} + \boldsymbol{\mathcal{L}_G}$$

$$\boldsymbol{\mathcal{L}_Y} = -(y_3 S\bar{T}t_R + y_2 S\bar{T}c_R + h.c.)$$

$$\boldsymbol{\mathcal{L}_G} = C_{Sg}(y_3, y_2, m_S, m_T)\,\frac{\alpha_s}{\pi} S^2 G^{\mu\nu} G_{\mu\nu}$$

$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2$$

$$\mathcal{L}_T = \bar{T}(iD - m_T)T$$

Quick Thoughts

- 4 parameters: couplings $\{y_3, y_2\}$, masses $\{m_S, m_T\}$.
- One can
  - fix benchmark $\{y_3, y_2\}$, to see $\{m_S, m_T\}$
    - DD bounds cover wide DM mass range
  - fix benchmark $\{m_S, m_T\}$, to see $\{y_3, y_2\}$
    - as a guideline for MFV construction of $\{y_3, y_2\}$
- In calculating DD scattering rate, DM-Charm interaction requires more careful treatment of RGE effects from $\mu_{EFT} \sim m_Z$ to $\mu_{QCD} \sim 1$ GeV.
- Top quark FCNC can be generated at both tree and loop level.
- More collider signals, MET + $t\bar{t}, tj, jj$

Quick Thoughts

Thermal relic

- $\sigma v \sim y_3^4 \,(\ldots)_{t\bar{t}} + y_3^2 y_2^2 \,(\ldots)_{\boldsymbol{t\bar{c}}} + y_2^4 \,(\ldots)_{c\bar{c}} + \cdots$

Direct Detection:

- $\sigma_p^{SI} \propto \left[C_{Sg}\right]^2 \sim [y_3^2 \,(\ldots)_t + y_2^2 \,(\ldots)_c]^2$

Top FCNC

- $t \to ST^* \to cSS \propto y_3^2 y_2^2$
- $t \to c + \{\gamma, g, Z\} \propto y_3^2 y_2^2$

Preliminary Results

Thermal Relic

$$r_S = \frac{m_S}{m_{top}}, \quad r_T = \frac{m_T}{m_S}$$

New pair-annihilation channels

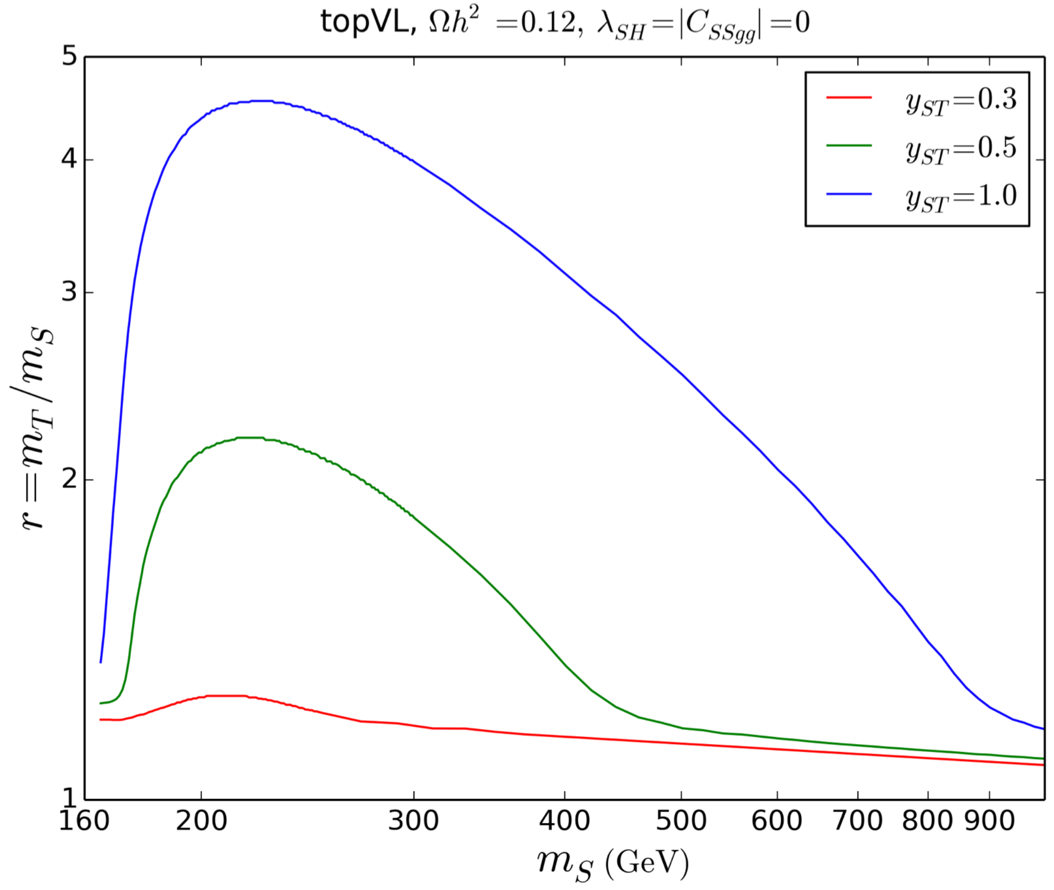
$$\sigma v(SS \to t\bar{c} + c\bar{t})_s = \boxed{[{y_2}^2 {y_3}^2]} \frac{3}{16\pi {m_t}^2} \frac{(1 - 4{r_S}^2)^2}{{r_S}^4 (1 - 2{r_S}^2({r_T}^2 + 1))^2}$$

$$\sigma v(SS \to t\bar{c} + c\bar{t})_p = \boxed{[{y_2}^2 {y_3}^2]} \frac{1}{32\pi {m_t}^2} \frac{1 - 4{r_S}^2}{{r_S}^4 (1 - 2{r_S}^2({r_T}^2 + 1))^4}$$
$$\times (64{r_S}^6(2{r_T}^2 + 1) - 4{r_S}^4(3{r_T}^4 + 16{r_T}^2 + 17) + 2{r_S}^2(7{r_T}^2 + 11) - 3)$$

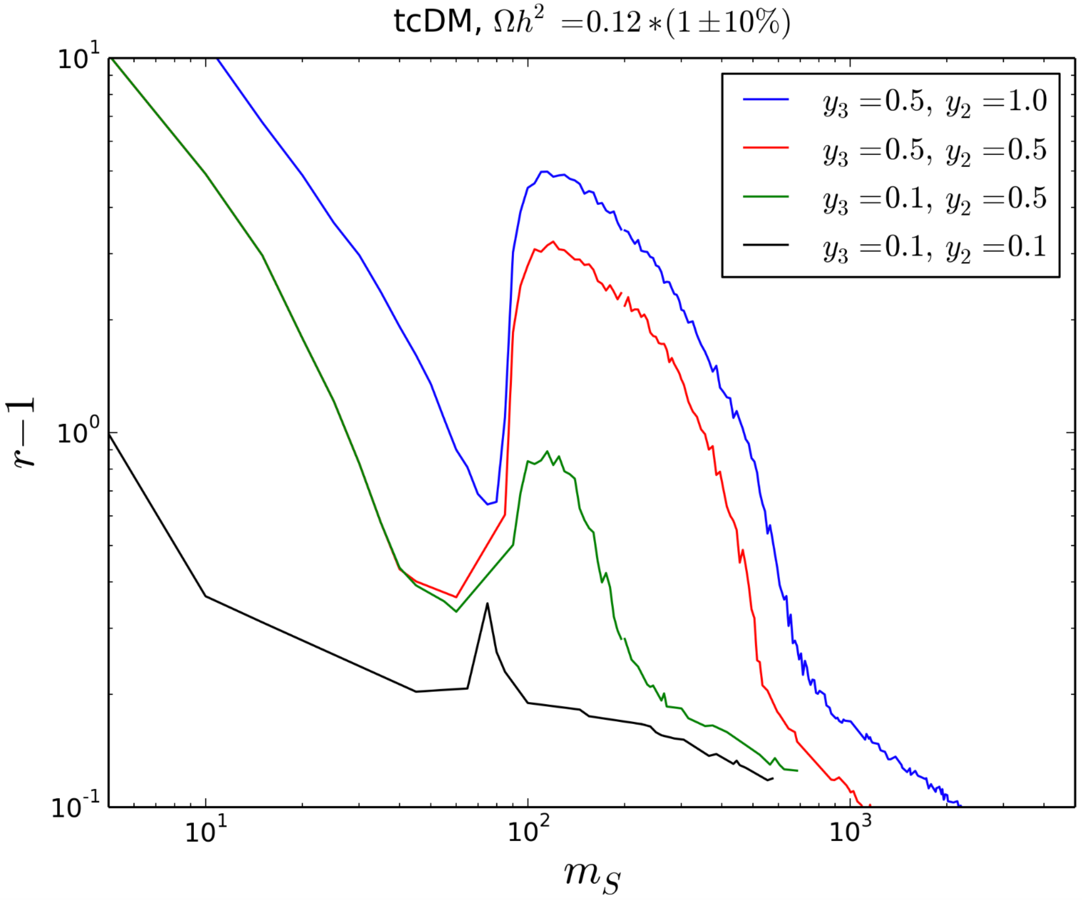
$$\sigma v \sim y_3^4\,(\ldots)_{t\bar{t}} + y_3^2 y_2^2\,(\ldots)_{t\bar{c}} + y_2^4\,(\ldots)_{c\bar{c}} + \cdots$$

Thermal Relic: fix $\{y_3, y_2\}$, find $\{m_S, m_T\}$

Top Flavored

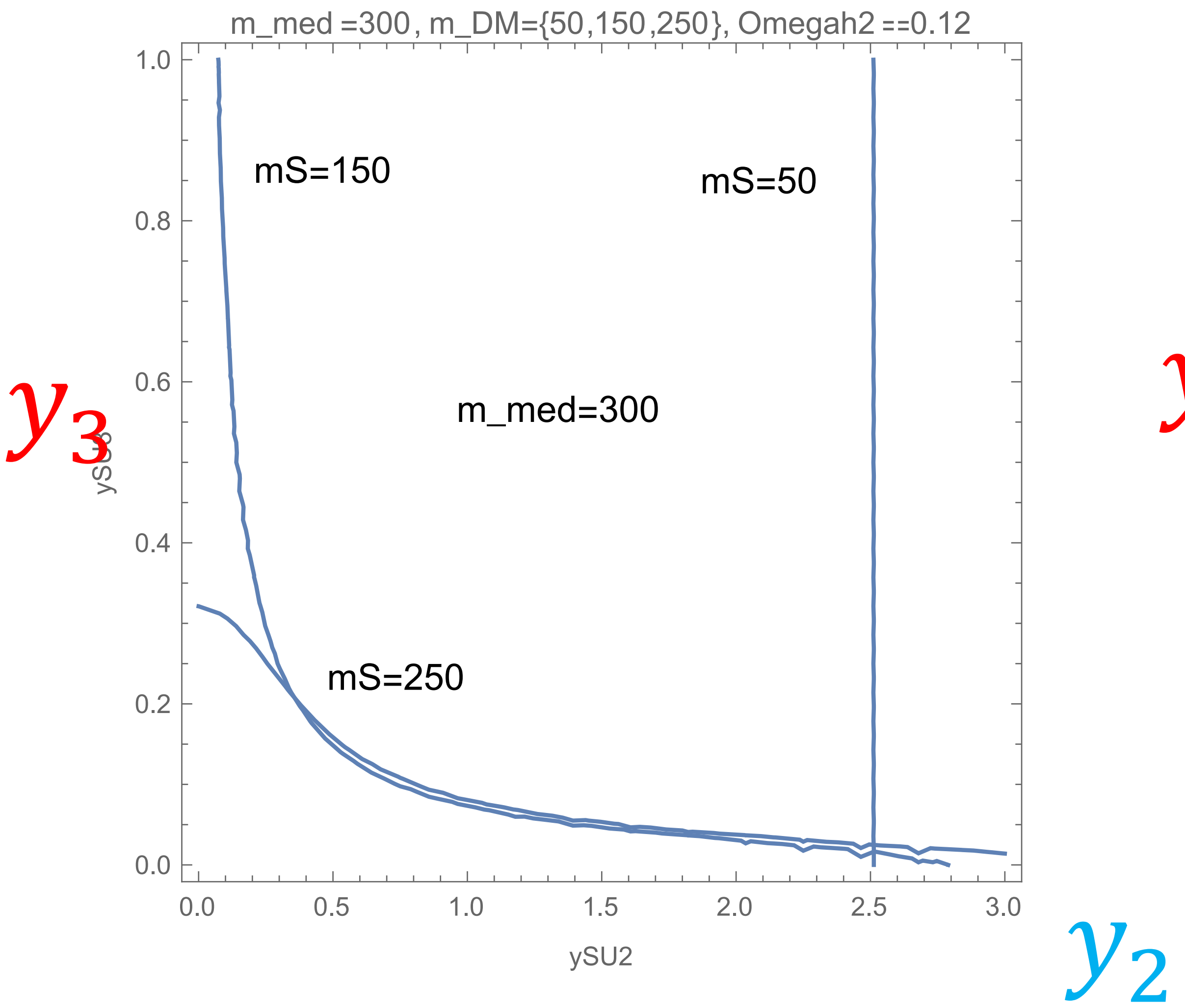


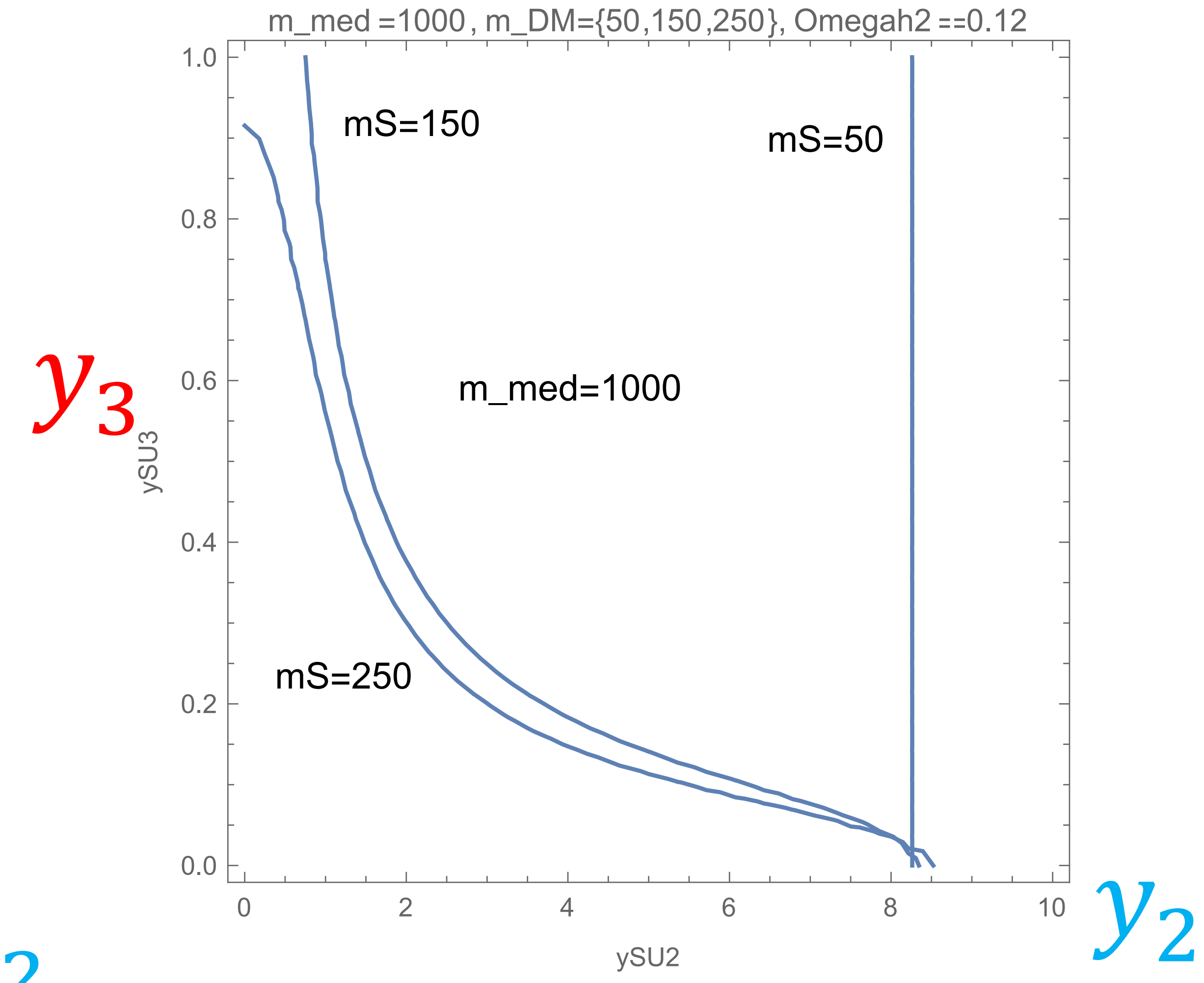
Top+Charm Flavored



$$\sigma v \sim y_3^4\,(\dots)_{t\bar{t}} + y_3^2 y_2^2\,(\dots)_{t\bar{c}} + y_2^4\,(\dots)_{c\bar{c}} + \cdots$$

Thermal Relic: fix $\{m_S, m_T\}$, find $\{y_3, y_2\}$





Direct Detection

Top Flavored **Top+Charm Flavored**

$$\{\mathcal{Q}_S^g\} \rightarrow \{\mathcal{Q}_S^g, \quad \mathcal{Q}_S^c\}$$

- $\mu_{EFT} \sim m_Z$

$$\mathcal{L}_{\rm eff} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p, \quad \mathcal{O}_S^q \equiv \phi^2 m_q \bar{q} q \ , \quad \mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi} \phi^2 G^{A\mu\nu} G^A_{\mu\nu}$$

- RGE

$$C_{\rm S}^q(\mu) = C_{\rm S}^q(\mu_0) - 4C_{\rm S}^G(\mu_0)\frac{\alpha_s^2(\mu_0)}{\beta(\alpha_s(\mu_0))}(\gamma_m(\mu) - \gamma_m(\mu_0)) \ ,$$

$$C_{\rm S}^G(\mu) = \frac{\beta(\alpha_s(\mu))}{\alpha_s^2(\mu)} \frac{\alpha_s^2(\mu_0)}{\beta(\alpha_s(\mu_0))} C_{\rm S}^G(\mu_0) \ .$$

- Quark thresholds

$$C_{\rm S}^q(\mu_b)|_{N_f=4} = C_{\rm S}^q(\mu_b)|_{N_f=5} \ ,$$

$$C_{\rm S}^G(\mu_b)|_{N_f=4} = -\frac{1}{12}\left[1 + \frac{11}{4\pi}\alpha_s(\mu_b)\right] C_{\rm S}^b(\mu_b)|_{N_f=5} + C_{\rm S}^G(\mu_b)|_{N_f=5}$$

- $\mu_{QCD} \sim 1$ GeV

$$\mathcal{L}_{\rm SI}^{(N)} = f_N \phi^2 \overline{N} N \ , \qquad f_N/m_N = \sum_{q=u,d,s} C_S^q(\mu_{\rm had}) f_{T_q}^{(N)} - \frac{8}{9} C_S^g(\mu_{\rm had}) f_{T_G}^{(N)}$$

$$\sigma = \frac{1}{\pi}\left(\frac{M_T}{M + M_T}\right)^2 |n_p f_p + n_n f_n|^2$$

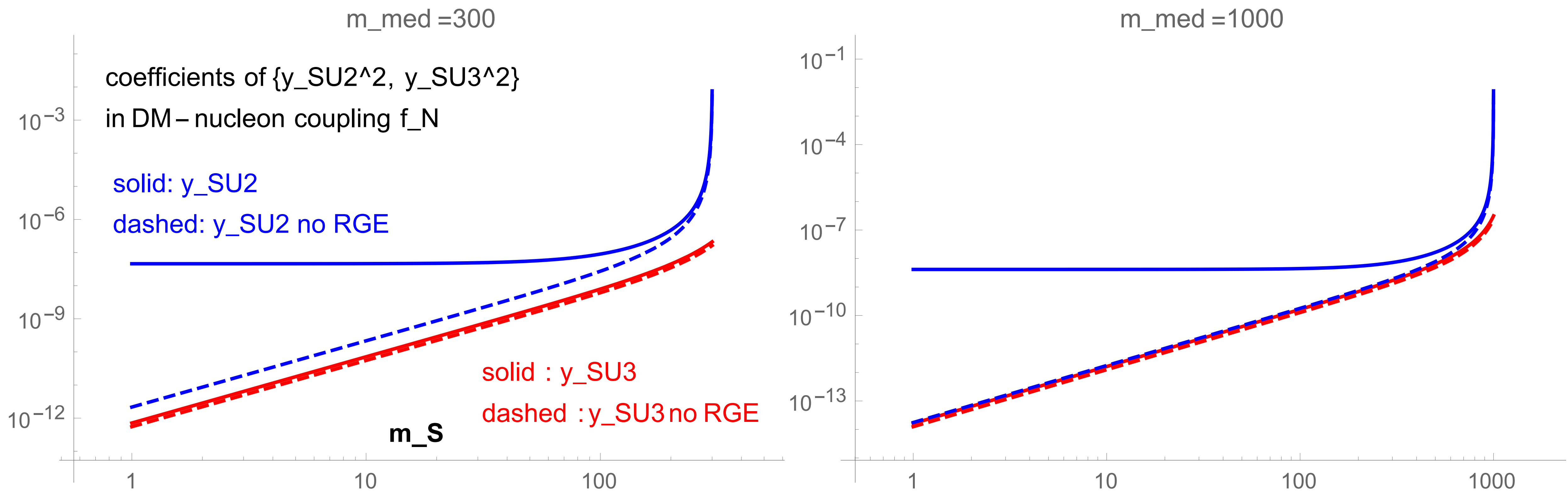
[Hisano et al, 1502.02244]

$$f_N = C_2 y_{U2}^2 + C_3 y_{U3}^2$$

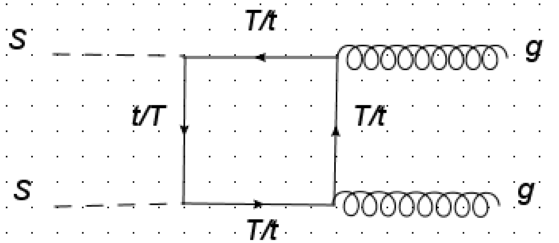
Direct Detection: RGE effects

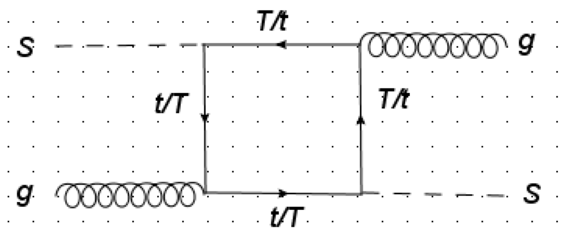
$$\mathcal{L}_{\rm SI}^{(N)} = f_N \phi^2 \overline{N} N \ , \quad f_N/m_N = \sum_{q=u,d,s} C_S^q(\mu_{\rm had}) f_{T_q}^{(N)} - \frac{8}{9} C_S^g(\mu_{\rm had}) f_{T_G}^{(N)}$$

$$\sigma = \frac{1}{\pi}\left(\frac{M_T}{M+M_T}\right)^2 |n_p f_p + n_n f_n|^2$$



Loop coupling C_{Sg}





$$\mathcal{L} = S\overline{\psi}(a_Q + b_Q\gamma^5)Q + h.c.$$

[1502.02244, Hisano *et al*]

$$C_S^g|_Q = \frac{1}{4}\sum_{i=a,b,c}\left[(a_Q^2+b_Q^2)f_+^{(i)}(M;m_Q,m_{\psi_Q}) + (a_Q^2-b_Q^2)f_-^{(i)}(M;m_Q,m_{\psi_Q})\right]$$

$$f_+^{(a)}(M;m_1,m_2) \equiv -\frac{m_1^2 m_2^4(M^2+m_1^2-m_2^2)}{\Delta^2}L - \frac{(-M^2+m_1^2+2m_2^2)\Delta + 6m_1^2m_2^2(M^2-m_1^2+m_2^2)}{6\Delta^2} ,$$

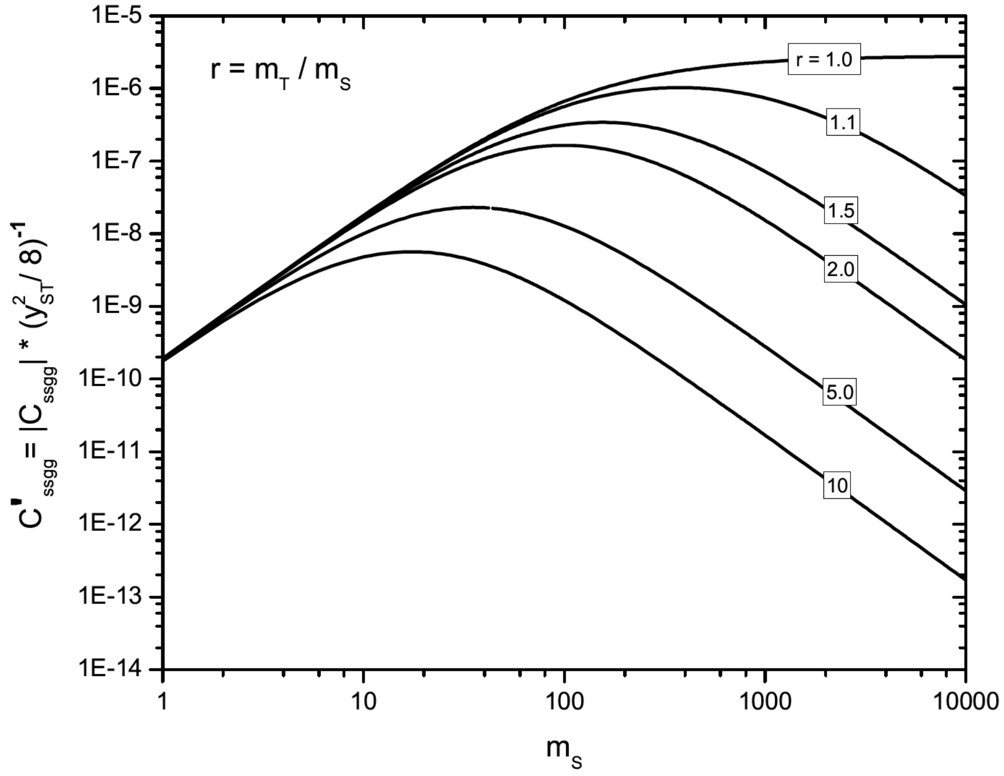
$$f_-^{(a)}(M;m_1,m_2) \equiv \frac{m_1 m_2^3\{\Delta + m_1^2(M^2-m_1^2+m_2^2)\}}{\Delta^2}L - \frac{m_2\{(-2M^2+m_1^2+2m_2^2)\Delta - 6m_1^2m_2^2(M^2+m_1^2-m_2^2)\}}{6m_1\Delta^2} ,$$

$$f_+^{(b)}(M;m_1,m_2) \equiv f_+^{(a)}(M;m_2,m_1) ,$$

$$f_-^{(b)}(M;m_1,m_2) \equiv f_-^{(a)}(M;m_2,m_1) ,$$

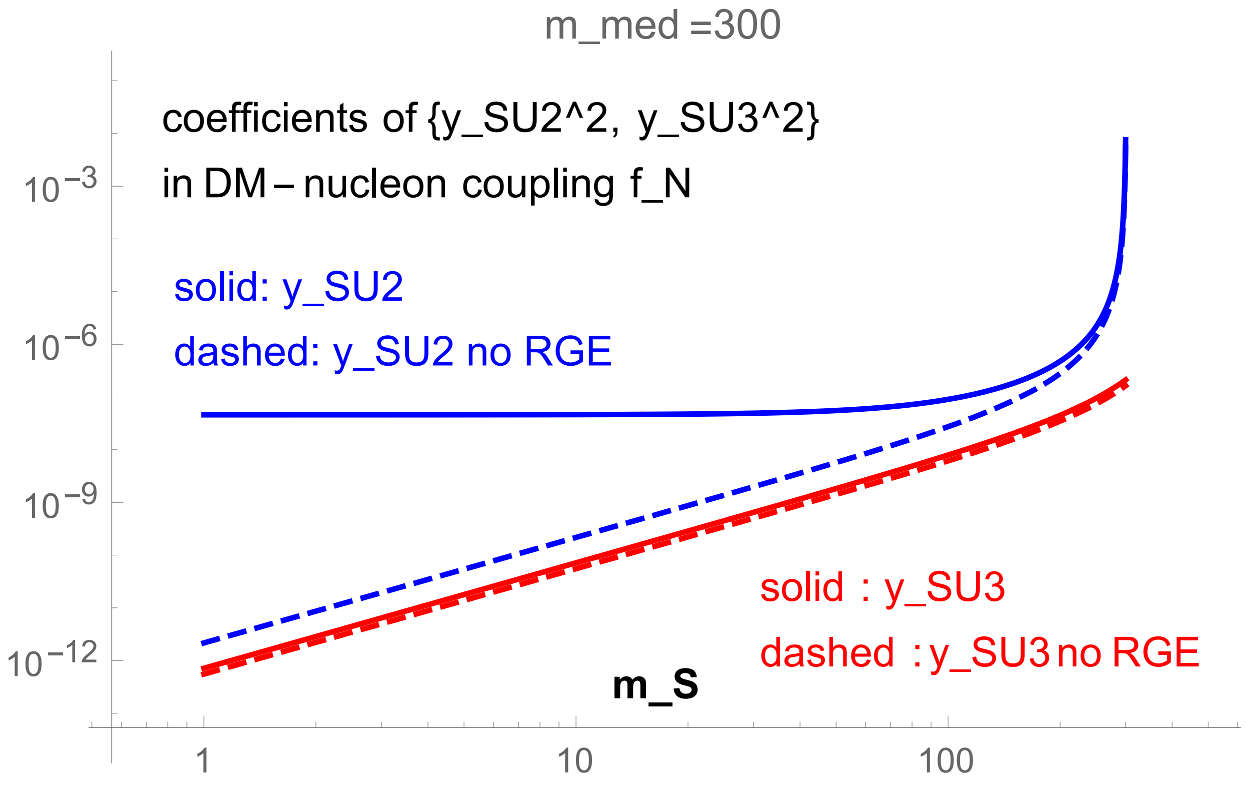
$$f_+^{(c)}(M;m_1,m_2) \equiv \frac{-M^2+m_1^2+m_2^2}{2\Delta} - \frac{m_1^2m_2^2}{\Delta}L ,$$

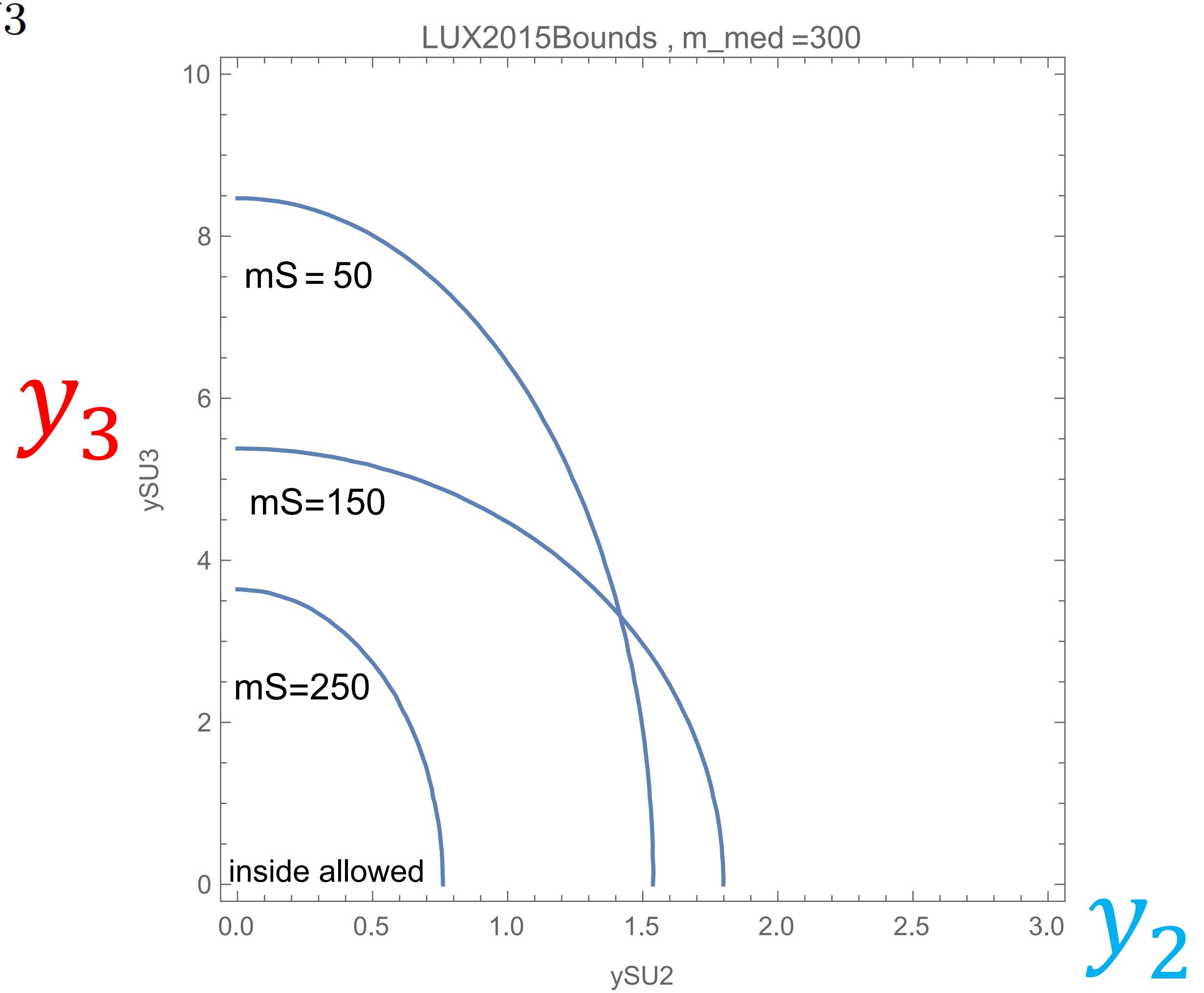
$$f_-^{(c)}(M;m_1,m_2) \equiv \frac{2m_1m_2}{\Delta} - \frac{m_1m_2(-M^2+m_1^2+m_2^2)}{\Delta}L ,$$



Direct Detection: fix $\{m_S, m_T\}$, find $\{y_3, y_2\}$

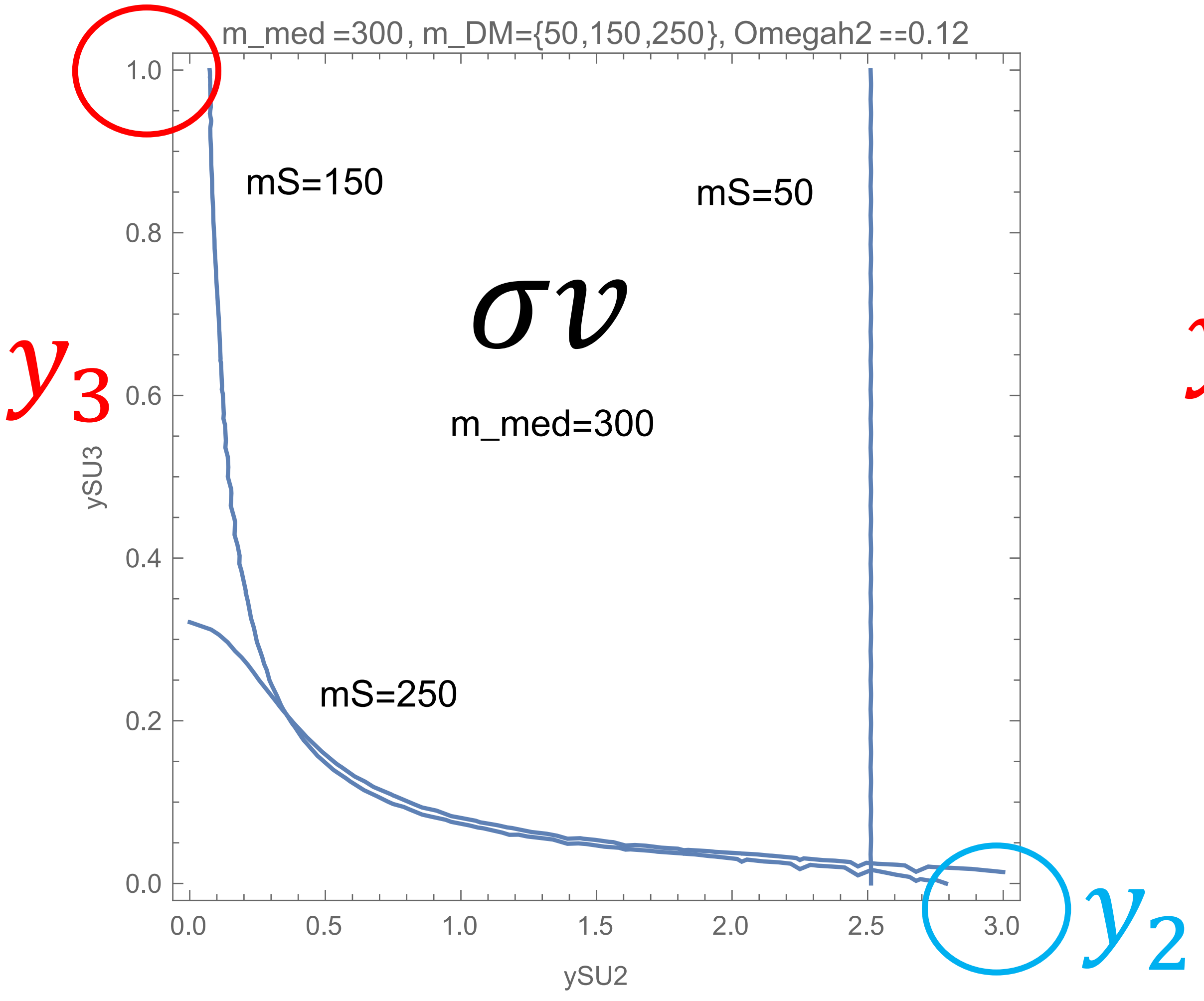
$$\mathcal{L}_{\rm SI}^{(N)} = f_N \phi^2 \overline{N} N \ , \quad f_N = C_2 y_{U2}^2 + C_3 y_{U3}^2$$

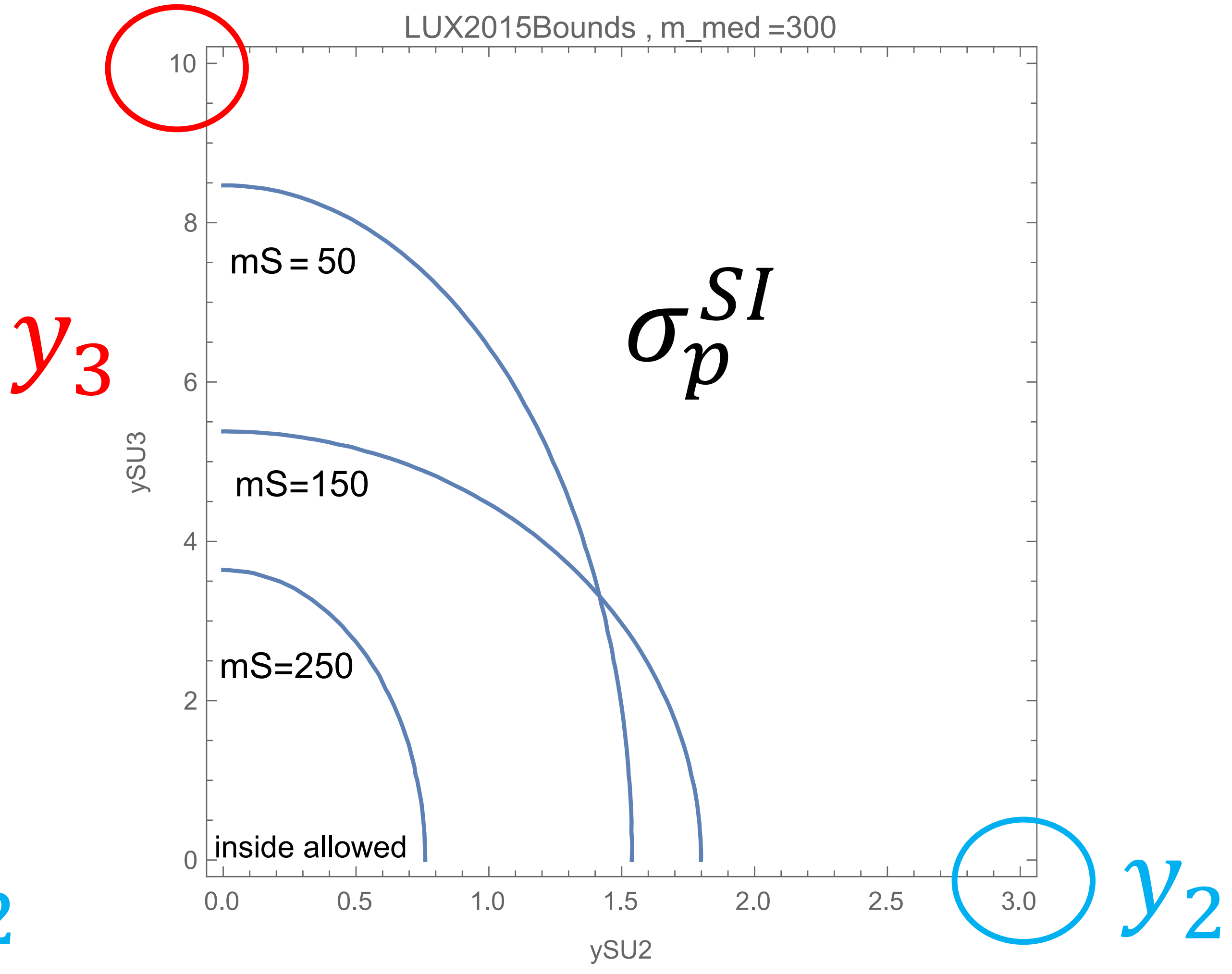




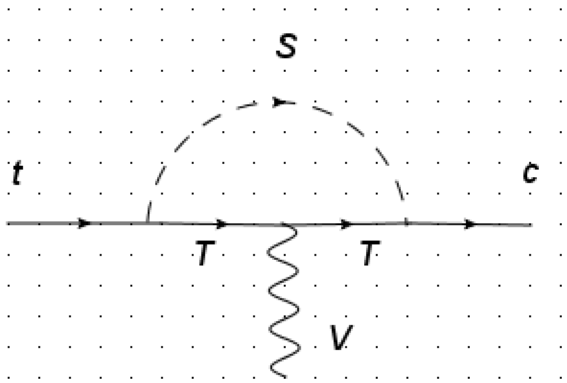
σv relies on top: $y_3^4\,(\dots)_{t\bar{t}} + y_3^2 y_2^2\,(\dots)_{t\bar{c}} + y_2^4\,(\dots)_{c\bar{c}} + \cdots$

σ_p^{SI} relies on charm: $\left[y_3^2\,(\dots)_t + y_2^2\,(\dots)_c \right]^2$





$t \to c + \{\gamma, g, Z\}$

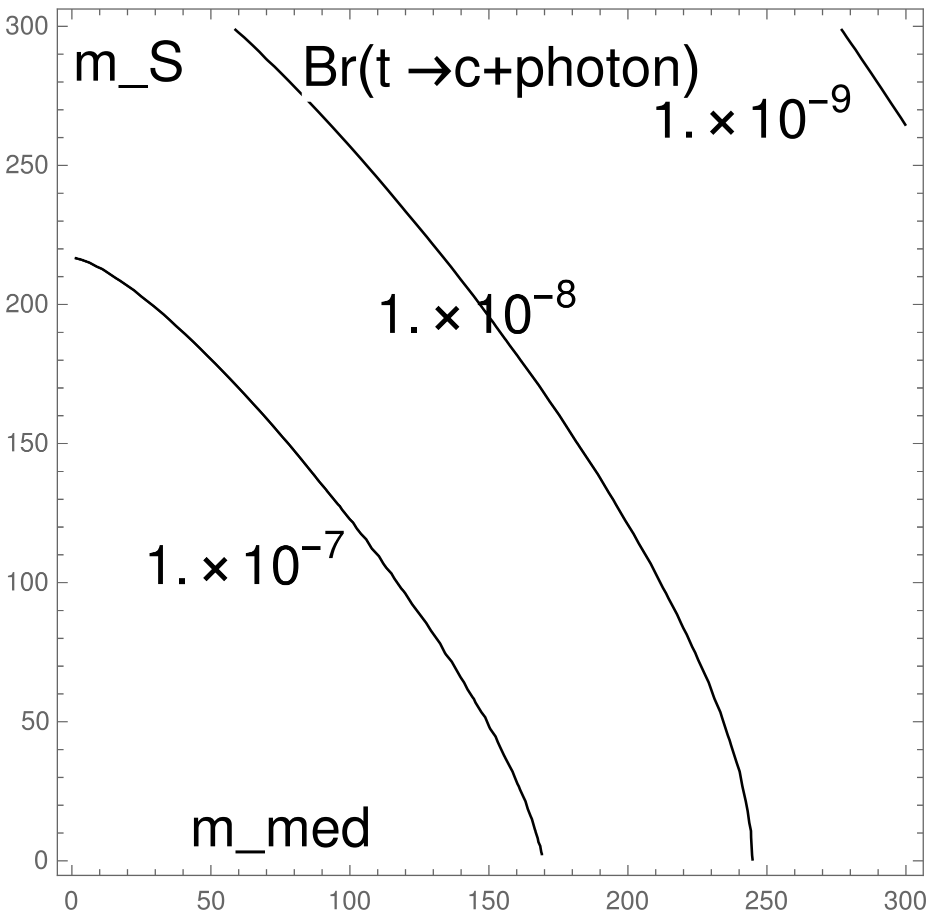


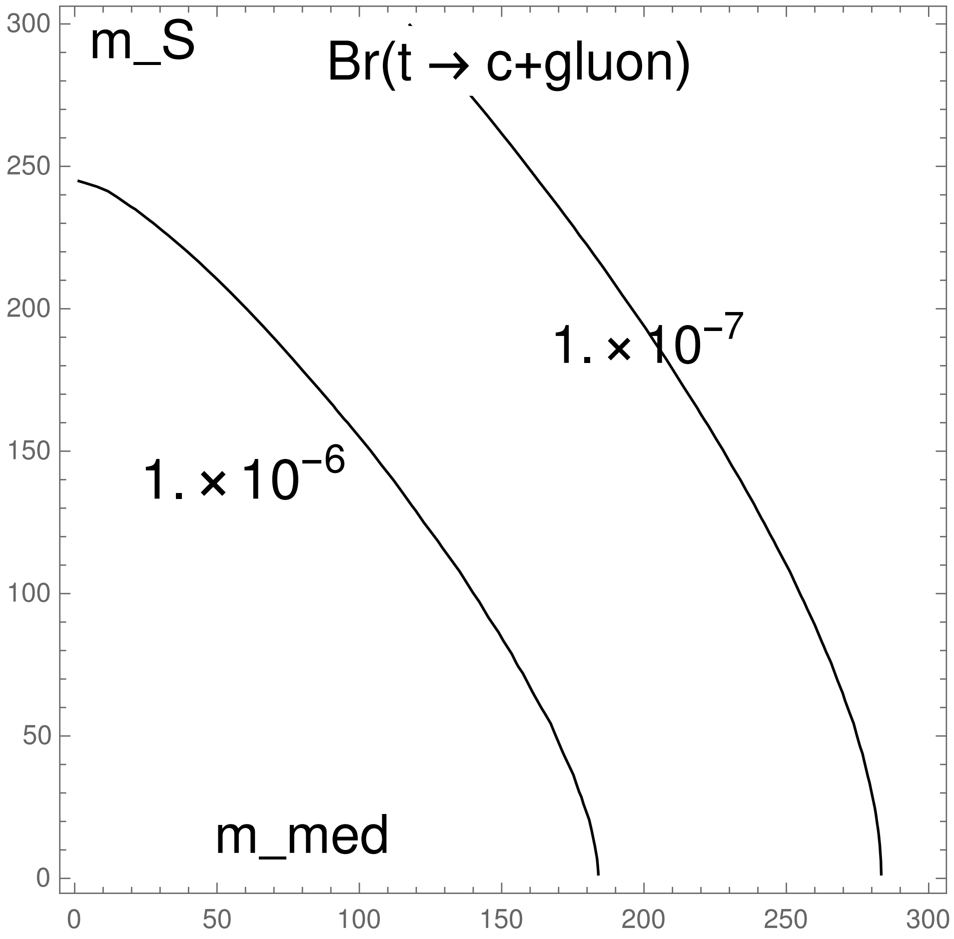
$$
\begin{aligned}
i\mathcal{M}_{tc\gamma} &= \bar{u}(p_c, m_c)\Gamma^\mu u(p_t, m_t)\epsilon^*_\mu(k) \\
\Gamma^\mu &= i\sigma^{\mu\nu}k_\nu(a_L P_L + a_R P_R)
\end{aligned}
$$

$$
\begin{aligned}
\Sigma_{tc}(p^2) &= c_{0,p^2}\not{p}P_R \\
\Gamma^\mu_{ren} &= -(y_2 y_3 \frac{i}{16\pi^2})(\frac{2}{3}e)\Lambda^\mu + \Gamma^\mu_{C.T.} \\
\Lambda^\mu &= \Big(c_1\gamma^\mu + c_2\not{k}\gamma^\mu\not{k} + c_3\not{p}_c\gamma^\mu\not{p}_c + c_4\not{p}_c\gamma^\mu\not{k} + c_5\not{k}\gamma^\mu\not{p}_c\Big)P_R \\
\Gamma^\mu_{C.T.} &= (-\frac{2}{3}e)\Big(c_6\gamma^\mu P_L + c_7\gamma^\mu P_R\Big)
\end{aligned}
$$

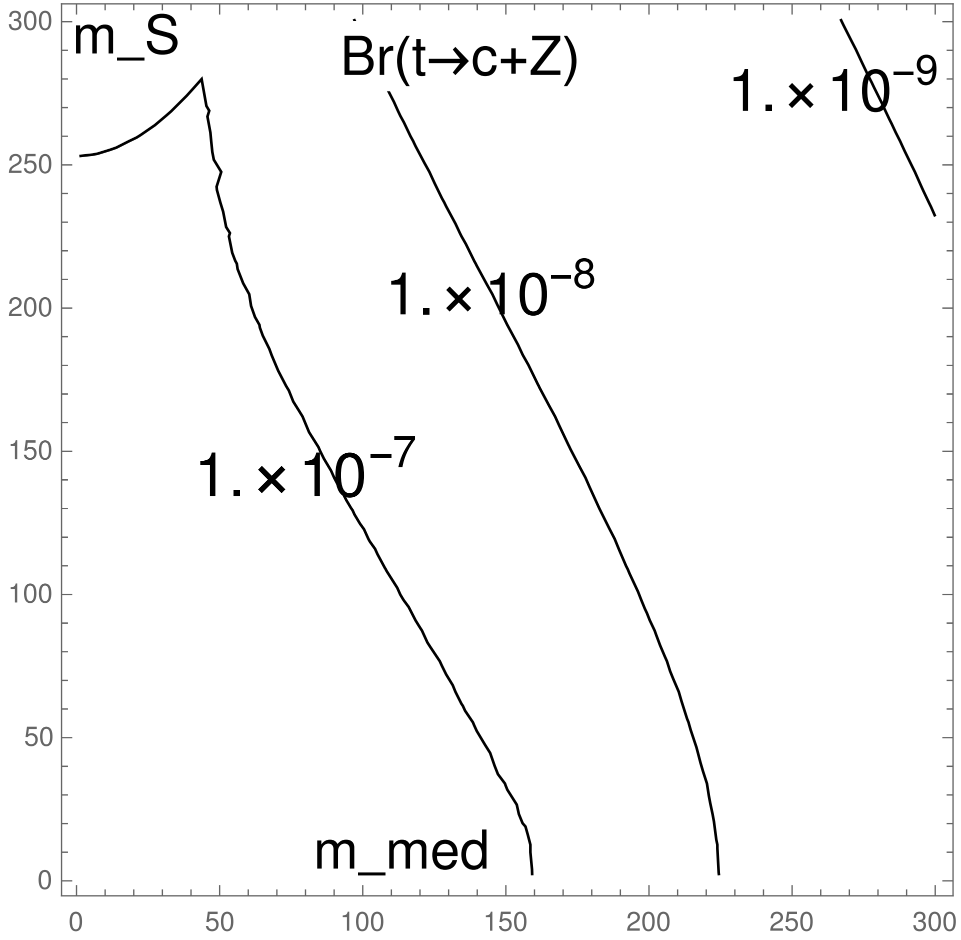
$$
\begin{aligned}
c_{0,p^2} &= (y_2 y_3 \frac{i}{16\pi^2})B_1[p^2; m_\psi^2, m_S^2] \\
c_1 &= -2C_{00} + m_\psi^2 C_0 \\
c_2 &= C_{11} + C_1 \\
c_3 &= C_{22} \\
c_4 &= -C_{12} - C_2 \\
c_5 &= -C_{12} \\
c_6 &= \frac{m_c m_t(c_{0,m_t^2} - c_{0,m_c^2})}{m_c^2 - m_t^2} \\
c_7 &= -\frac{m_c^2 c_{0,m_c^2} - m_t^2 c_{0,m_t^2}}{m_c^2 - m_t^2}
\end{aligned}
$$

$t \to c + \{\gamma, g, Z\}$





$t \to c + \{\gamma, g, Z\}$



Conclusion

- No confirmed DD signal, DM may small direct coupling to u/d quarks
- Top flavored real scalar DM S, a colored fermion mediator T
  - Yukawa interaction $\mathcal{L} = -y_3 S\overline{T_L} t_R + h.c.$
  - $\langle \sigma v \rangle$ benefits from m_{top}, co-annihilations are important
  - DD via $SSG^{\mu\nu}G_{\mu\nu}$; ID via $SS \to gg, t\bar{t}$; future DD and ID can test $m_S < (>)\, m_{top}$
  - $t\bar{t} + E_T^{miss}$ exclude wider m_T range than $\tilde{t}$ in SUSY
- Top+Charm flavored $\mathcal{L} = -y_3 S\overline{T_L} t_R - y_2 S\overline{T_L} c_R + h.c.$
  - $t \to c + \{SS, \gamma, g, Z\}$
  - easier to get $\langle \sigma v \rangle \sim 1pb \cdot c$ for $m_S < m_t$, better projections in future DD/ID
  - more collider signals
- Future experiments are promising in testing heavy quark flavored DM

Thank you for your attention

Back up slides

Why Top quark for Real scalar DM?

- Real Scalar DM: both s/p-wave are ***chirally*** suppressed
- mass ratio: $r_q = m_q/m_\chi$

$$\sigma(\chi\bar{\chi} \to \bar{q}q)v = a + bv^2 + O(v^4)$$

[N.F. Bell et al, 0805.3423] [Markus Luty *et al,* 1307.8120]

$$a \overset{r\to 0}{\simeq} r\frac{3m_\chi^2\lambda^4}{4\pi\left(m_Q^2+m_\chi^2\right)^2}$$

$$b \overset{r\to 0}{\simeq} -r\frac{m_\chi^4\left(2m_Q^2+m_\chi^2\right)\lambda^4}{2\pi\left(m_Q^2+m_\chi^2\right)^4}$$

$$a \overset{r\to 0}{\simeq} \frac{3m_\chi^2 r\lambda^4}{32\pi(m_Q^2+m_\chi^2)^2}$$

$$a \overset{r\to 0}{\simeq} \frac{3\lambda^4 m_\chi^2 r}{16\pi(m_Q^2+m_\chi^2)^2}$$

Model		Relic Abundance	Direct Detection
χ	Q		
Majorana fermion	Complex scalar	$a \sim m_q^2$ $\lambda \sim 0.5-2$	Suppressed $\sigma_{\rm SI} \overset{m_Q\gg m_\chi}{\sim} \frac{m_p^4}{m_Q^4}\sigma_{\rm ann}$
Dirac fermion	Complex scalar	$\lambda \sim 0.2-1$	Unsuppressed $\sigma_{\rm SI} \overset{m_Q\gg m_\chi}{\sim} \frac{m_p^2}{m_\chi^2}\sigma_{\rm ann}$
Real scalar	Dirac fermion	$a, b \sim m_q^2$ $\lambda \sim 0.5-5$	Suppressed if $m_\chi > m_t$ $\sigma_{\rm SI} \overset{m_Q\gg m_\chi}{\sim} \frac{m_p^4}{m_q^2 m_\chi^2}\sigma_{\rm ann}$
Complex scalar	Dirac fermion	$a \sim m_q^2$ $\lambda \sim 0.5-2$	Unsuppressed $\sigma_{\rm SI} \overset{m_Q\gg m_\chi}{\sim} \frac{m_p^2}{m_\chi^2}\sigma_{\rm ann}$
Real vector	Dirac fermion	$\lambda \sim 0.05-0.5$	Suppressed $\sigma_{\rm SI} \overset{m_Q\gg m_\chi}{\sim} \frac{m_p^4}{m_\chi^4}\sigma_{\rm ann}$
Complex vector	Dirac fermion	$\lambda \sim 0.07-0.7$	Unsuppressed $\sigma_{\rm SI} \overset{m_Q\gg m_\chi}{\sim} \frac{m_p^2}{m_\chi^2}\sigma_{\rm ann}$

Heavy top partner / Vector-like Fermion

D. Yamaguchi, ATLAS

H. Tholen, CMS

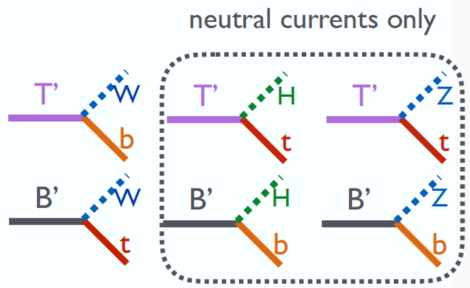
Vector-Like Quarks

- Many models beyond the Standard Model predict the existence of vector-like quarks (VLQ) to cancel the quadratic divergences arising from radiative corrections of Higgs mass
  - e.g. Little Higgs, Composite Higgs, Extra-dimensions, etc
- VLQ: spin 1/2, color-triplet, L&R-handed components under SU(3)xSU(2)xU(1)
  - Mix with SM quarks by Yukawa coupling, and allowed from experimental constraints (EW/Higgs measurement) unlike 4th generation of quarks

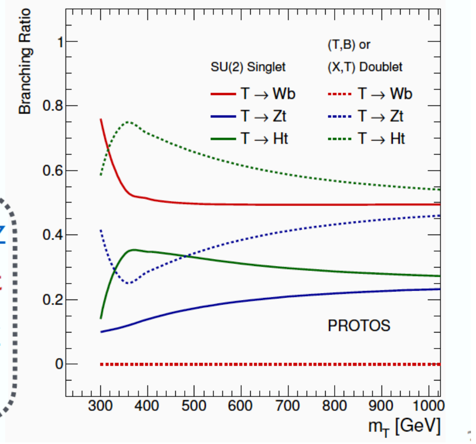
		SM	SU(2) Singlet	SU(2) Doublet	SU(2) Triplet
EM charge	5/3			X	X
	2/3	u c t	(T)	T, T	T, T
	-1/3	d s b	(B)	B, B	B, B
	-4/3			Y	Y
Mass		from Higgs	e.g.) generated by Yukawa coupling to a scalar singlet with VEV v' >> v(=246 GeV)		

vector-like quarks
(VLQ)

- quarks! colored, charged, spin 1/2
- vector-like: same coupling to lh and rh currents
  => mass terms without gauge inv. violation
- not constrained through Higgs discovery
  (unlike chiral 4[th]-gen quarks)
- simplest colored extra-fermions allowed by data
- common in SM-extensions:
  - e.g. little Higgs, composite Higgs, warped/extra dimensions
  - solve the Hierarchy problem
  - stabilize the Higgs mass



[JHEP 08 (2015) 105]

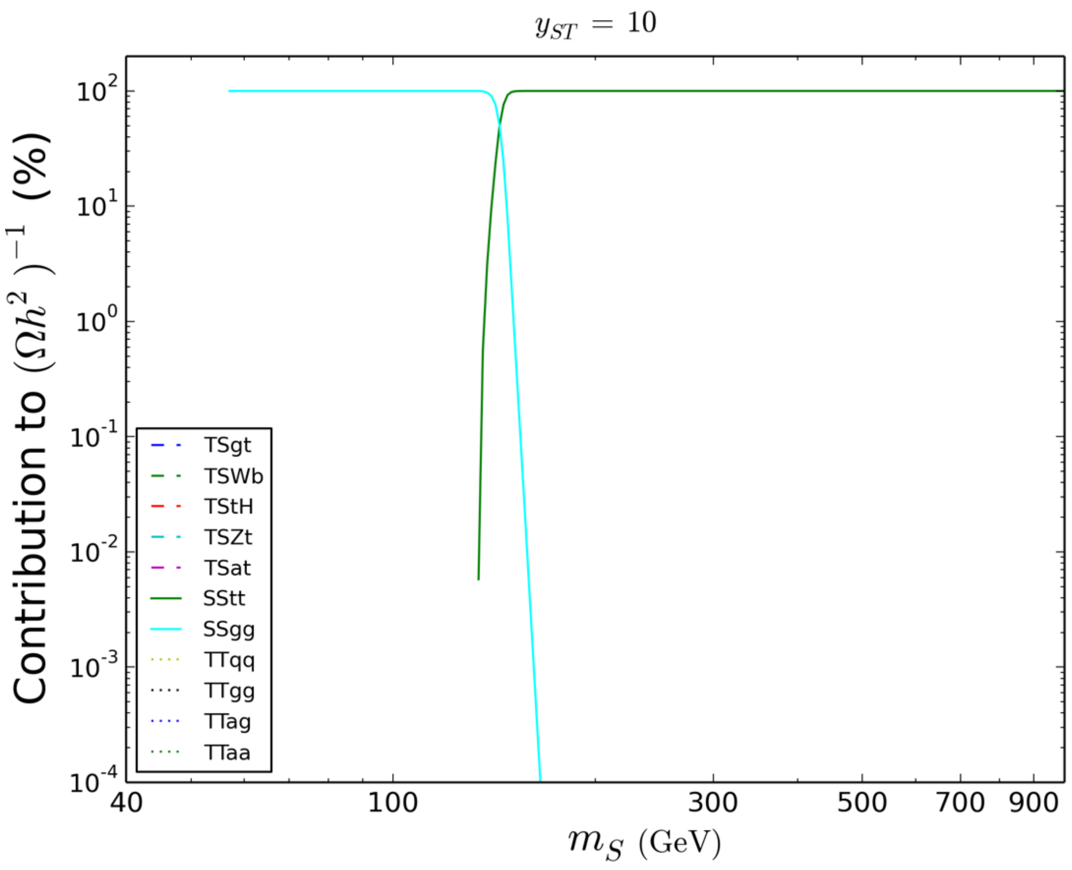


$$\sigma v \sim y_3^4\,(\ldots)_{t\bar{t}} + y_3^2 y_2^2\,(\ldots)_{t\bar{c}} + y_2^4\,(\ldots)_{c\bar{c}} + \cdots$$

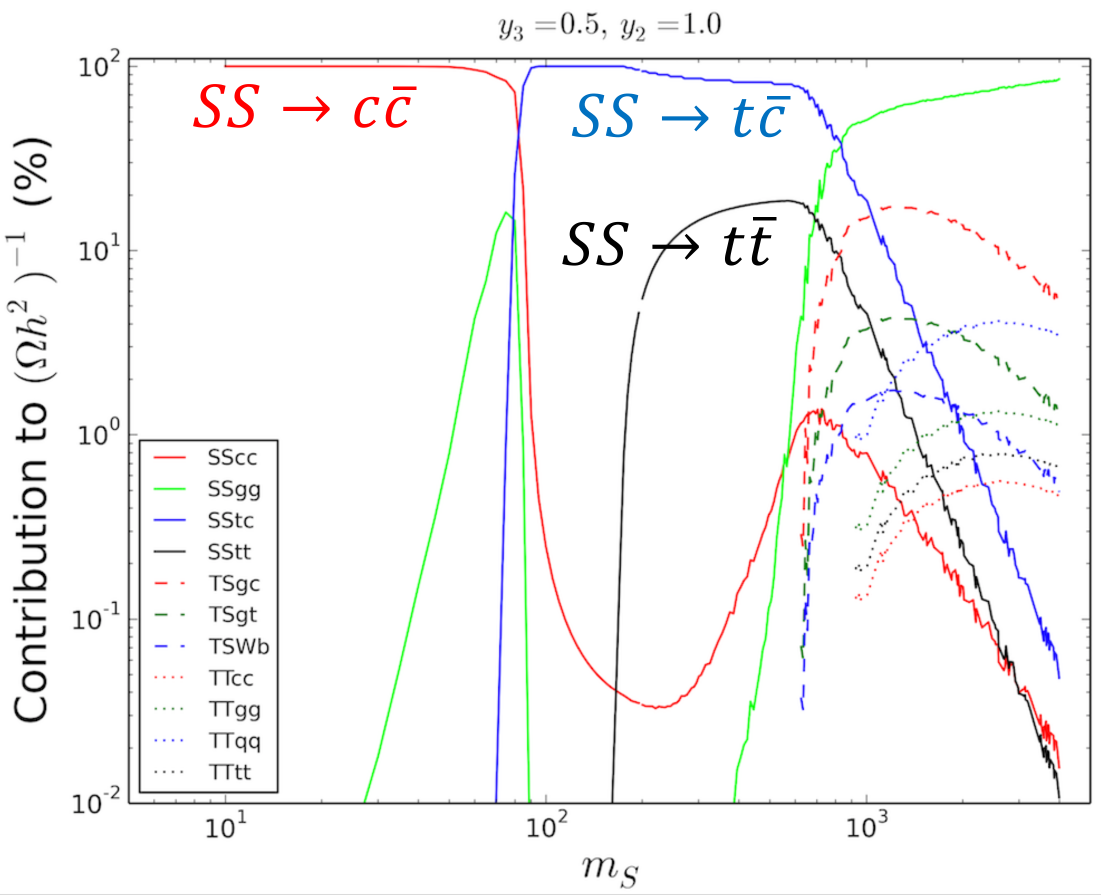
$y_2 = 1.0$
$y_3 = 0.5$

Annihilation Contribution

Top Flavored



Top+Charm Flavored



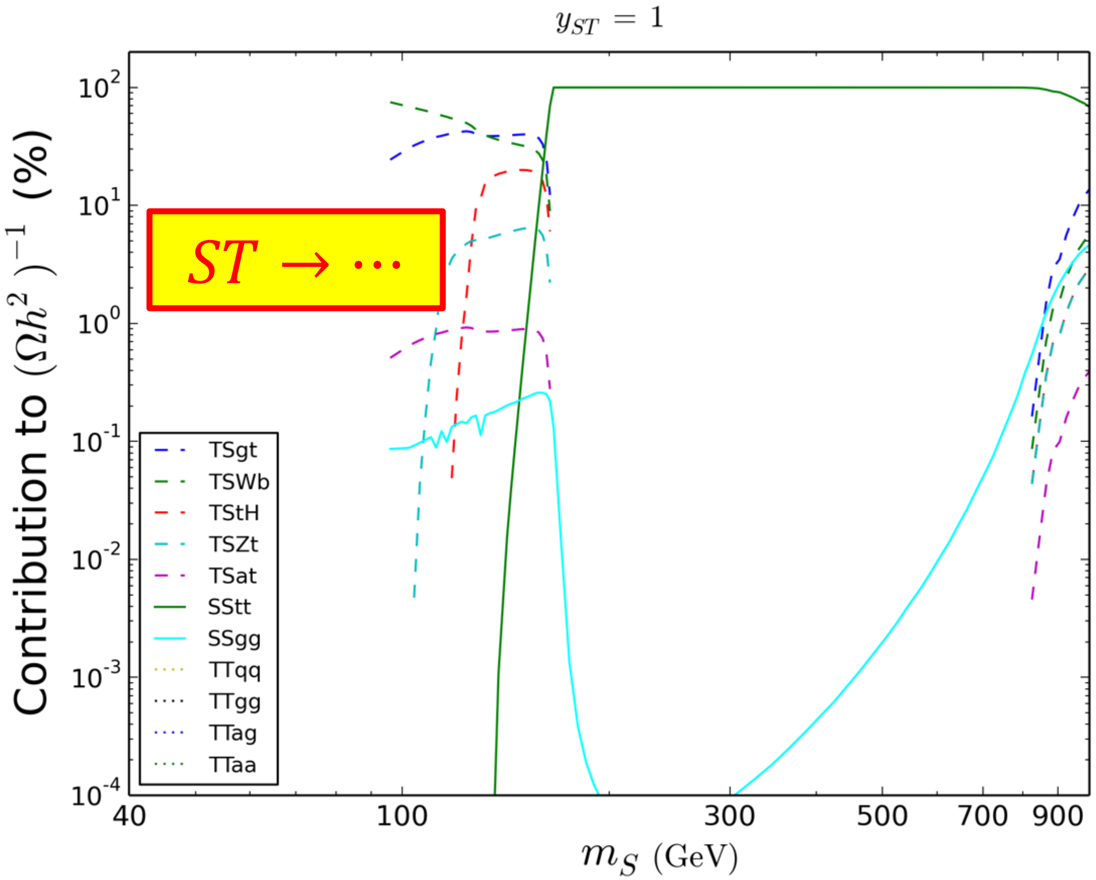
$$\sigma v \sim y_3^4\,(\ldots)_{t\bar{t}} + y_3^2 y_2^2\,(\ldots)_{t\bar{c}} + y_2^4\,(\ldots)_{c\bar{c}} + \cdots$$

$y_2 = 0.5$

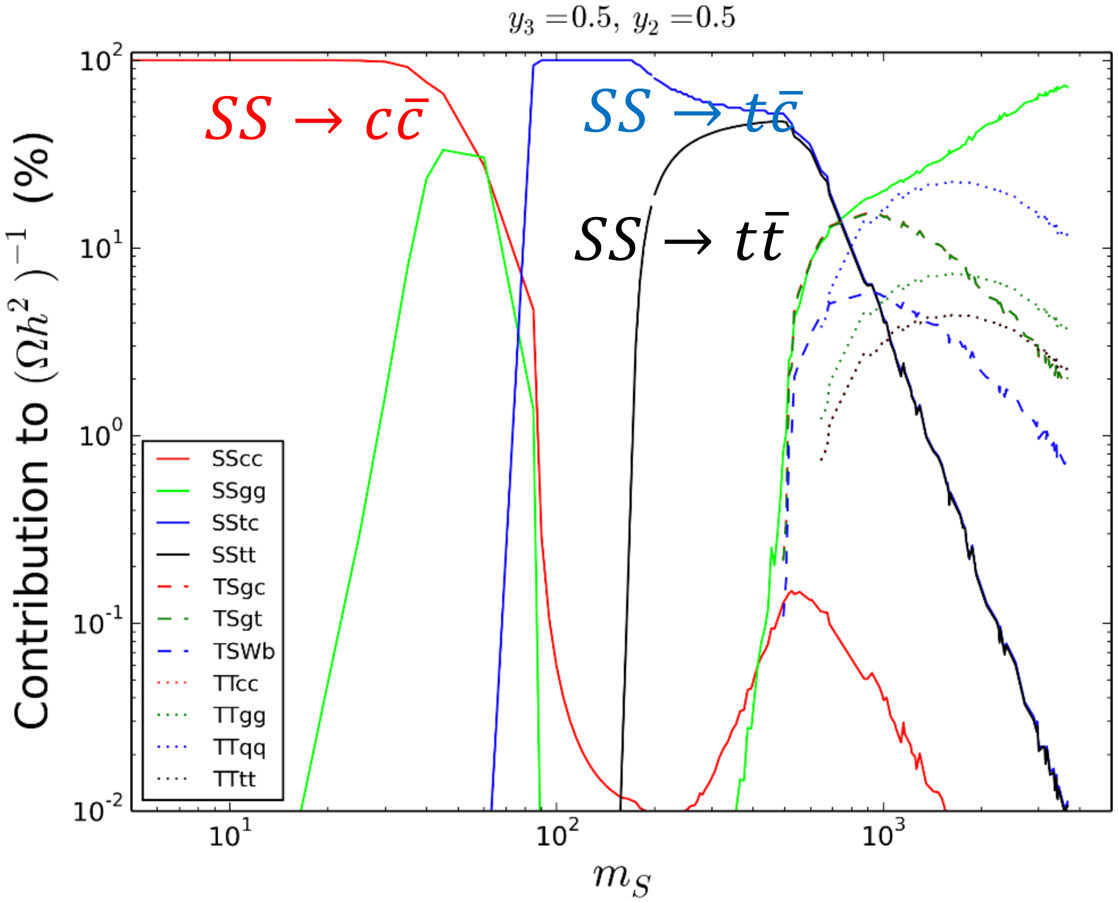
$y_3 = 0.5$

Annihilation Contribution

Top Flavored



Top+Charm Flavored

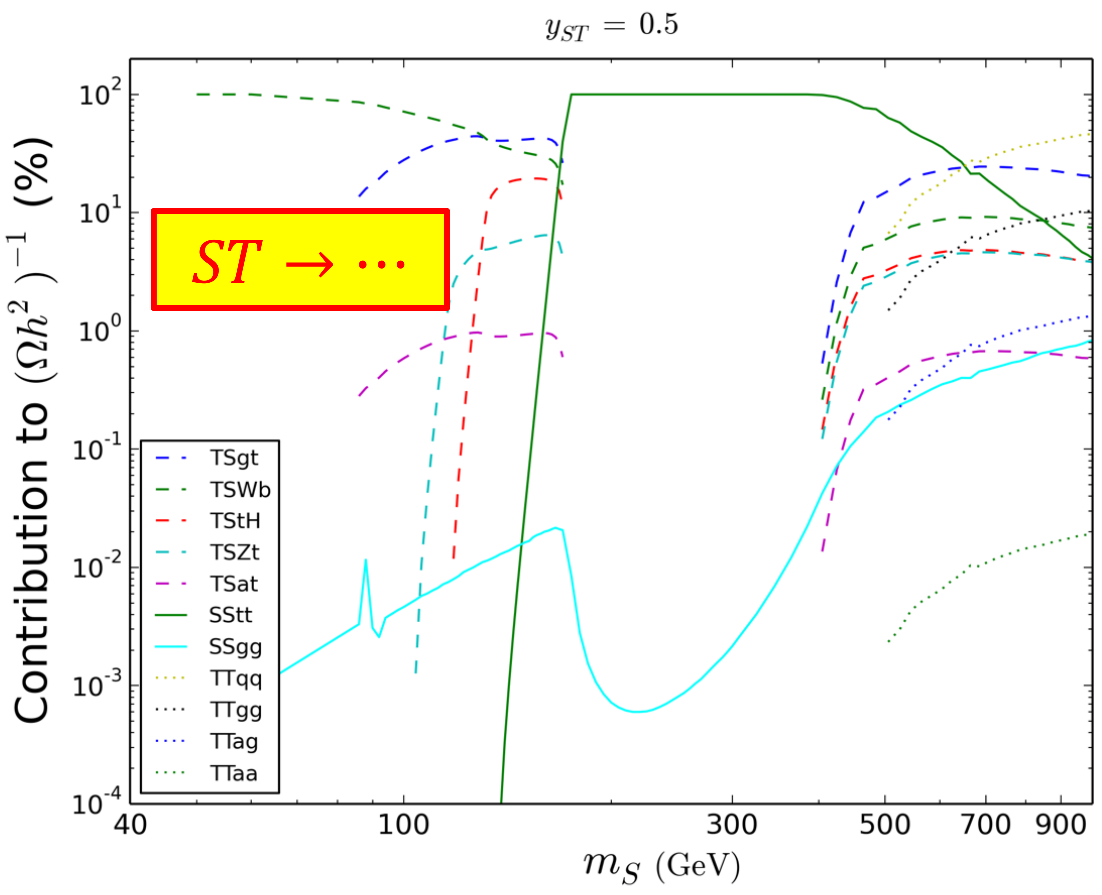


$$\sigma v \sim y_3^4\,(\ldots)_{t\bar{t}} + y_3^2 y_2^2\,(\ldots)_{t\bar{c}} + y_2^4\,(\ldots)_{c\bar{c}} + \cdots$$

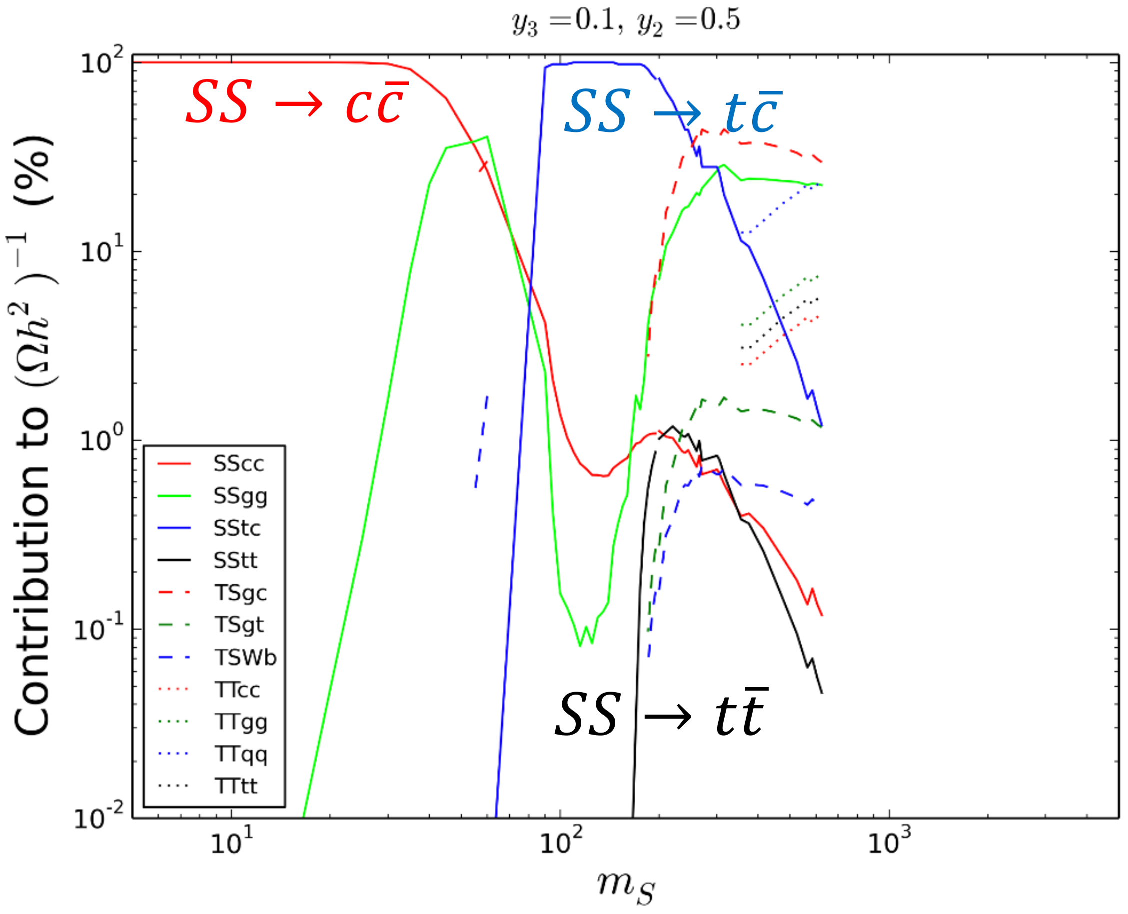
$y_2 = 0.5$
$y_3 = 0.1$

Annihilation Contribution

Top Flavored



Top+Charm Flavored



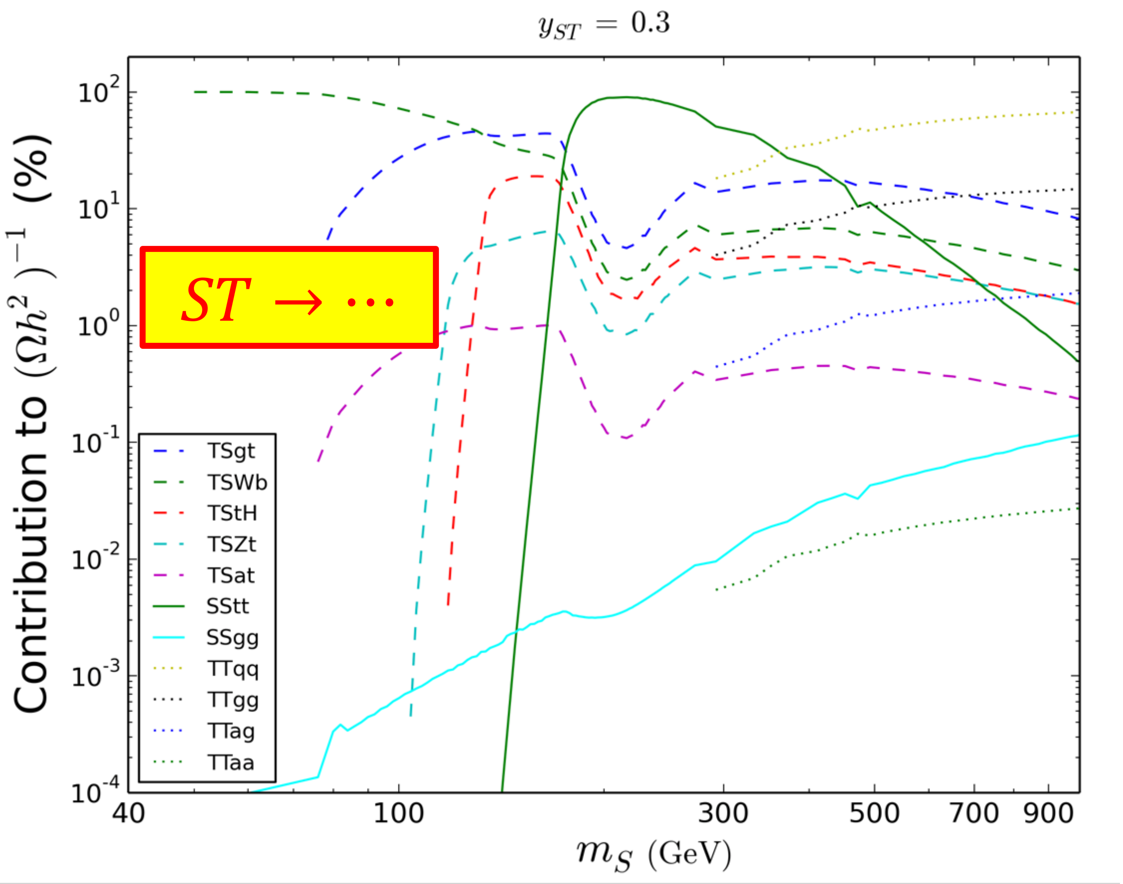
$$\sigma v \sim y_3^4\,(\ldots)_{t\bar{t}} + y_3^2 y_2^2\,(\ldots)_{t\bar{c}} + y_2^4\,(\ldots)_{c\bar{c}} + \cdots$$

$y_2 = 0.1$

$y_3 = 0.1$

Annihilation Contribution

Top Flavored



Top+Charm Flavored