Heavy Quark(s) Flavored Scalar Dark Matter with a Vector-like Fermion Mediator

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Collaborated with Pyungwon Ko, Seungwon Baek

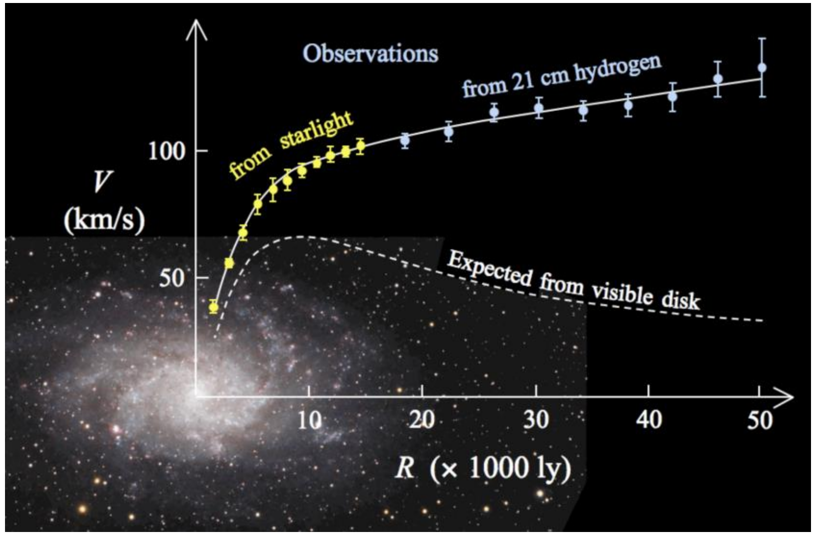
based on arXiv: 1606.00072 and 1703.*****

Outline

- Motivation
  - Why heavy quark flavored DM?
- Model description
- Properties
  - Thermal relic density
  - Direct/Indirect detection
  - Collider search
- Conclusion

Observational Hints of DM

- galactic rotation curve
- bullet cluster collision
- …

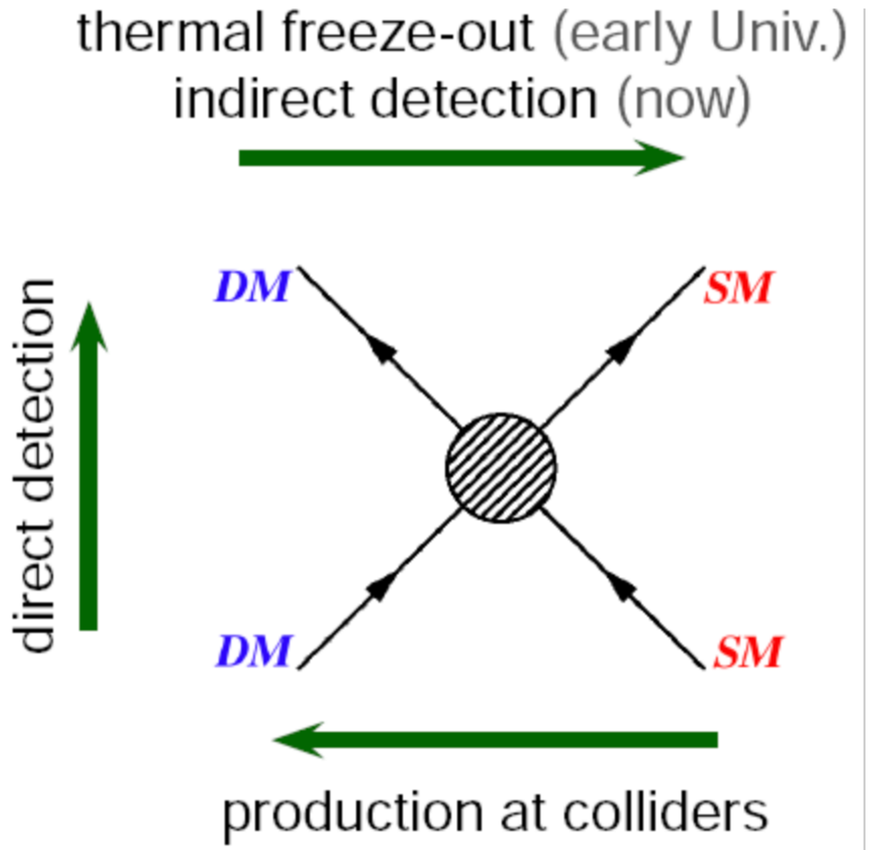


Credit: Stefania.deluca
https://en.wikipedia.org/wiki/File:M33_rotation_curve_HI.gif

Credit: NASA/CXC/CfA/ M.Markevitch et al.
https://apod.nasa.gov/apod/ap060824.html

Detection Methods of DM

- Direct Detection
  - scattering between DM and nucleons
- Indirect Detection
  - DM annihilation/decay today in the sky
- Collider Searches
  - missing energy/momentum carried by DM



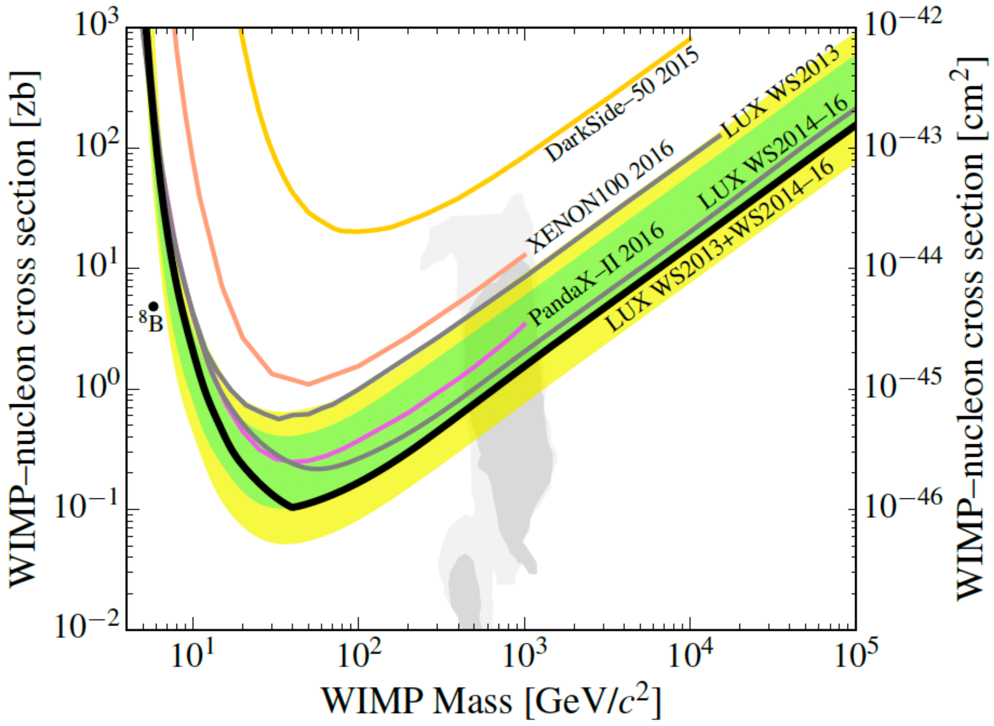
https://www.mpi-hd.mpg.de/lin/research_DM.en.html

No confirmed DD signal yet

- WIMP may couple weakly to light quarks

- If DM couple dominantly to heavy quark(s)
  - what are the main properties?
  - can it be tested in future experiments?

[1608.07648, LUX]



Model: Top-flavored Scalar DM

- DM: real scalar S
  - SM singlet, couple only to t_R
  - Higgs portal, strongly constrained
    - $\lambda_{SH} S^2 |H|^2$ turned off [1306.4710, J. Cline *et al*]
- top partner: 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 $(S, H), (T, t)$
  - $Br\left(T \to S t^{(*)}\right) = 100\%$
  - LHC searches for VL (T, B) do not apply

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

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

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

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

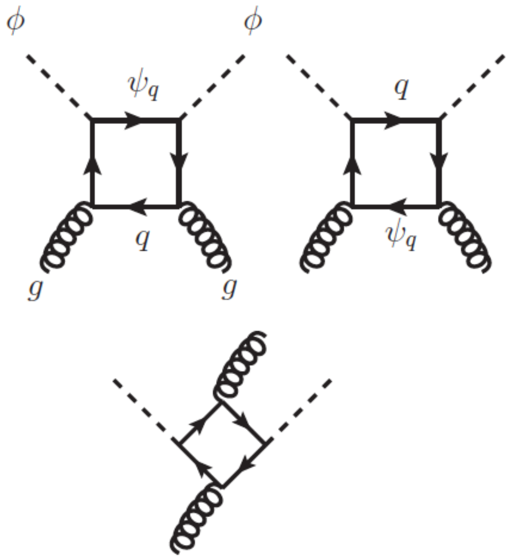
$$\mathcal{L}_T = \bar{T}(i\not{D} - m_T) T$$

Thermal Relic

- pair annihilation (t-channel)
  - $SS \to t\bar{t} \quad \propto y_{ST}^{4}$
- co-annihilation (s/t-channel)
  - $ST \to t^* \to bW^+$
  - $ST \to t + \{g, \gamma, Z, h\},\ \langle \sigma v \rangle_{ST} \propto y_{ST}^{2}$

  - $T\bar{T} \to SM + SM^{(\prime)}$

- loop coupling C_{Sg}
  - [1502.02244, Junji Hisano *et al*]
  - $SS \to gg$
  - $\langle \sigma v \rangle_{gg} \propto y_{ST}^{4} g_s^4$
    - can be sizable when $y_{ST} \sim \mathcal{O}(10)$



Thermal Relic

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

for fixed $\boldsymbol{m_S}$

look at how $\boldsymbol{m_f}$ matters

Real (Complex) Scalar DM:

s/p (s) -wave chiral suppression

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

$$\sigma v(SS \to t\bar{t})_p = [y_3{}^4] \frac{3}{4\pi m_S{}^2} \frac{r_t{}^2 \sqrt{1 - r_t{}^2}}{(r_T{}^2 - r_t{}^2 + 1)^4} \times \left(9 r_T{}^4 r_t{}^2 - 2 r_T{}^2 \left(9 r_t{}^4 - 25 r_t{}^2 + 16\right) + \left(r_t{}^2 - 1\right)^2 \left(9 r_t{}^2 - 16\right)\right)$$

Thermal Relic

$$\frac{1}{r_t} = r_S = \frac{m_S}{m_{top}}, \quad r_T = \frac{m_T}{m_S}$$

for fixed $\boldsymbol{m_f}$

look at how $\boldsymbol{m_S}$ matters

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

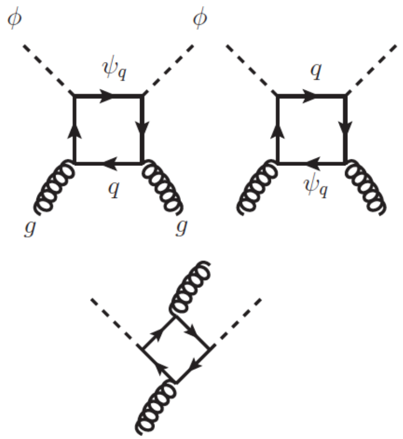
$$\sigma v(SS \to t\bar{t})_p = [y_3{}^4] \frac{1}{32\pi m_t{}^2} \frac{\sqrt{r_S{}^2 - 1}}{r_S{}^3(r_S{}^2(r_T{}^2+1)-1)^4}$$
$$\times(-16 r_S{}^6(2r_T{}^2+1) + r_S{}^4(r_T{}^2+1)(9r_T{}^2+41) - 2r_S{}^2(9r_T{}^2+17)+9)$$

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

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

$SSgg$ Loop coupling

- no valence top quark in nucleon
- $C_{Sg} \propto y_{ST}^2 \times f_{loop}(m_S, m_T, m_t)$
  - sizable when $y_{ST} \sim \mathcal{O}(10)$
  - can be suppressed by large $r_T = m_T/m_S$



$$\mathcal{L}_{\rm eff} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p + \sum_{p=q,g} C_{T_2}^p \mathcal{O}_{T_2}^p$$

$$\mathcal{O}_S^q \equiv \phi^2 m_q \bar{q} q \ ,$$
$$\mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi} \phi^2 G^{A\mu\nu} G^A_{\mu\nu} \ ,$$
$$\mathcal{O}_{T_2}^q \equiv \frac{1}{M^2} \phi i\partial^\mu i\partial^\nu \phi \mathcal{O}^q_{\mu\nu}$$
$$\mathcal{O}_{T_2}^g \equiv \frac{1}{M^2} \phi i\partial^\mu i\partial^\nu \phi \mathcal{O}^g_{\mu\nu}$$

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

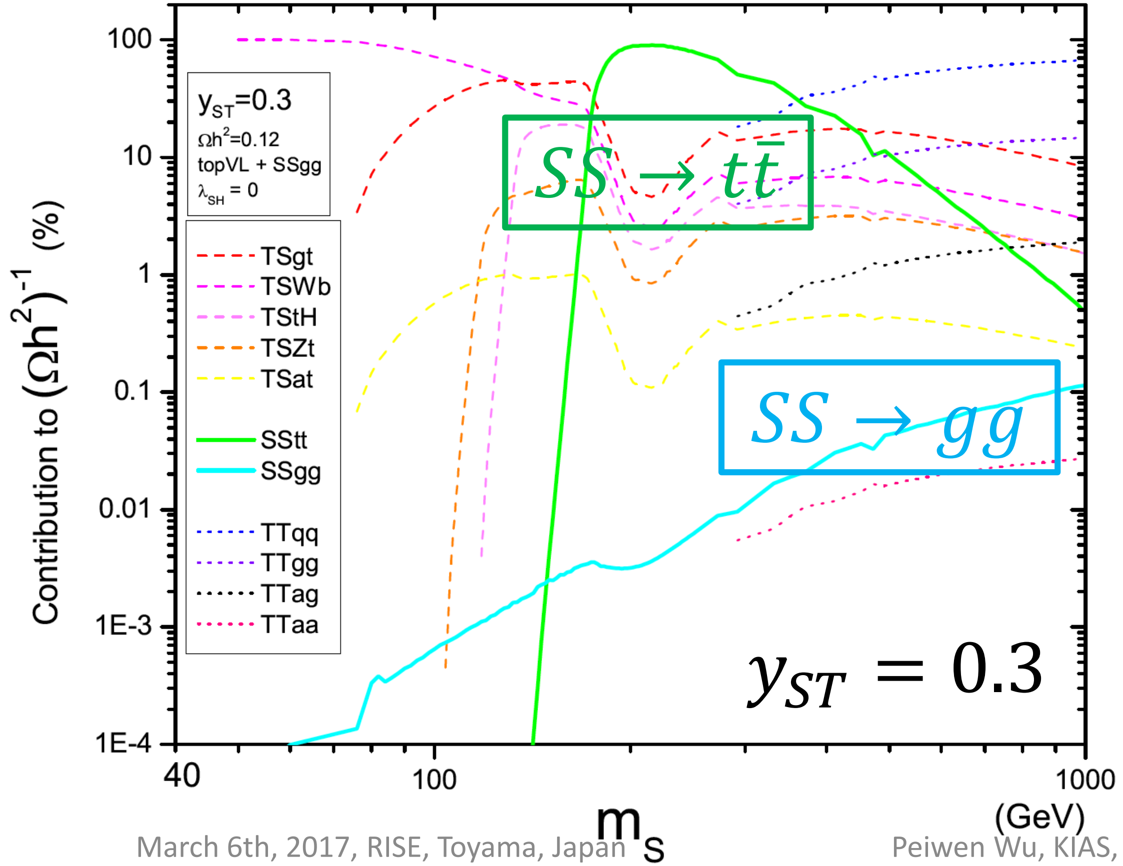
$\langle\sigma v\rangle_{ST} \propto y_{ST}^{2}$

$\langle\sigma v\rangle_{t\bar{t}} \propto y_{ST}^{4}$

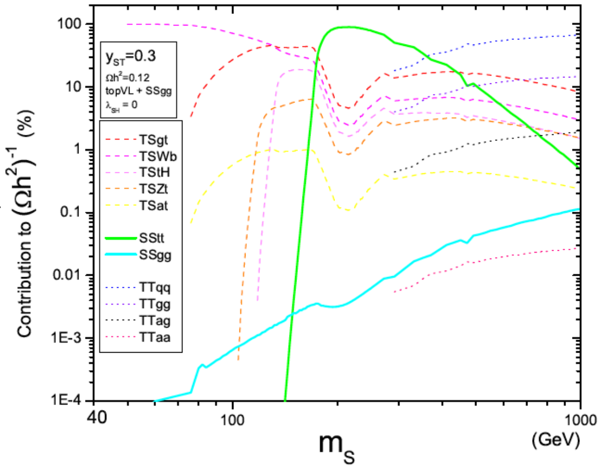
$\langle\sigma v\rangle_{gg} \propto y_{ST}^{4}\, g_s^4$

$Br_{chan.}$ to $\langle\sigma v\rangle_{FO} \sim 3\, pb \cdot c$

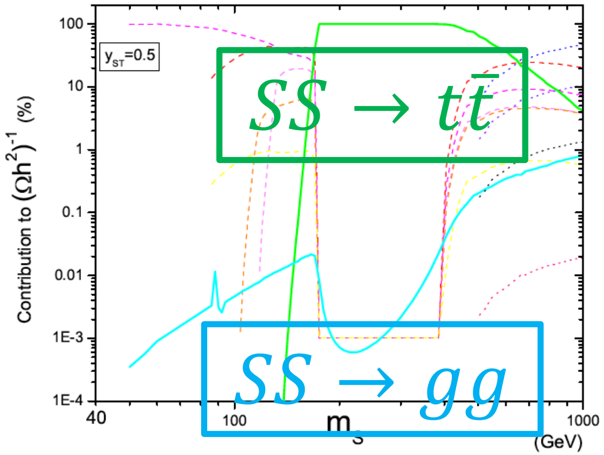
- $\Omega_{DM} h^2 (y_{ST}, m_S, m_T) \sim 0.12$
- given $\{y_{ST}, m_S\}$, m_T and Br are fixed



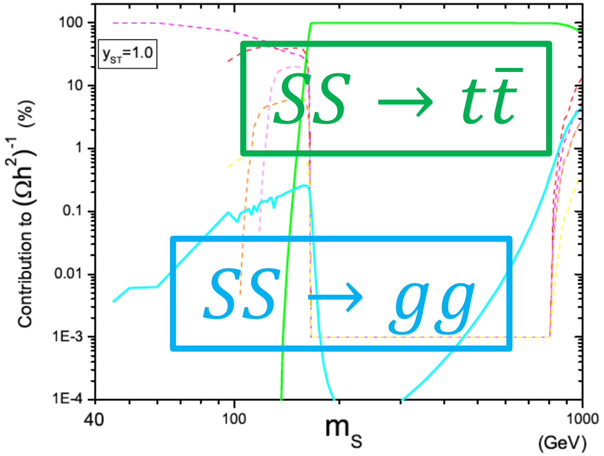
$y_{ST} = 0.3$



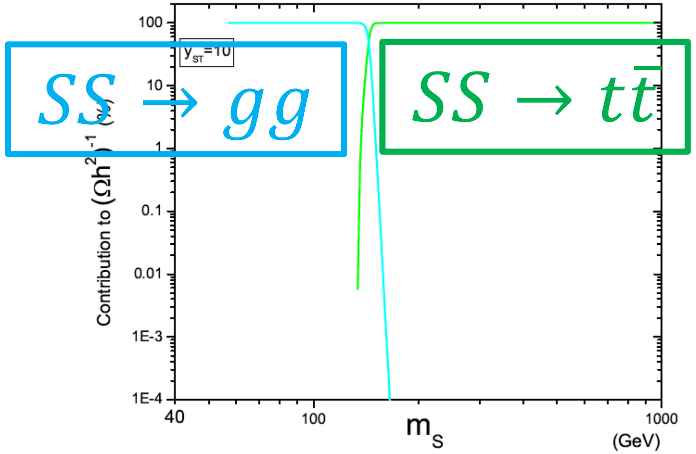
$y_{ST} = 0.5$



$y_{ST} = 1$



$y_{ST} = 10$

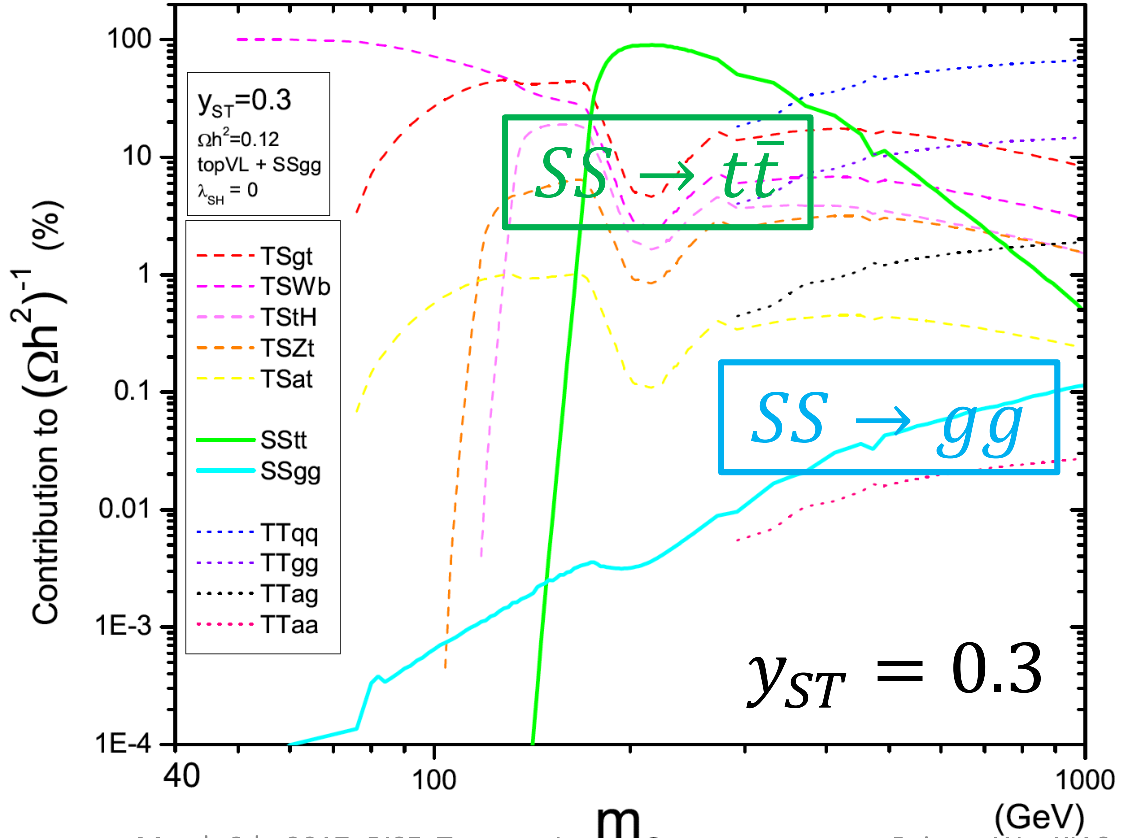


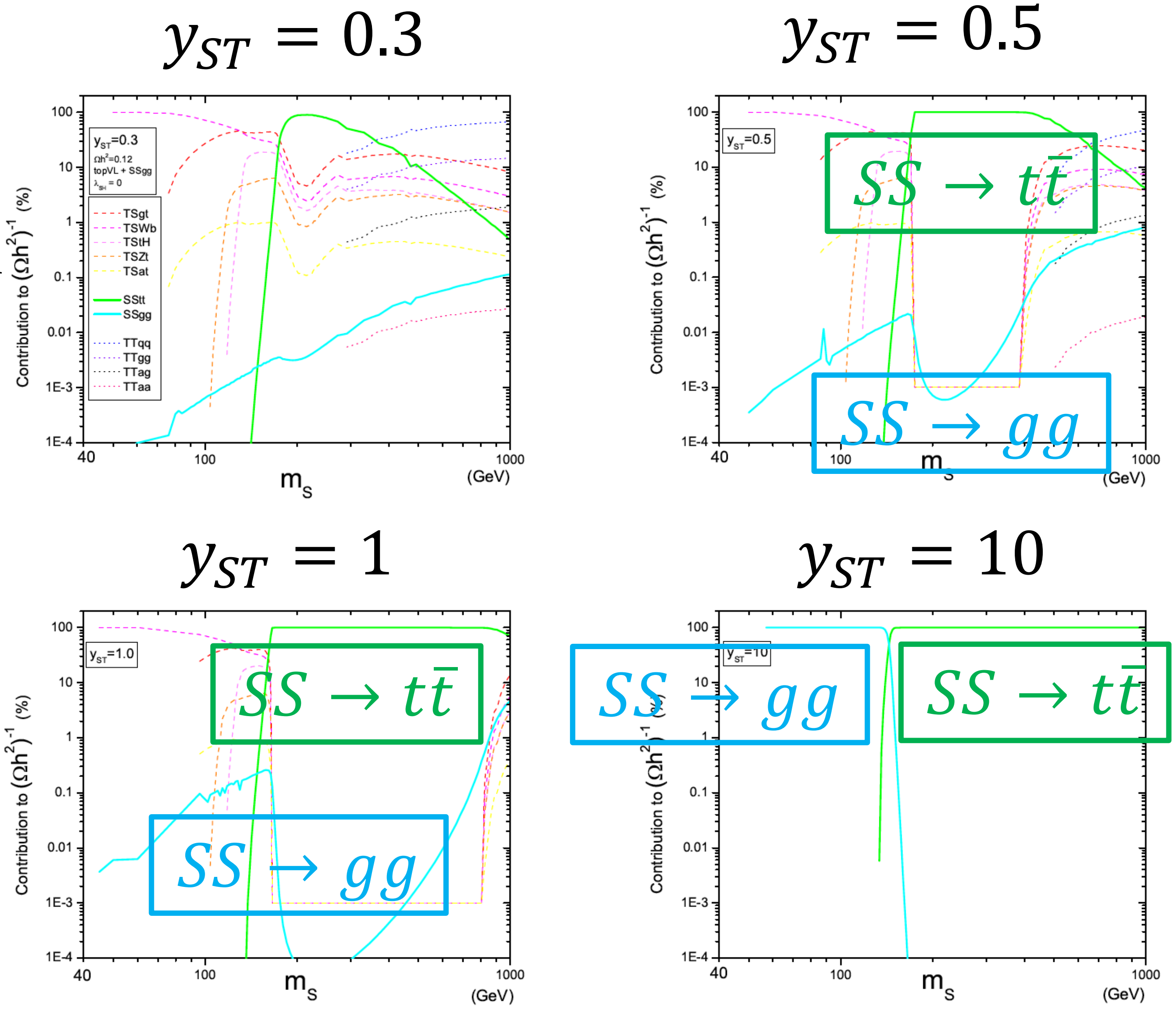
$\langle \sigma v \rangle_{gg} \propto y_{ST}^4 \, g_s^4$

$SS \to gg$ is small (**large**) for $y_{ST} < (>) \, \mathcal{O}(1)$

$Br_{chan.}$ to $\langle \sigma v \rangle_{FO} \sim 3 \, pb \cdot c$

- $\Omega_{DM} h^2 (y_{ST}, m_S, m_T) \sim 0.12$
- given $\{y_{ST}, m_S\}$, m_T and Br are fixed





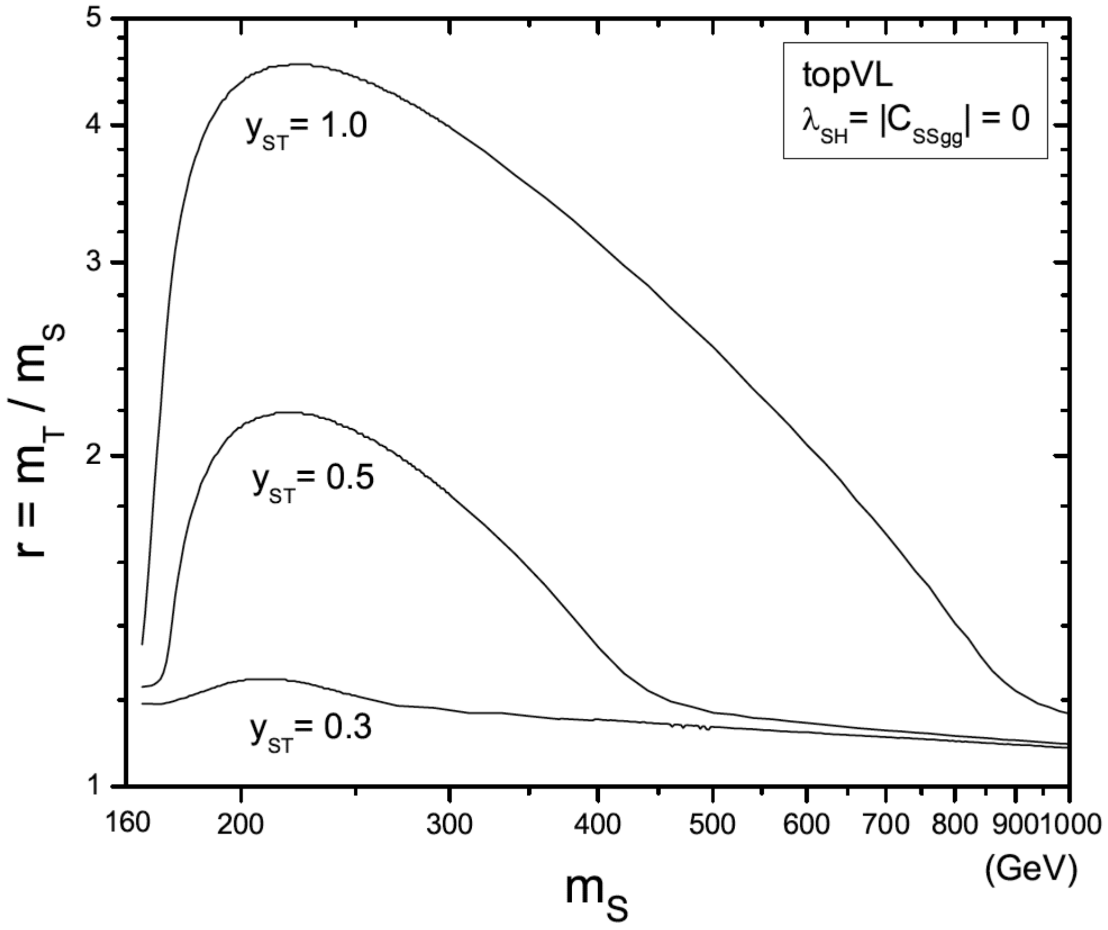
Thermal Relic

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

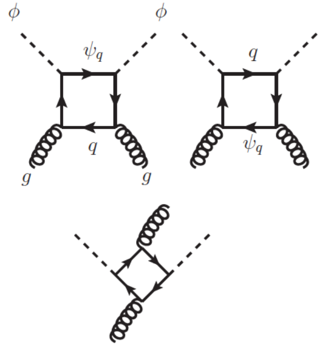
$$\sigma v(SS \to t\bar{t})_p = [y_3{}^4]\frac{1}{32\pi m_t{}^2}\frac{\sqrt{r_S{}^2 - 1}}{r_S{}^3(r_S{}^2(r_T{}^2 + 1) - 1)^4}$$
$$\times(-16r_S{}^6(2r_T{}^2 + 1) + r_S{}^4(r_T{}^2 + 1)(9r_T{}^2 + 41) - 2r_S{}^2(9r_T{}^2 + 17) + 9)$$

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

- 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

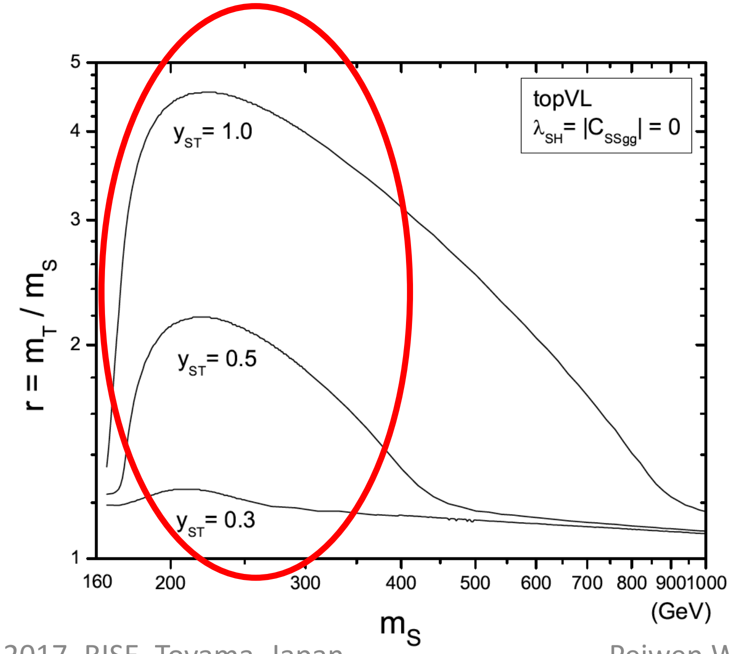


Thermal Relic

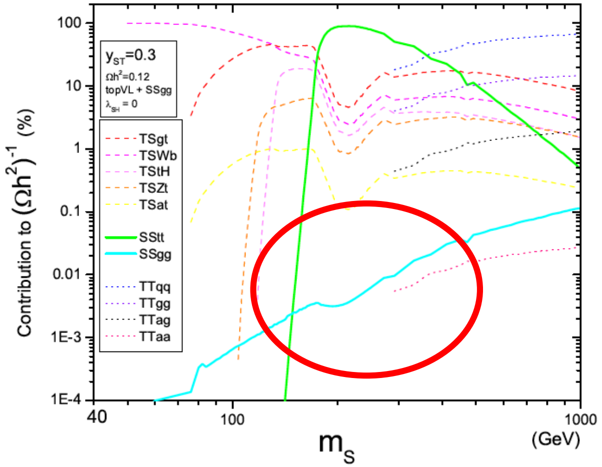


$SS \to t\bar{t}$, $SS \to gg$

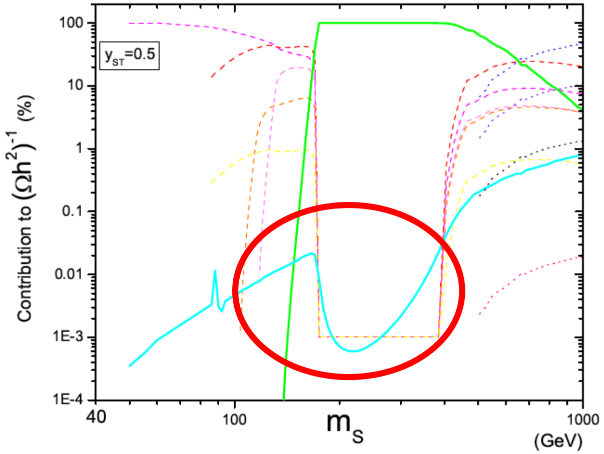
- when $SS \to t\bar{t}$ is open
  - suppressed C_{Sg}
    - affect the **direct detection**



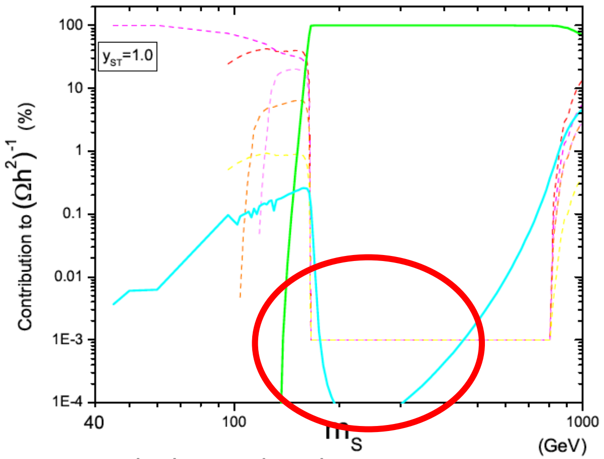
$y_{ST} = 0.3$



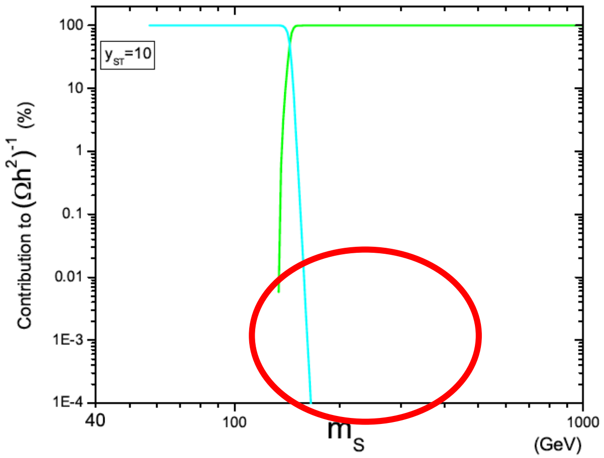
$y_{ST} = 0.5$



$y_{ST} = 1$

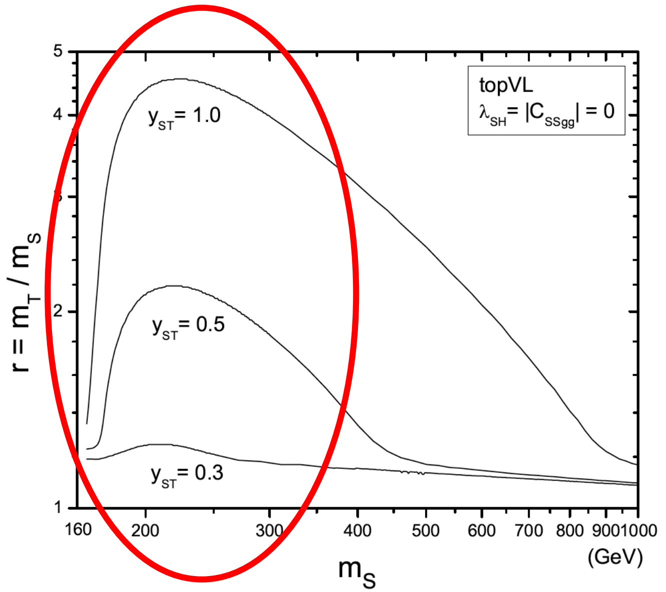


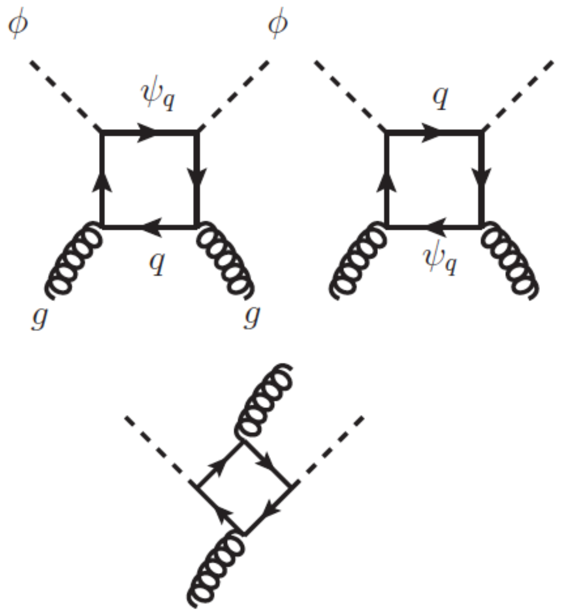
$y_{ST} = 10$

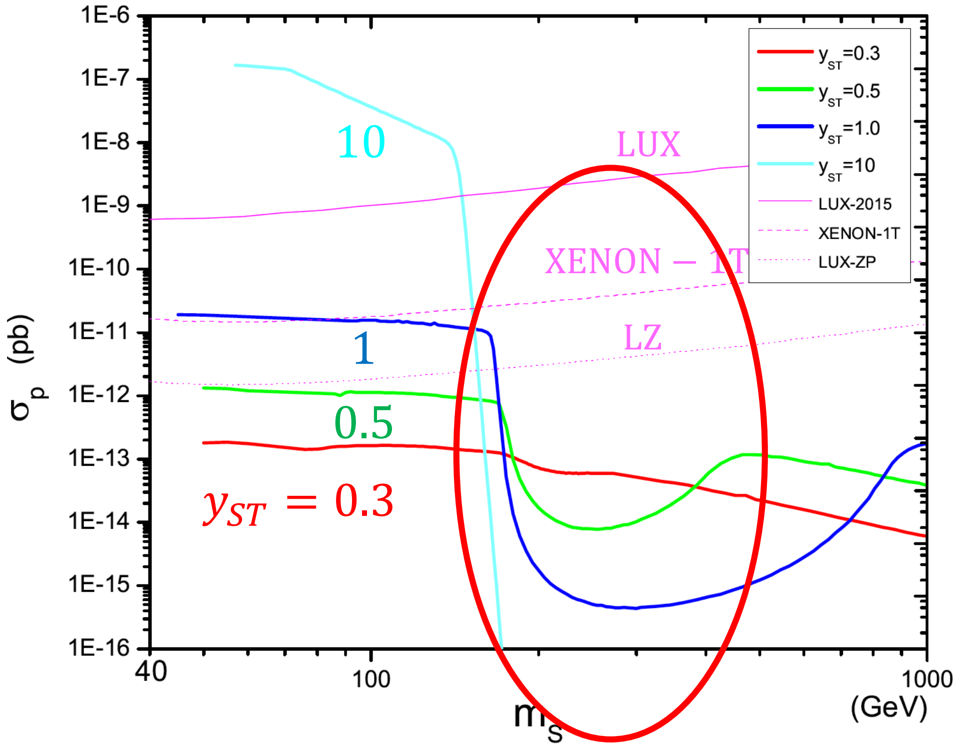


Direct detection

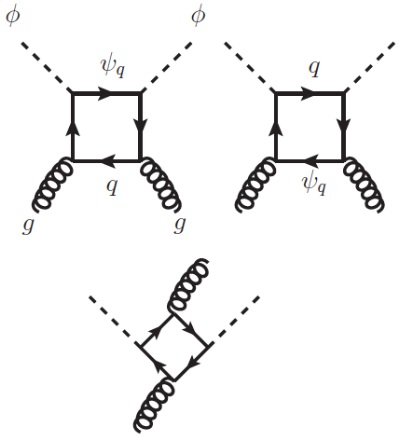
- for $m_S > m_t$, where $SS \to t\bar{t}$ and $r_T = \frac{m_T}{m_S}$
  - generally heavier m_T
  - suppressed C_{Sg} and σ_{SI}





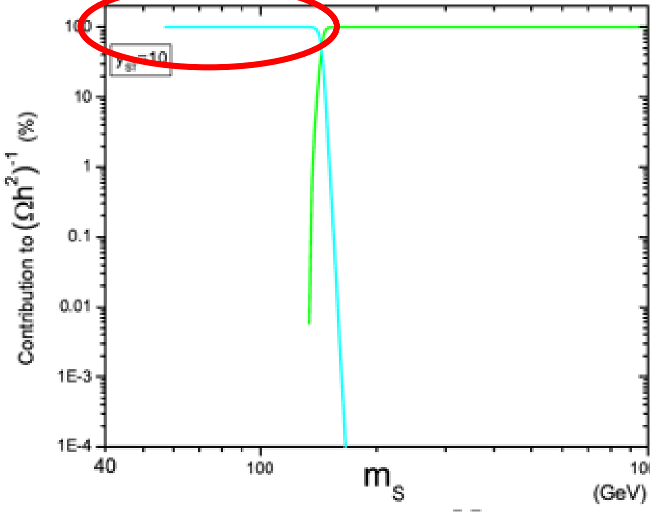


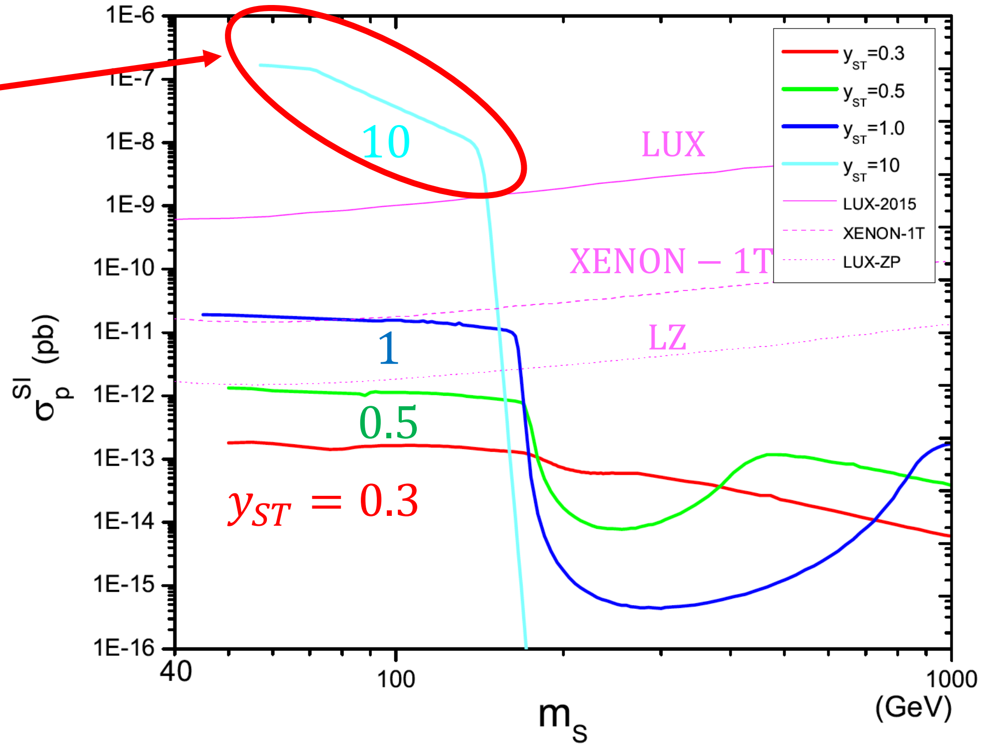
Direct detection



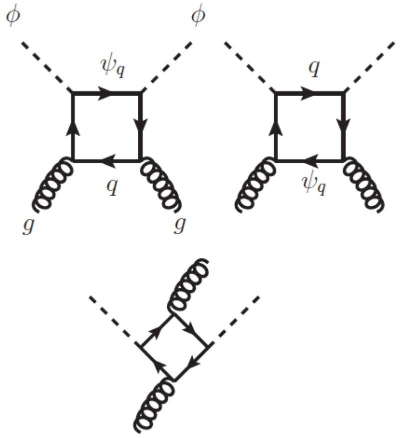
- $C_{Sg} \propto y_{ST}^2 \times f_{loop}(m_S, m_T, m_t)$
- for $m_S < m_t$,large $y_{ST} \sim O(10)$
  - $SS \rightarrow gg$ dominate in light m_S
  - σ_{SI} locked by canonical $\langle \sigma v \rangle \sim 1\, pb \cdot c$
  - excluded by LUX-2015

$y_{ST} = 10$

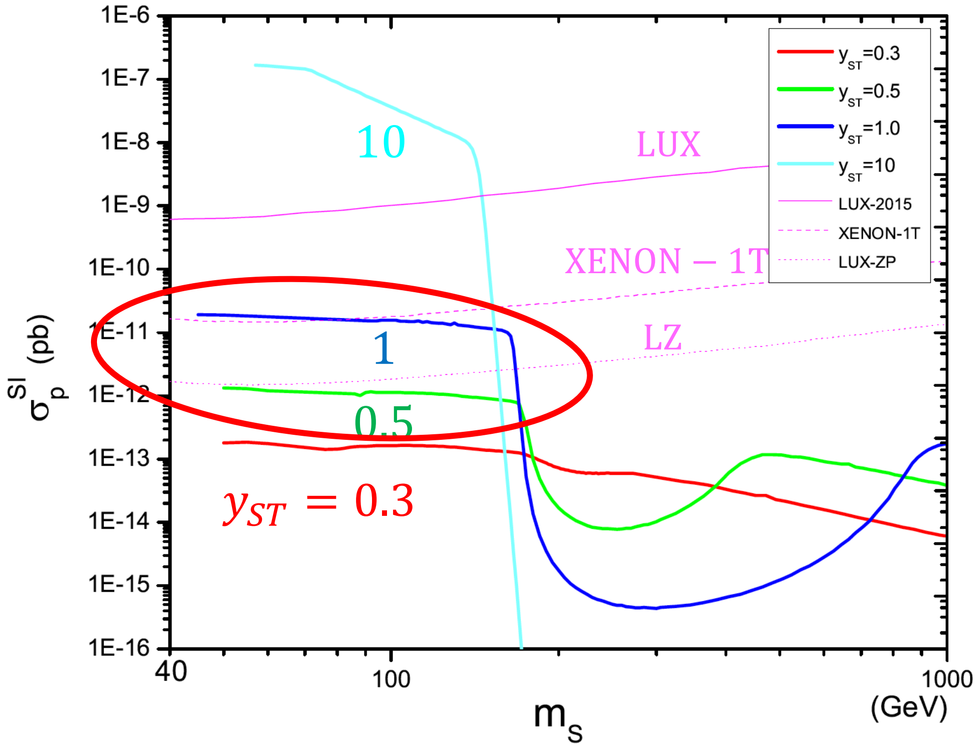




Direct detection



- $y_{ST} > 0.5$
  - light $m_S < m_t$ can be tested at LZ

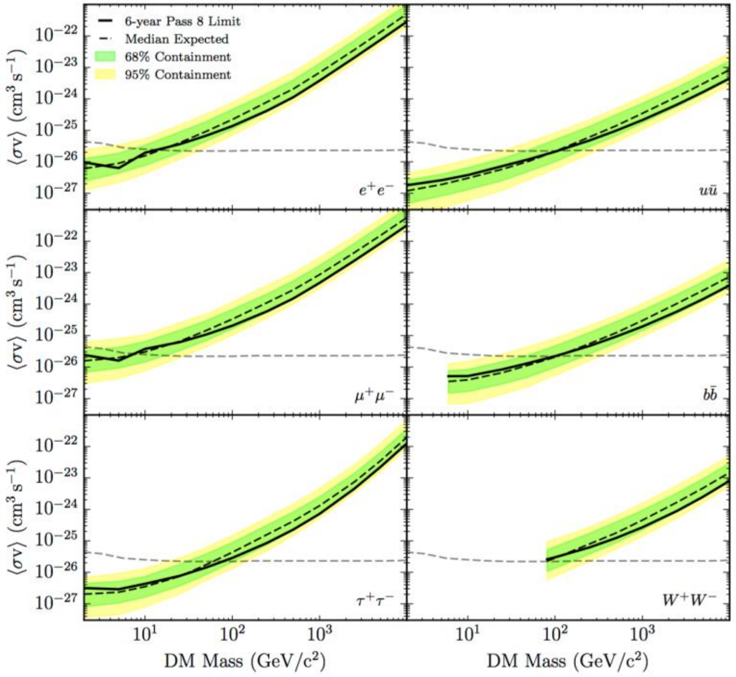


Indirect detection (γ-ray)

- current ID bounds are approaching canonical $\langle \sigma v \rangle \sim 1\, pb \cdot c$

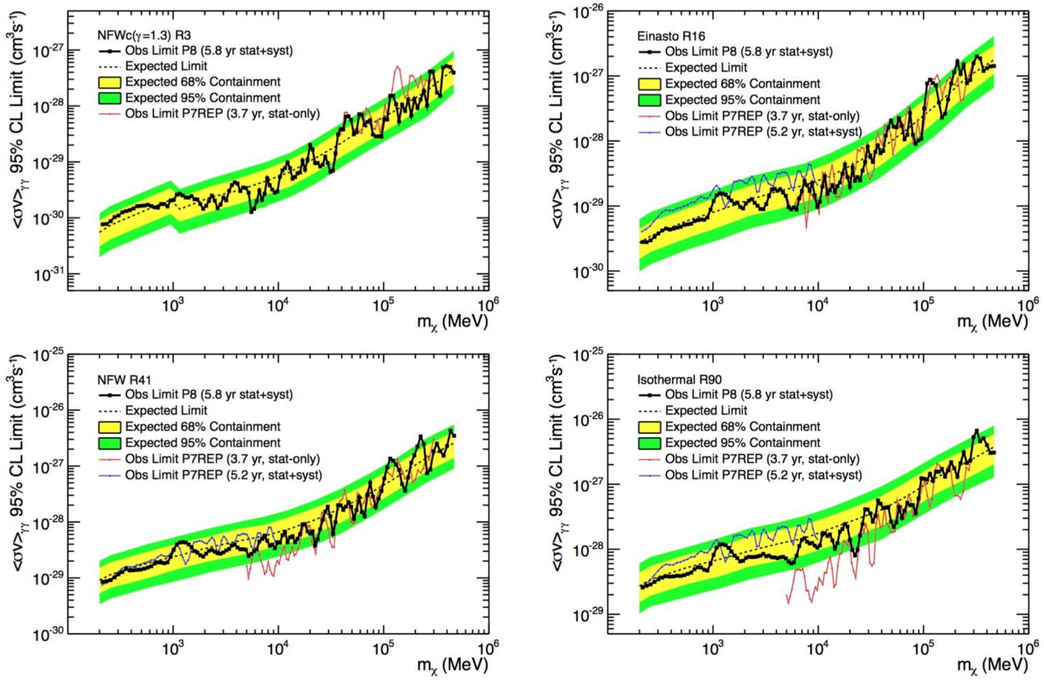
[arXiv: 1503.02641, Fermi]

Dwarf **continuous** γ-spectrum



[arXiv: 1506.00013, Fermi]

Galactic Center **line** γ-spectrum



Indirect detection (γ-ray)

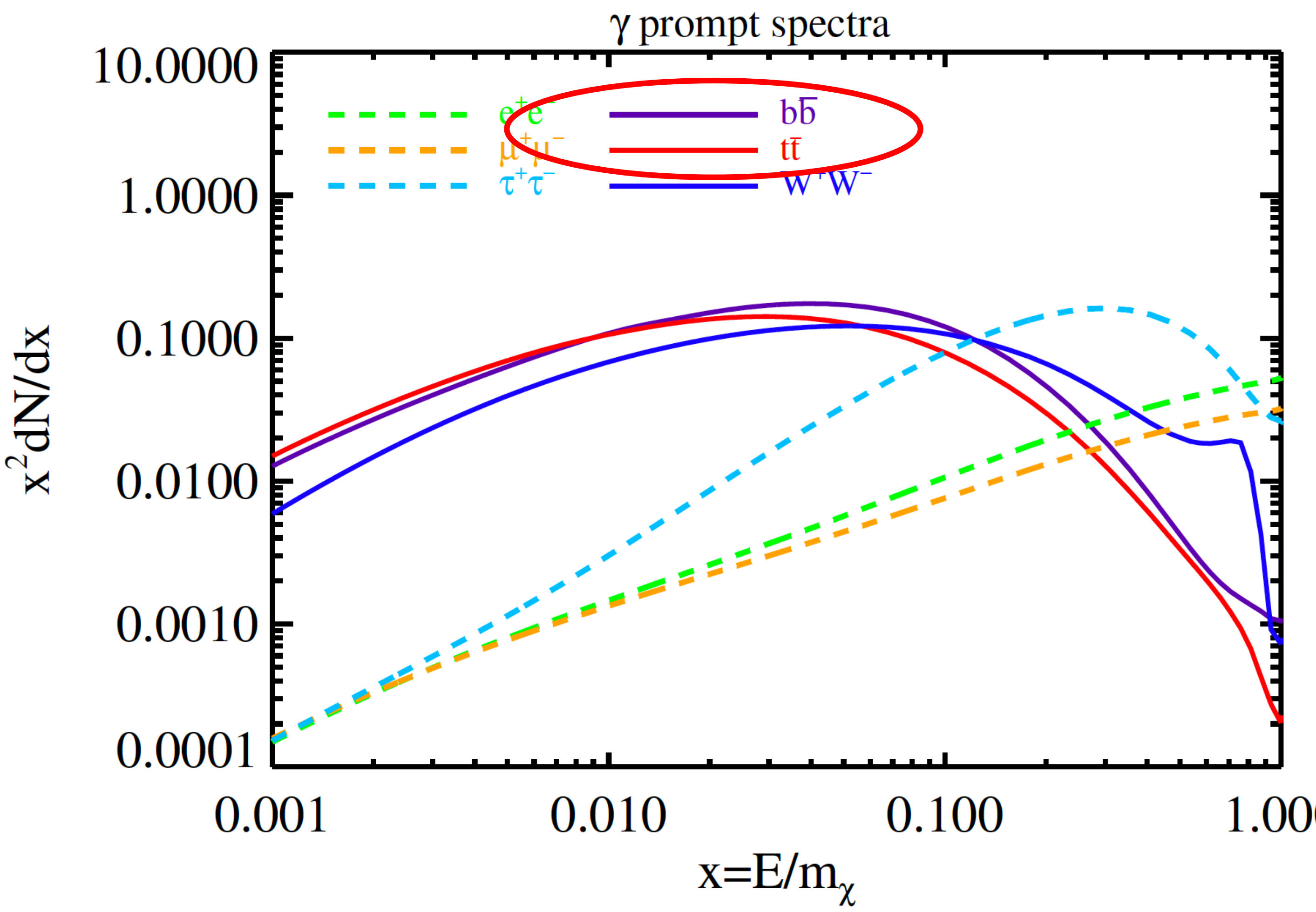
[1604.00014, Jennifer Gaskins]

- continuous spectrum
- no $t\bar{t}$?
  - rescale from others, e.g. $b\bar{b}$
  - $\langle\sigma v\rangle_{gg}$ obtained from $u\bar{u}$

  [1511.04452 F. Giacchino *et al*]

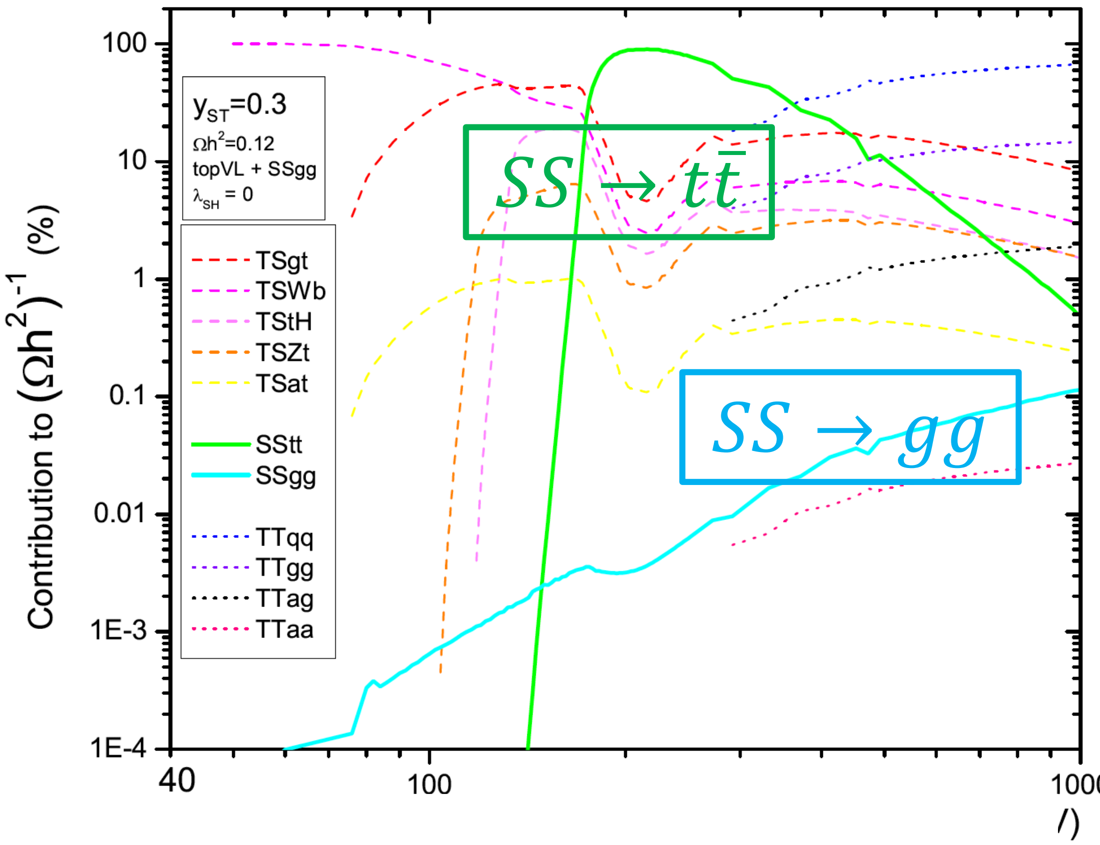
$$N_{\gamma,f} = \int_{E_{\rm th}}^{m_\chi} \frac{dN_f}{dE} dE$$

$$\langle\sigma v\rangle_{t\bar{t}} = \langle\sigma v\rangle_{b\bar{b}} N_{\gamma,b\bar{b}}/N_{\gamma,t\bar{t}}$$



Indirect detection (γ-ray)

- ***s*-wave** component in $\langle \sigma v \rangle$
  - only $SS \to t\bar{t}$, $SS \to gg$ in today's Universe
    - no co-annihilation
  - For a channel in Fermi's plots, when its ***s*-wave** dominates in producing $\Omega_{DM} h^2 \sim 0.1$ it is about to be constrained



***s*-wave**

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

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

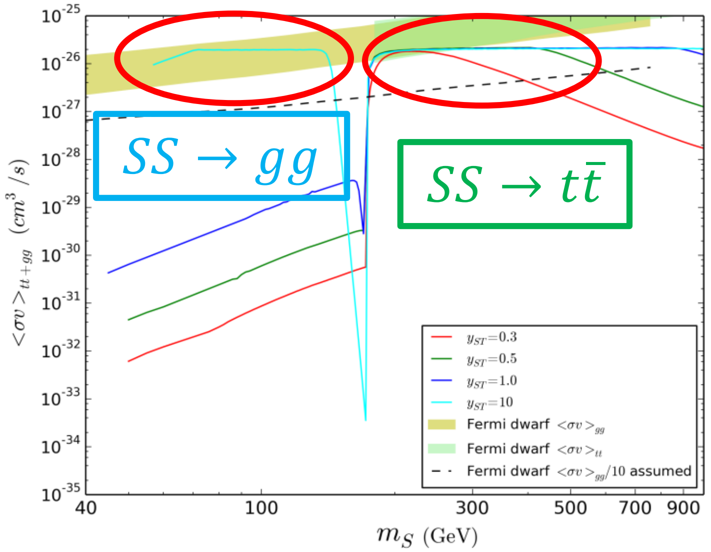
***p*-wave**

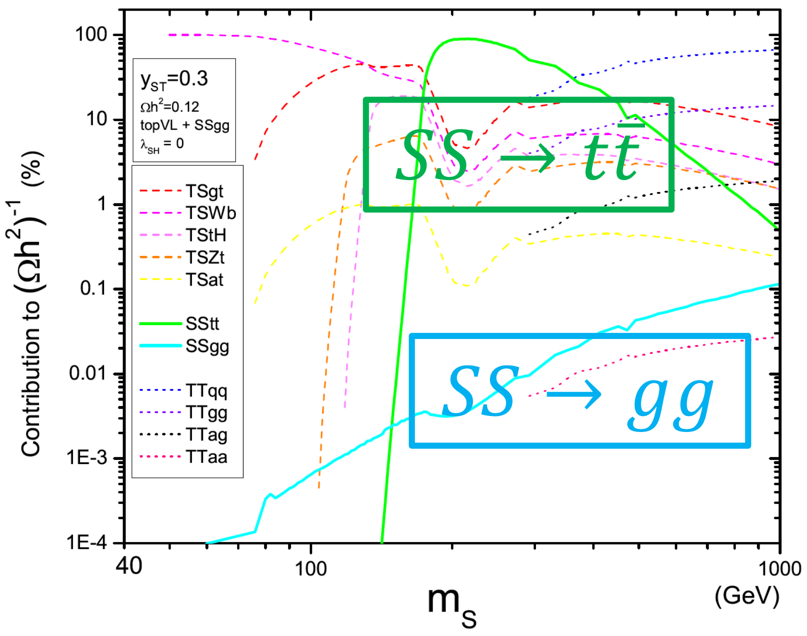
$$\times(-16 r_S{}^6 (2 r_T{}^2 + 1) + r_S{}^4 (r_T{}^2 + 1)(9 r_T{}^2 + 41) - 2 r_S{}^2 (9 r_T{}^2 + 17) + 9)$$

Indirect detection (γ-ray)

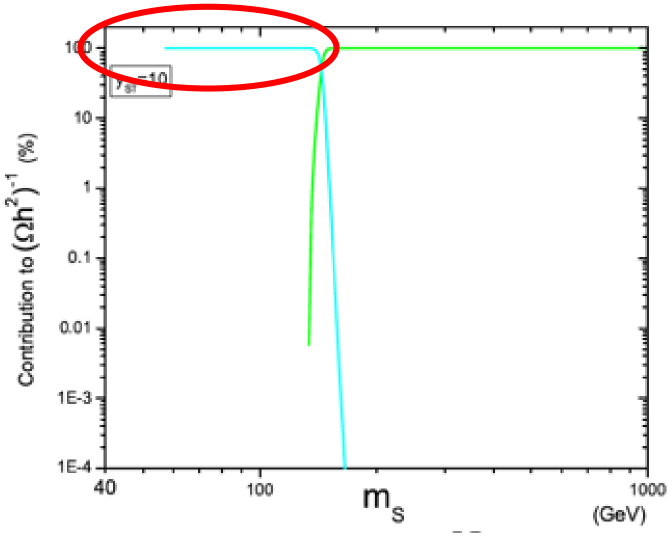
- current bounds are about to be able to constrain
- sensitivities × 10 can cover wide regions in $m_S > m_t$
  - complementary to DD

Dwarf **continuous** γ-spectrum

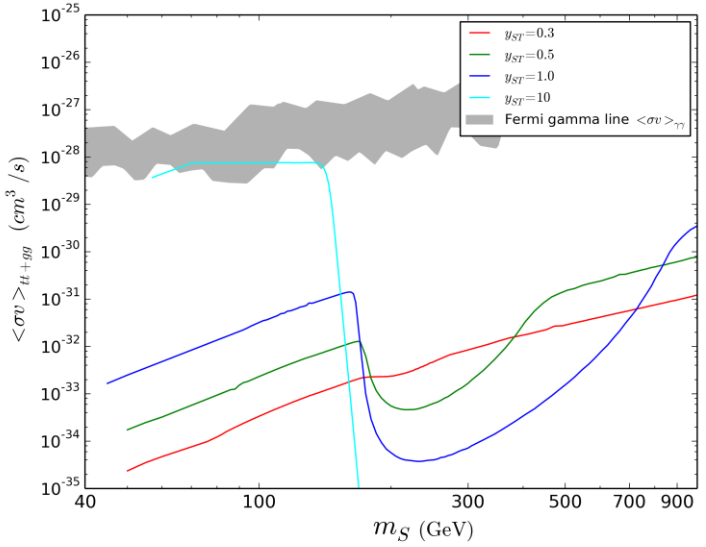




$y_{ST} = 10$



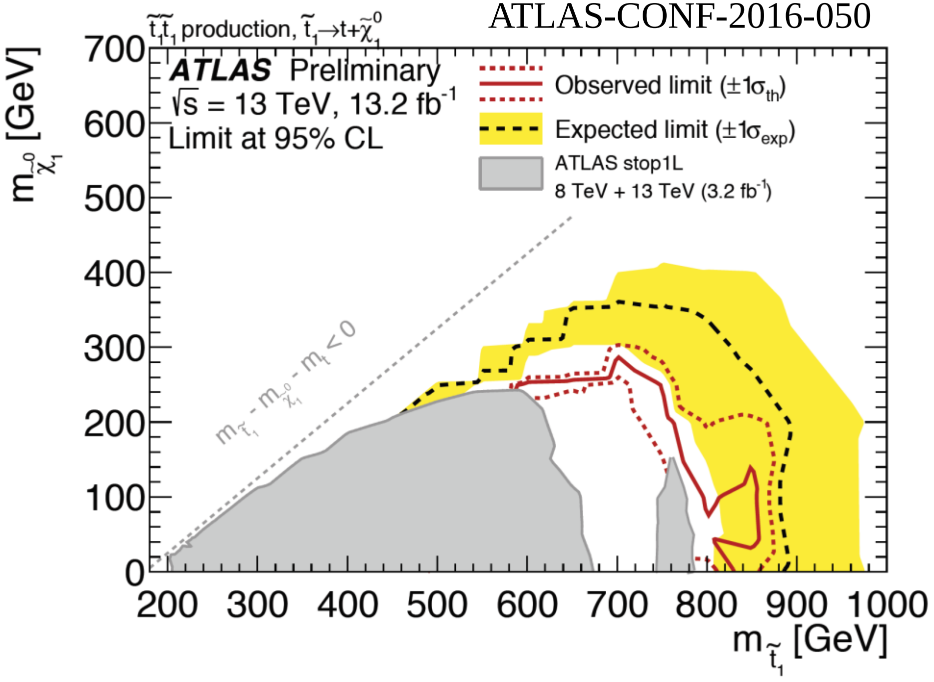
Galactic Center **line** γ-spectrum

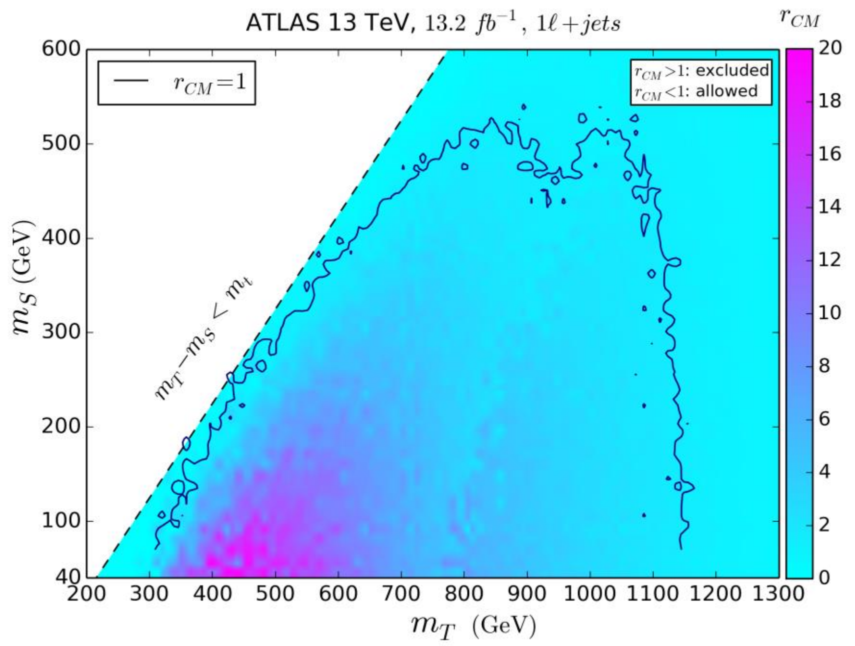


Collider search (ATLAS 13.2 fb^{-1} @ 13 TeV)

- $pp \to T\bar{T} \to t\bar{t} + MET$
  - 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)

ATLAS-CONF-2016-050

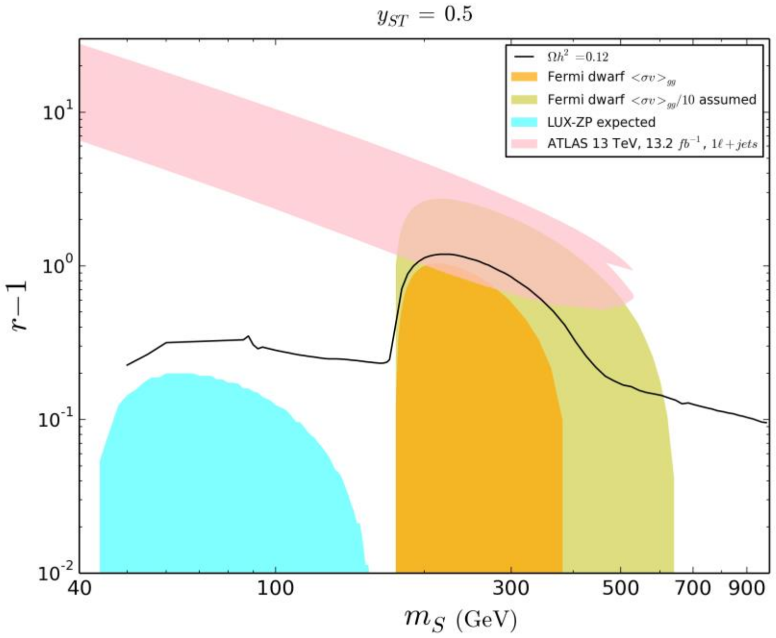




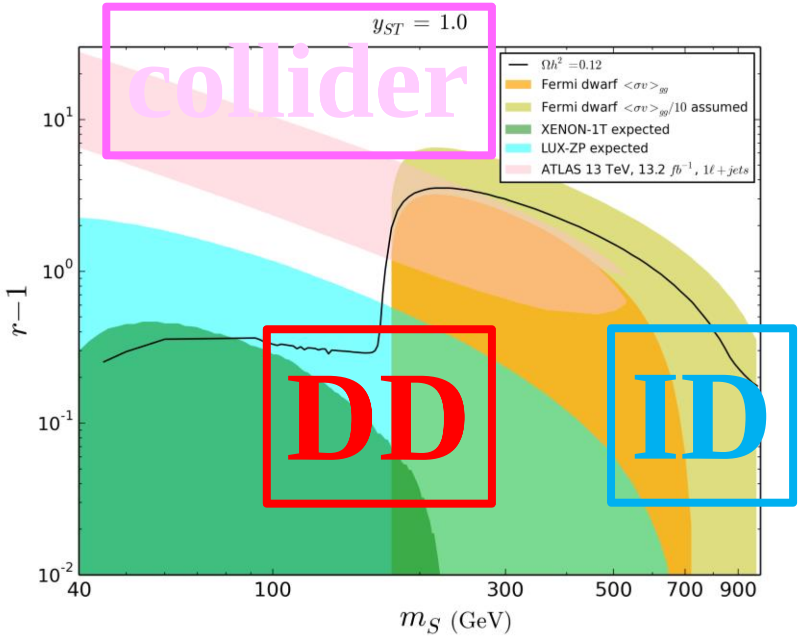
Quick Summary for Top-flavored Scalar DM

- 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

$y_{ST} = 0.5$



$y_{ST} = 1$



Generalization: Top+Charm Flavored

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

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

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

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

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

Before calculation, Quick Thoughts

Top FCNC decays

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

0409342, J.A.Aguilar-Saavedra

Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY	TC2
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	—
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	—
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	—
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	$\sim 10^{-4}$
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}	$\sim 10^{-4}$

Before calculation, Quick Thoughts

Top FCNC decays

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

Thermal relic **Top** **Charm**

- $\sigma v \sim y_3^4\,(\ldots)_{t\bar{t}} + y_3^2 y_2^2\,(\ldots)_{t\bar{c}} + y_2^4\,(\ldots)_{c\bar{c}} + [c_{Sg}]^2$
- $y_2^4\,(\ldots)_{c\bar{c}}$ takes over for $m_S < m_t/2$

$SSgg$ Loop

Before calculation, Quick Thoughts

Top FCNC decays

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

Thermal relic **Top** **Charm**

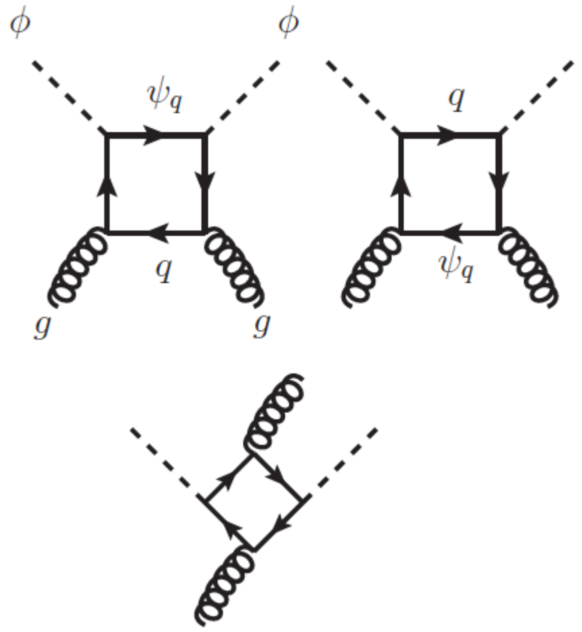
- $\sigma v \sim y_3^4 \, (\dots)_{t\bar{t}} + y_3^2 y_2^2 \, (\dots)_{t\bar{c}} + y_2^4 \, (\dots)_{c\bar{c}} + [c_{Sg}]^2$
- $y_2^4 \, (\dots)_{c\bar{c}}$ takes over for $m_S < m_t/2$

c-loop dominates over t-loop

Direct Detection:

- $[c_{Sg}]^2 \sim [y_3^2 \, (\dots)_t + y_2^2 \, (\dots)_c]^2$
- larger rate for light m_S

***SSgg* Loop**



Before calculation, Quick Thoughts

Top FCNC decays

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

Thermal relic **Top** **Charm**

- $\sigma v \sim y_3^4 \,(\dots)_{t\bar{t}} + y_3^2 y_2^2 \,(\dots)_{t\bar{c}} + y_2^4 \,(\dots)_{c\bar{c}} + [c_{Sg}]^2$
- $y_2^4 \,(\dots)_{c\bar{c}}$ takes over for $m_S < m_t/2$

Direct Detection:

c-loop dominates over t-loop

- $[c_{Sg}]^2 \sim [y_3^2 \,(\dots)_t + y_2^2 \,(\dots)_c]^2$
- larger rate for light m_S

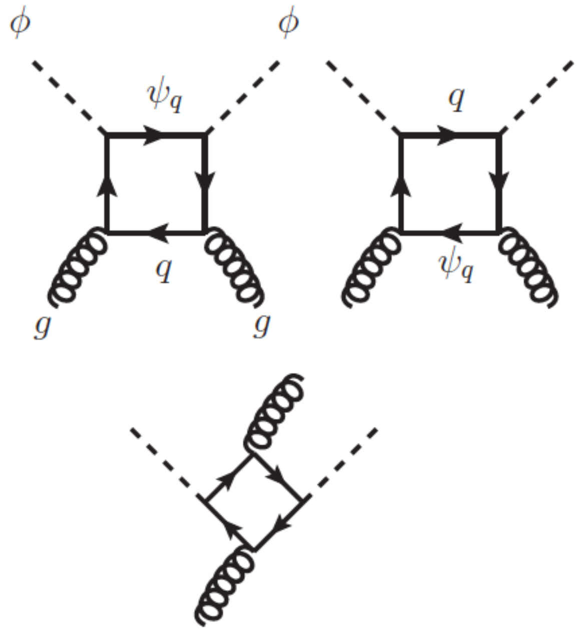
$SSgg$ Loop

Indirect Detection:

- more s-wave components for $m_S < m_t/2$

Collider signal

- MET + $t\bar{t}, tj, jj$



Preliminary Results

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

Exotic Top decay

$$\Gamma(t \to ST) = [y_3^2]\frac{m_t}{32\pi}(1 - r_S^2 + r_T^2)\sqrt{(1-(r_S - r_T)^2)(1-(r_S + r_T)^2)}$$

$$\Gamma(t \to cSS) = [{y_2}^2 {y_3}^2]\frac{m_t}{1024\pi^3}\int dr_{SS}\int dr_{Sc}$$

$$\frac{1}{(r_{Sc} - {r_S}^2{r_T}^2)^2(r_{SS} + r_{Sc} + {r_S}^2{r_T}^2 - 2{r_S}^2 - 1)^2}$$

$$\times\{r_{SS}(8{r_{Sc}}^3 - {r_{Sc}}^2(20{r_S}^2 + 9) + r_{Sc}(16{r_S}^4 + {r_S}^2(4{r_T}^2 + 6) + 1)$$

$$-{r_S}^2(4{r_S}^4 + {r_S}^2({r_T}^4 + 2{r_T}^2 - 2) - 2)) + 4{r_{Sc}}^4 - 8{r_{Sc}}^3(2{r_S}^2 + 1)$$

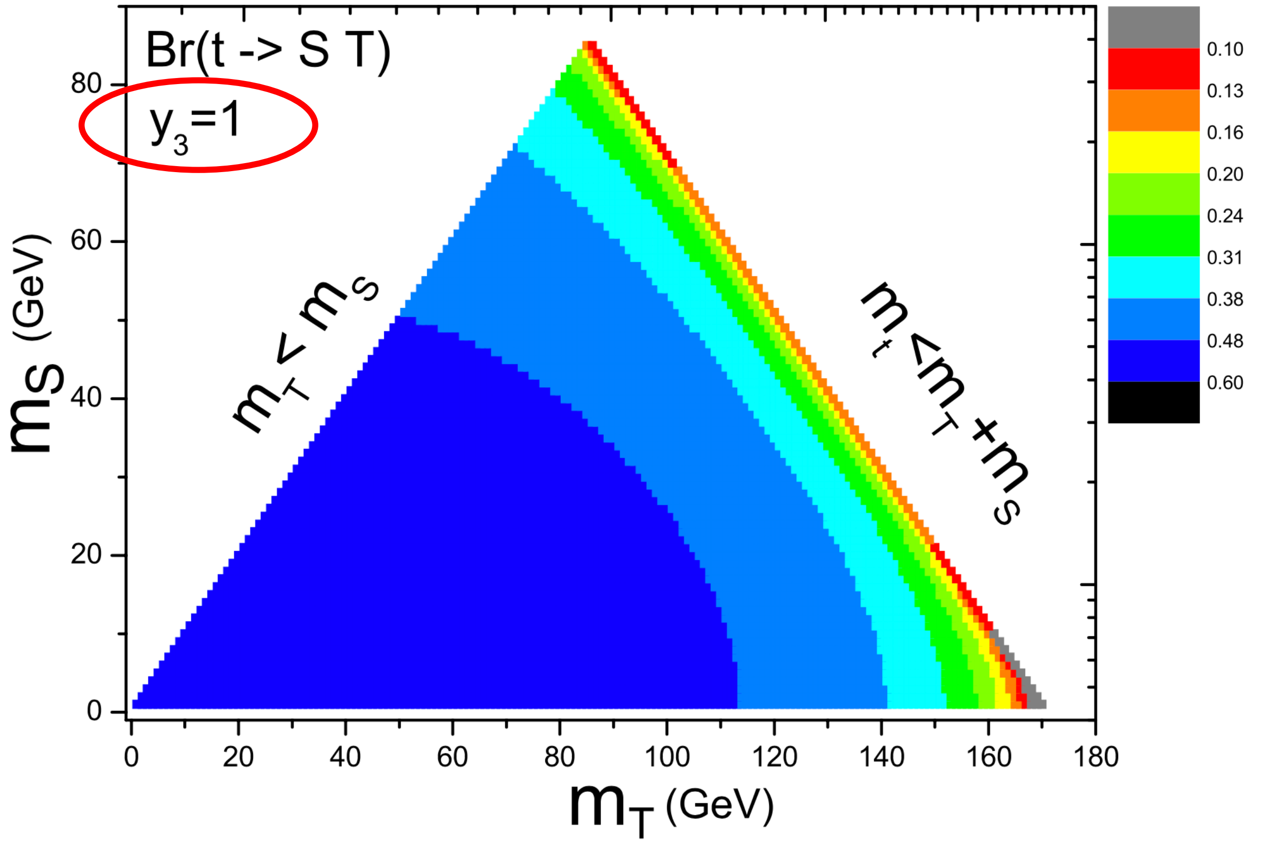
$$+{r_{SS}}^3 r_{Sc} + {r_{SS}}^2(5{r_{Sc}}^2 - 6r_{Sc}{r_S}^2 - 2r_{Sc} + {r_S}^4 - {r_S}^2)$$

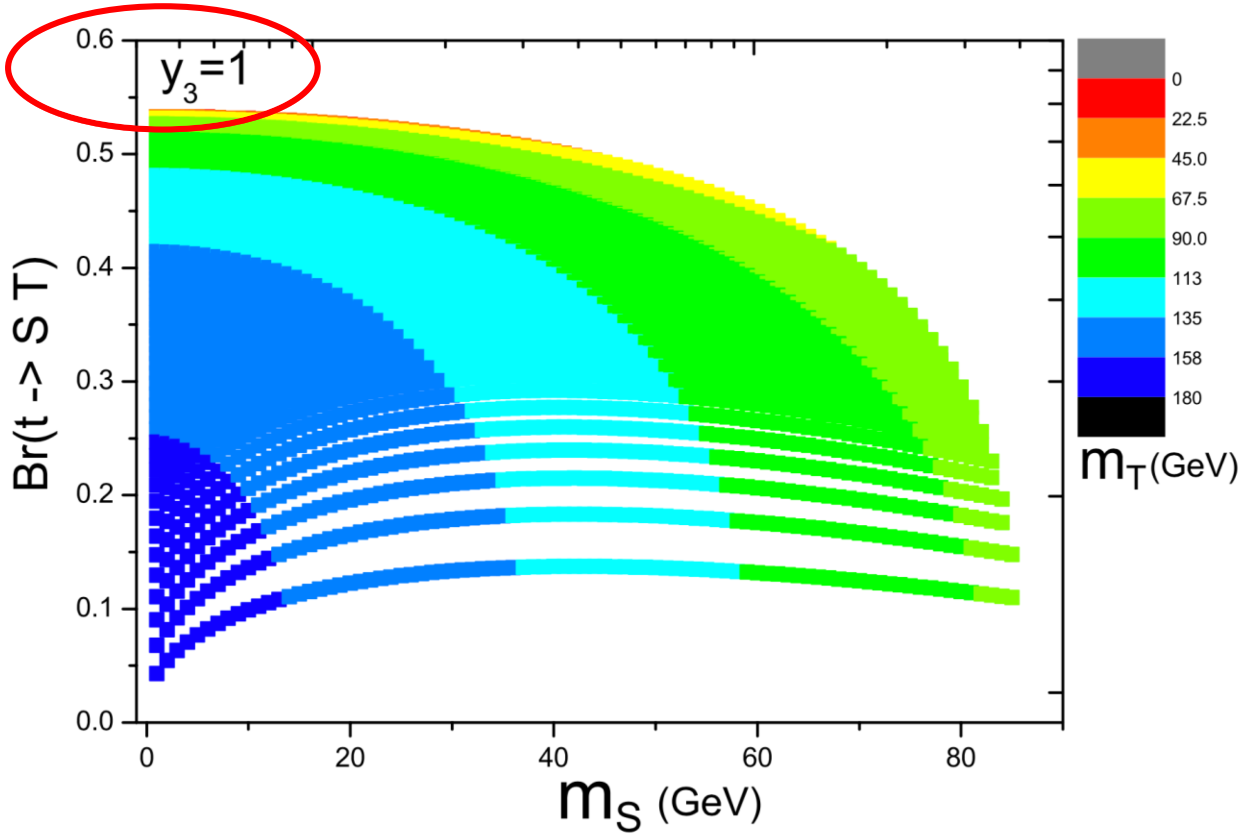
$$+4{r_{Sc}}^2(6{r_S}^4 + {r_S}^2({r_T}^2 + 4) + 1) - 4r_{Sc}{r_S}^2(2{r_S}^2 + 1)(2{r_S}^2 + {r_T}^2)$$

$$+{r_S}^2(4{r_S}^6 + 4{r_S}^4{r_T}^2 + {r_S}^2({r_T}^4 + 2{r_T}^2 - 3) - 1)\}$$

$$Br(t \to TS) \propto y_3^2$$

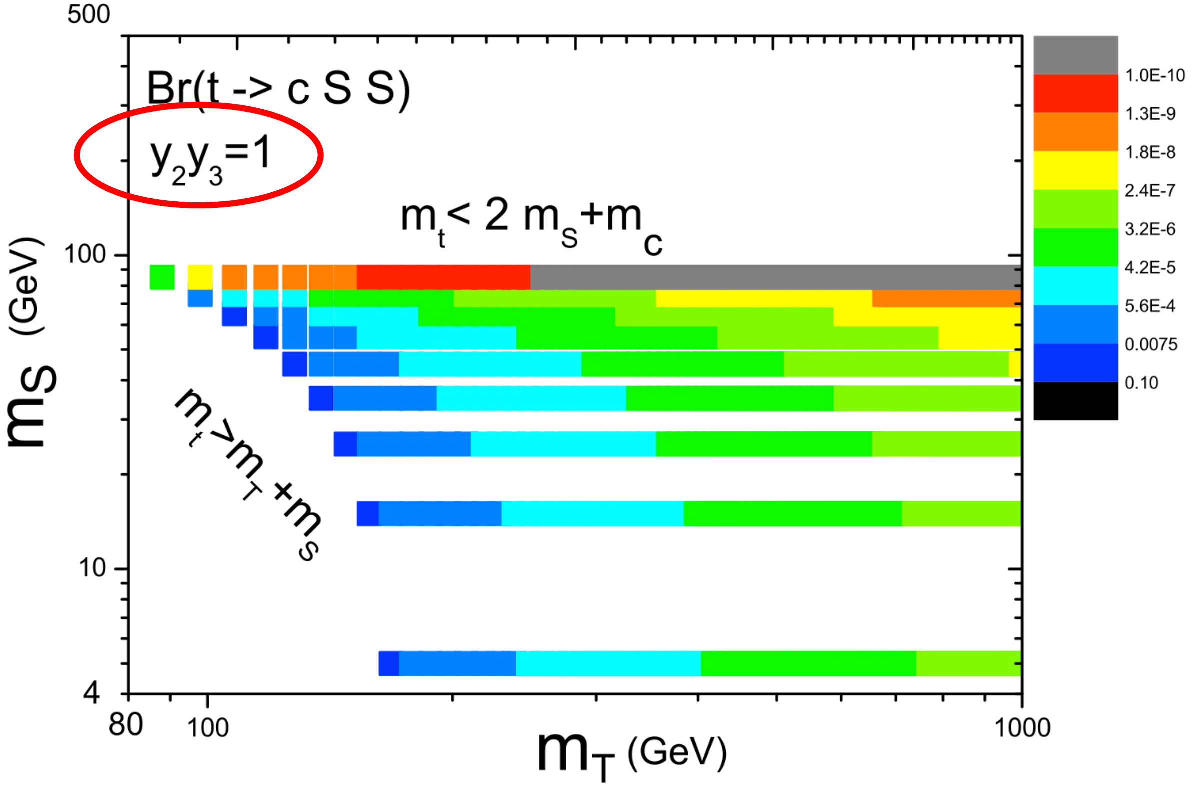
- $\Gamma_{t,SM}$~1.5 GeV, current measurements still allow sizable deviation

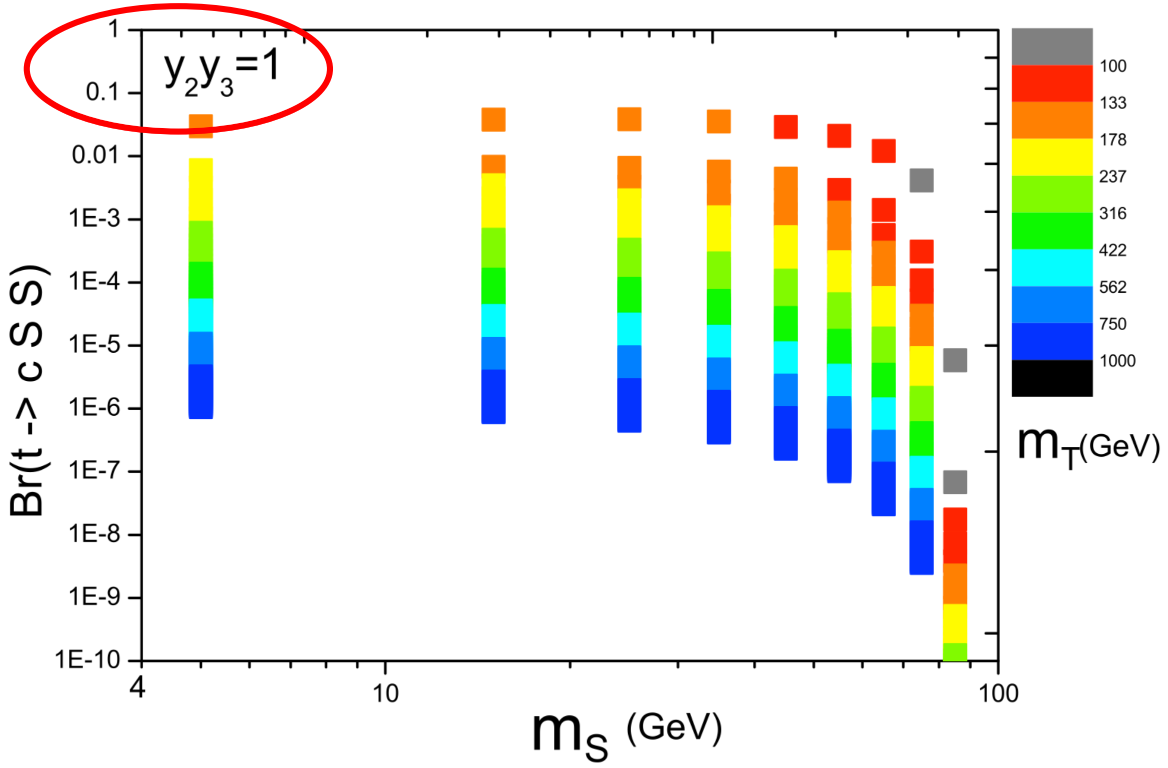




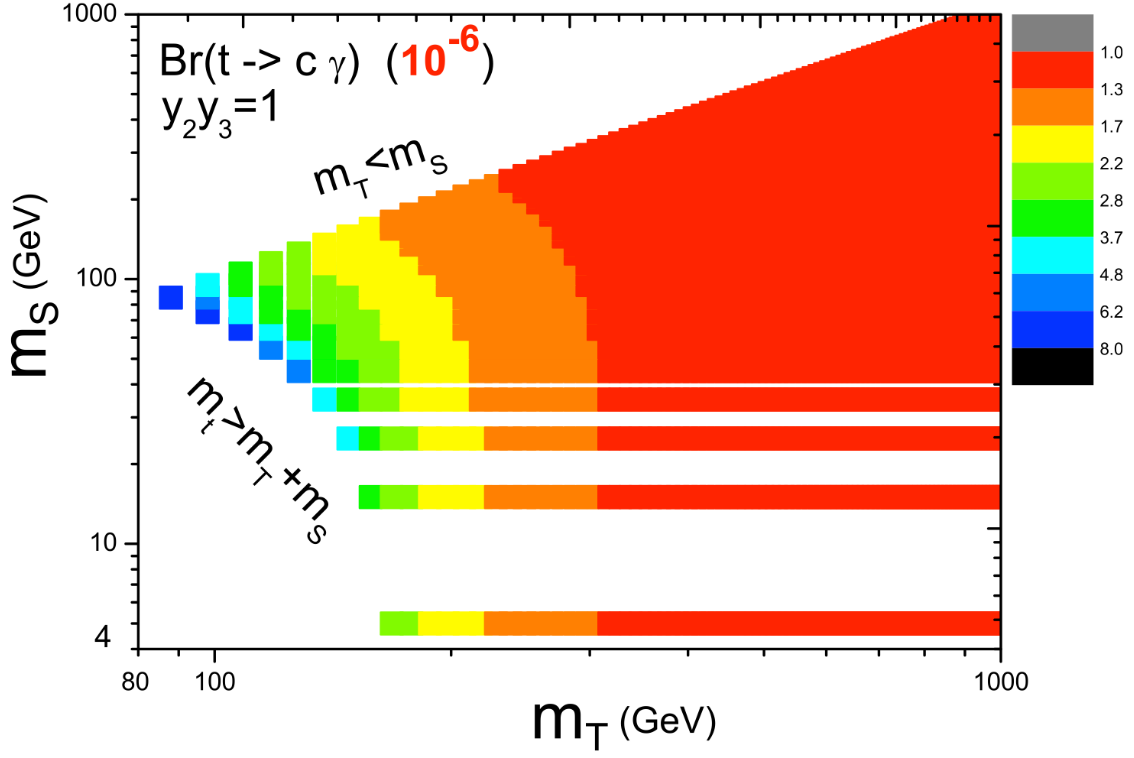
$$Br(t \to T^* S \to cSS) \propto y_3^2 y_2^2$$

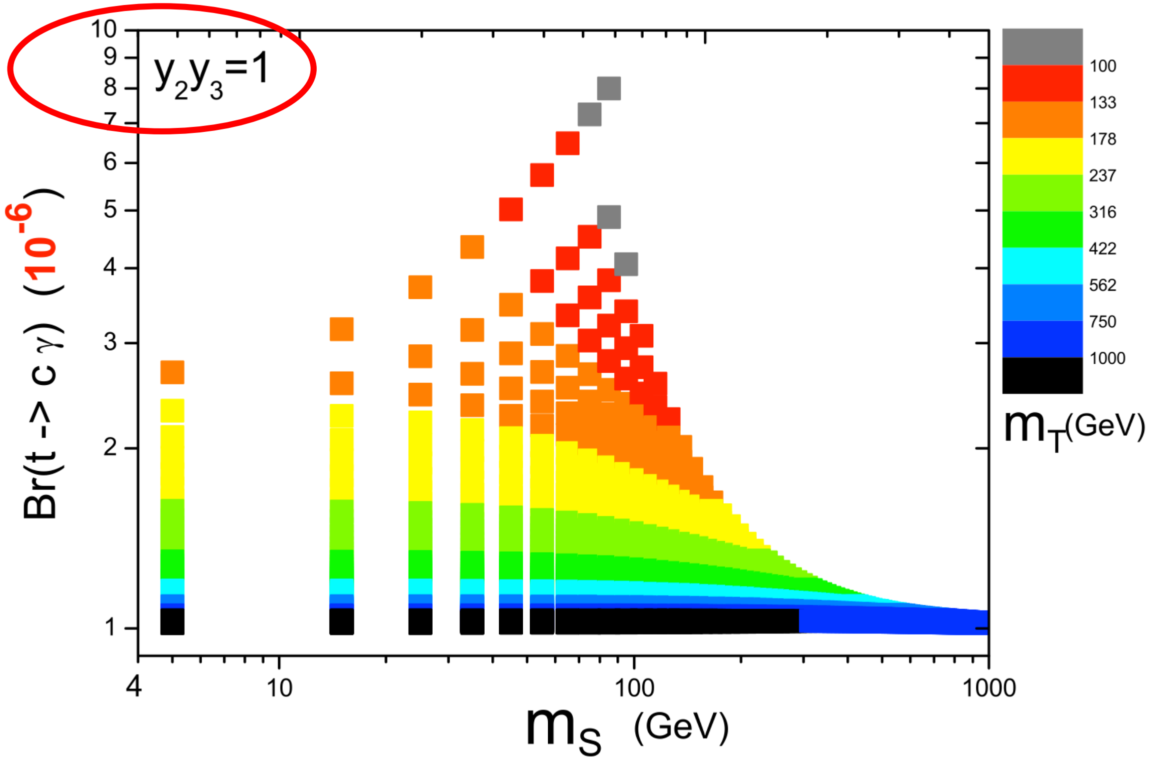
- 3-body decay, smaller than 2-body $t \to TS$



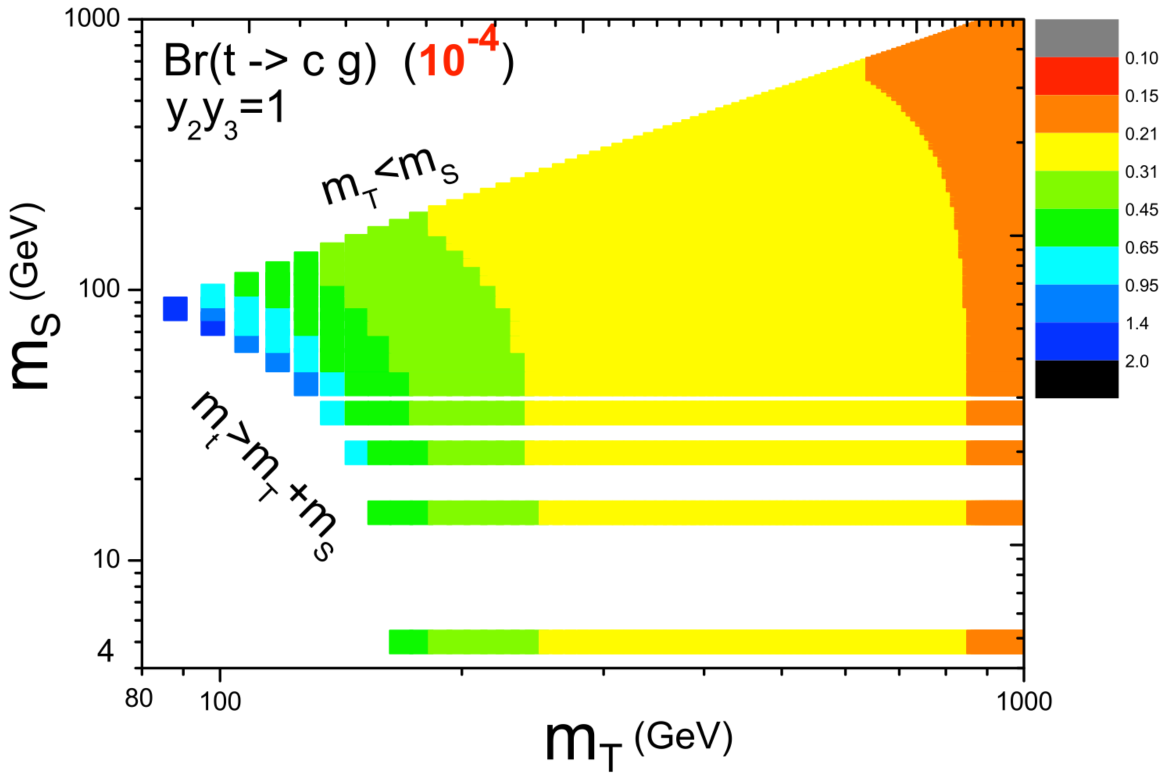


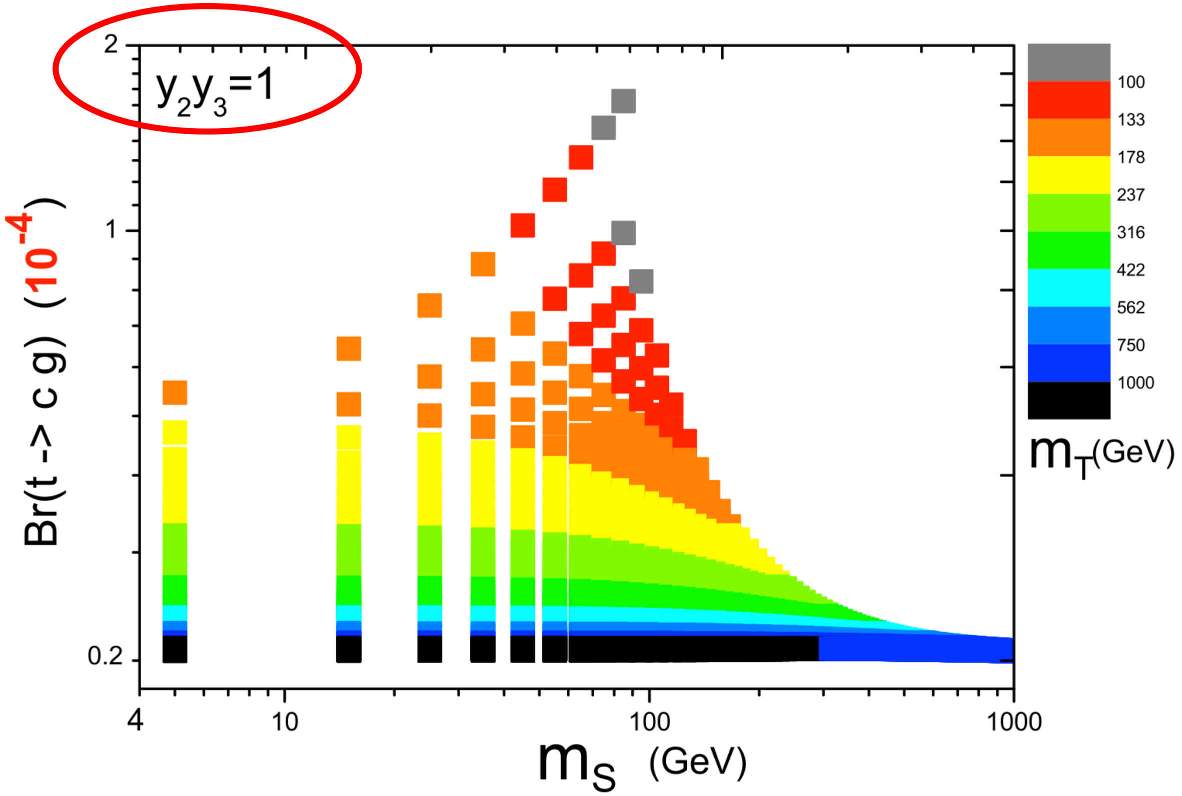
$$Br(t \to c\gamma) \quad \propto y_3^2 y_2^2$$



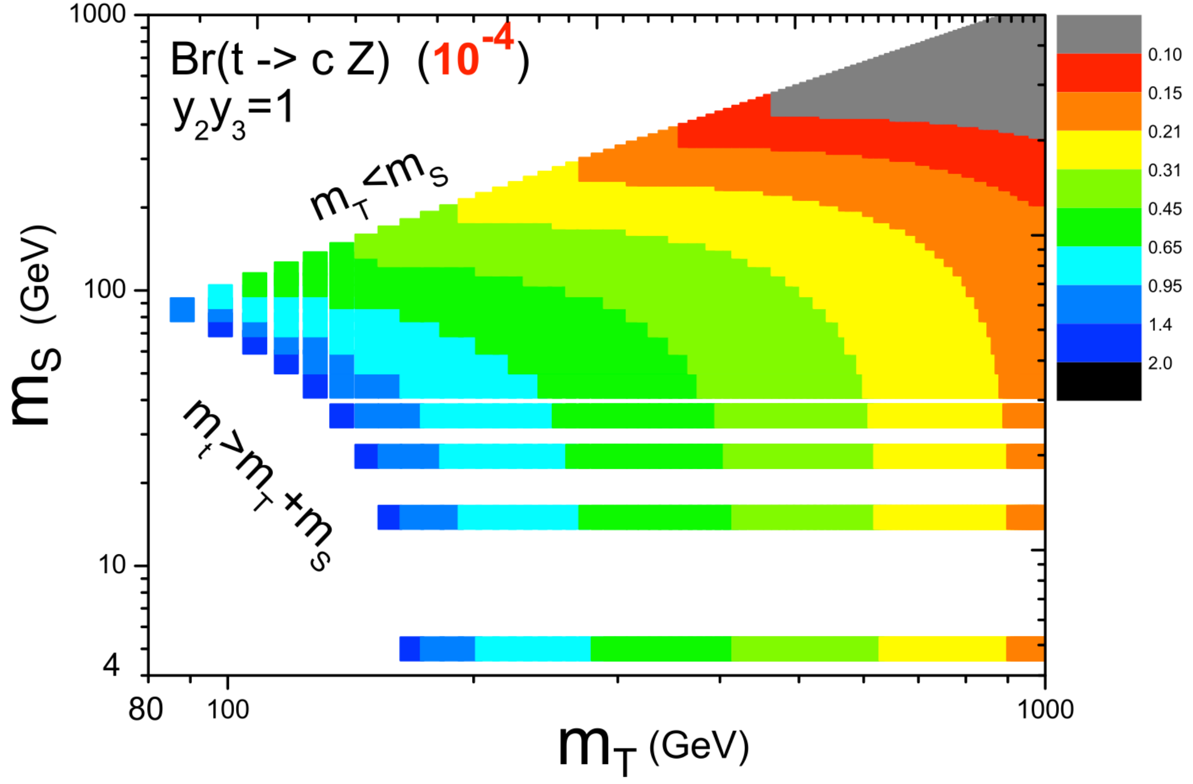


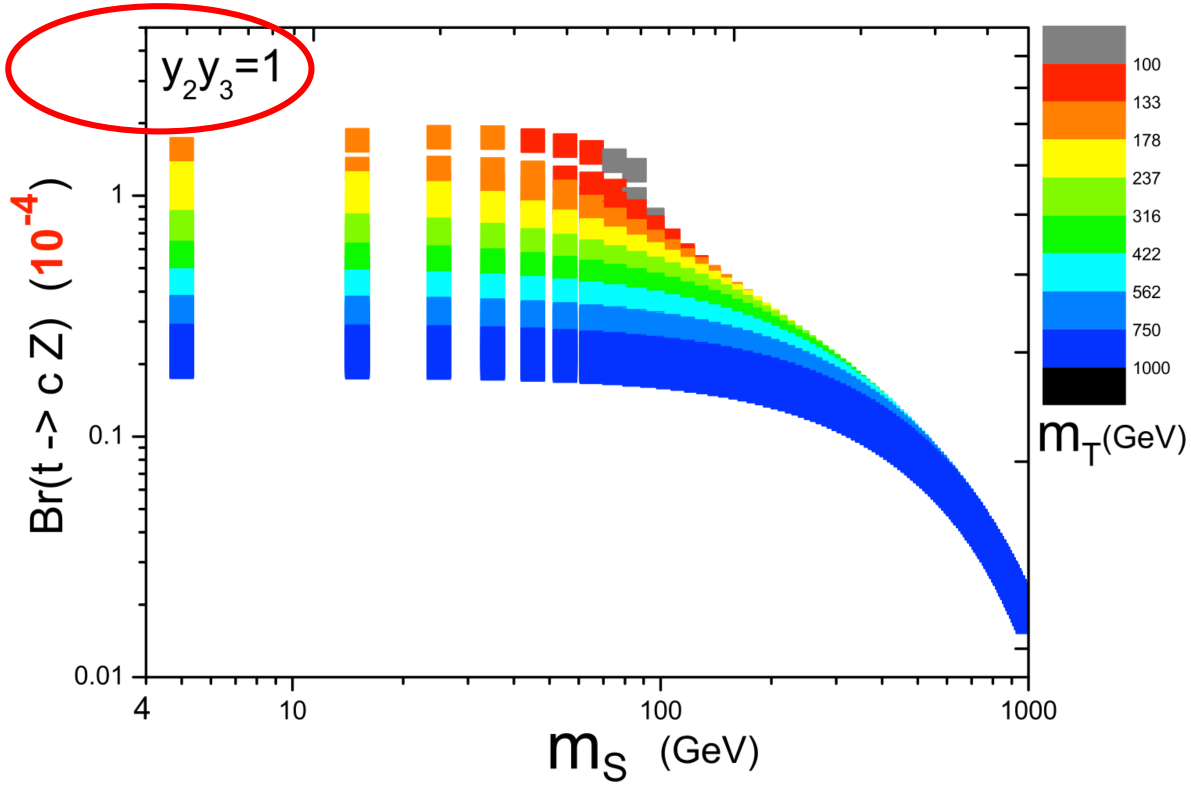
$$Br(t \to cg) \quad \propto y_3^2 y_2^2$$





$$Br(t \to cZ) \propto y_3^2 y_2^2$$





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

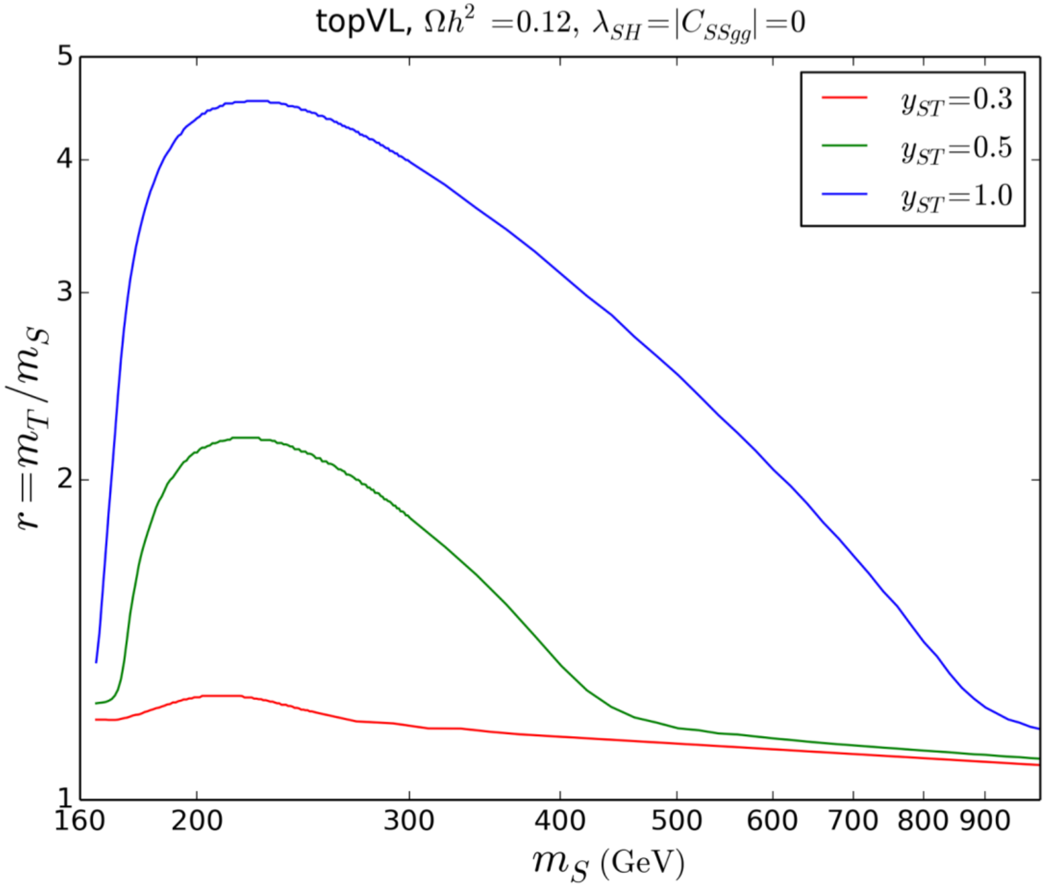
New Annihilation Channels

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

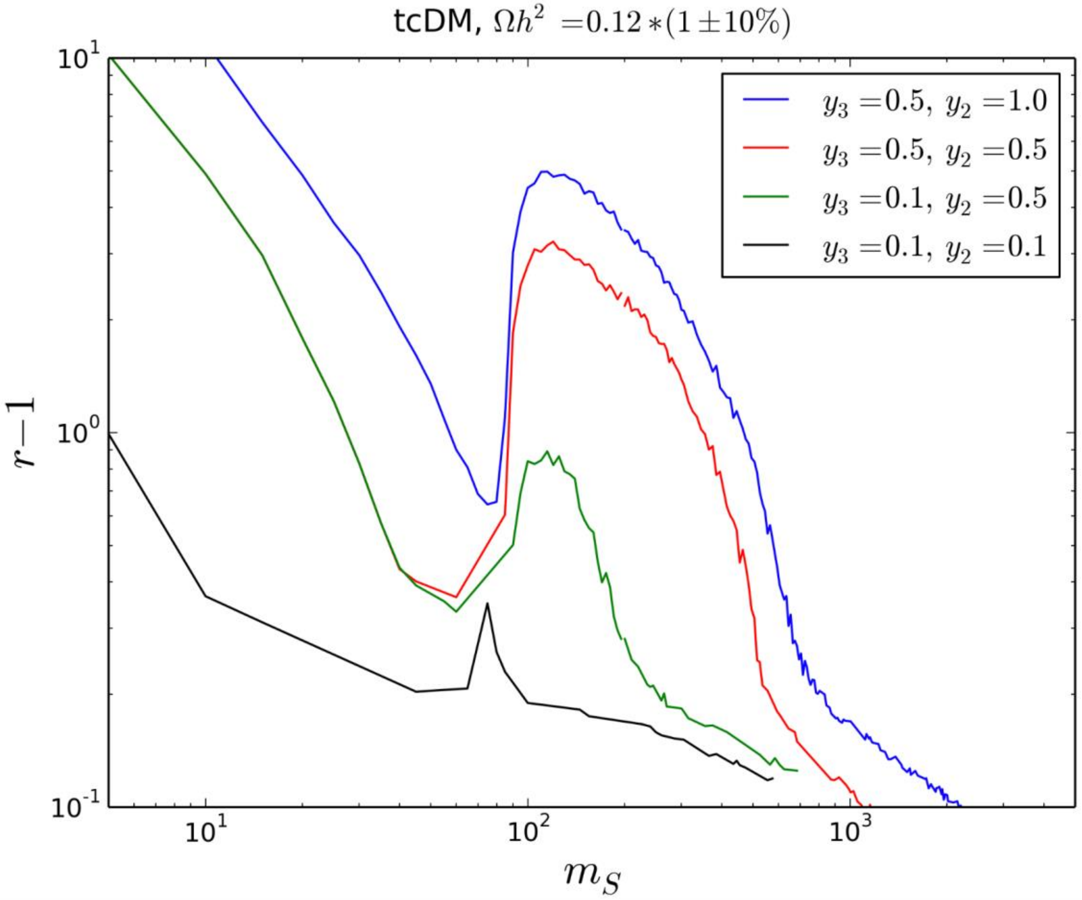
$$\sigma v(SS \to t\bar{c} + c\bar{t})_p = [y_2{}^2 y_3{}^2] \frac{1}{32\pi m_t{}^2} \frac{1 - 4r_S{}^2}{r_S{}^4(1 - 2r_S{}^2(r_T{}^2 + 1))^4} \times (64r_S{}^6(2r_T{}^2 + 1) - 4r_S{}^4(3r_T{}^4 + 16r_T{}^2 + 17) + 2r_S{}^2(7r_T{}^2 + 11) - 3)$$

Thermal Relic

Top Flavored

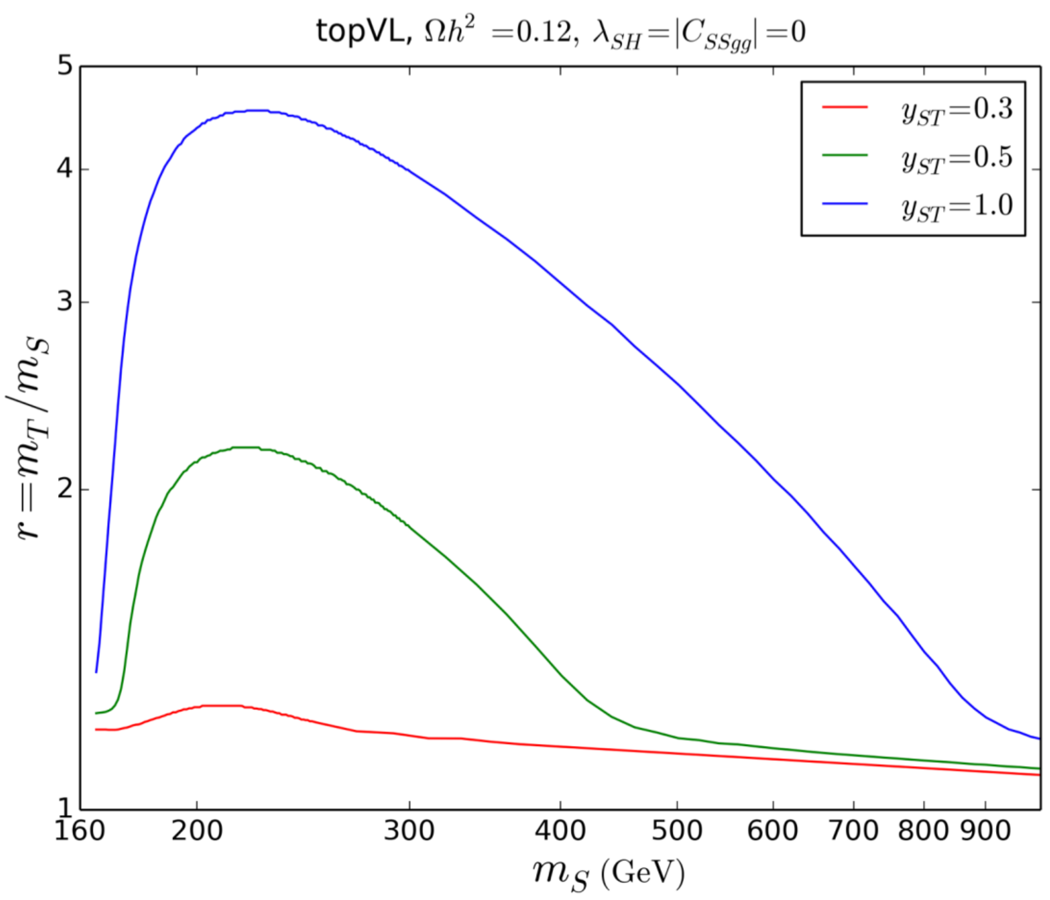


Top+Charm Flavored

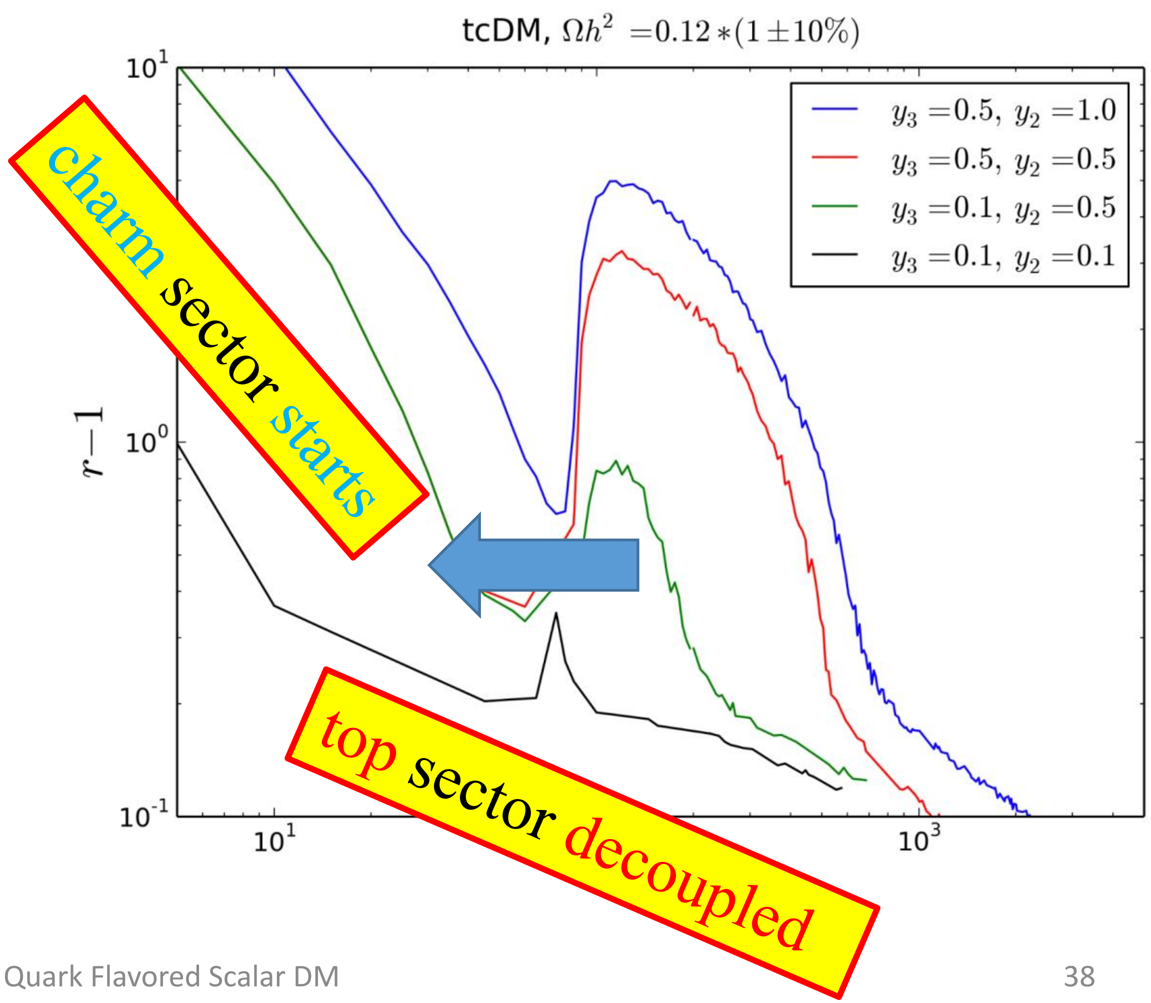


Thermal Relic

Top Flavored



Top+Charm Flavored

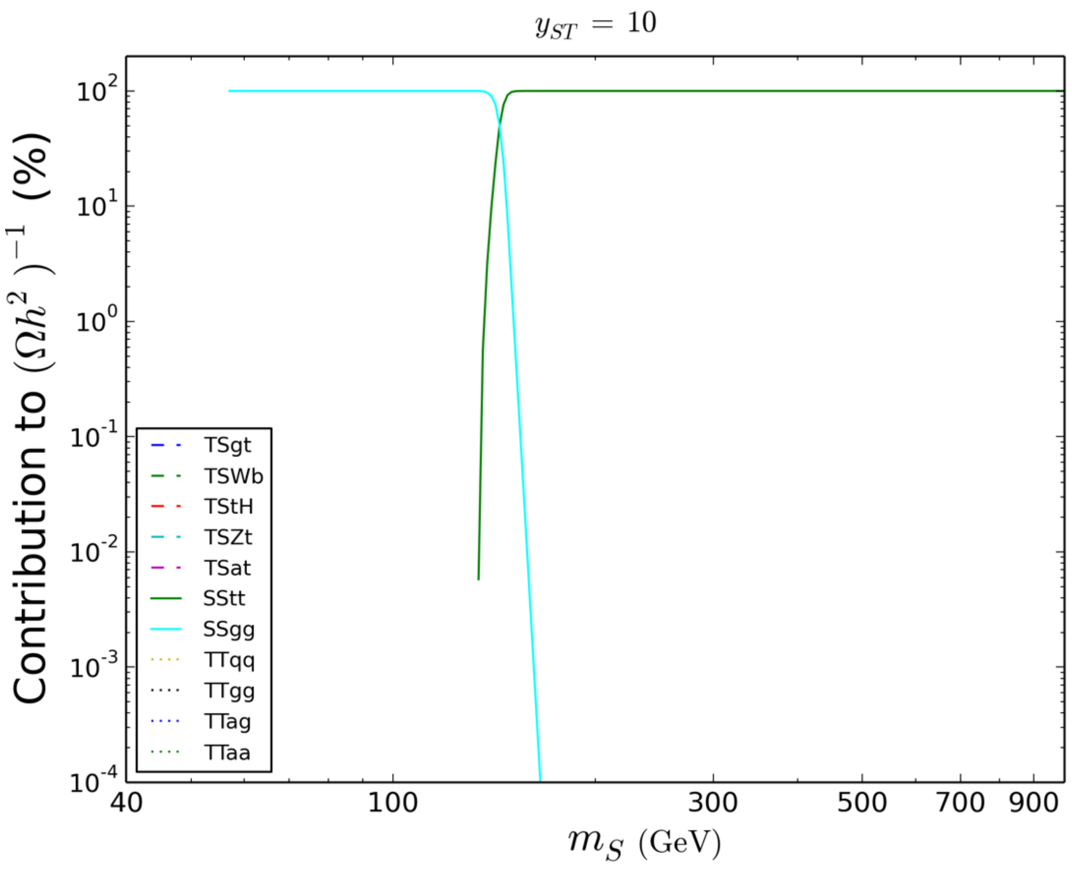


$$\sigma v \sim y_3^4\,(\dots)_{t\bar{t}} + y_3^2 y_2^2\,(\dots)_{t\bar{c}} + y_2^4\,(\dots)_{c\bar{c}} + \cdots$$

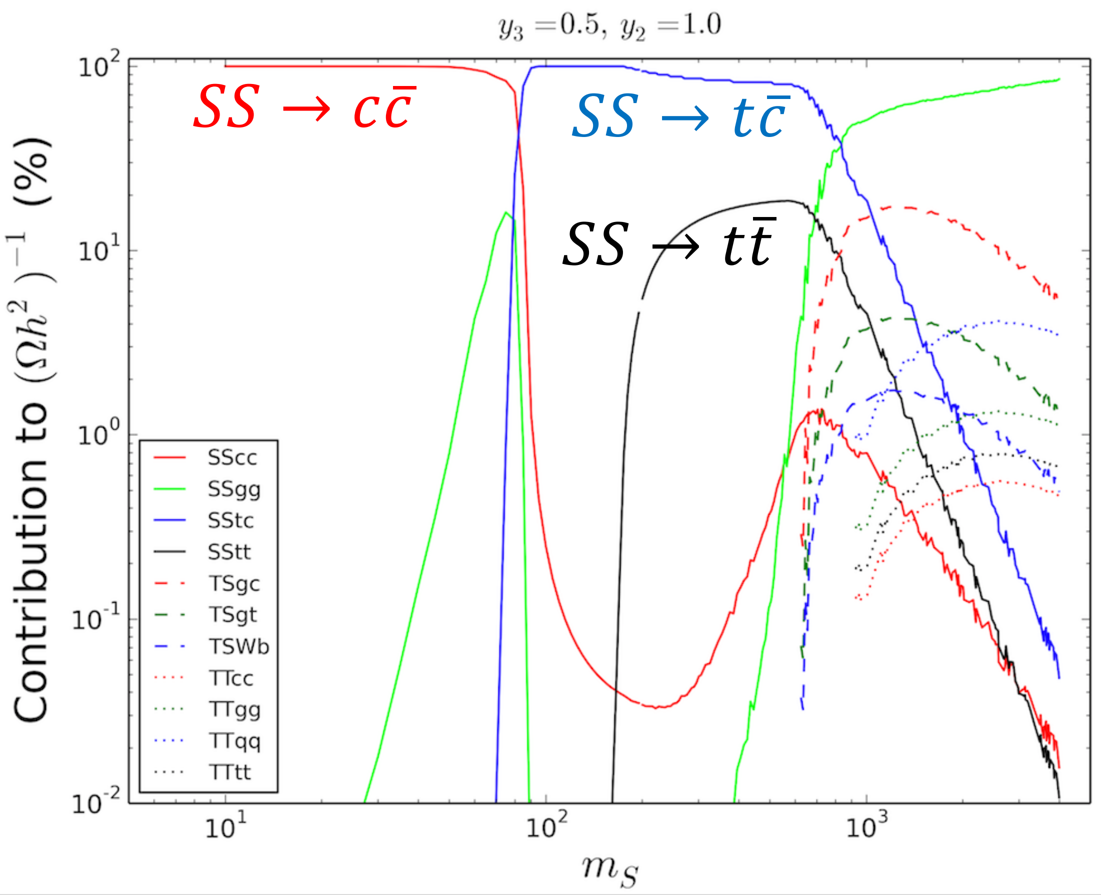
$y_2 = 1.0$
$y_3 = 0.5$

Annihilation Contribution

Top Flavored



Top+Charm Flavored

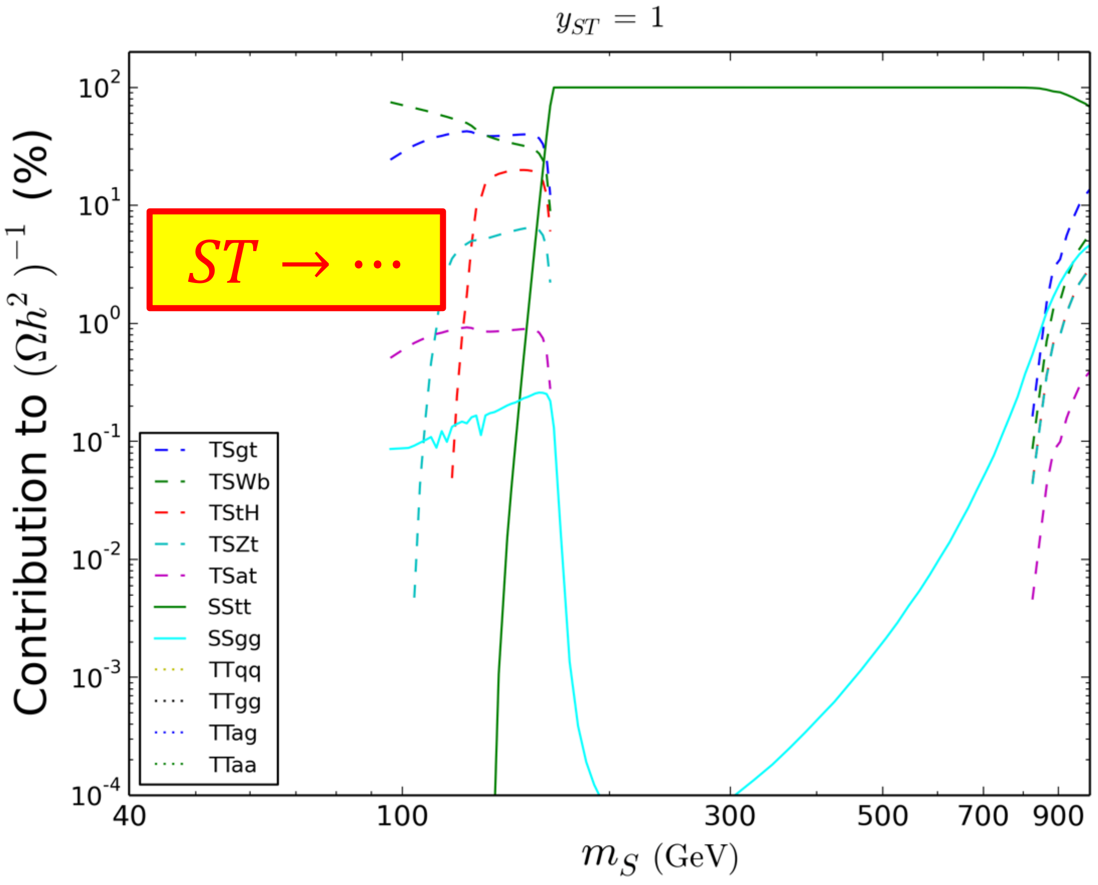


$$\sigma v \sim y_3^4 (\dots)_{t\bar{t}} + y_3^2 y_2^2 (\dots)_{t\bar{c}} + y_2^4 (\dots)_{c\bar{c}} + \cdots$$

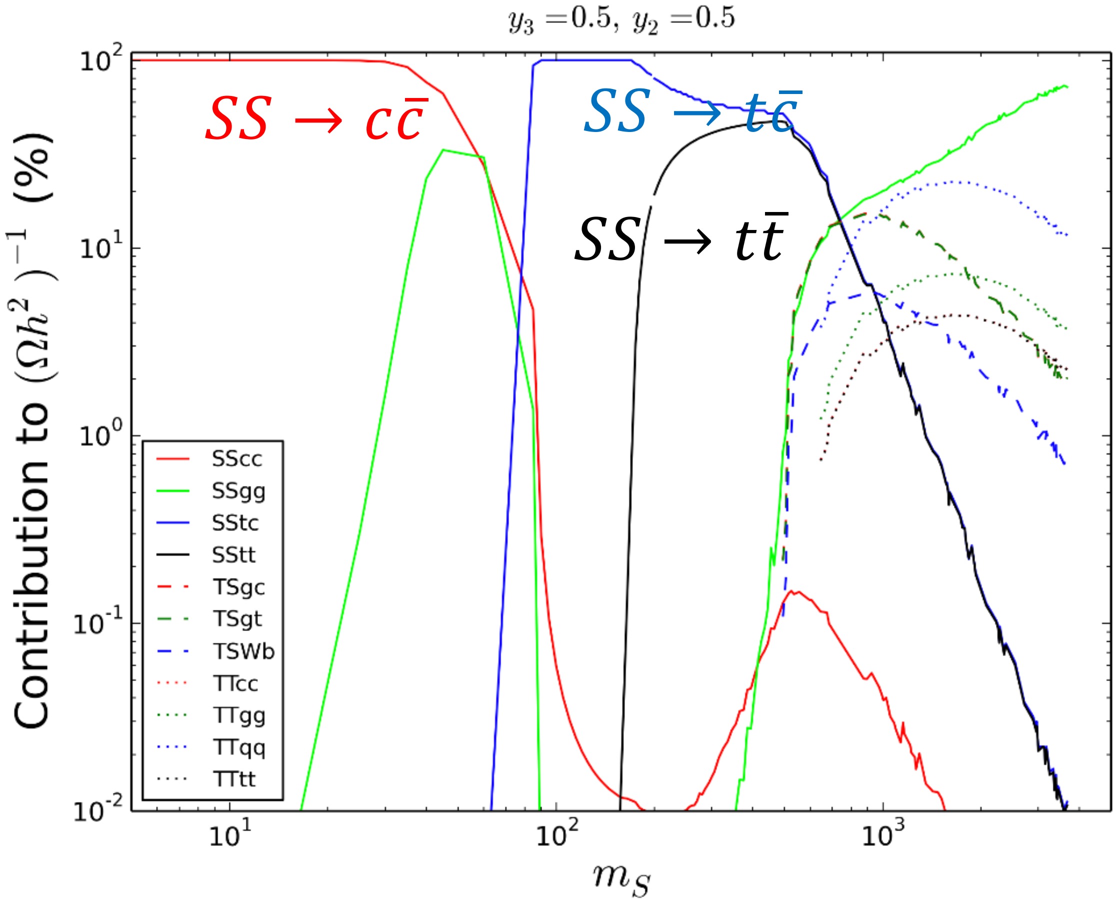
$y_2 = 0.5$
$y_3 = 0.5$

Annihilation Contribution

Top Flavored



Top+Charm Flavored



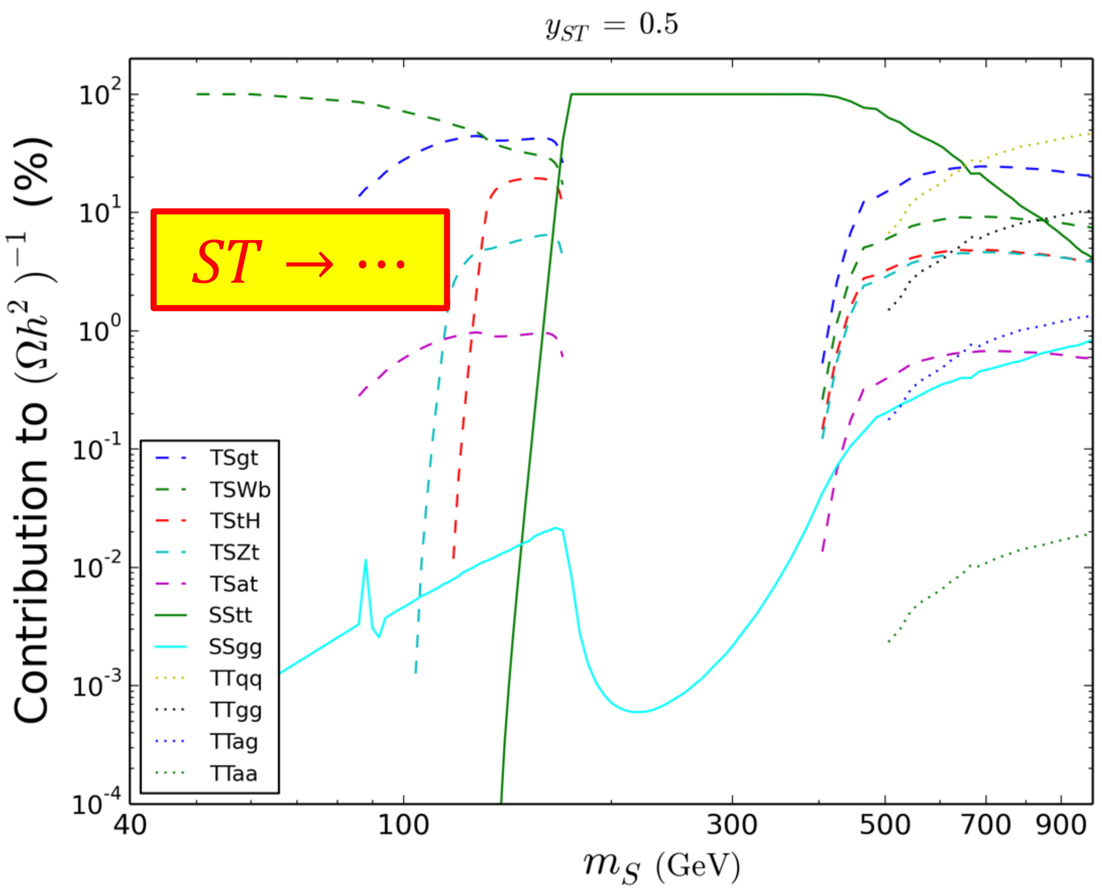
$\sigma v \sim y_3^4\,(\ldots)_{t\bar{t}} + y_3^2 y_2^2\,(\ldots)_{t\bar{c}} + y_2^4\,(\ldots)_{c\bar{c}} + \cdots$

$y_2 = 0.5$

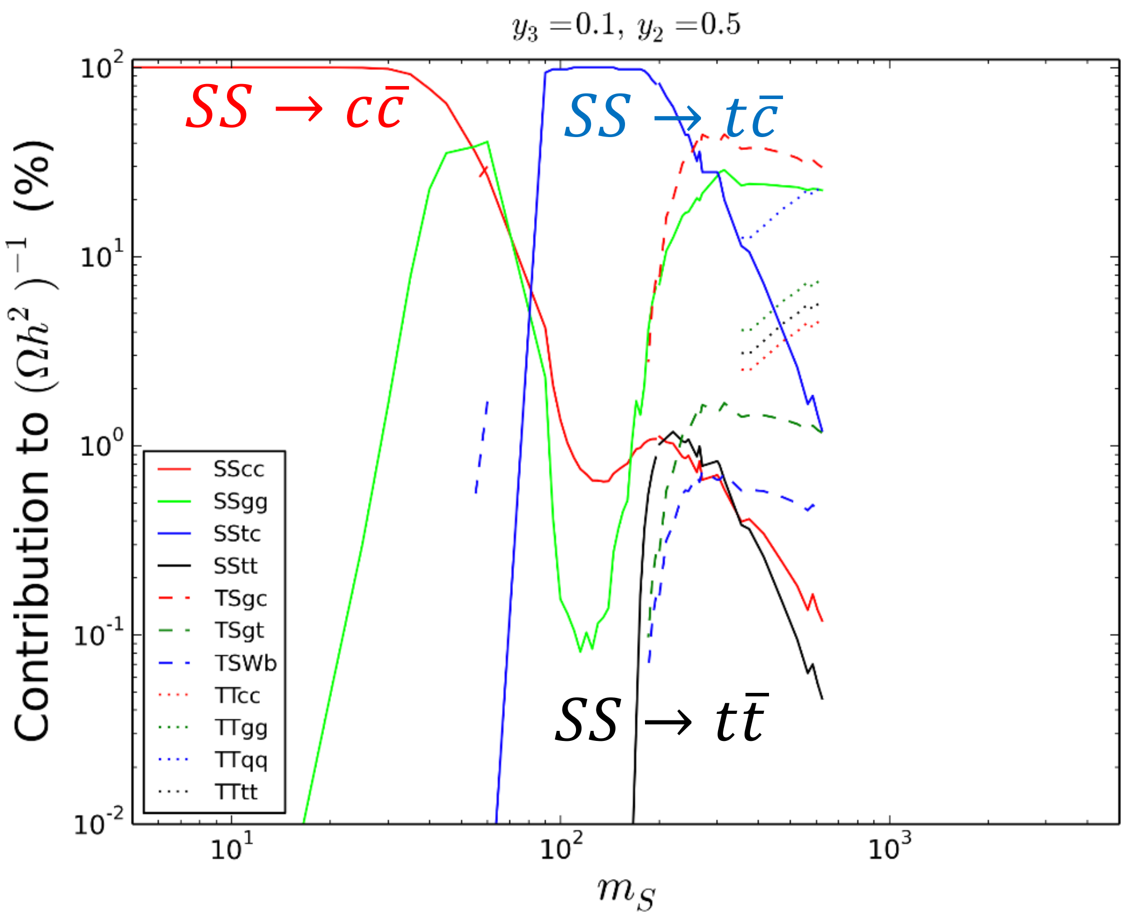
$y_3 = 0.1$

Annihilation Contribution

Top Flavored



Top+Charm Flavored



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

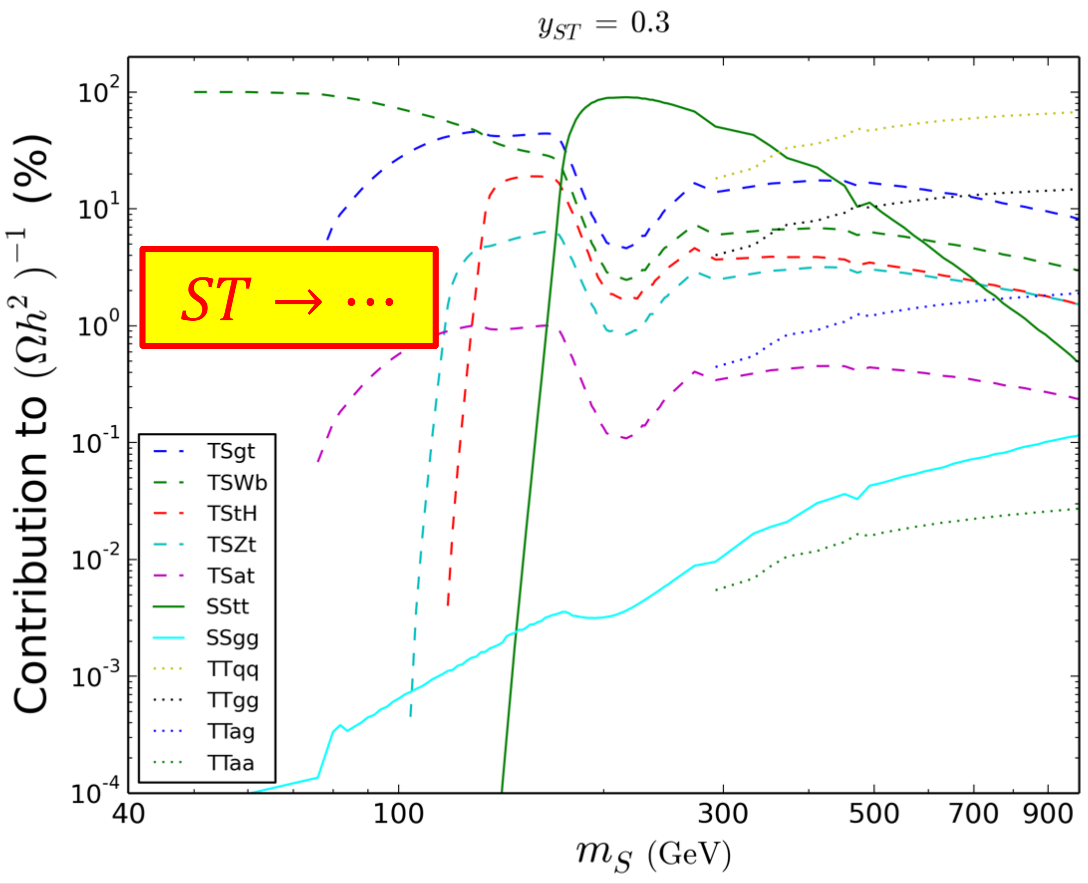
$y_2 = 0.1$

$y_3 = 0.1$

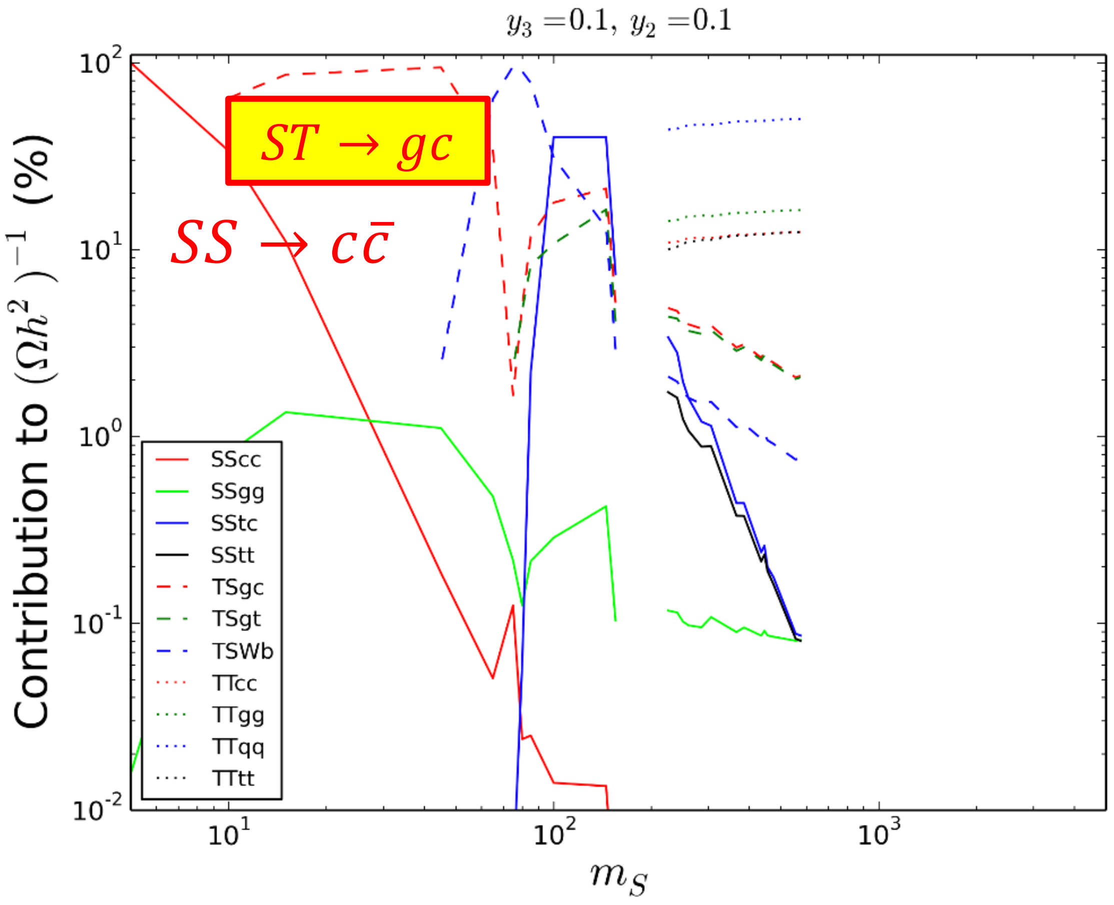
Annihilation Contribution

small couplings, need co-annihilation

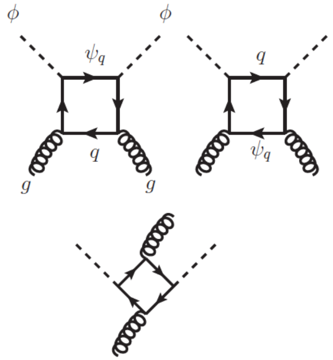
Top Flavored



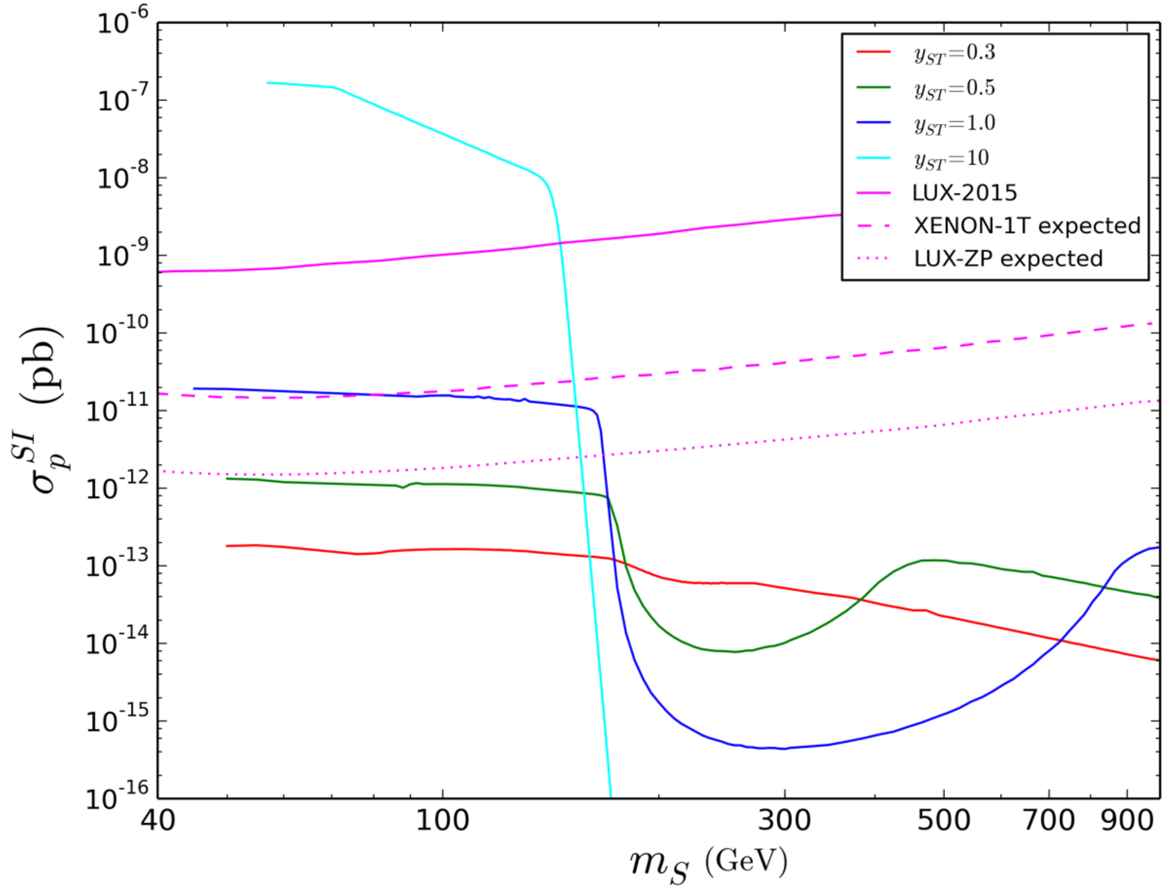
Top+Charm Flavored



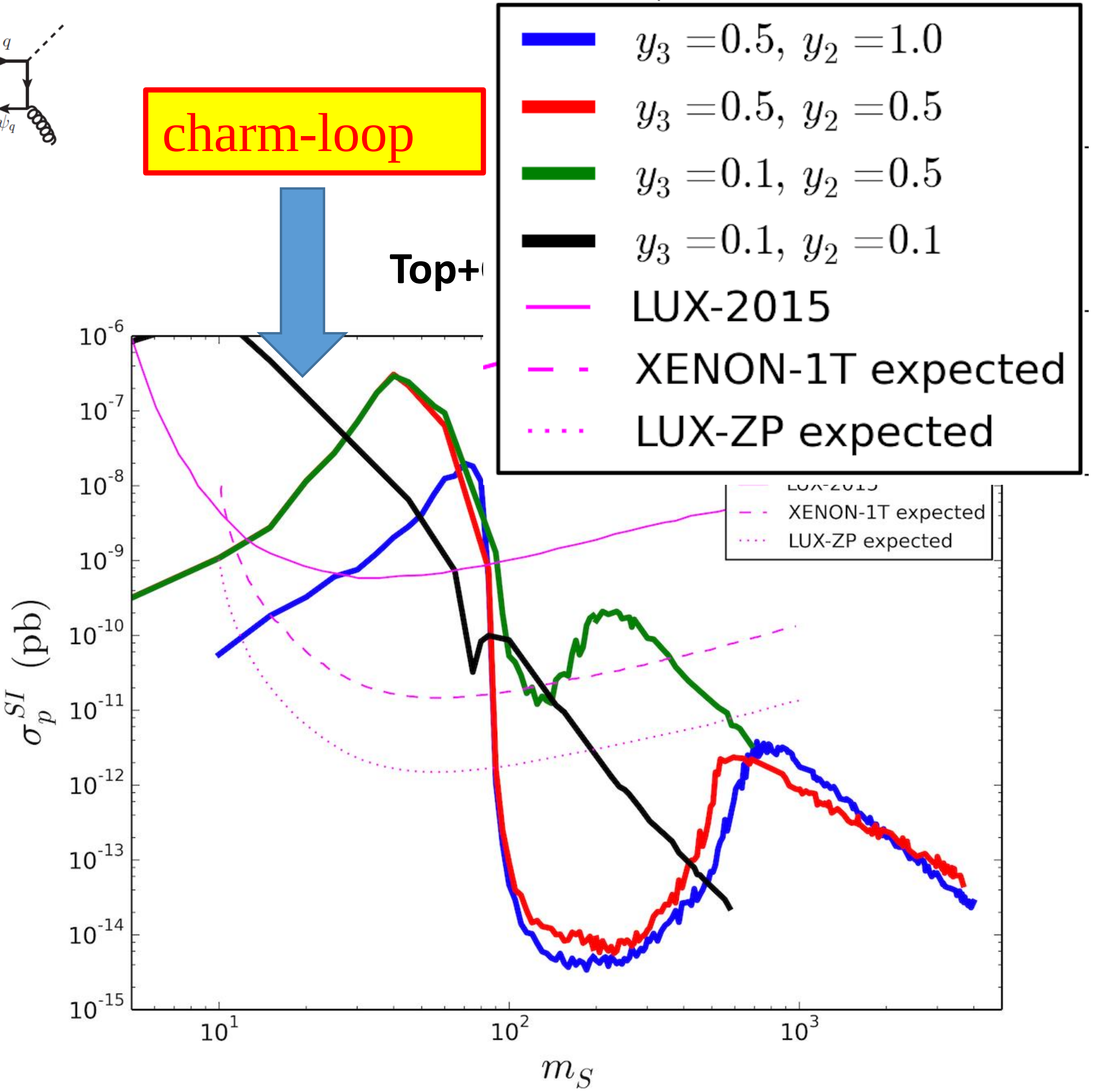
Direct Detection



Top Flavored



Top+

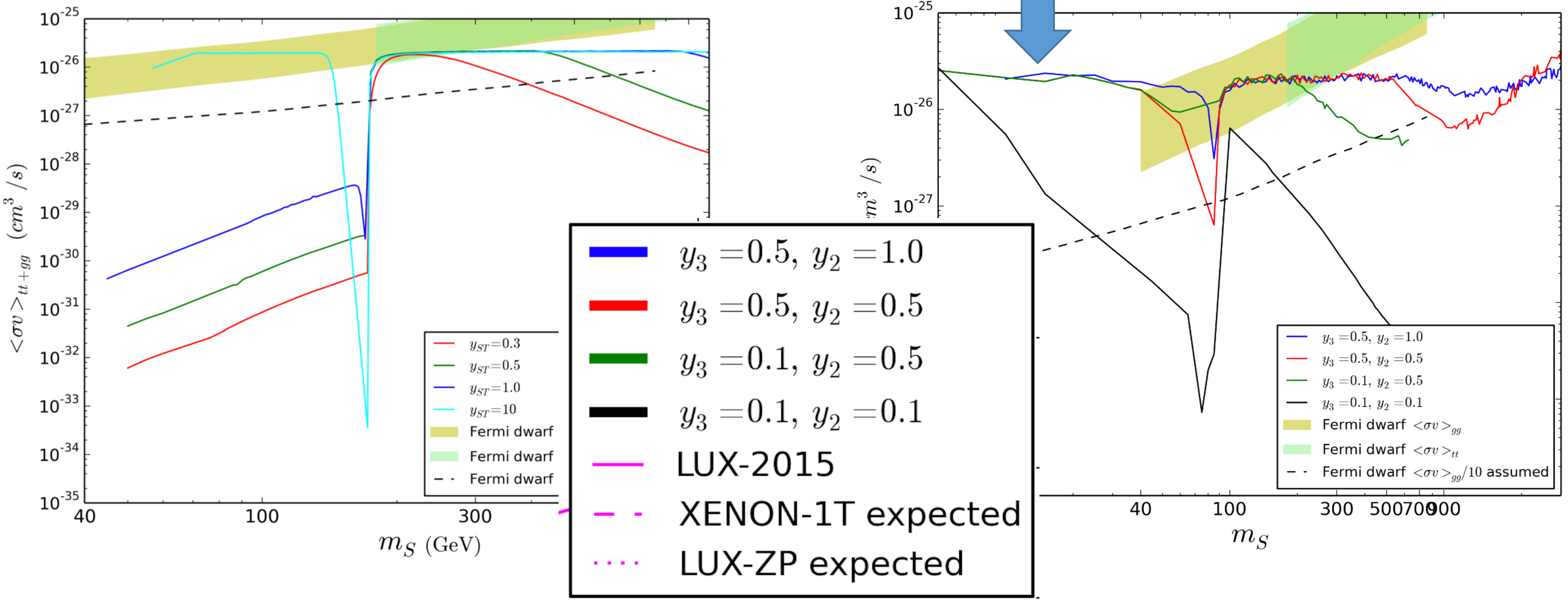


Indirect Detection

s-wave in
$SS \to c\bar{c}$

Top Flavored

Top+Charm Flavored



Conclusion

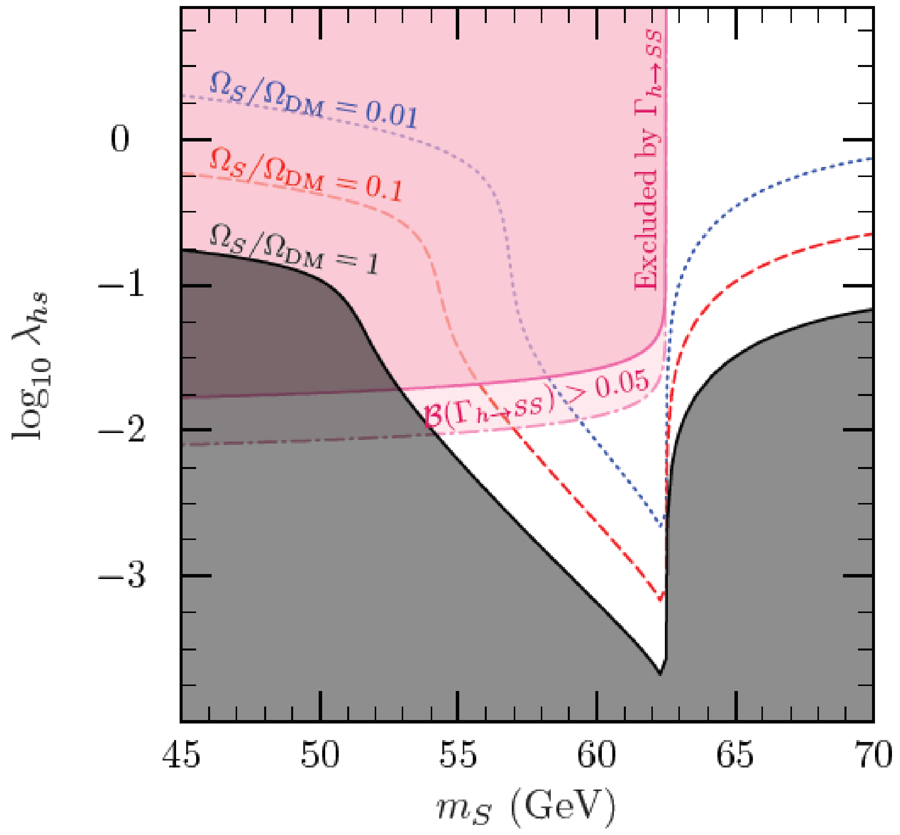
- No confirmed DD signal, DM may couple dominantly to heavy quark(s)
- Top flavored real scalar DM S, a colored fermion mediator T
  - Yukawa interaction $\mathcal{L} = -y_3 S \overline{T_L} t_R + h.c.$
  - $\langle \sigma v \rangle$ benefits from m_{top}, co-annihilations are important
  - DD via $SSG^{\mu\nu}G_{\mu\nu}$; 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

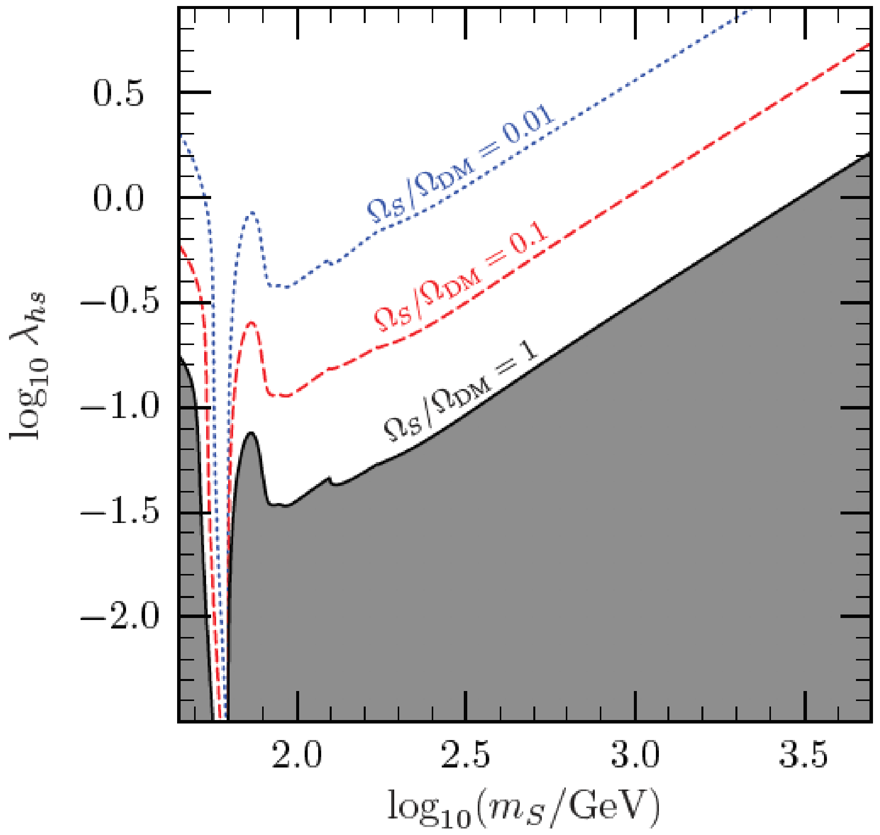
Thank you for your attention

Back up

Higgs Portal-Relic Density

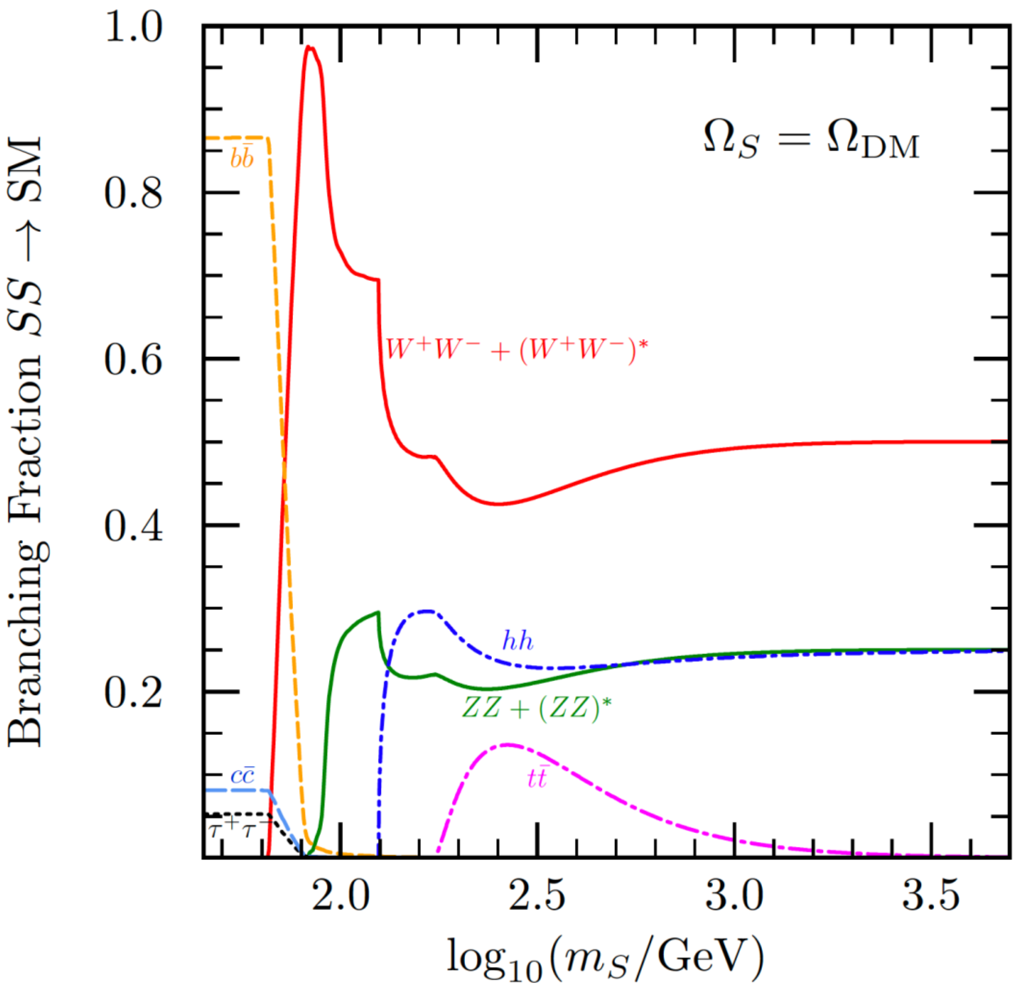
[arXiv: 1306.4710, James Cline *et al*]





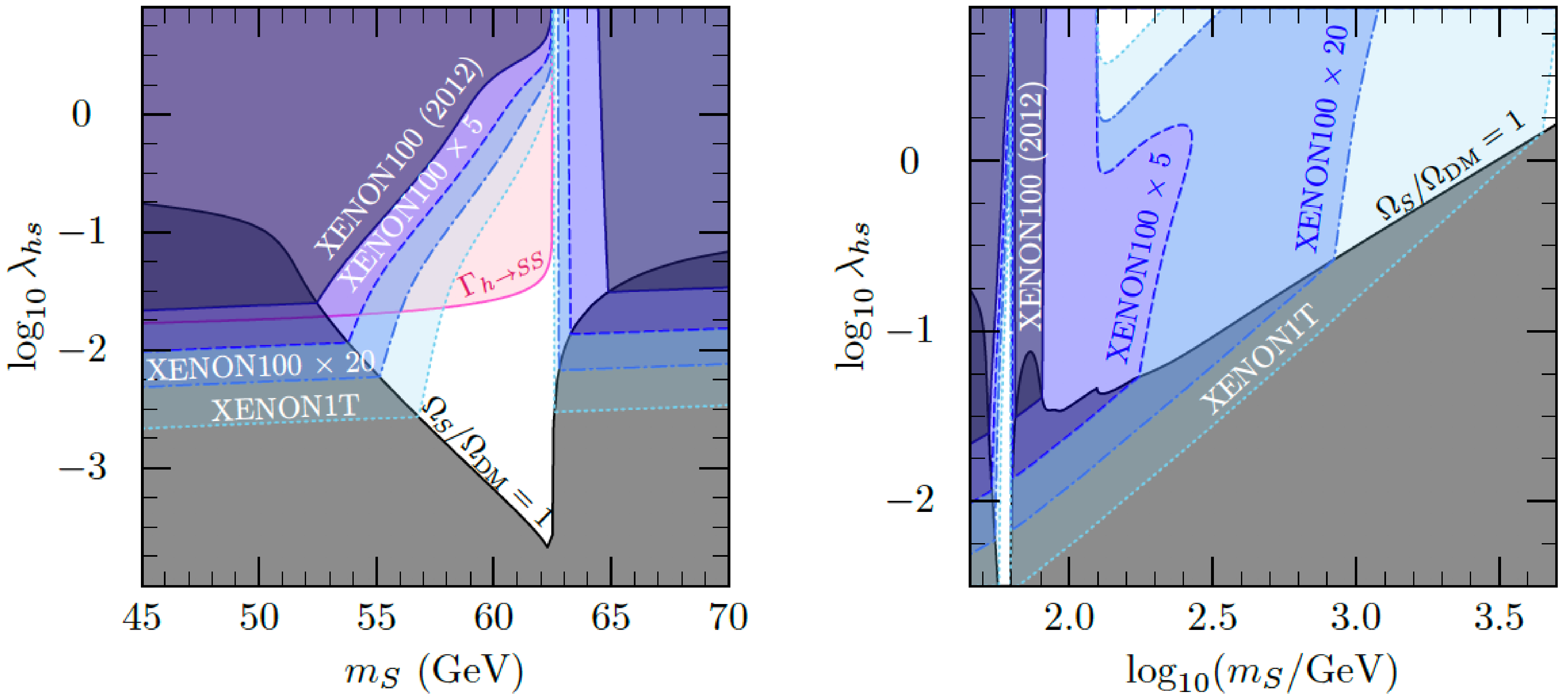
Higgs Portal-Relic Density

[arXiv: 1306.4710, James Cline *et al*]



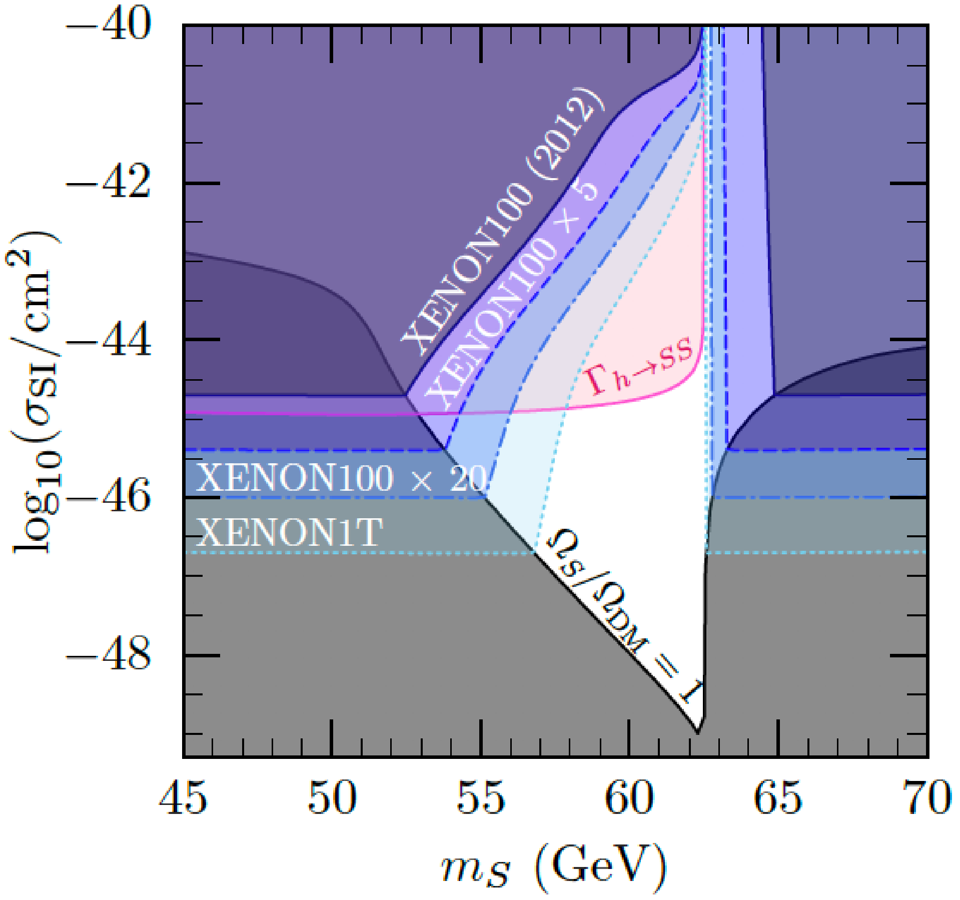
Higgs Portal-DD

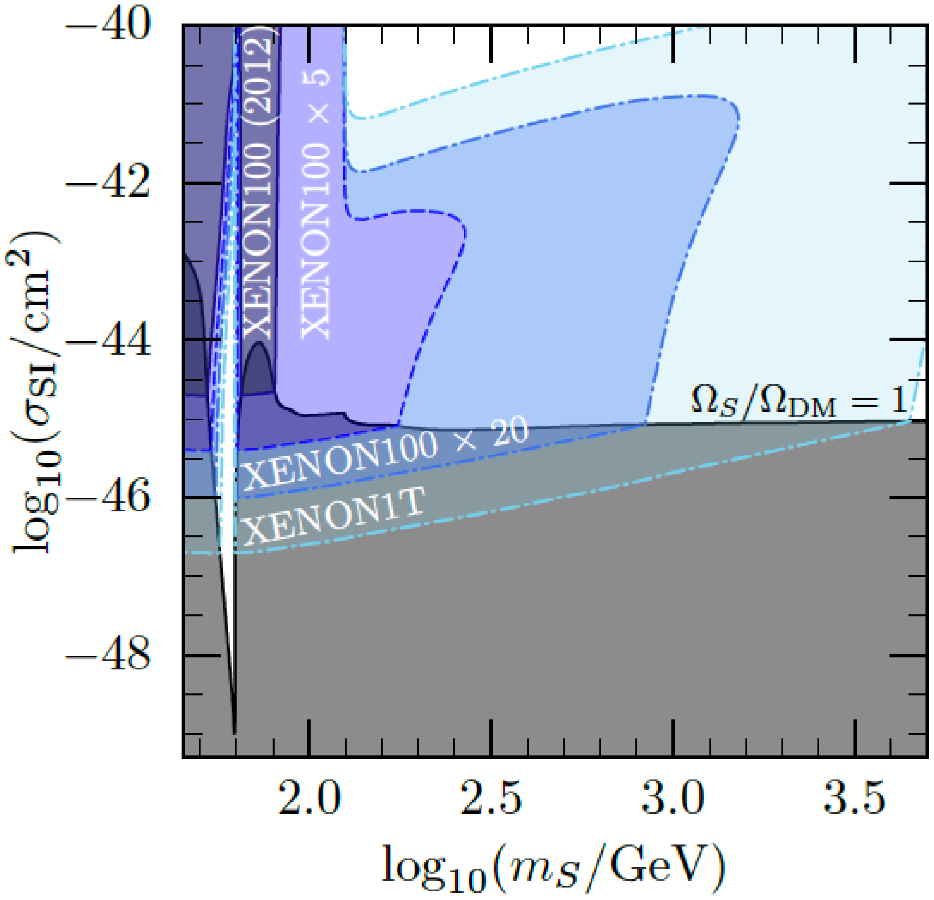
[arXiv: 1306.4710, James Cline *et al*]



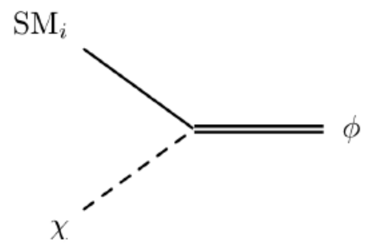
Higgs Portal-DD

[arXiv: 1306.4710, James Cline *et al*]





Scalar / Fermionic / Vector DM: Annihilation



- velocity averaged cross section
  - s/p-wave contribution
- mass ratio: $r_q = m_q/m_\chi$
  - s/p-wave different when $r \to 0$

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

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

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

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

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

[arXiv: 1307.8120, S. Chang *et al*]

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

Scalar / Fermionic / Vector DM: Direct Detection

- Different low energy effective operators
  - Scalar: no SD scattering
  - Majorana: no vector current term

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

Real Scalar

$$\mathcal{L}_{\text{eff}} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p + \sum_{p=q,g} C_{T_2}^p \mathcal{O}_{T_2}^p$$

$$\mathcal{O}_S^q \equiv \phi^2 m_q \bar{q} q \ ,$$
$$\mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi} \phi^2 G^{A\mu\nu} G^A_{\mu\nu} \ ,$$
$$\mathcal{O}_{T_2}^q \equiv \frac{1}{M^2} \phi i\partial^\mu i\partial^\nu \phi \mathcal{O}^q_{\mu\nu}$$
$$\mathcal{O}_{T_2}^g \equiv \frac{1}{M^2} \phi i\partial^\mu i\partial^\nu \phi \mathcal{O}^g_{\mu\nu}$$

Majorana

$$\mathcal{L}_{\text{eff}} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p + \sum_{i=1,2} \sum_{p=q,g} C_{T_i}^p \mathcal{O}_{T_i}^p + \sum_q C_{AV}^q \mathcal{O}_{AV}^q$$

$$\mathcal{O}_S^q \equiv \overline{\tilde{\chi}^0} \tilde{\chi}^0 m_q \bar{q} q \ ,$$
$$\mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi} \overline{\tilde{\chi}^0} \tilde{\chi}^0 G^A_{\mu\nu} G^{A\mu\nu} \ ,$$
$$\mathcal{O}_{T_1}^p \equiv \frac{1}{M} \overline{\tilde{\chi}^0} i\partial^\mu \gamma^\nu \tilde{\chi}^0 \mathcal{O}^p_{\mu\nu} \ ,$$
$$\mathcal{O}_{T_2}^p \equiv \frac{1}{M^2} \overline{\tilde{\chi}^0} i\partial^\mu i\partial^\nu \tilde{\chi}^0 \mathcal{O}^p_{\mu\nu} \ ,$$
$$\mathcal{O}_{AV}^q \equiv \overline{\tilde{\chi}^0} \gamma_\mu \gamma_5 \tilde{\chi}^0 \bar{q} \gamma^\mu \gamma_5 q \ .$$

Real Vector

$$\mathcal{L}_{\text{eff}} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p + \sum_{p=q,g} C_{T_2}^p \mathcal{O}_{T_2}^p + \sum_q C_{AV}^q \mathcal{O}_{AV}^q$$

$$\mathcal{O}_S^q \equiv B^\mu B_\mu m_q \bar{q} q \ ,$$
$$\mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi} B^\rho B_\rho G^{A\mu\nu} G^A_{\mu\nu} \ ,$$
$$\mathcal{O}_{T_2}^q \equiv \frac{1}{M^2} B^\rho i\partial^\mu i\partial^\nu B_\rho \mathcal{O}^q_{\mu\nu} \ ,$$
$$\mathcal{O}_{T_2}^g \equiv \frac{1}{M^2} B^\rho i\partial^\mu i\partial^\nu B_\rho \mathcal{O}^g_{\mu\nu} \ ,$$
$$\mathcal{O}_{AV}^q \equiv \frac{1}{M} \epsilon_{\mu\nu\rho\sigma} B^\mu i\partial^\nu B^\rho \bar{q} \gamma^\sigma \gamma_5 q \ ,$$

Heavy top partner / Vector-like Fermion

D. Yamaguchi, ATLAS

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

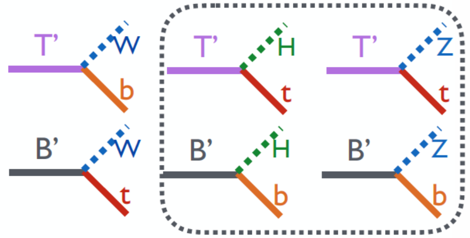
	SM	SU(2) Singlet	SU(2) Doublet	SU(2) Triplet
EM charge 5/3			(X, T)	(X, T, B)
EM charge 2/3	(u, d) (c, s) (t, b)	(T)	(T, B)	(T, B, Y)
EM charge -1/3		(B)	(B, Y)	
EM charge -4/3				
Mass	from Higgs	e.g.) generated by Yukawa coupling to a scalar singlet with VEV v' >> v(=246 GeV)		

H. Tholen, CMS

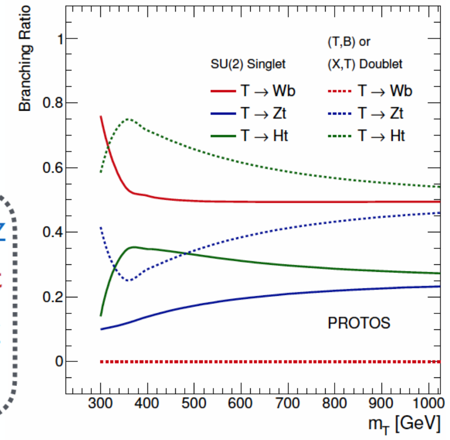
vector-like quarks
(VLQ)

- 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 4th-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

neutral currents only



[JHEP 08 (2015) 105]



Loop coupling C_{Sg} [arXiv: 1502.02244, Junji Hisano *et al*]

diagrams, we compute the contribution of a heavy quark Q to the coefficient of the gluon scalar-type operator C_S^g as

$$C_S^g|_Q = \frac{1}{4}\sum_{i=a,b,c}\left[(a_Q^2+b_Q^2)f_+^{(i)}(M;m_Q,m_{\psi_Q}) + (a_Q^2-b_Q^2)f_-^{(i)}(M;m_Q,m_{\psi_Q})\right] , \quad (53)$$

where $f_+^{(i)}$ and $f_-^{(i)}$ $(i=a,b,c)$ correspond to the contribution of the diagram (i) in Fig. 9. They are given as follows:

$$f_+^{(a)}(M;m_1,m_2) \equiv -\frac{m_1^2 m_2^4(M^2+m_1^2-m_2^2)}{\Delta^2}L - \frac{(-M^2+m_1^2+2m_2^2)\Delta + 6m_1^2m_2^2(M^2-m_1^2+m_2^2)}{6\Delta^2} , \quad (54)$$

$$f_-^{(a)}(M;m_1,m_2) \equiv \frac{m_1 m_2^3\{\Delta + m_1^2(M^2-m_1^2+m_2^2)\}}{\Delta^2}L - \frac{m_2\{(-2M^2+m_1^2+2m_2^2)\Delta - 6m_1^2m_2^2(M^2+m_1^2-m_2^2)\}}{6m_1\Delta^2} , \quad (55)$$

$$f_+^{(b)}(M;m_1,m_2) \equiv f_+^{(a)}(M;m_2,m_1) , \quad (56)$$

$$f_-^{(b)}(M;m_1,m_2) \equiv f_-^{(a)}(M;m_2,m_1) , \quad (57)$$

$$f_+^{(c)}(M;m_1,m_2) \equiv \frac{-M^2+m_1^2+m_2^2}{2\Delta} - \frac{m_1^2m_2^2}{\Delta}L , \quad (58)$$

$$f_-^{(c)}(M;m_1,m_2) \equiv \frac{2m_1m_2}{\Delta} - \frac{m_1m_2(-M^2+m_1^2+m_2^2)}{\Delta}L , \quad (59)$$

with

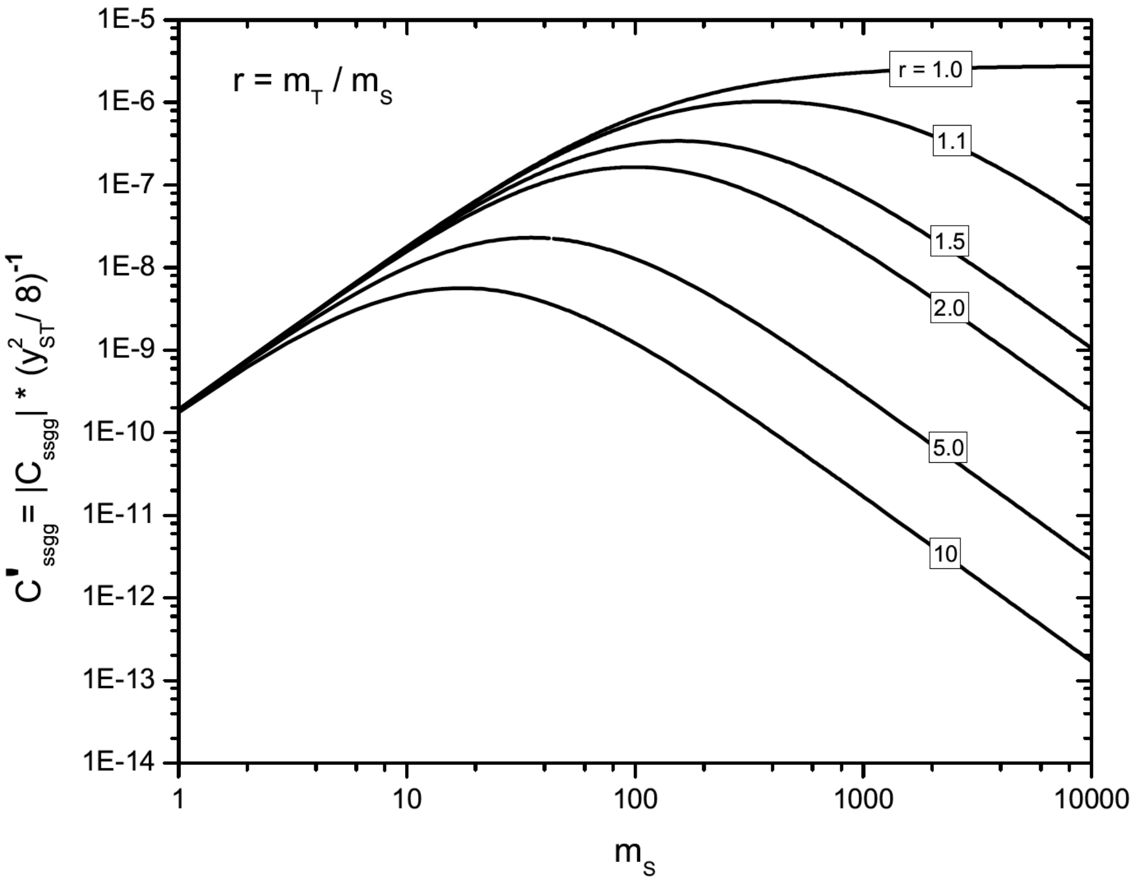
$$\Delta(M;m_1,m_2) \equiv M^4 - 2M^2(m_1^2+m_2^2) + (m_2^2-m_1^2)^2 , \quad (60)$$

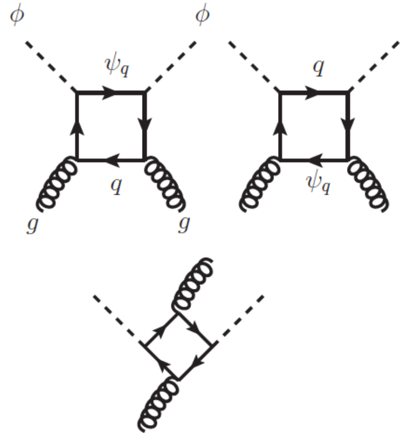
$$L(M;m_1,m_2) \equiv \begin{cases} \frac{1}{\sqrt{|\Delta|}}\ln\left(\frac{m_1^2+m_2^2-M^2+\sqrt{|\Delta|}}{m_1^2+m_2^2-M^2-\sqrt{|\Delta|}}\right) & (\Delta > 0) \\ \frac{2}{\sqrt{|\Delta|}}\arctan\left(\frac{\sqrt{|\Delta|}}{m_1^2+m_2^2-M^2}\right) & (\Delta < 0) \end{cases} . \quad (61)$$

SSgg Loop coupling

$$\mathcal{L}_{\text{eff}} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p + \sum_{p=q,g} C_{T_2}^p \mathcal{O}_{T_2}^p$$

$$\mathcal{O}_S^q \equiv \phi^2 m_q \bar{q} q \ ,$$
$$\mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi} \phi^2 G^{A\mu\nu} G^A_{\mu\nu} \ ,$$
$$\mathcal{O}_{T_2}^q \equiv \frac{1}{M^2} \phi i\partial^\mu i\partial^\nu \phi \mathcal{O}^q_{\mu\nu}$$
$$\mathcal{O}_{T_2}^g \equiv \frac{1}{M^2} \phi i\partial^\mu i\partial^\nu \phi \mathcal{O}^g_{\mu\nu}$$





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

Direct detection

- parton effective coupling
  - $\mathcal{L}_{eff} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p$
    - $\mathcal{O}_S^q = m_q S^2 \bar{q} q$
    - $\mathcal{O}_S^g = \frac{\alpha_s}{\pi} S^2 G^{A\mu\nu} G_{\mu\nu}^A$
- nucleon effective coupling
  - $\mathcal{L}_{SI}^{(N)} = f_N S^2 \bar{N} N$
    - $f_N / m_N = \sum_{q=uds} C_S^q f_{T_q}^{(N)} - \frac{8}{9} C_S^g f_{T_g}^{(N)}$
- nucleus scattering
  - $\sigma = \frac{1}{\pi} \left(\frac{m_{tar}}{m_S + m_{tar}} \right)^2 |n_p f_p + n_n f_n|^2$

Direct detection

- General formalism
  - refer to 1502.02244
- Effective Langragian
- DM-parton coupling
  - $C_S^p = C_S^p(y_{ST}, m_S, r)$

3 Formalism: real scalar boson DM

Next we briefly show the results for the case of real scalar boson DM. We may use a similar procedure to that given in the previous section to formulate effective theories for the WIMP.

3.1 Effective Lagrangian

The effective interactions of the real scalar ϕ with quarks and gluon are expressed by

$$\mathcal{L}_{\text{eff}} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p + \sum_{p=q,g} C_{T_2}^p \mathcal{O}_{T_2}^p \ , \tag{29}$$

with

$$\begin{aligned} \mathcal{O}_S^q &\equiv \phi^2 m_q \bar{q} q \ , \\ \mathcal{O}_S^g &\equiv \frac{\alpha_s}{\pi} \phi^2 G^{A\mu\nu} G^A_{\mu\nu} \ , \\ \mathcal{O}_{T_2}^q &\equiv \frac{1}{M^2} \phi i\partial^\mu i\partial^\nu \phi \mathcal{O}_{\mu\nu}^q \ , \\ \mathcal{O}_{T_2}^g &\equiv \frac{1}{M^2} \phi i\partial^\mu i\partial^\nu \phi \mathcal{O}_{\mu\nu}^g \ . \end{aligned} \tag{30}$$

Note that there is no spin-dependent interactions in the case of scalar boson DM.

Direct detection

- DM-nucleon coupling
  - $f_N = f_N(C_S^q, C_S^g)$
- scattering cross section
  - $\sigma = \sigma(f_N, m_S)$

3.3 Scattering cross sections

We now ready to evaluate the scattering cross section of the real scalar boson with a target nucleus. The spin-independent coupling of the real scalar boson with a nucleon defined by

$$\mathcal{L}_{\rm SI}^{(N)} = f_N \phi^2 \overline{N} N \ , \tag{36}$$

is evaluated as

$$f_N/m_N = \sum_{q=u,d,s} C_S^q(\mu_{\rm had}) f_{T_q}^{(N)} - \frac{8}{9} C_S^g(\mu_{\rm had}) f_{T_G}^{(N)} + \frac{3}{4} \sum_q^{N_f} C_{T_2}^q(\mu)[q(2;\mu) + \overline{q}(2;\mu)] - \frac{3}{4} C_{T_2}^g(\mu) g(2;\mu) \ . \tag{37}$$

In the scalar boson case, there is no spin-dependent coupling with a nucleon. By using the effective coupling, we calculate the scattering cross section of the real scalar boson with a target nucleus as follows:

$$\sigma = \frac{1}{\pi} \left(\frac{M_T}{M + M_T} \right)^2 |n_p f_p + n_n f_n|^2 \ . \tag{38}$$

Direct detection

- mass fraction $f_{T_q}^N$
  - quantum mechanics
  - expectation value

As for the scalar-type quark operators $\mathcal{O}_S^q$, we use the results from the lattice QCD simulations. The expectation values of the scalar bilinear operators of light quarks between the nucleon states at rest, $|N\rangle$ $(N = p, n)$, are parametrized as

$$f_{T_q}^{(N)} \equiv \langle N|m_q \bar{q}q|N\rangle / m_N \ , \tag{4}$$

which are called the mass fractions. These values are shown in Table 1. Here, m_N is the nucleon mass. They are taken from Ref. [12], in which the mass fractions are computed by using the results from Refs. [13, 14].

up to the leading order in α_s. The relation beyond the leading order in α_s is also readily obtained from the trace-anomaly formula. By evaluating the operator (5) in the nucleon states $|N\rangle$, from $\langle N|\Theta^\mu{}_\mu|N\rangle = m_N$ we then obtain

$$\langle N|\frac{\alpha_s}{\pi} G^A_{\mu\nu} G^{A\mu\nu}|N\rangle = -\frac{8}{9} m_N f_{TG}^{(N)} \ , \tag{6}$$

with $f_{TG}^{(N)} \equiv 1 - \sum_{q=u,d,s} f_{T_q}^{(N)}$. Notice that the r.h.s. of Eq. (6) is the order of the typical hadronic scale, $\mathcal{O}(m_N)$. That is, although we include a factor of α_s/π in the definition of $\mathcal{O}_S^g$, its nucleon matrix element is not suppressed by α_s/π. This is the reason why we have defined $\mathcal{O}_S^g$ to contain α_s/π.

Direct detection

[0803.2360, G. Belanger *et al*]

The anomaly of the trace of energy-momentum tensor in QCD implies [77]

$$M_N\langle N|N\rangle = \langle N|\sum_{q\le n_f} m_q\overline{\psi}_q\psi_q(1+\gamma) + (\frac{\beta^{n_f}}{2\alpha_s^2})\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle \tag{44}$$

where γ is the anomalous dimension of the quark field operator, α_s the strong coupling constant, $G_{\mu\nu}$ the gluon field tensor and $\beta^{n_f} = -\alpha_s^2/4\pi(11-2n_f/3+\alpha_s/4\pi(102-38n_f/3))$. In the leading order approximation for three flavours, Eq.(44) is simplified to

$$M_N\langle N|N\rangle = \langle N|\sum_{q=u,d,s} m_q\bar{\psi}_q\psi_q - \frac{9}{8\pi}\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle \tag{45}$$

Comparing Eq. 44 for n_f and n_f+1 one finds the contribution of one heavy quark flavour to the nucleon mass, relating the heavy quark content of the nucleon to the gluon condensate

$$\langle N|m_Q\bar{\psi}_Q\psi_Q|N\rangle = -\frac{\Delta\beta}{2\alpha_s^2(1+\gamma)}\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle \tag{46}$$

where $\Delta\beta$ is a contribution of one quark flavor to the QCD β-function. This formula agrees with the effective $HG_{\mu\nu}G^{\mu\nu}$ vertex at small q^2 [96]. Up to order α_s^2,

$$\langle N|m_Q\bar{\psi}_Q\psi_Q|N\rangle = -\frac{1}{12\pi}(1+\frac{11\alpha_s(m_Q)}{4\pi})\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle \tag{47}$$

Keeping only the leading order and combining with Eq. 45 will lead to the usual relation Eq. 26. Note that the NLO terms in Eq. 44 partially cancel the effect of the NLO corrections in Eq. 47 so that the QCD corrections to Eq. 26 are small. See also [97] for an alternative estimate of the heavy quark content of the nucleon.

Direct detection

[0803.2360, G. Belanger *et al*]

The simplest way to take into account dominant QCD corrections to Higgs exchange is then to consider WIMP heavy quark interactions through Higgs exchange and introduce an effective vertex for heavy quarks in the nucleon with Eq. 26 modified to include one-loop QCD corrections, Eq. 47. The equivalence of this approach with the description of the Higgs coupling to the nucleon through gluons is confirmed by a direct computation of the triangle diagram of Fig.1 in the limit where $Q^2 \ll M_Q$. Recall that the typical transfer momentum is $Q \approx 100$ MeV, Eq. 1. Note that for light quarks the corrections that would arise from their contribution to the triangle diagram that couples a Higgs to gluon are all absorbed into the definition of the light quark content of the nucleon.

While triangle diagrams can be treated using effective heavy quark nucleon condensate instead of performing an explicit one-loop calculation, such a simple treatment is not justified in general for box diagrams. Such an approximation would be valid only when $m_q/(M_{\tilde{q}} - M_\chi) \ll 1$ as shown explicitly in [57] for the MSSM. In that case the tree-level approach works well for c and b quarks but would fail for t-quarks unless the associated squark is much heavier. Nevertheless this is the approximation we use by default in `micrOMEGAs`, the main reason being that in many models the contribution of the Higgs exchange diagram is much larger than the one from the box diagrams. The user can always ignore this simple treatment and implement a more complete calculation of the box diagrams. For example in the case of MSSM-like we have implemented the one-loop computation of the neutralino nucleon scattering of Ref. [57], see Section 4 and Appendix A.

In a generic new physics model, new heavy coloured particles can also contribute to the WIMP gluon amplitude, for instance squarks in the MSSM. For heavy quarks, the computation of the triangle diagrams involving squarks, or any other scalar colour triplet, also reduces to a calculation of WIMP-squark scattering with an estimation of the squark content in the nucleon. The latter can be obtained by calculating the contribution of squarks to the QCD β-function just as was done for heavy quarks, Eq. 46. Note however that the contribution of scalars to the trace anomaly has an additional factor of 2 due to the different dimension of scalar and fermion fields. After substituting $\Delta\beta$ and γ we get at order α_s,

$$\langle N|2M_{\tilde{Q}}^2 \phi_{\tilde{Q}}^* \phi_{\tilde{Q}}|N\rangle = -\frac{1}{48\pi}\left(1+\frac{25\alpha_s}{6\pi}\right)\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle \tag{48}$$

Thus the contribution of scalars is expected to be small because of small scalar content in the nucleon. This relation is also known to order α_s^2 [95]. On the other hand other new particles such as a heavy Majorana fermion or a real scalar which belong to adjoint color representation have very large nucleon densities

$$\langle N|m_Q \bar{\psi}_Q \psi_Q|N\rangle = -\frac{1}{2\pi}\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle \tag{49}$$

$$\langle N|2M_{\tilde{Q}}^2 \phi_{\tilde{Q}} \phi_{\tilde{Q}}|N\rangle = -\frac{1}{8\pi}\langle N|\alpha_s G_{\mu\nu}G^{\mu\nu}|N\rangle \tag{50}$$

In summary, in `micrOMEGAs` we check the list of coloured particles in the model and according to their spin and colour define the nucleon content for each particle using Eq. 47-50. We then compute the contributions from all WIMP-coloured particles processes. The coefficients of the operators for such interactions are calculated automatically in the same manner as the coefficients for WIMP-quarks interactions as described in Section 3.1. The case of of a color octet vector particle is not treated.

Indirect detection

[arXiv: 1108.2914 A.G. Sameth *et al*]

- General formalism, two factors

$$\mu_\gamma(\Phi_{\rm PP}) \equiv (A_{\rm eff} T_{\rm obs}) \Phi_{\rm PP} J,$$

  - astrophysical

$$J \equiv \int_{\Delta\Omega(\psi)} \int_\ell [\rho(\ell,\psi)]^2 d\ell d\Omega(\psi),$$

  - particle physics

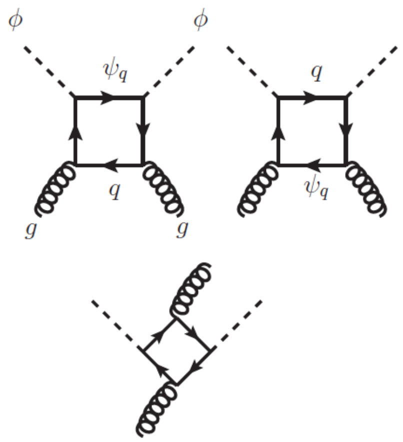
$$\Phi_{\rm PP} \equiv \frac{\langle \sigma_A v \rangle}{8\pi m_\chi^2} \int_{E_{\rm th}}^{m_\chi} \sum_f B_f \frac{dN_f}{dE} dE,$$

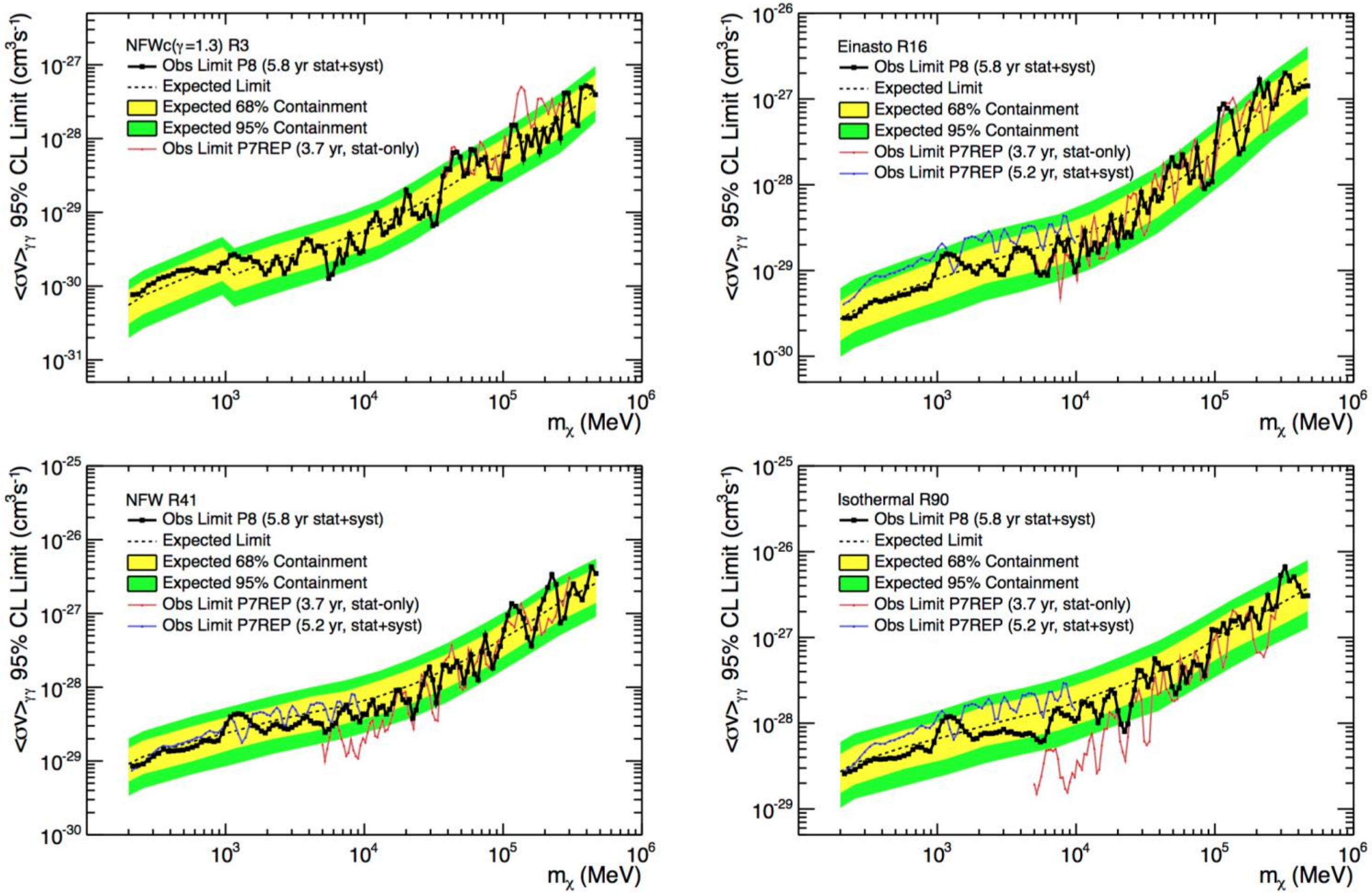
Indirect detection (gamma-ray)

- line: galactic region
  - [arXiv: 1506.00013, Fermi]

- conversion from gg to $\gamma\gamma$

$$\frac{\langle\sigma v\rangle_{\gamma\gamma}}{\langle\sigma v\rangle_{gg}} = \frac{9}{2}Q_t^4\left(\frac{\alpha_{em}}{\alpha_s}\right)^2 \approx 3.8\times 10^{-3},$$





Indirect detection (γ-ray)

[1604.00014, Jennifer Gaskins]