imagine the impossible

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Top-philic Scalar Dark Matter with a Vector-like Top Partner

Peiwen Wu

Korea Institute for Advanced Study (KIAS)

Collaborated with Pyungwon Ko, Seungwon Baek

based on arXiv: 1606.00072

Outline

- Motivation
  - why flavored DM? why top-flavored?
- Model description
- Properties
  - Thermal relic density
  - Direct/Indirect detection
  - Collider search
  - Complementarity
- Conclusion

SUSY → SM flavor → Quark+DM flavor → MFV → U-flavored → top-flavored

- SUSY is beautiful and powerful
  - starts from
    - fine tuning of Δm_h
  - ends in
    - (partially) solve fine tuning of Δm_h
    - gauge coupling unification
    - DM candidate
- How about a different starting point?

SUSY → **SM flavor** → Quark+DM flavor → MFV → U-flavored → top-flavored

- SM flavor structure
  - all matters have 3 flavors/generations
  - significant mass hierarchy in both quark and lepton sector
  - broken by SM Yukawa interaction
  - approximate flavor symmetry $U(3)^5$
    - $U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$
      - ignore the neutrino masses

SUSY → SM flavor → Quark+**DM flavor** → MFV → U-flavored → top-flavored

- Maybe a similar flavor structure in new physics sector
  - extend SM flavor to [arXiv: 1109.3516 Can Kilic *et al*]
    - $U(3)^5 \times U(3)_{DM}$, if DM is complex
    - $U(3)^5 \times O(3)_{DM}$, if DM is real
  - $U(3)_{DM}, O(3)_{DM}$ can be
    - **exact**: **degenerate** DM multiplet
    - broken: mass splitting between DM flavors
  - DM is the lightest particle in the dark sector

SUSY → SM flavor → **Quark+DM flavor** → MFV → U-flavored → top-flavored

- LHC is a hadron collider, consider the quark sector
- renormalizable interaction ∝ $(Quark)^i * [\lambda]_i{}^\alpha * (DM)_\alpha * (med.)$
  - $(med.)$ can transform under flavor of
    - both $(Quark)$ and (DM)
    - one of them
    - none (simplest)
  - if $(med.)$ is singlet
    - flavors of $(Quark)$ and (DM) are associated
    - breaking of $(Quark)$ flavor may transfer to (DM)
      - mass splitting in (DM) sector

SUSY → SM flavor → Quark+DM flavor → MFV → U-flavored → top-flavored

- Generally, FCNC generated by $(Quark) * [\lambda] * (DM) * (med.)$
  - alleviated by
    - $m_{med.} \sim 500$ GeV
      - but harder to detect
    - $\lambda \sim 10^{-2}$
      - but **small annihilation**, cannot obtain $\boldsymbol{\Omega_{DM} h^2} \sim 0.1$
      - or, make DM couple to SM gauge bosons, more complex model
      - if DM is SM singlet, $[\lambda]$ should be $O(1)$.

SUSY → SM flavor → Quark+DM flavor → **MFV** → **U-flavored** → top-flavored

- Minimal Flavor Violation (MFV)
  - All flavor violation comes only from SM Yukawa
  - $U(3)_{DM}$ is identified as $U(3)_{Quark} = \{Q, U, D\}$, which one?
    - Q: more complicate spectrum
    - D: flavor constraints from K, B mesons
    - U: **simple** and **safe**
      - **top quark** is special in SM, a portal to explore new physics
      - largest **hierarchy** in quark sector
        - may cause significant **splitting** in dark sector

SUSY → SM flavor → Quark+DM flavor → **MFV** → **U-flavored** → top-flavored

- Quark-flavored DM: $\mathcal{L} \supset U^i [\lambda]_i^{\ j} (DM)_j (med.)$
- under MFV, expansion of $\lambda_i^{\ j}, m_{DM}$ in terms of SM Yukawa Y
  - keep lowest order [arXiv: 1109.3516 Can Kilic *et al*]
    - $[\lambda]_i^{\ j} = (\alpha \cdot 1 + \beta\, Y^+ Y)_i^{\ j}$, $[m_{DM}]_i^{\ j} = (m_0 \cdot 1 + \Delta m\, Y^+ Y)_i^{\ j}$
    - $\{\alpha, \beta, m_0, \Delta m\}$ are constants determined by UV complete theory

SUSY → SM flavor → SM+DM flavor → MFV → U-flavored → top-flavored

- Quark-flavored DM: $\mathcal{L} \supset U^i [\lambda]_i{}^j (DM)_j (med.)$
- under MFV
    - $[\lambda]_i{}^j = (\alpha \cdot 1 + \beta\, Y^+ Y\,)_i{}^j$, $[m_{DM}]_i{}^j = (m_0 \cdot 1 + \Delta m\, Y^+ Y\,)_i{}^j$
    - $\alpha \geq \beta\, y_t^2$, $m_0 \geq \Delta m\, y_t^2$
  - almost degenerate in first 2 generation $DM_{u,c}$
    - small FCNC coupling, less flavor constraints
  - considerable splitting between $DM_{u,c}$ and DM_{top}
    - $DM_{u/top}$ is the lightest, depending on (+/-) of Δm
  - assume DM_{top} is the lightest
    - arrange $\{\alpha, \beta, m_0, \Delta m\}$ to decouple masses/couplings of $DM_{u,c}$

SUSY → SM flavor → SM+DM flavor → MFV → U-flavored → top-flavored

- no valence top quark in nucleon
- DM coupling to gluons
  - loop calculation (SUSY) [arXiv: 1007.2601 Junji Hisano *et al*]
    - (DM, mediator)=(fermion, scalar)
  - extreme case: gluon-philic DM [arXiv: 1506.01408 R.M. Godbole *et al*]
    - (DM, mediator)=(scalar, scalar)
- top-philic DM, EFT operator [arXiv:1009.0618 Kingman Cheung *et al*]
  - (DM, mediator)=(fermion, scalar/vector)

- Our model: (DM, mediator)=(scalar, fermion)

Model description

- DM: real scalar S
  - SM singlet, couple only to top quark
  - Higgs portal, well studied [arXiv: 1306.4710 J. Cline *et al*]
    - $\lambda_{SH} S^2 |H|^2$ turned off here
- top partner: Vector-like (VL) fermion T
- Z_2 parity: S, T are odd
  - no mass mixing $(S, H), (T, t)$
  - $Br(T \to S t^{(*)}) = 100\%$
  - LHC searches for VL (T, B) do not apply
- gauge invariance

  see SUSY2016 talks by H. Tholen, D. Yamaguchi
  - (T, t_R) same quantum number

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

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

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

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

$$\mathcal{L}_G = C_{Sg} \frac{\alpha_s}{\pi} S^2 G^{A\mu\nu} G^A_{\mu\nu}$$

Thermal Relic

- pair annihilation
  - $SS \to t\bar{t}$
- co-annihilation
  - $ST \to t^* \to bW^+$
  - $ST \to t + SM$
    - $SM = g, \gamma, Z, h$

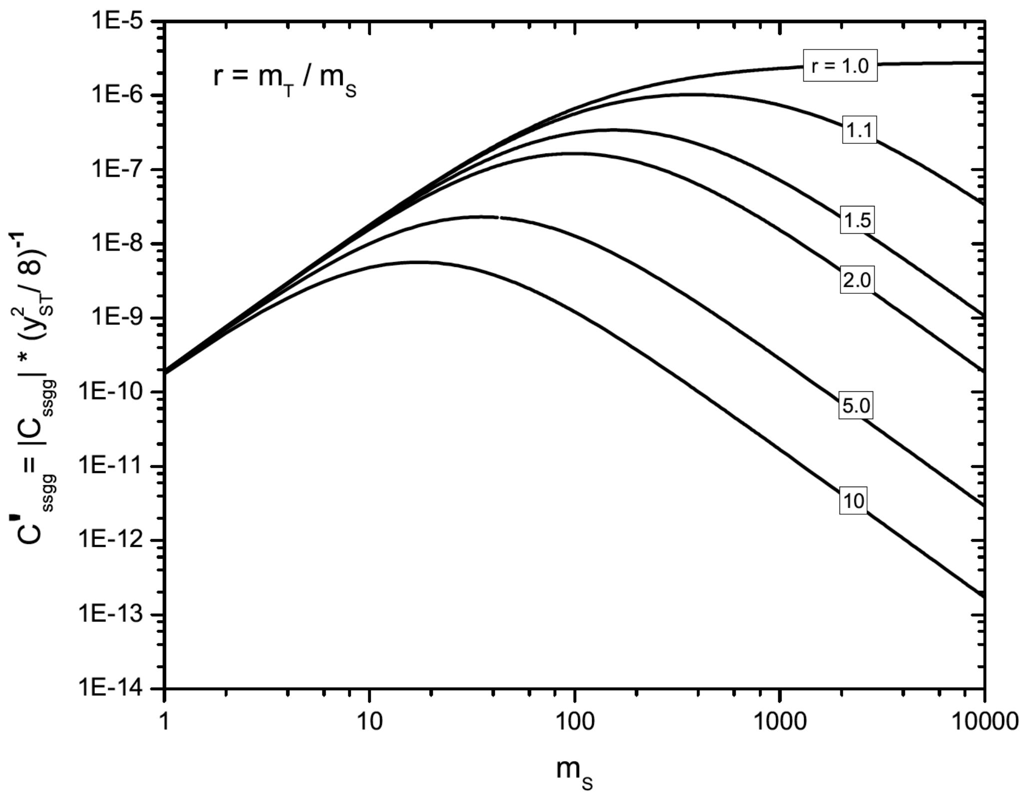
  - $S + t/\bar{t} \to T/\bar{T} + SM$
  - $SS \to T\bar{T}$

  - $T\bar{T} \to SM + SM'$

- loop coupling C_{Sg}
  - [arXiv: 1502.02244, Junji Hisano *et al*]
  - $SS \to gg$
    - small for $SS \to SM + SM'$
      - $SM = g, \gamma, Z, h$
  - proportional to y_{ST}^2
    - important when $y_{ST} > \mathcal{O}(1)$

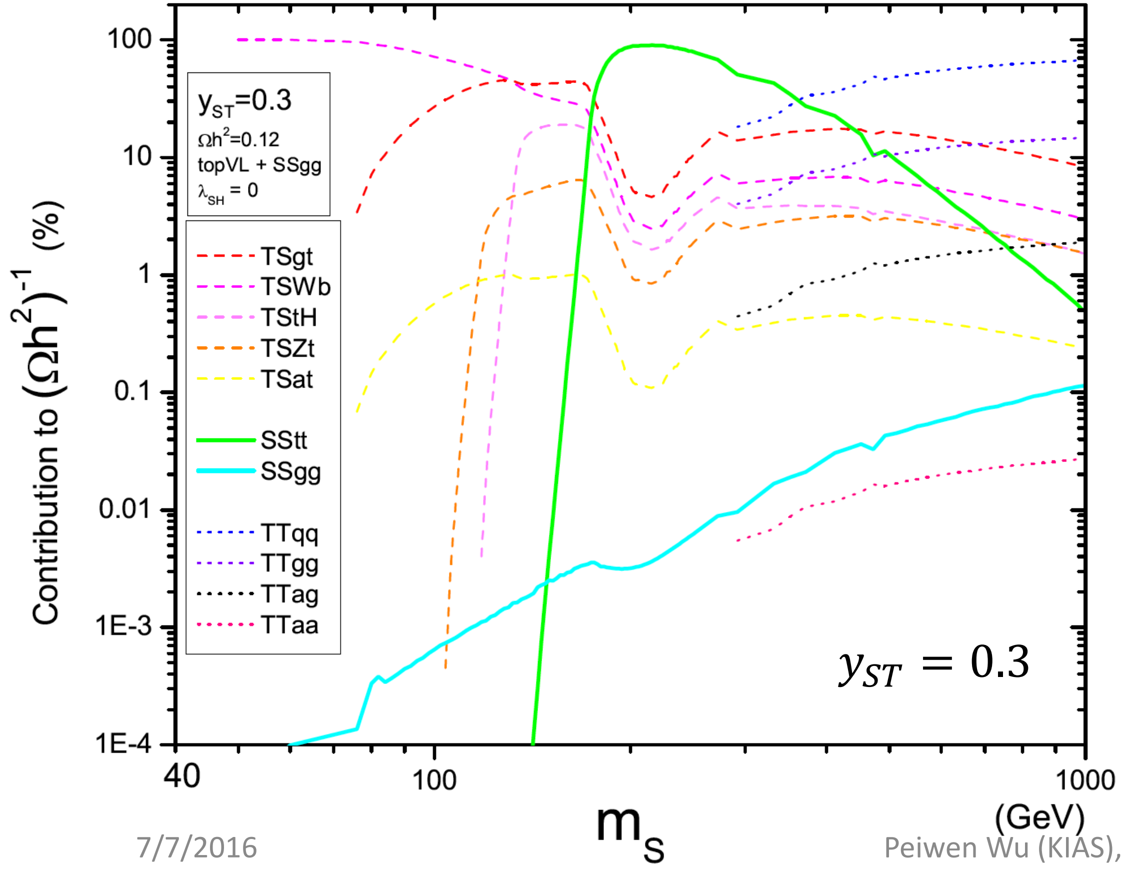
Thermal Relic

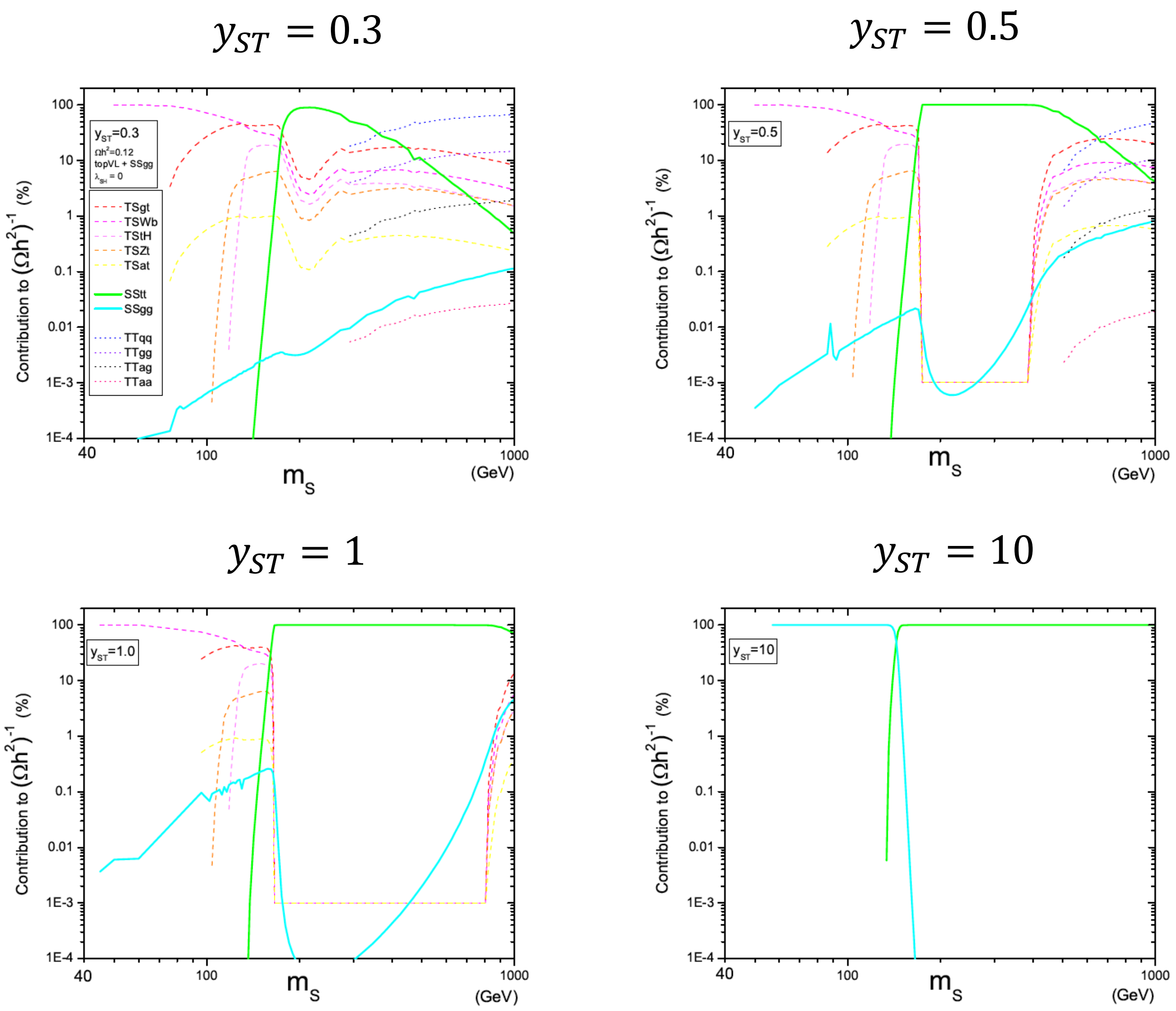
- loop coupling C_{Sg}
  - proportional to y_{ST}^2
    - important when $y_{ST} > \mathcal{O}(1)$
  - suppressed by large $r = m_T/m_S$
    - heavier particles in the loop



Thermal Relic

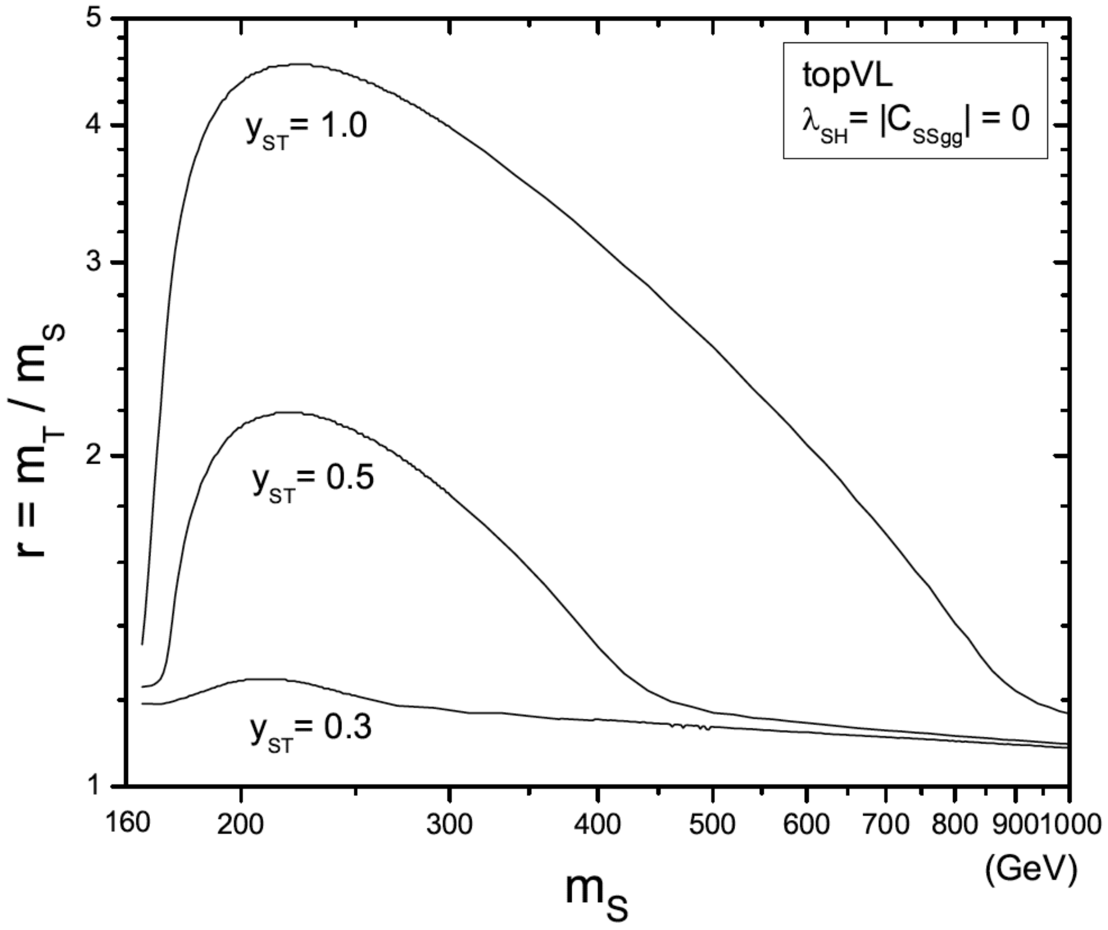
- $SS \to t\bar{t}$, $SS \to gg$
- channels evolve with y_{ST}





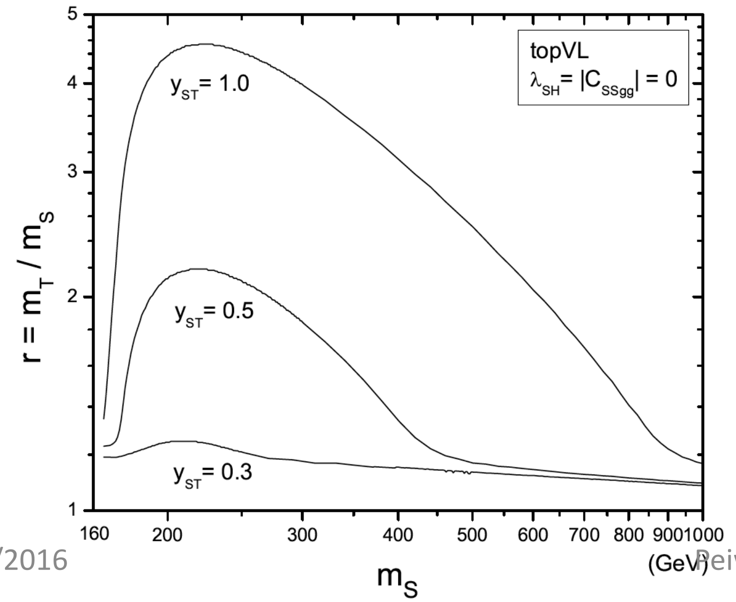
Thermal Relic

- $SS \to gg$ ignored for $y_{ST} < \mathcal{O}(1)$
- when $SS \to t\bar{t}$ is open
  - relaxed r
  - larger y_{ST} is more helpful
  - further suppressed C_{Sg}
    - affect the direct detection



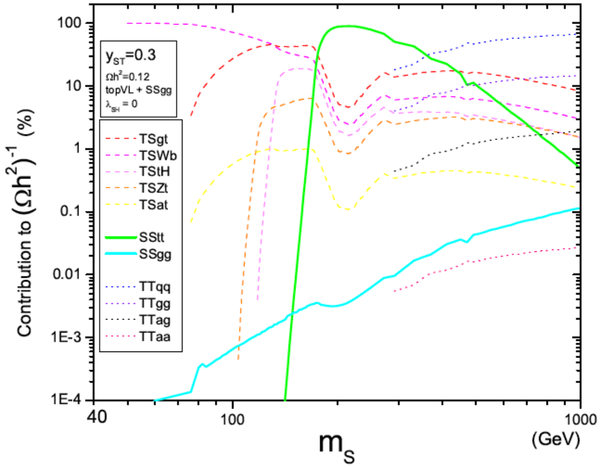
Thermal Relic

- when $SS \to t\bar{t}$ is open
  - relaxed r
  - larger y_{ST} is more helpful
  - further suppressed C_{Sg}
    - affect the direct detection

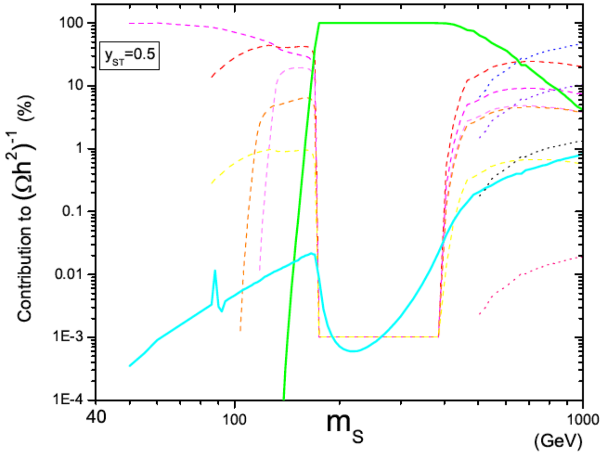


$SS \to t\bar{t}$, $SS \to gg$

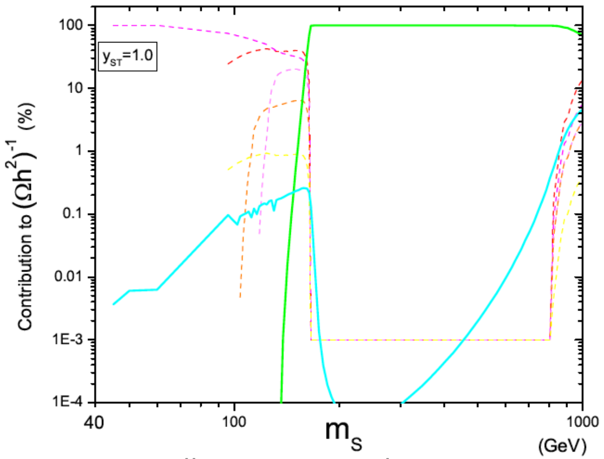
$y_{ST} = 0.3$



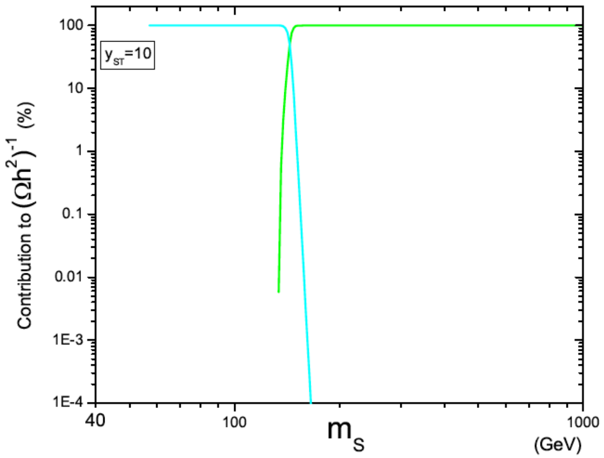
$y_{ST} = 0.5$



$y_{ST} = 1$

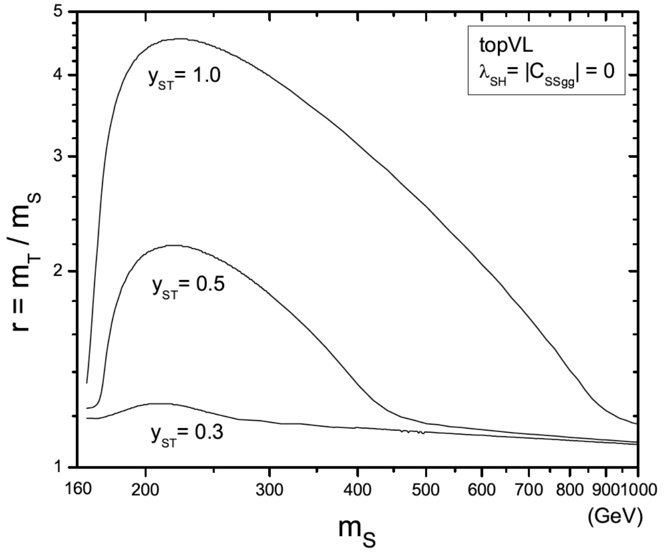


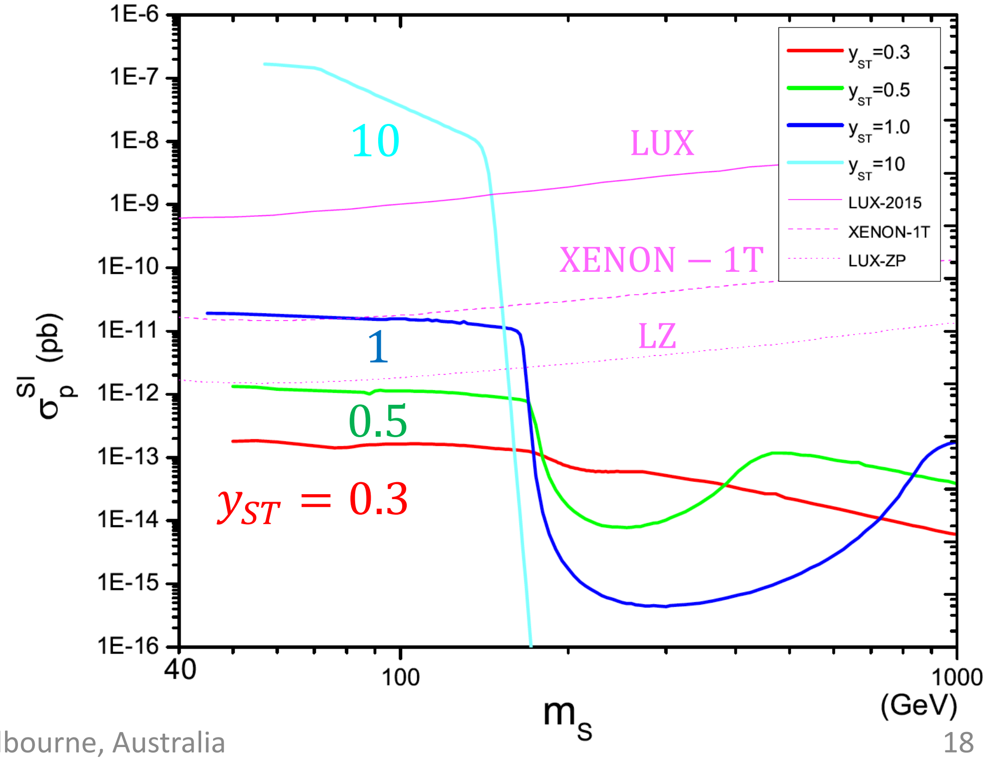
$y_{ST} = 10$



Direct detection

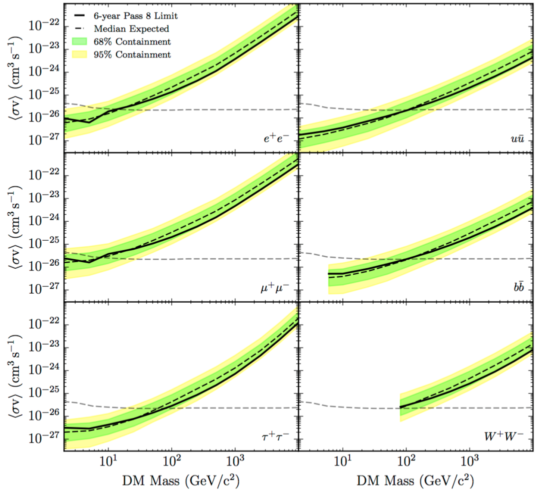
- large y_{ST}
  - $SS \to gg$ can dominate in light m_S region
  - σ_{SI} is correlated with $\Omega_{DM} h^2$
  - excluded by LUX-2015
- $y_{ST} \approx 1$
  - difficult for XENON-1T
  - possibly covered by LZ
- $y_{ST} < 0.5$
  - difficult to detect

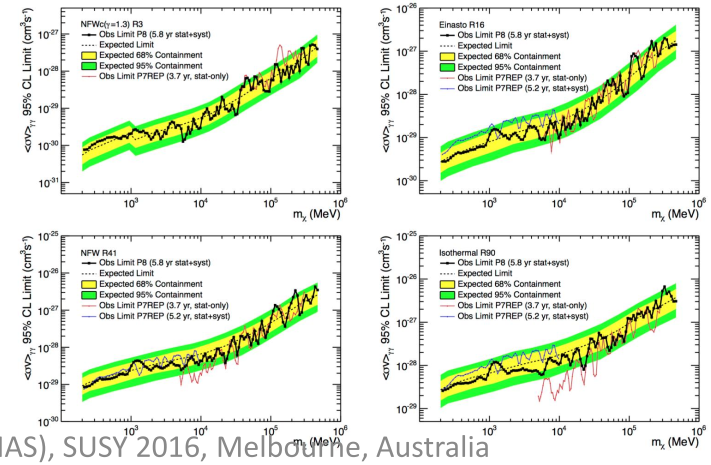




Indirect detection (gamma-ray)

- gamma-ray spectrum
  - continuous: dwarf galaxies
  - line: galactic region





Indirect detection (gamma-ray)

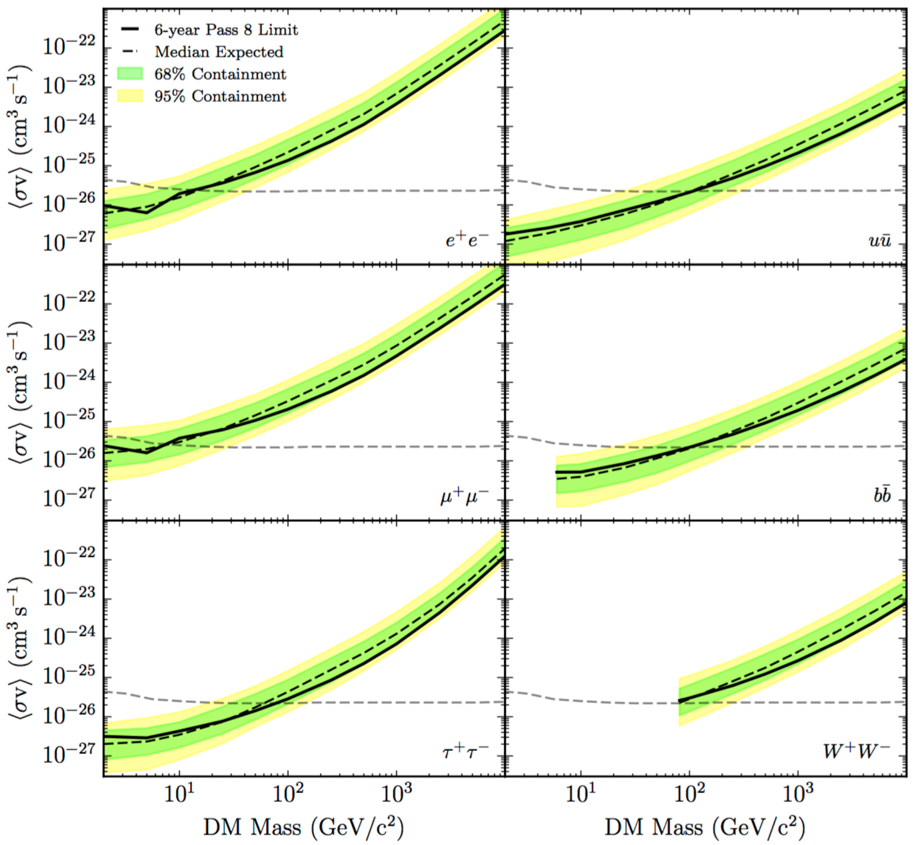
- continuous: dwarf galaxies
  - [arXiv: 1503.02641, Fermi]

- no $t\bar{t}$?
  - rescale from $b\bar{b}$
  - $\langle\sigma v\rangle_{gg}$ obtained from $u\bar{u}$

  [arXiv: 1511.04452 F. Giacchino *et al*]

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

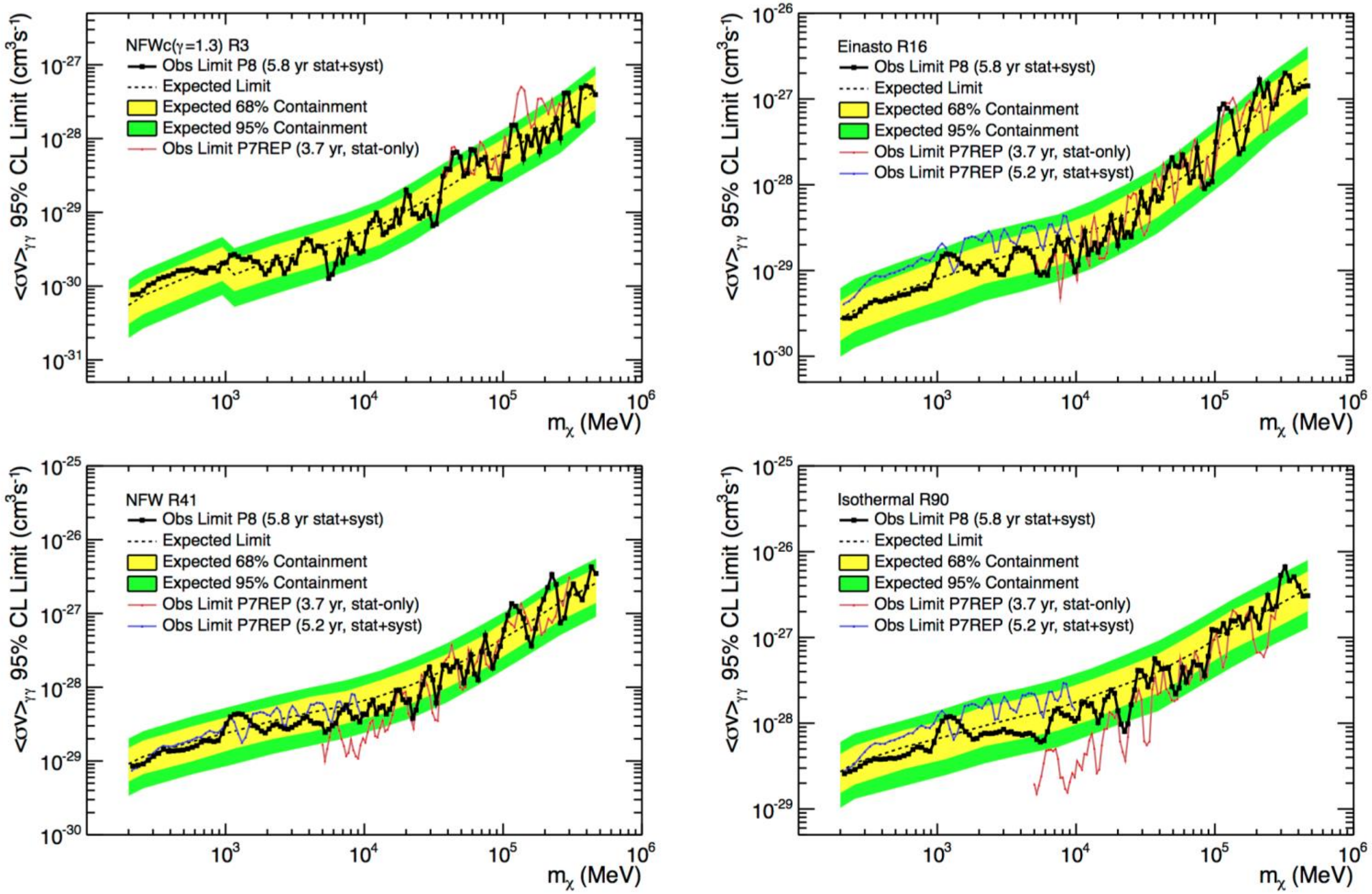
$$\langle\sigma v\rangle_{t\bar{t}} = \langle\sigma v\rangle_{b\bar{b}}\, N_{\gamma,b\bar{b}}/N_{\gamma,t\bar{t}}$$



Indirect detection (gamma-ray)

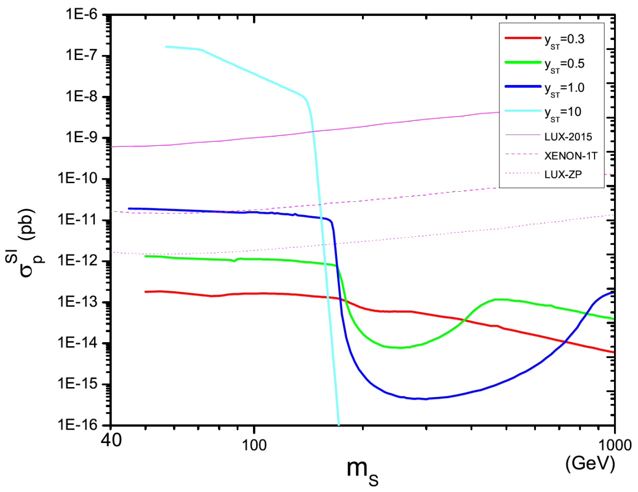
- line: galactic region
  - [arXiv: 1506.00013, Fermi]
- conversion from gg to $\gamma\gamma$

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

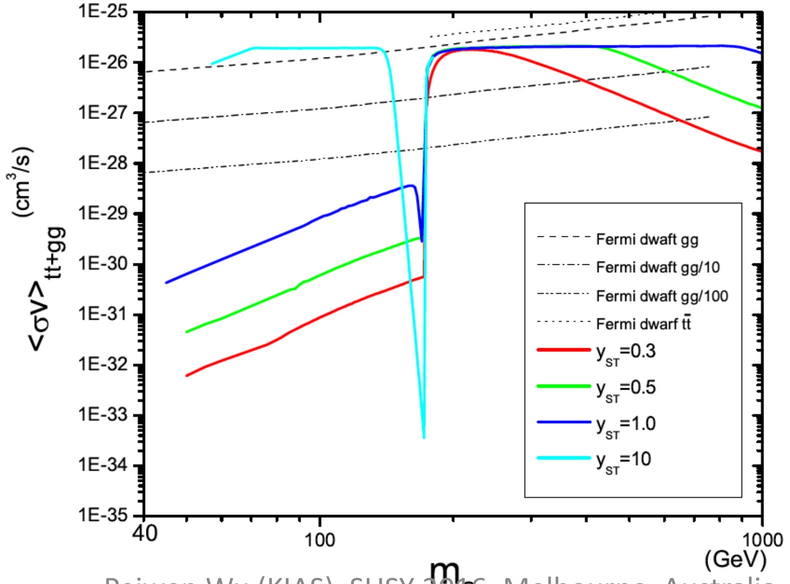


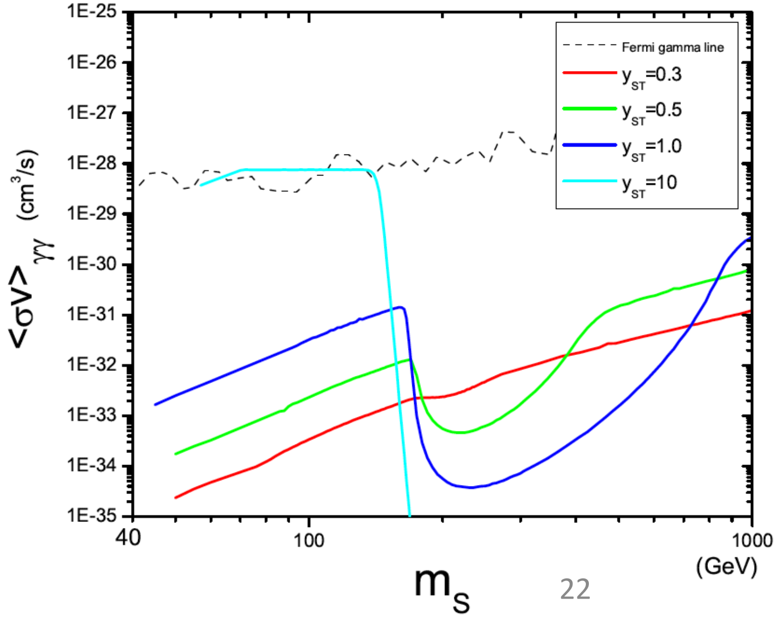
Indirect detection (gamma-ray)

Direct Detection



- promising to detect $m_S > m_t$
  - complementary to DD
- current results just about to test this model
- improved sensitivity can cover wide regions in $m_S > m_t$





Collider search

- $pp \to T\bar{T} \to t\bar{t} + MET$
  - similar to stop search
- CMS 8 TeV [arXiv: 1504.01398]

$$\mathcal{L}_{\mathrm{EFT}} = \frac{m_t}{M_*^3}\bar{t}t\bar{\chi}\chi,$$

χ: Dirac fermion

$$\begin{aligned} \text{preselection}: \not{E}_T &> 160\,\mathrm{GeV}, \\ \not{E}_T &> 320\,\mathrm{GeV}, \\ M_T &> 160\,\mathrm{GeV}, \\ M_{\mathrm{T2}}^W &> 200\,\mathrm{GeV}, \\ min\Delta\phi(j_{1,2}, \vec{\not{p}}_T) &> 1.2. \end{aligned}$$

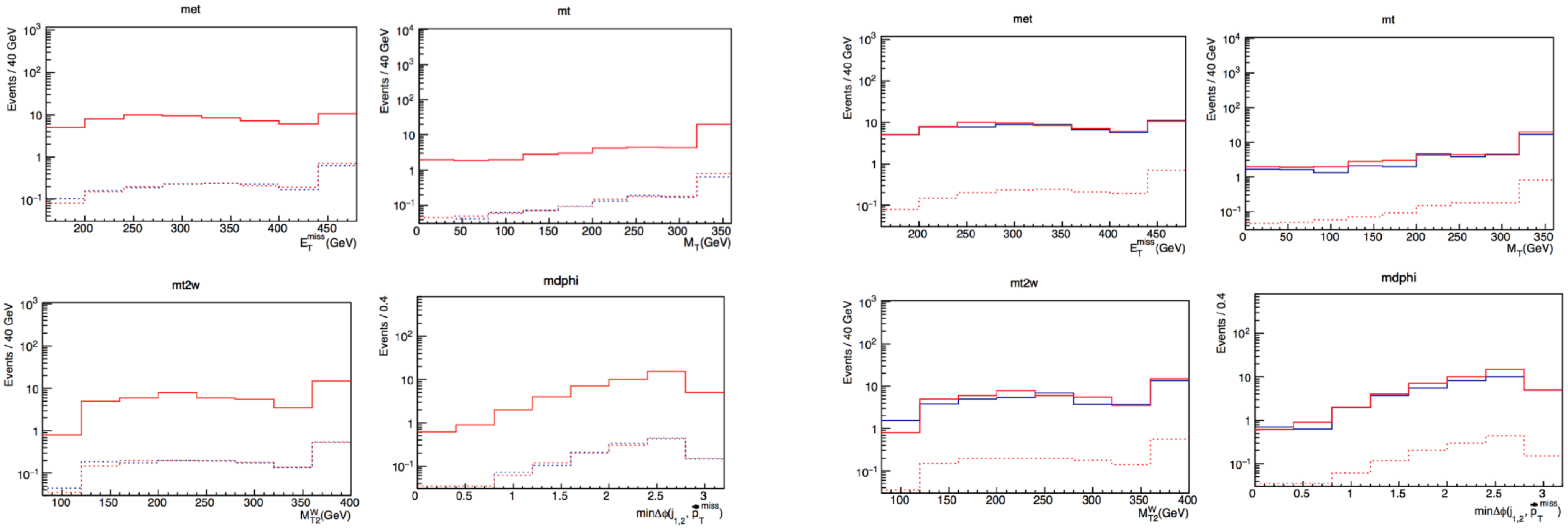
Collider search

- Validation
  - cut efficiency for a wide range of m_χ

Signal Region	SR	
Process	$pp \to t\bar{t}\chi\chi$	
Source	CMS [8]	CheckMATE-1.2.2
M_χ (GeV)	Signal efficiency (%)(±stat)	Signal efficiency (%)
1	1.01 ± 0.02	1.10
10	1.01 ± 0.02	1.19
50	1.20 ± 0.02	1.31
100	1.46 ± 0.02	1.48
200	1.73 ± 0.02	1.72
600	2.40 ± 0.03	2.48
1000	2.76 ± 0.04	2.90

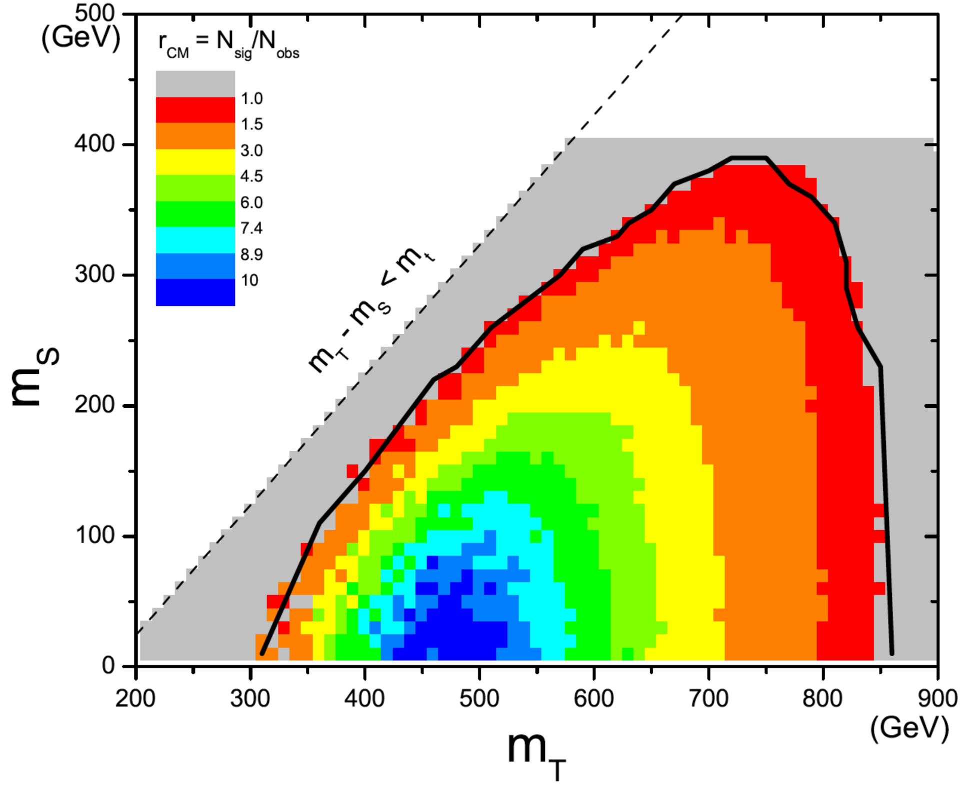
Collider search

- Validation
  - kinematic variables: $\not{E}_T, m_T, m_{T2}^W, min\ \Delta\phi(j_{1,2}, \vec{\not{p}}_T)$



Collider search

- Results
  - exclude m_T from 300 (450)-850 GeV for $m_S = 0\ (200)$ GeV

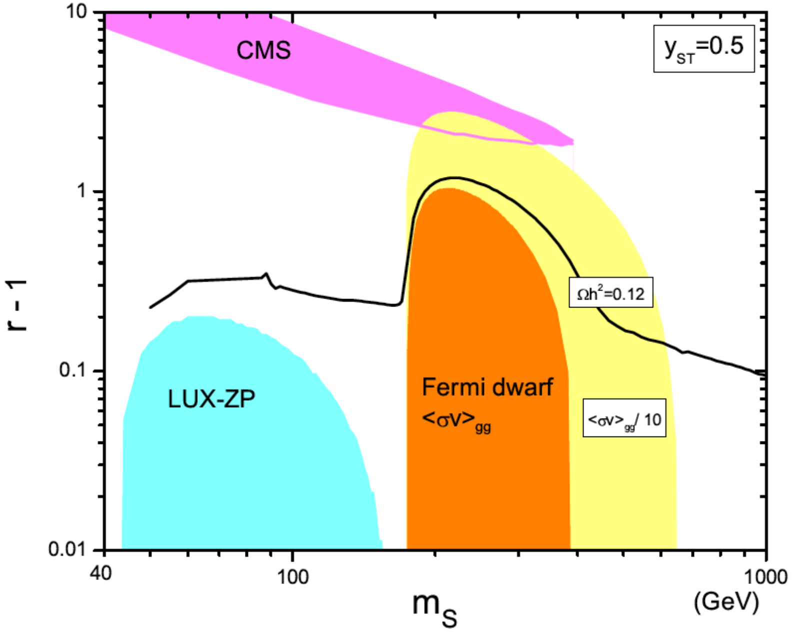


- future improvement:
  - off-shell $t, W^{\pm}$
  - mono-jet

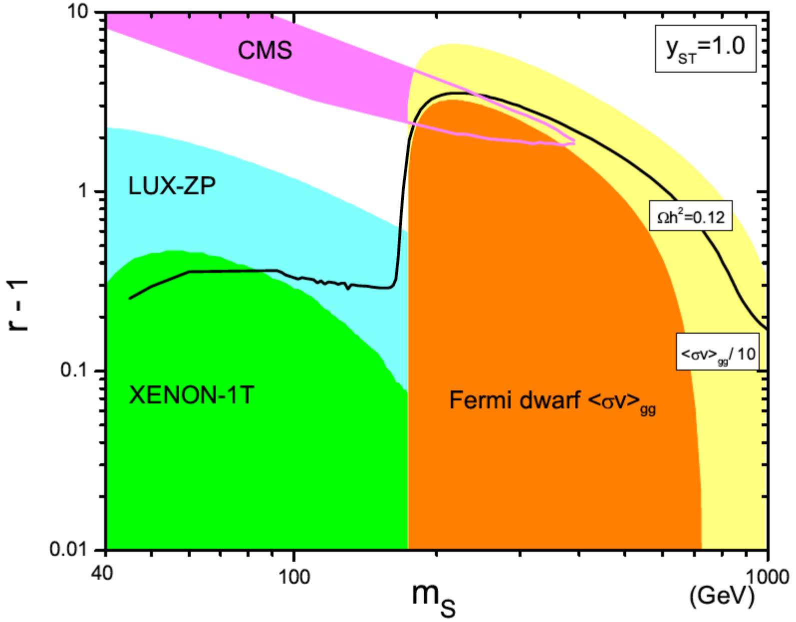
Combination

- complementarity between DD/ID
- large y_{ST}: excluded by LUX and Fermi
- perturbative $y_{ST} \in (0.5, 1)$: about to be tested in future

$y_{ST} = 0.5$



$y_{ST} = 1$



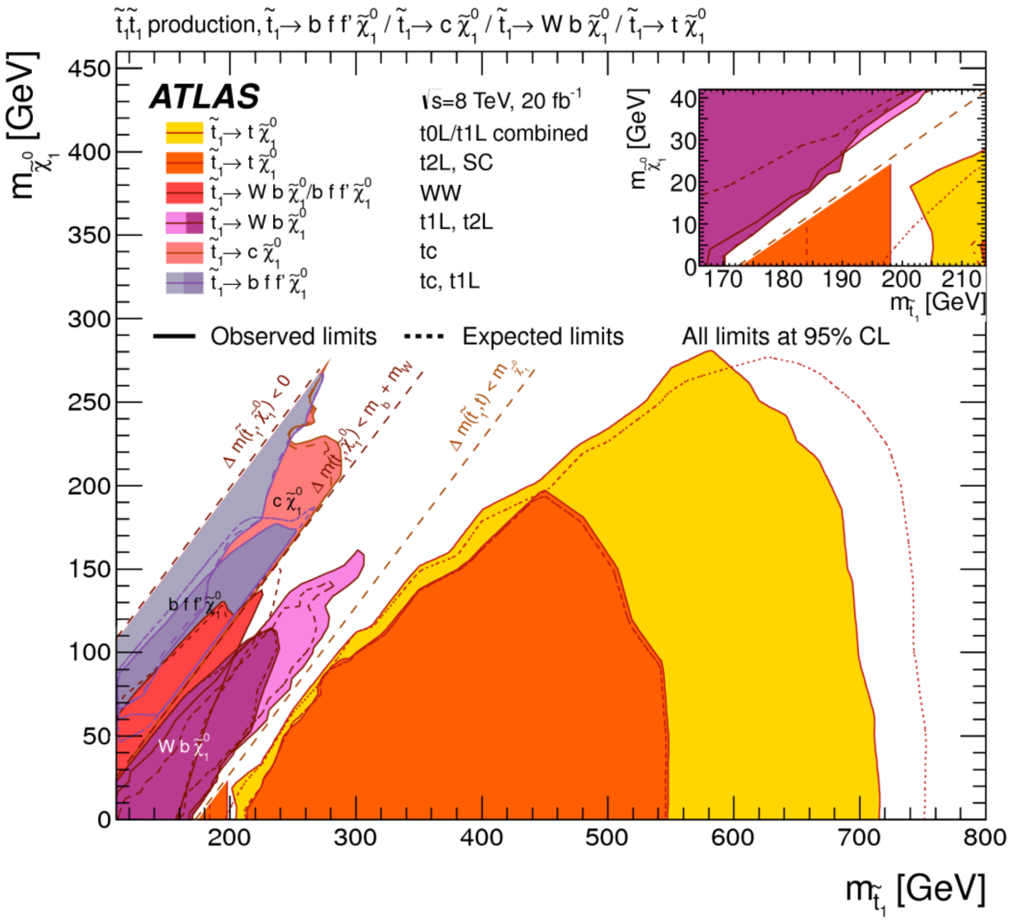
Conclusion

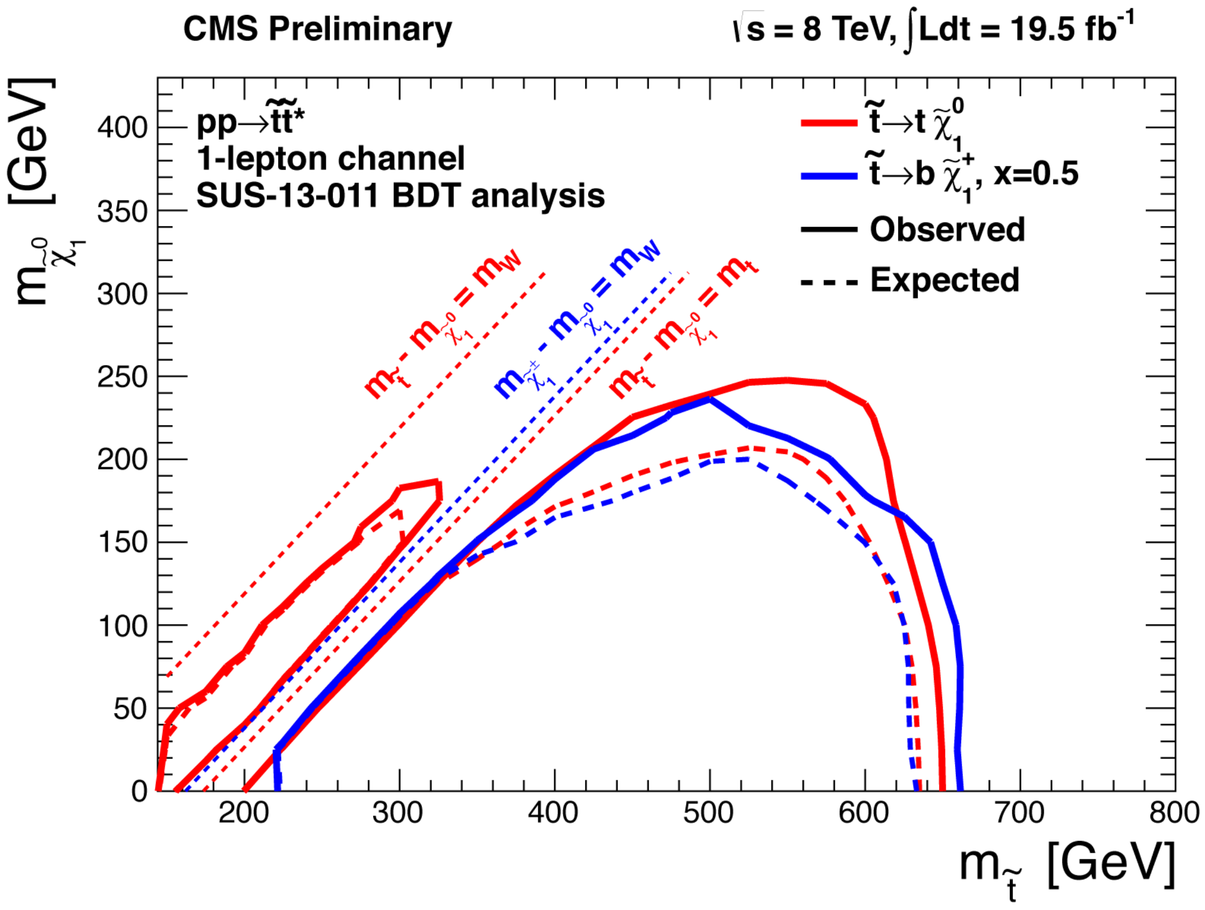
- Flavored DM is an interesting framework
  - rich particle spectrum
- Top-flavored, 3 parameters $\{y_{ST}, m_S, m_T\}$
  - annihilation: $m_S < m_t$: (ST), moderate m_t : (SS), large m_t: $(T\bar{T})$
  - DD/ID: large y_{ST}, $SS \to gg$ dominant, excluded by LUX and Fermi
    - **Complementarity**: DD (ID) in $m_S < (>) m_t$
  - Collider: m_T excluded between 300 (450)-850 GeV for $m_S = 0\ (200)$ GeV
- LHC Run-2 will further test Flavored DM

Thank you

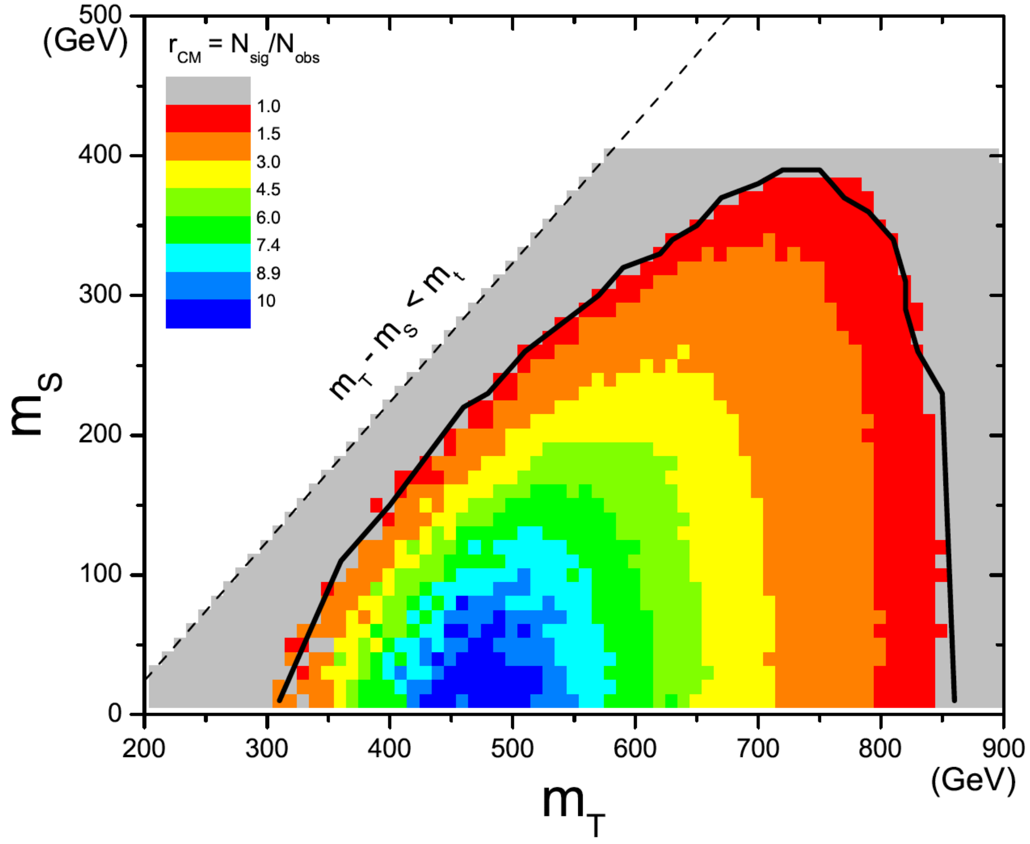
Back up

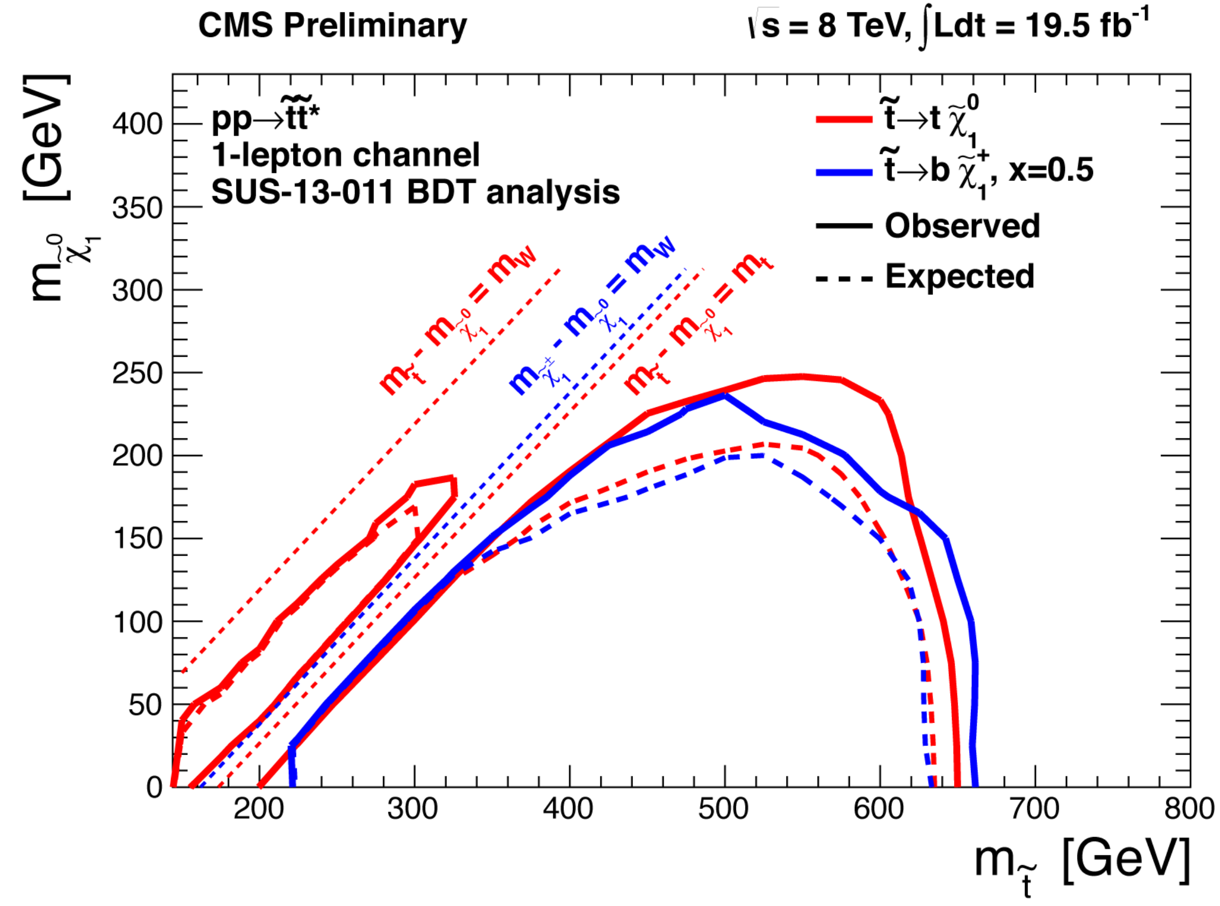
stop search, CMS





stop search, EXO vs SUSY in boosted top





Loop coupling Csg [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

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

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:

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

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

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

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

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

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

with

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

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

co-annihilation

Conditions for coannihilation to reduce LSP relic density

If there is another R-odd species χ_2 almost degenerate in mass with the LSP χ_1,

and if χ_2 has a big annihilation cross section with itself and/or with χ_1,

and if χ_1 can efficiently convert to χ_2,

then χ_1 and χ_2 can freeze out together at a lower temperature resulting in a smaller dark matter abundance than if without the existence of χ_2.

$$\chi_1\chi_1 \leftrightarrow SM,\ \chi_1\chi_2 \leftrightarrow SM,\ \chi_2\chi_2 \leftrightarrow SM$$
$$\chi_1 SM \leftrightarrow \chi_2 SM,\ \chi_2 \leftrightarrow \chi_1 SM$$

efficient conversion: $\langle\Gamma\rangle_{1SM\to 2SM} + \langle\Gamma\rangle_{1SM\to 2} \gg H$

$\Rightarrow n_1/n_2 \approx n_1^{eq}/n_2^{eq}$ (this can be checked by explicitly solving for n_1 and n_2)

$$\frac{dn}{dt} + 3Hn = -\sum_{i,j=1}^{2} \langle\sigma v\rangle_{ij\to SM} \frac{n_i^{eq} n_j^{eq}}{n_{eq}^2} \left[n^2 - n_{eq}^2\right]$$

(Recall w/o coannihilation: $\frac{dn_\chi}{dt} + 3H(T)n_\chi = -\langle\sigma v\rangle_{\chi\chi\to SM's}\left[n_\chi^2 - (n_\chi^{eq})^2\right]$)

co-annihilation [arXiv: 9704361 Joakim Edsjo *et al*]

3.1 Review of the Boltzmann equation with coannihilations

Consider annihilation of N supersymmetric particles χ_i $(i = 1, \ldots, N)$ with masses m_i and internal degrees of freedom (statistical weights) g_i. Also assume that $m_1 \leq m_2 \leq \cdots \leq m_{N-1} \leq m_N$ and that R-parity is conserved. Note that for the mass of the lightest neutralino we will use the notation m_χ and m_1 interchangeably.

The evolution of the number density n_i of particle i is

$$\begin{aligned}\frac{dn_i}{dt} &= -3Hn_i - \sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\rm eq} n_j^{\rm eq} \right) \\ &- \sum_{j \neq i} \left[\langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{\rm eq} n_X^{\rm eq} \right) - \langle \sigma'_{Xji} v_{ij} \rangle \left(n_j n_X - n_j^{\rm eq} n_X^{\rm eq} \right) \right] \\ &- \sum_{j \neq i} \left[\Gamma_{ij} \left(n_i - n_i^{\rm eq} \right) - \Gamma_{ji} \left(n_j - n_j^{\rm eq} \right) \right]. \end{aligned} \tag{27}$$

The first term on the right-hand side is the dilution due to the expansion of the Universe. H is the Hubble parameter. The second term describes $\chi_i \chi_j$ annihilations, whose total annihilation cross section is

$$\sigma_{ij} = \sum_X \sigma(\chi_i \chi_j \to X). \tag{28}$$

The third term describes $\chi_i \to \chi_j$ conversions by scattering off the cosmic thermal background,

$$\sigma'_{Xij} = \sum_Y \sigma(\chi_i X \to \chi_j Y) \tag{29}$$

being the inclusive scattering cross section. The last term accounts for χ_i decays, with inclusive decay rates

$$\Gamma_{ij} = \sum_X \Gamma(\chi_i \to \chi_j X). \tag{30}$$

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

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

with

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

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

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

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.

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

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

Gluon-philic DM [arXiv: 1506.01408 R.M. Godbole *et al*]

2 Simplified Model

The basic module consists of a massive scalar (assumed complex for simplicity, though the modification to a real field is simple) χ that is a gauge singlet to play the role of dark matter, and a set of massive (typically complex) colored scalars ϕ (in representation r of $SU(3)_C$) to act as the mediator with the SM. These basic pieces are described by the Lagrangian,

$$\mathcal{L} \supset \partial_\mu \chi^* \partial^\mu \chi - m_\chi^2 |\chi|^2 + (D_\mu \phi)^\dagger D^\mu \phi - m_\phi^2 |\phi|^2 \qquad (2.1)$$

where $D_\mu \phi$ is a covariant derivative that includes interactions with the electroweak gauge fields (in cases where ϕ is charged under $SU(2) \times U(1)$) and coupling to the gluons G_μ^a:

$$D_\mu \phi \equiv \partial_\mu \phi - i g_s \frac{\lambda_r^a}{2} G_\mu^a \phi + \text{ Electroweak} \qquad (2.2)$$

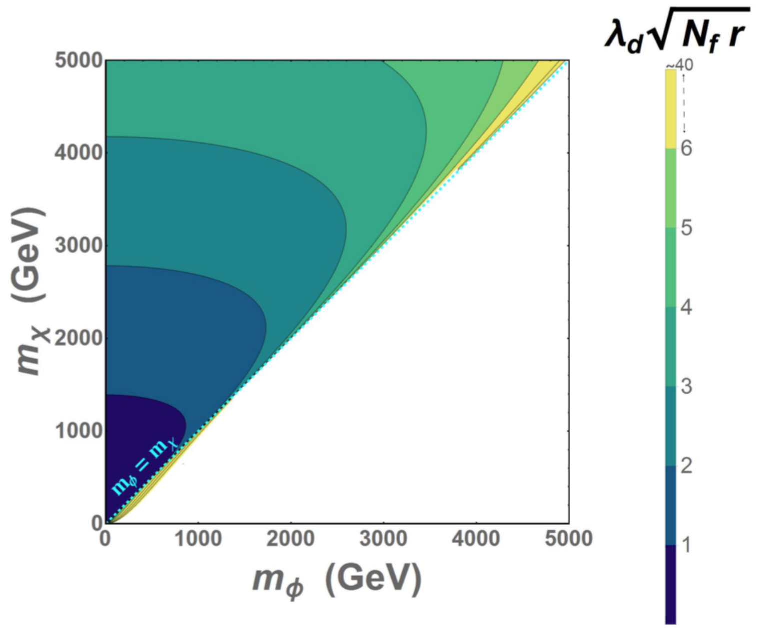


Figure 2: The product of quartic interaction λ_d with the square root of product of r dimensional color representation of ϕ and N_f number of flavors with mass less than m_χ, required to saturate the observed dark matter density as a thermal relic, are represented as colored contours in the plane of m_ϕ-m_χ. Almost all the parameter space where $m_\phi < m_\chi$ is compatible with a thermal relic density. Where $m_\phi > m_\chi$, the DM annihilation proceeds via loops and, only a small region of parameter space is allowed without including any additional couplings.

Gluon-philic DM [arXiv: 1506.01408 R.M. Godbole *et al*]

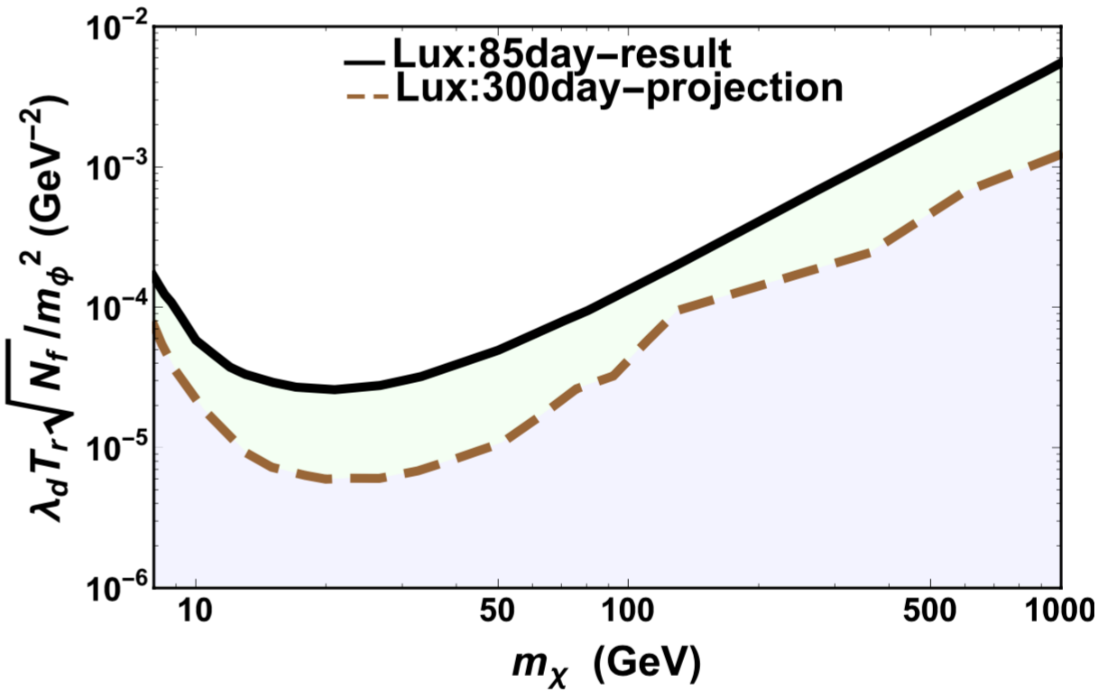


Figure 3: Current (solid line) and projected (dashed line) bounds on $\sum \lambda_d T_r \sqrt{N_f}/m_\phi^2$ based on searches for dark matter-Xenon scattering by LUX. The region above the solid line is excluded.