Heavy quark flavored dark matter confronting experiments

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In process, collaboration with

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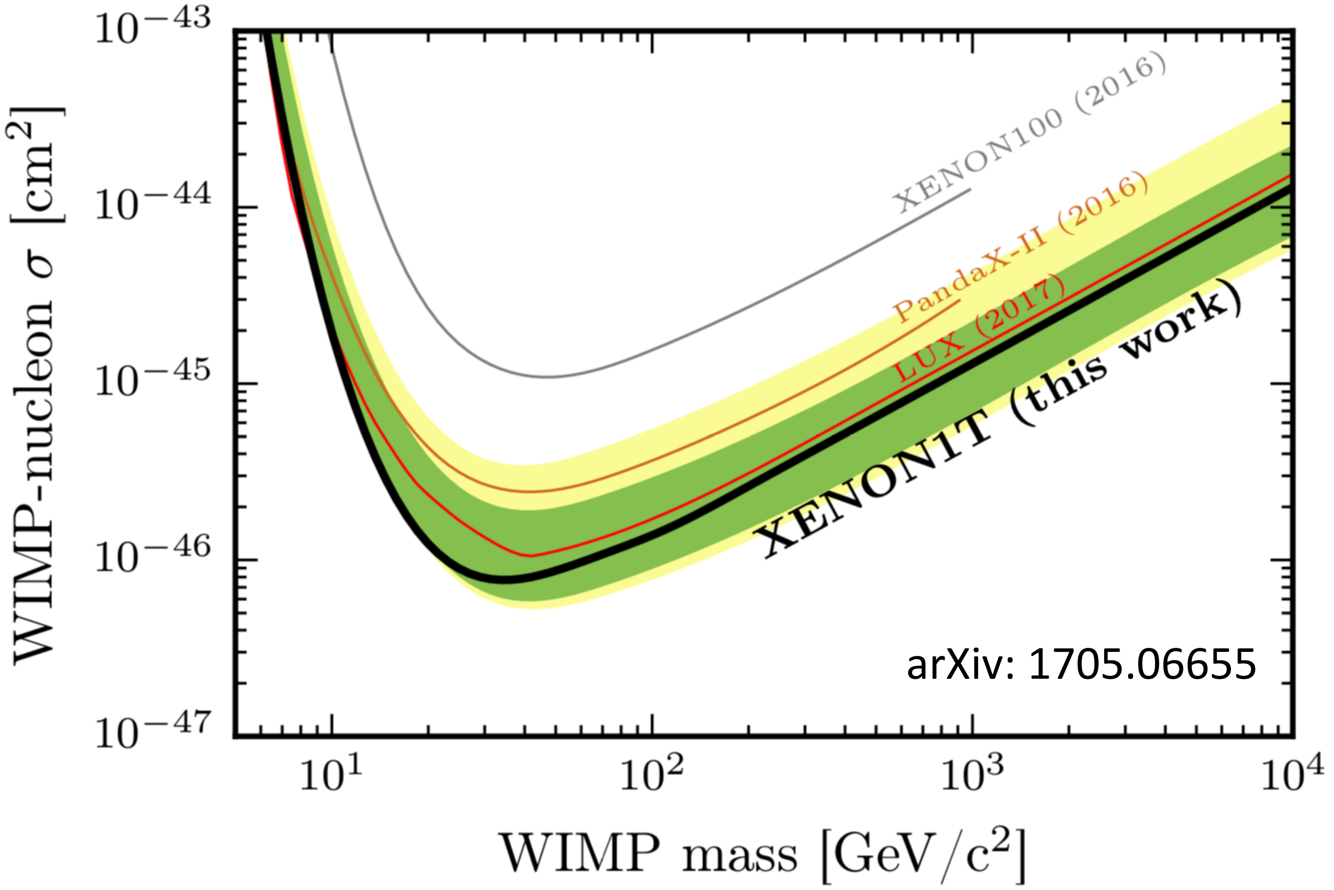
Self introduction

- 2019.08 – Now Junior
  - Southeast University
- 2015 – 2019 PD
  - KIAS
- 2010 – 2015 PhD
  - ITP, CAS
- 2006 – 2010 UG
  - Nanjing University

Outline

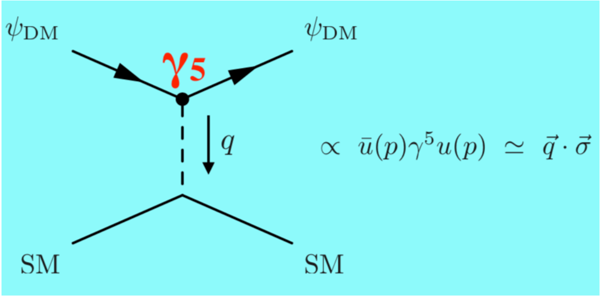
- Absence of DM signal
  - Joint DM constraints are important
- Flavor structure in DM-SM interactions
  - Heavy quark sector, interesting scenarios
- Joint analysis
- Summary

No DM signal yet



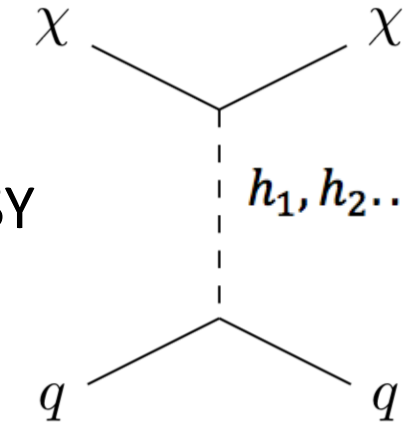
No DM signal: Reason?

- Small leading-order DM-nucleon scattering rate
  - missing: DM is heavy quark-flavored
  - suppressed: dependent on transferred momentum



Abe *et al*, 2019

- Cancellation
  - multi-mediators, e.g. 2HDM/SUSY



- Ultra-light DM
  - not enough incoming kinetic energy, e.g. MeV DM, axions

No DM signal: Reason?

- Small leading-order DM-nucleon scattering rate
  - missing: DM is heavy quark-flavored

- Top quark: close relation to EWSB

- Multi-flavor coupling
  - constraints from flavor constraints, e.g. FCNC

Model set-up

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + D_\mu \eta^\dagger D^\mu \eta - m_\eta^2 |\eta|^2 - \frac{\lambda_\eta}{4}|\eta|^4 - \lambda_{\eta H}|H|^2|\eta|^2 - \left\{ y_\chi \overline{\chi} \eta^\dagger (t_R \cos\theta + c_R \sin\theta) + H.c. \right\}$$

- DM: Majorana fermion χ
- Mediator: a single complex scalar η $\quad m_\eta > m_\chi$
  - (η, U_i) : same quantum number
  - U_i: right-handed Up-type quark
- Stability of DM: Z_2-parity
  - χ, η : odd
  - SM: even
- Phenomenologically motivated
  - no full flavor symmetry
  - a sub-set of complete framework

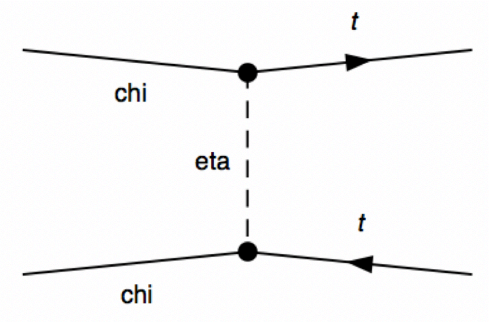
Related Phenomenology

- Thermal relic / indirect detections
  - tree-process dominates, while NLO may also be needed
- DM-nucleon scattering
  - Loop processes
- Top quark FCNC decay
  - Tree/loop-processes
- Collider signals

Thermal Relic: heavy quark mass helps

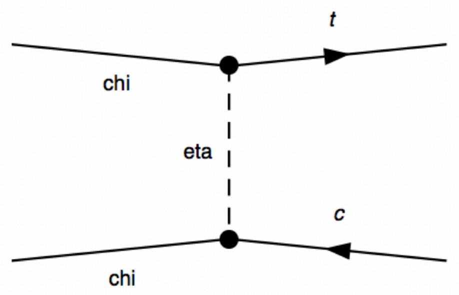
- Majorana DM: s-wave includes chirality flipping

$\chi\chi \to t\bar{t}, c\bar{c}$



+ cross

$\chi\chi \to t\bar{c}, c\bar{t}$



+ cross

+ co-annihilations, NLO corrections…

1405.6921, 1405.6917, 1511.04452, 1804.05068…

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

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

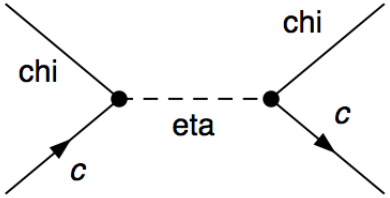
Model: χ	Model: Q	Relic Abundance	Direct Detection
Majorana fermion	Complex scalar	$a \sim m_q^2$ $\lambda \sim 0.5 - 2$	Suppressed $\sigma_{SI} \overset{m_Q \gg m_\chi}{\sim} \frac{m_p^4}{m_Q^4}\sigma_{ann}$
Dirac fermion	Complex scalar	$\lambda \sim 0.2 - 1$	Unsuppressed $\sigma_{SI} \overset{m_Q \gg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

Direct detection

Also Higgs precision measurements

Yukawa-portal

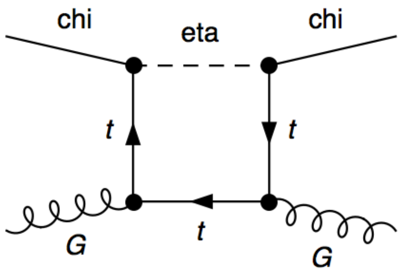
y_2^2

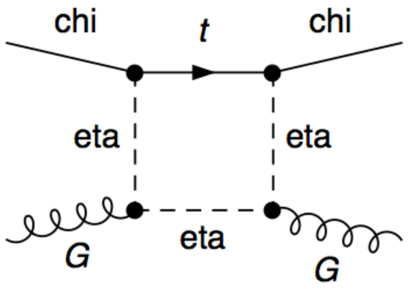


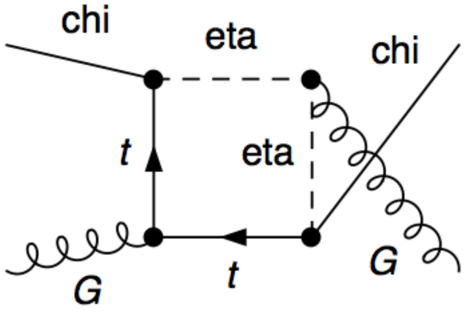
twist-2 c-quark operator

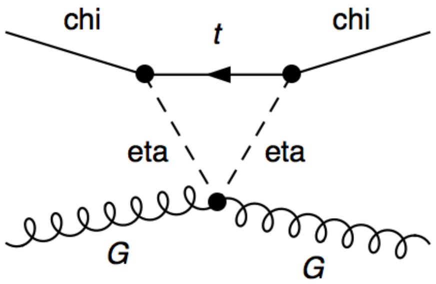
y_2^2

y_3^2









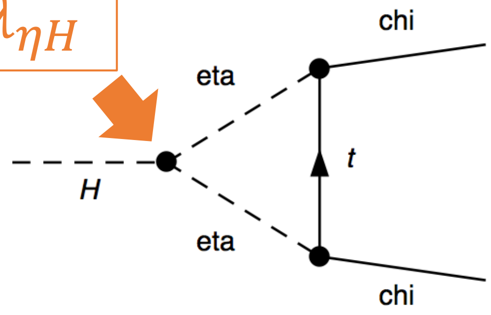
+ cross

Hisano et al
1007.2601

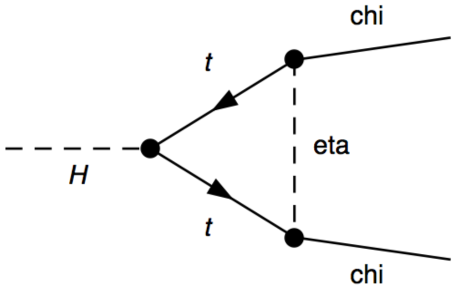
Higgs-portal

$\lambda_{\eta H}$

quark
gluon

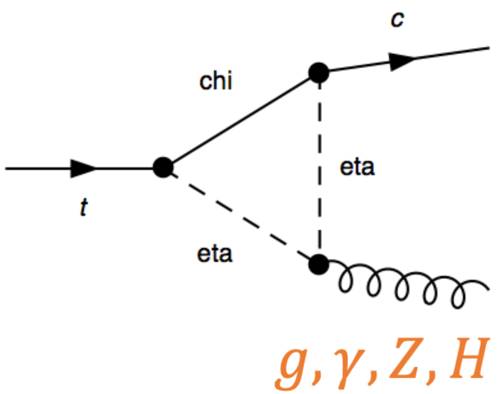


quark
gluon

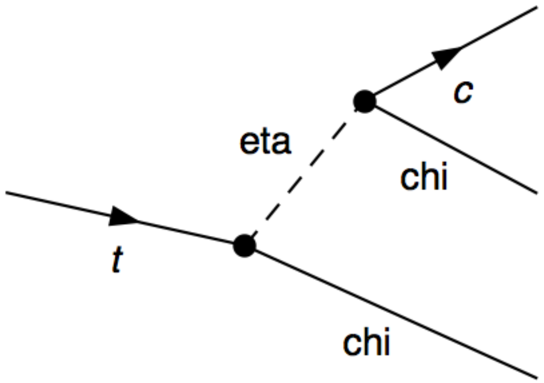


+ cross

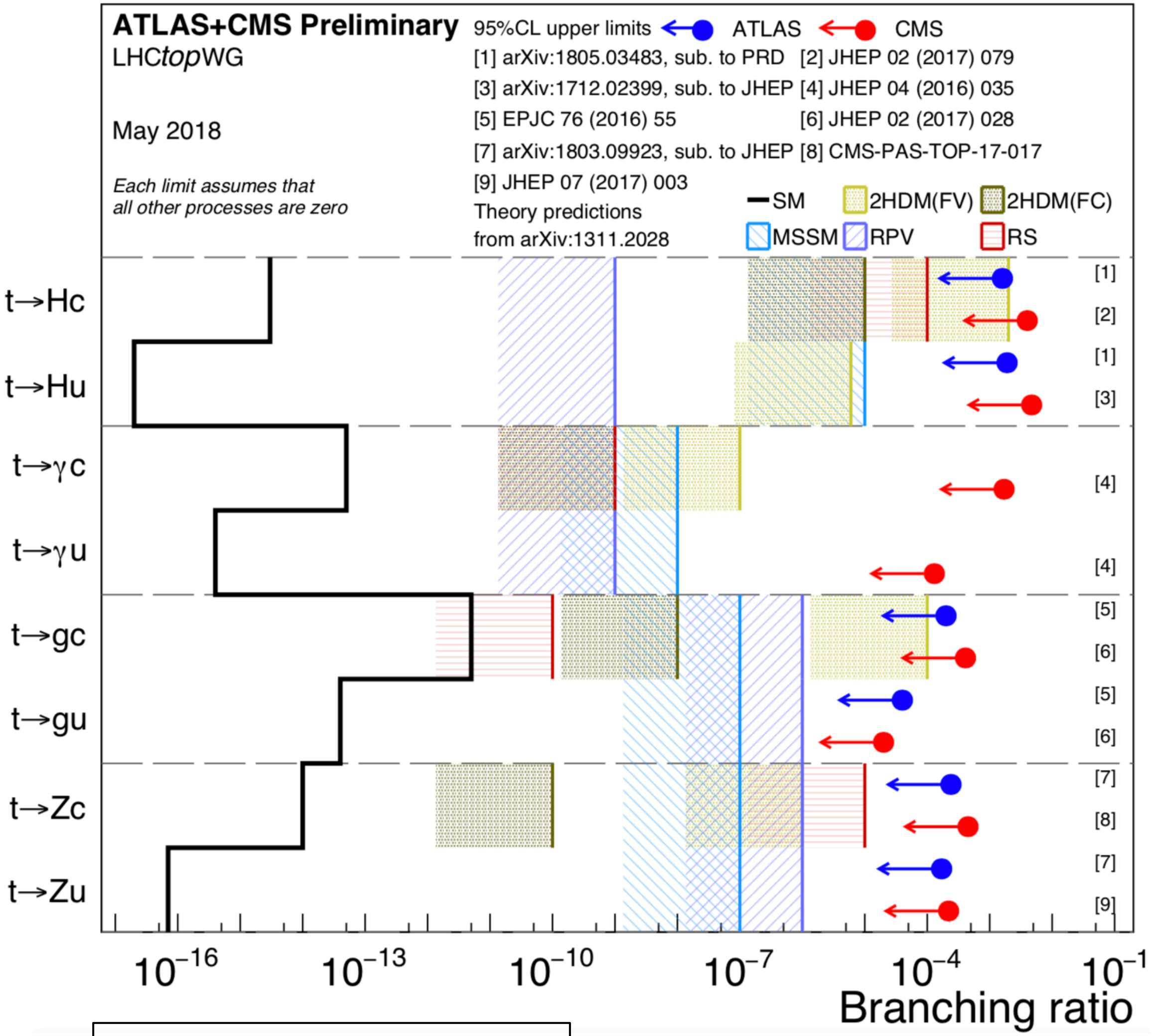
Top FCNC



+ eternal leg loops



+ cross

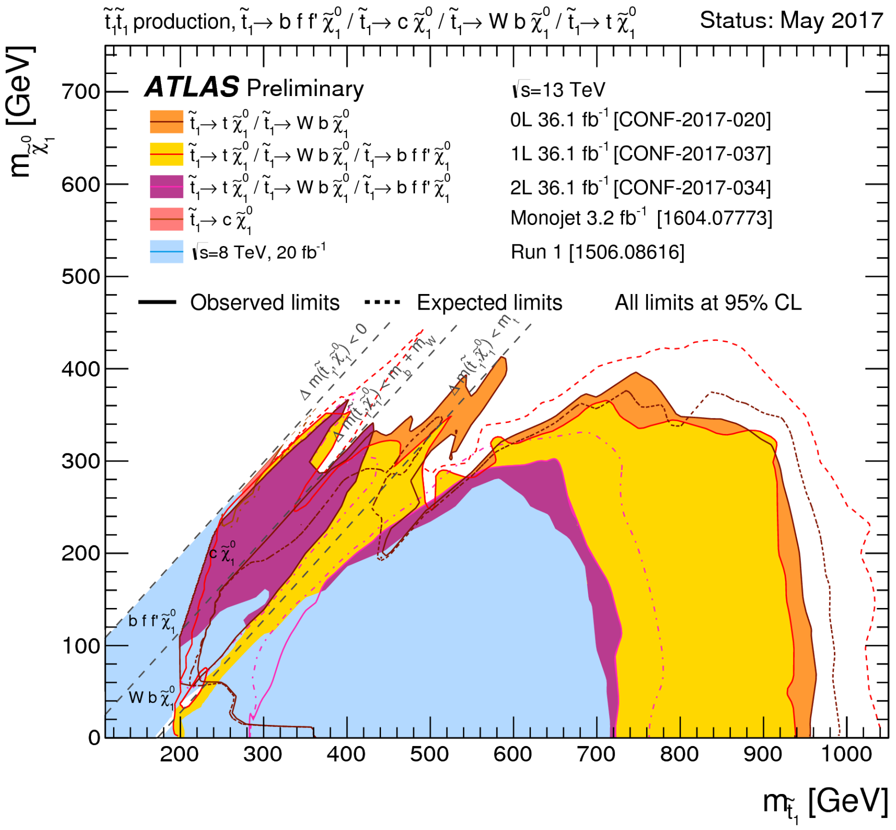


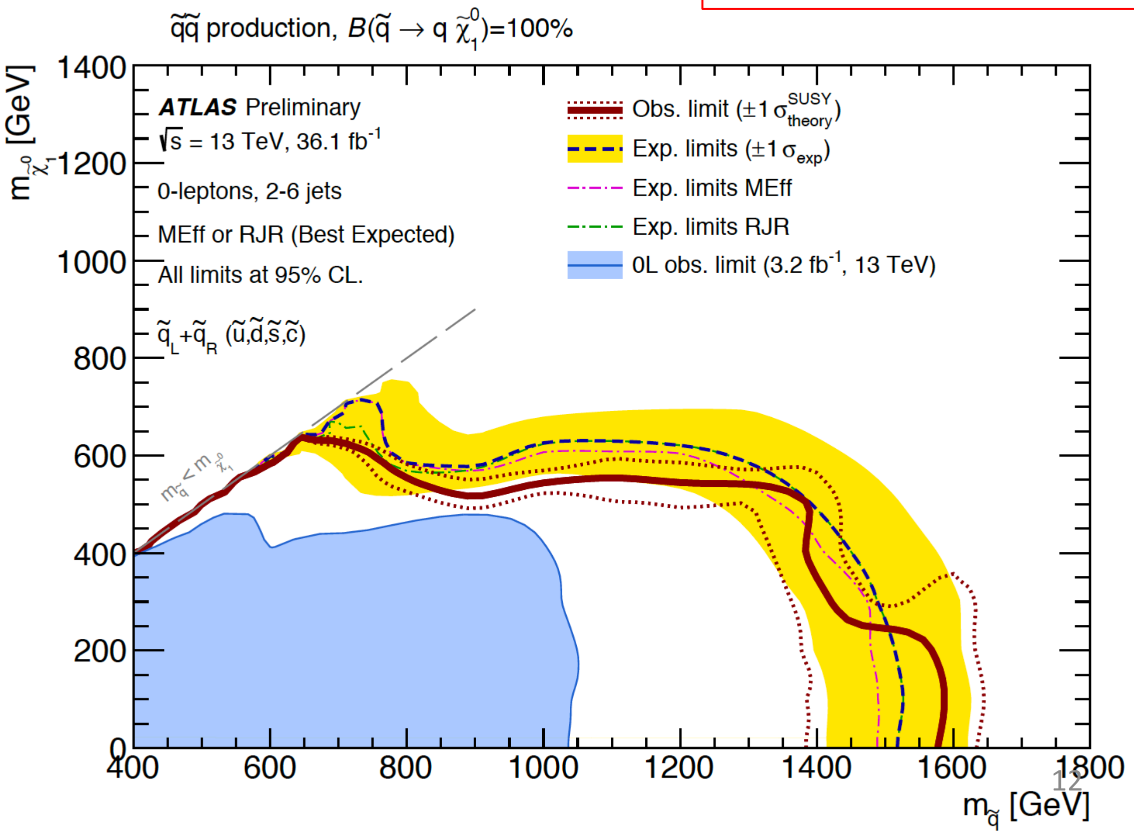
courtesy to Taejeong Kim

Collider signals

- $pp \to \eta^+\eta \to \chi\chi + t/c + t/c,$ i.e. $E_t^{miss} + t\bar{t}, jj,$ tj
- ~ SUSY squark searches (3rd , 1st & 2nd gen.)

1808.07488, Chakraborty et al, *Flavour-violating decays of mixed top-charm squarks at the LHC*





4 parameters: $\{m_\chi, m_\eta\}$, $\{y_2, y_3\}$

- How does the heavy quark flavored DM confront current experiments?

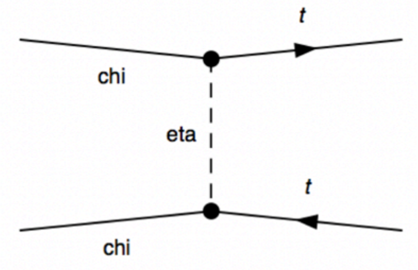
- For chosen $\{m_\chi, m_\eta\}$
  - how much space are available for $\{y_2, y_3\}$?
  - how large values can the predicted observables reach?

Relic abundance

- $\Omega_\chi h^2 \sim$

$$\frac{1}{\theta(m_\chi - m_c)\, y_2^4(\ldots) + \theta\left(m_\chi - \frac{m_c + m_t}{2}\right) y_2^2 y_3^2(\ldots) + \theta(m_\chi - m_t) y_3^4(\ldots) + (co-annhi.+NLO)}$$

$\chi\chi \to t\bar{t}, c\bar{c}$



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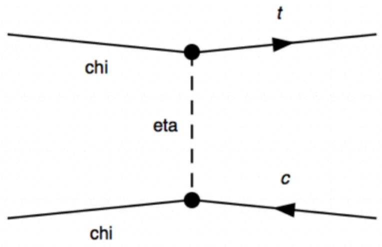
$\chi\chi \to t\bar{c}, c\bar{t}$



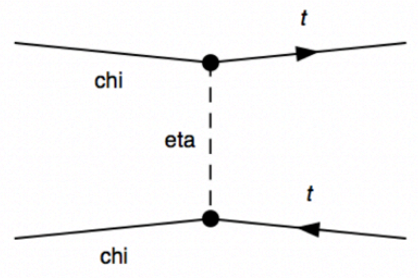
+ cross

+ co-annihilations, NLO corrections…

Relic abundance

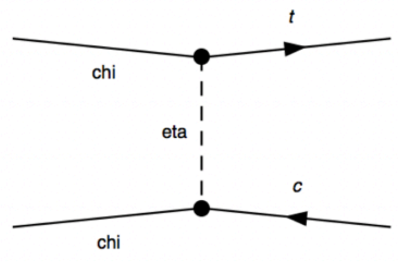
- $\Omega_\chi h^2 \sim \dfrac{1}{\theta(m_\chi - m_c)\, y_2^4(\dots) + \theta\left(m_\chi - \frac{m_c + m_t}{2}\right) y_2^2 y_3^2(\dots) + \theta(m_\chi - m_t)\, y_3^4(\dots) + (co\text{-}annhi. + NLO)}$

$\chi\chi \to t\bar{t}, c\bar{c}$



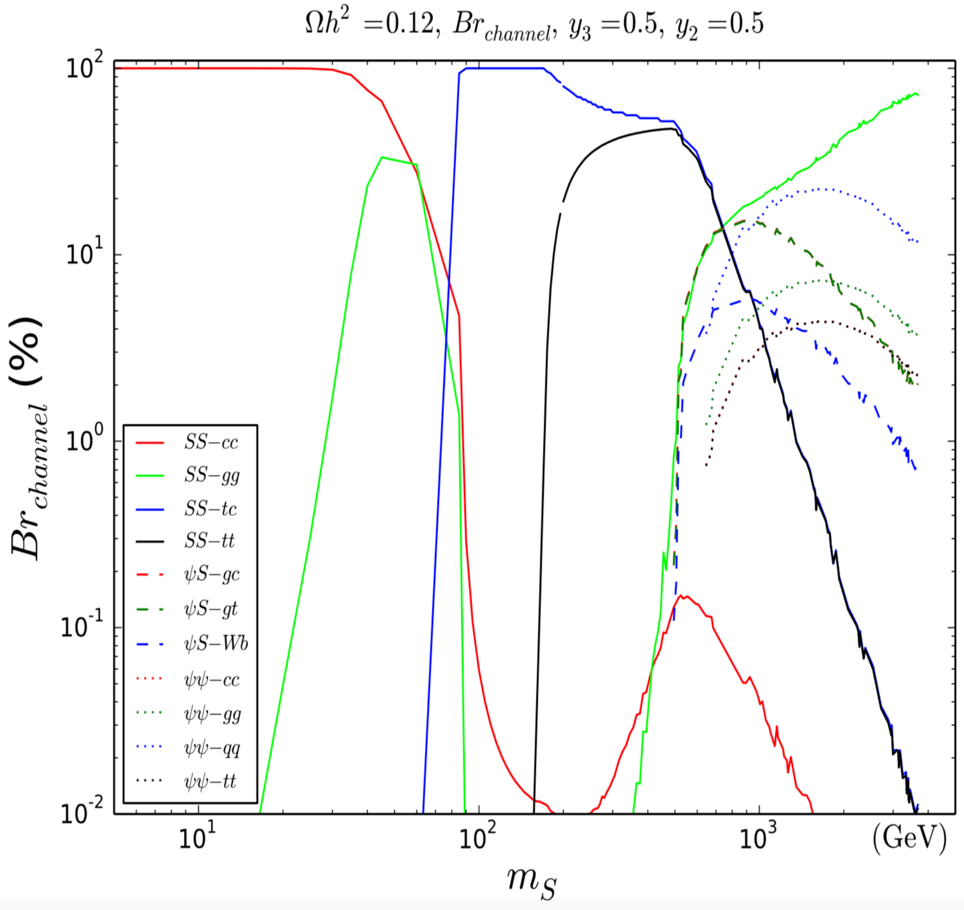
+ cross

$\chi\chi \to t\bar{c}, c\bar{t}$

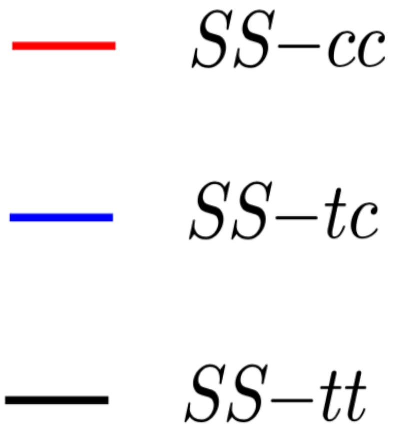


+ cross

+ co-annihilations, NLO corrections…



Real scalar DM self-conjugate analogous case

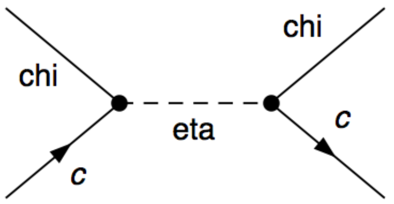


Also Higgs precision measurements

Direct detection

Yukawa-portal

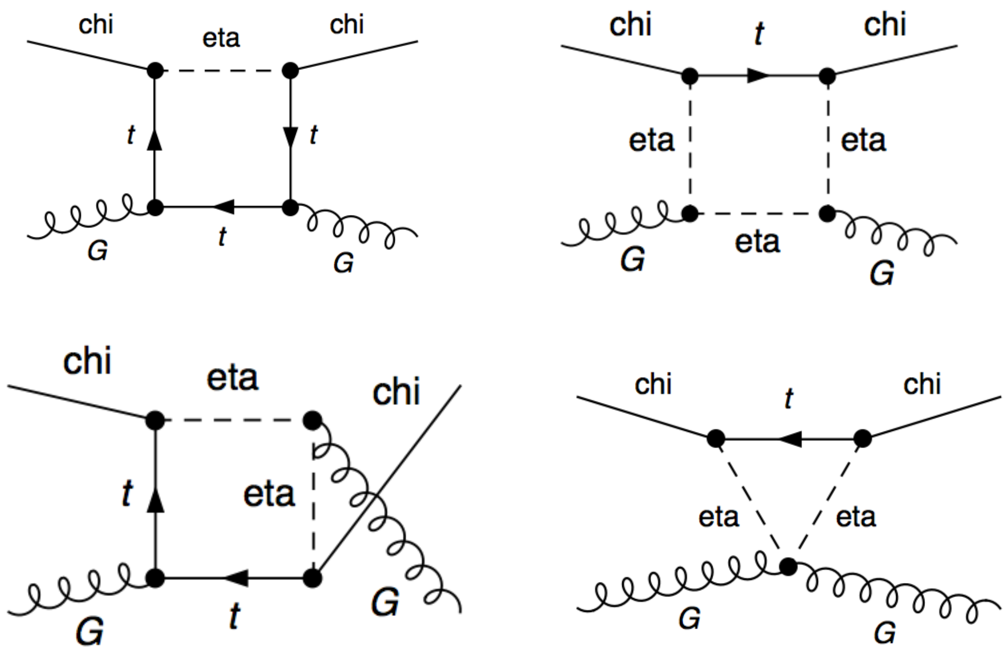
y_2^2



twist-2 c-quark operator

y_2^2

y_3^2

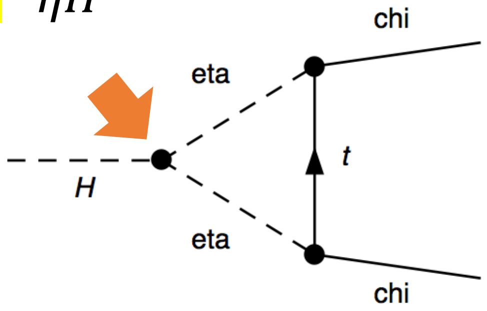


+ cross

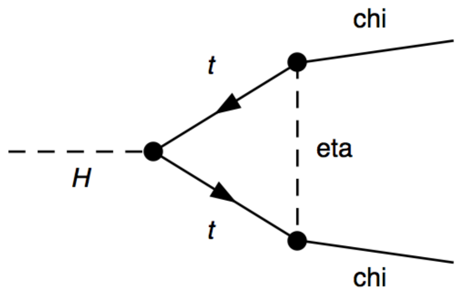
We first ignore quartic coupling $\lambda_{\eta H}$

Higgs-portal

quark
gluon



quark
gluon



+ cross

Direct detection

Yukawa-portal

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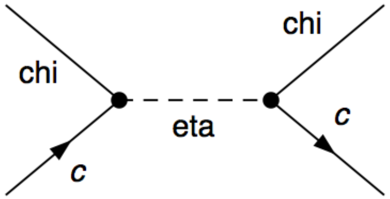
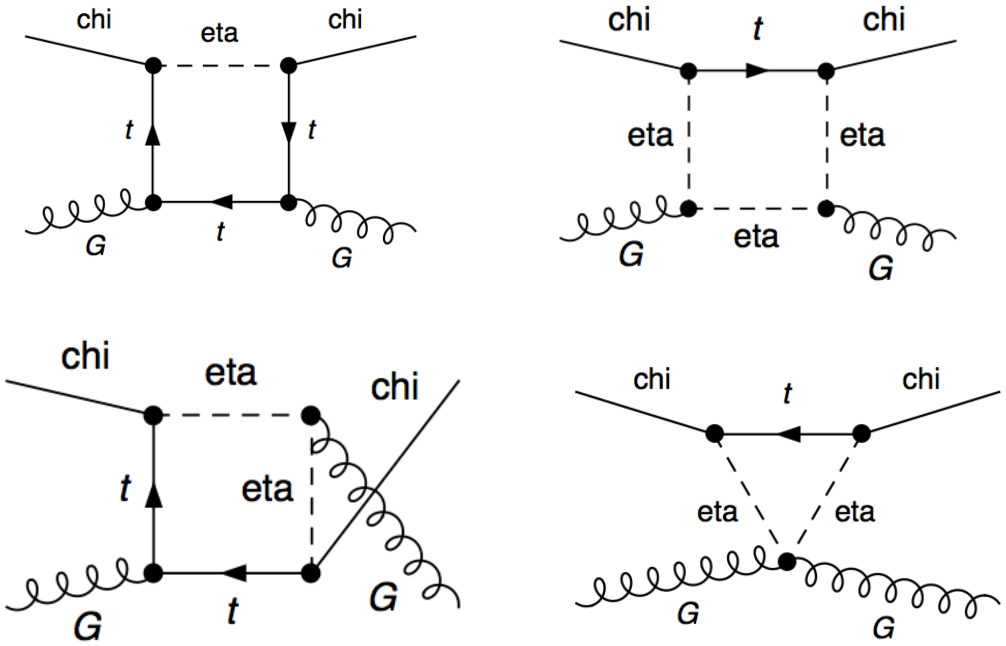


twist-2 c-quark operator

$$\sigma_{\chi-p}^{SI} \sim \left| y_2^2(\ldots) + y_3^2(\ldots) \right|^2$$

y_2^2

y_3^2



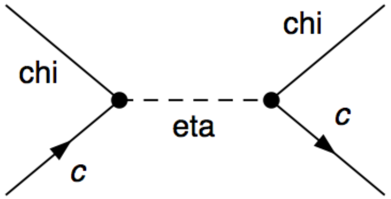
+ cross

+ cross

Direct detection

Yukawa-portal

y_2^2



twist-2 c-quark operator

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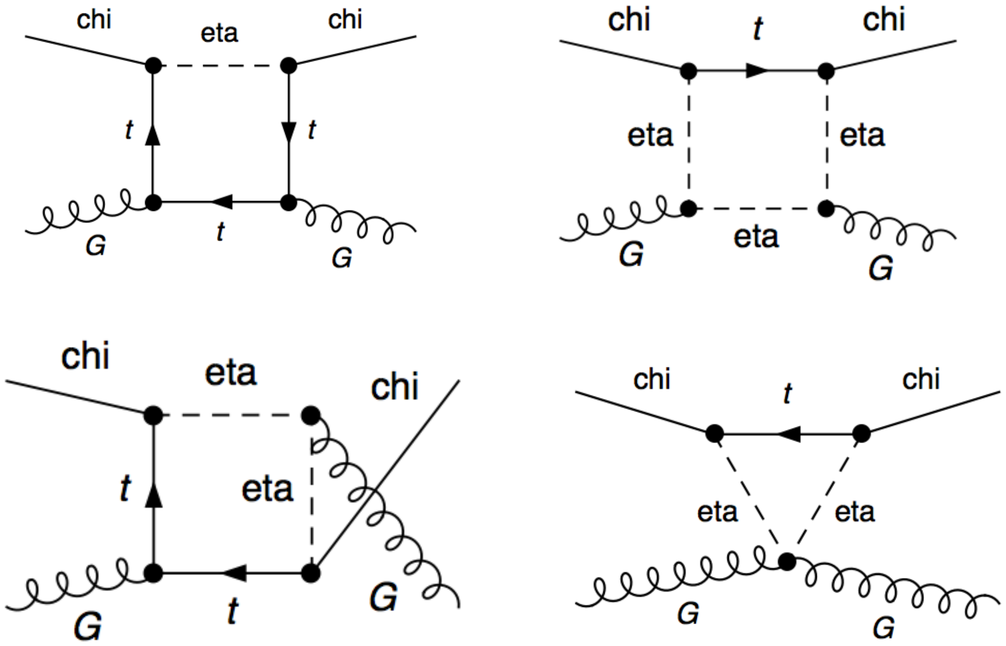
y_3^2



+ cross

$$\sigma^{SI}_{\chi-p} \sim \left| y_2^2(\dots) + y_3^2(\dots) \right|^2$$

What if $\frac{\rho_\chi}{\rho_{DM}} < 1$?

i.e.

χ annihilates too fast,

thus contributing only part of DM?

+ cross

Direct detection with $\frac{\rho_\chi}{\rho_{DM}} < 1$

- Number of scattering event depends on $\frac{\rho_\chi}{\rho_{DM}} = \frac{\Omega_\chi h^2}{\Omega_{DM} h^2 (\simeq 0.12)}$

- $N^{SI}_{\chi-p} \propto \frac{\Omega_\chi h^2}{\Omega_{DM} h^2 (\simeq 0.12)} \sigma^{SI}_{\chi-p} \sim$

$$\frac{\left| y_2^2(\dots) + y_3^2(\dots) \right|^2}{\theta(m_\chi - m_c)\, y_2^4(\dots) + \theta\left(m_\chi - \frac{m_c + m_t}{2}\right) y_2^2 y_3^2(\dots) + \theta(m_\chi - m_t) y_3^4(\dots) + (co-annhi.+NLO)}$$

Direct detection with $\frac{\rho_\chi}{\rho_{DM}} < 1$

- Number of scattering event
- $N_{\chi-p}^{SI} \propto$

$$\frac{\left|y_2^2(\dots) + y_3^2(\dots)\right|^2}{\theta(m_\chi - m_c)\, y_2^4(\dots) + \theta\left(m_\chi - \frac{m_c + m_t}{2}\right) y_2^2 y_3^2(\dots) + \theta(m_\chi - m_t) y_3^4(\dots) + (co - annhi. + NLO)}$$

- Single flavor case, e.g. $y_2 \neq 0,\ y_3 = 0$
  - cancelation, $N_{\chi-p}^{SI}$ is nearly independent of y_2
- $N_{\chi-p}^{SI} \propto \frac{\left|y_2^2(\dots)\right|^2}{y_2^4(\dots) + (co - annhi. + NLO)}$

Direct detection with $\frac{\rho_\chi}{\rho_{DM}} < 1$

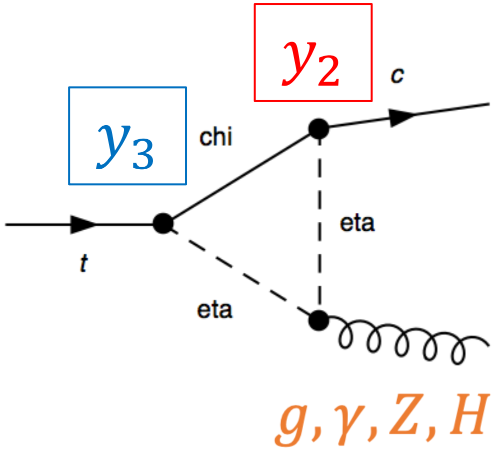
- Number of scattering event
- $N^{SI}_{\chi-p} \propto$

$$\frac{\left|y_2^2(\dots) + y_3^2(\dots)\right|^2}{\theta(m_\chi - m_c)\, y_2^4(\dots) + \theta\left(m_\chi - \frac{m_c + m_t}{2}\right) y_2^2 y_3^2(\dots) + \theta(m_\chi - m_t) y_3^4(\dots) + (co - annhi. + NLO)}$$

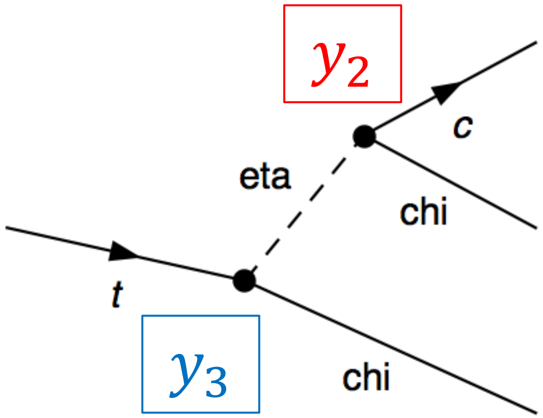
- multi-flavor case : needs more involved analysis
  - depending on range of m_χ

- When utilizing the Xenon-1T bounds, we assume that χ generates all BSM scatterings

Top FCNC



+ eternal leg loops



+ cross

$$Br(t \to cV)$$

$$\sim |SM + y_2 y_3|^2$$

$$\sim SM + y_2 y_3(\ldots) + y_2^2 y_3^2(\ldots)$$

Other constraints to include

- Indirect detections: comic-ray signals from DM annihilations today
  - simple particle number counting or likelihood fit

- Collider signals
  - expected to be strong for QCD-colored mediators

Benchmark mass spectrum

- The range of m_χ is essential, determining
  - the available annihilation modes
  - scaled DM-nucleon scattering rate / event numbers

$\chi\chi \to c\bar{c}$ + co-annhi. + NLO

$$\{m_\chi, m_\eta\} = \{80,\ 2 * m_\chi\}\ \text{GeV}$$

$$m_\chi,\ m_\eta,\ \sigma^{SI}_{exp.}(m_\chi) = 80,\quad 160 \quad (\text{GeV}), \quad 1.17182\times10^{-10} \quad (\text{pb})$$

$$\Omega_\chi h^2 = \frac{0.0237267}{y2^4}$$

$$\sigma^{SI}_{the.} = \frac{\Omega_\chi h^2}{\Omega_{DM} h^2}\ \sigma^{SI}_{\chi-p} = \frac{7.4914\times10^{-10}\left(0. + 1.\ y2^2 + \left(0.0846242 - 2.68229\times10^{-17}\ i\right) y3^2\right)^2}{y2^4},$$

$$Br(t\text{->}c\ g) = 5.78191\times10^{-12} + 7.88311\times10^{-12}\ y2\ y3 + 1.81181\times10^{-6}\ y2^2\ y3^2$$

$$Br(t\text{->}c\ \gamma) = 5.35038\times10^{-14} - 1.54561\times10^{-13}\ y2\ y3 + 3.98813\times10^{-8}\ y2^2\ y3^2$$

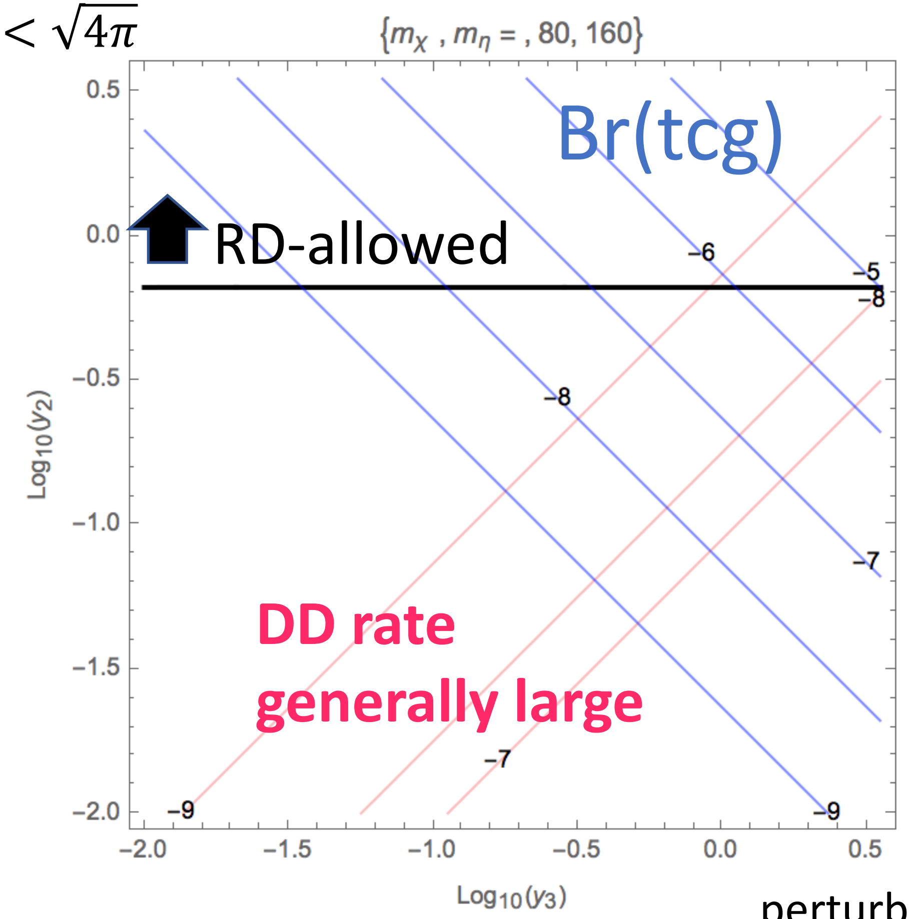
$$Br(t\text{->}c\ Z) = 1.22242\times10^{-14} - 2.65471\times10^{-13}\ y2\ y3 + 4.16737\times10^{-9}\ y2^2\ y3^2$$

$\chi\chi \to c\bar{c}$ + co-annhi. + NLO

$\{m_\chi, m_\eta\} = \{80,\ 2 * m_\chi\}$ GeV

perturb. bound

$< \sqrt{4\pi}$



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- y_2 needs to be sizable to reduce RD
- scaled DD rate is bounded from below
- generally too large, excld. by exp.

1.17182×10^{-10} (pb)

$\chi\chi \to c\bar{c}, t\bar{c}, c\bar{t}$

$$\{m_\chi, m_\eta\} = \{100,\ 2 * m_\chi\}\ \text{GeV}$$

$$m_\chi,\ m_\eta,\ \sigma^{SI}_{exp.}(m_\chi) = 100,\quad 200\quad (\text{GeV}),\quad 1.38922\times10^{-10}\quad (\text{pb})$$

$$\Omega_\chi h^2 = \frac{0.0371312}{1.\, y2^4 + 8.70416\, y2^2\, y3^2}$$

$$\sigma^{SI}_{the.} = \frac{\Omega_\chi h^2}{\Omega_{DM} h^2}\ \sigma^{SI}_{\chi-p} = \frac{3.09038\times10^{-10}\left(0. + 1.\, y2^2 + (0.11292 + 1.37228\times10^{-18}\, i)\, y3^2\right)^2}{1.\, y2^4 + 8.70416\, y2^2\, y3^2},$$

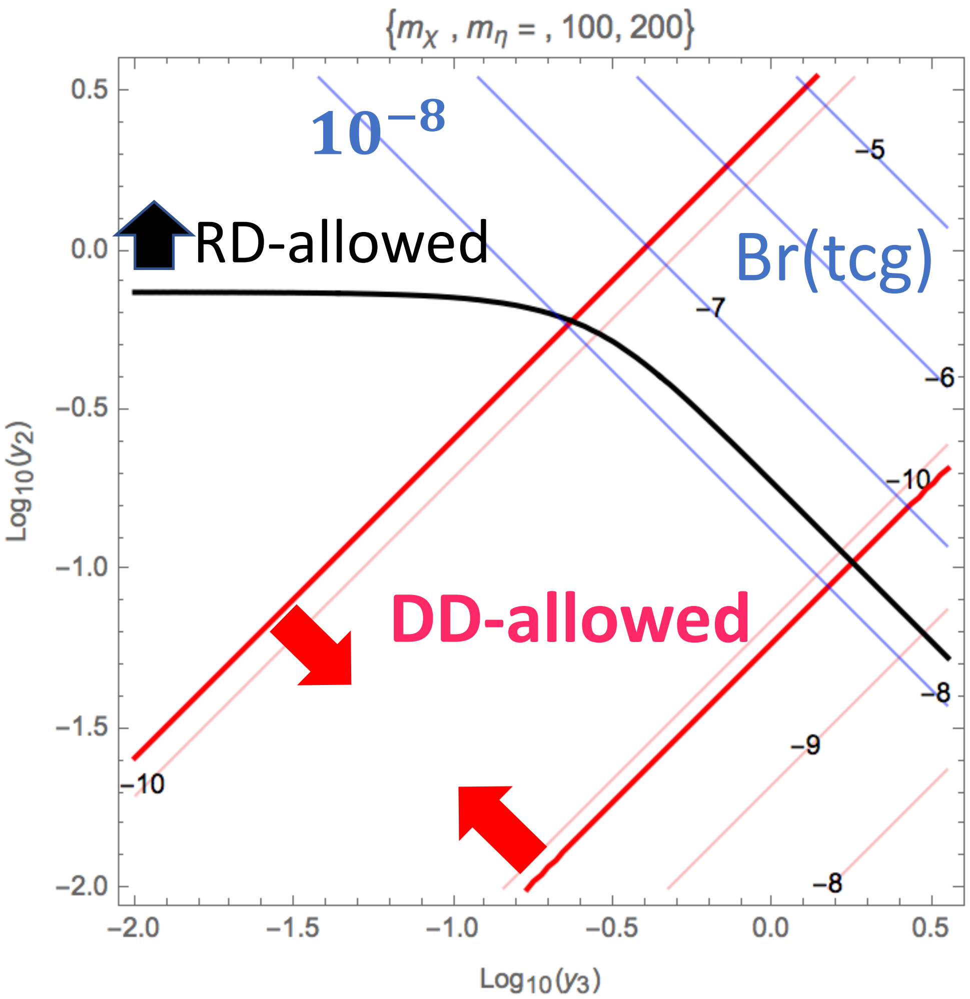
$$Br(t\to c\ g) = 5.78191\times10^{-12} + 5.00541\times10^{-12}\, y2\, y3 + 5.65793\times10^{-7}\, y2^2\, y3^2$$

$$Br(t\to c\ \gamma) = 5.35038\times10^{-14} - 9.59942\times10^{-14}\, y2\, y3 + 1.24541\times10^{-8}\, y2^2\, y3^2$$

$$Br(t\to c\ Z) = 1.22242\times10^{-14} - 1.52369\times10^{-13}\, y2\, y3 + 1.25457\times10^{-9}\, y2^2\, y3^2$$

$\chi\chi \to c\bar{c}, t\bar{c}, c\bar{t}$

$\{m_\chi, m_\eta\} = \{100,\ 2 * m_\chi\}$ GeV



$$m_\chi,\ m_\eta,\ \sigma^{SI}_{exp.}(m_\chi) = 100,\quad 200 \quad (\text{GeV}),\quad 1.38922\times10^{-10} \quad (\text{pb})$$

$$\Omega_\chi h^2 = \frac{0.0371312}{1.\,y2^4 + 8.70416\,y2^2\,y3^2}$$

$$\sigma^{SI}_{the.} = \frac{\Omega_\chi h^2}{\Omega_{DM} h^2}\,\sigma^{SI}_{\chi-p} = \frac{3.09038\times10^{-10}\left(0. + 1.\,y2^2 + \left(0.11292 + 1.37228\times10^{-18}\,i\right) y3^2\right)^2}{1.\,y2^4 + 8.70416\,y2^2\,y3^2},$$

$$\text{Br}(t\text{->}c\ g) = 5.78191\times10^{-12} + 5.00541\times10^{-12}\,y2\,y3 + 5.65793\times10^{-7}\,y2^2\,y3^2$$

$$\text{Br}(t\text{->}c\ \gamma) = 5.35038\times10^{-14} - 9.59942\times10^{-14}\,y2\,y3 + 1.24541\times10^{-8}\,y2^2\,y3^2$$

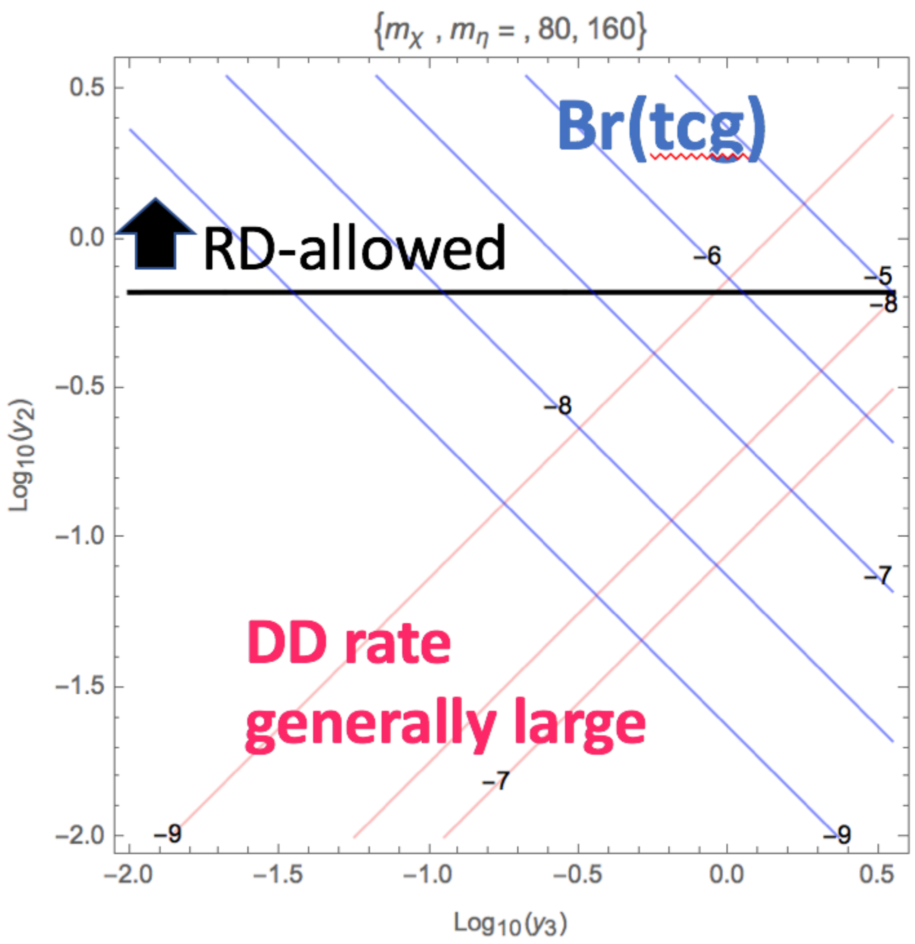
$$\text{Br}(t\text{->}c\ Z) = 1.22242\times10^{-14} - 1.52369\times10^{-13}\,y2\,y3 + 1.25457\times10^{-9}\,y2^2\,y3^2$$

Maximum value of Br(t->cg)

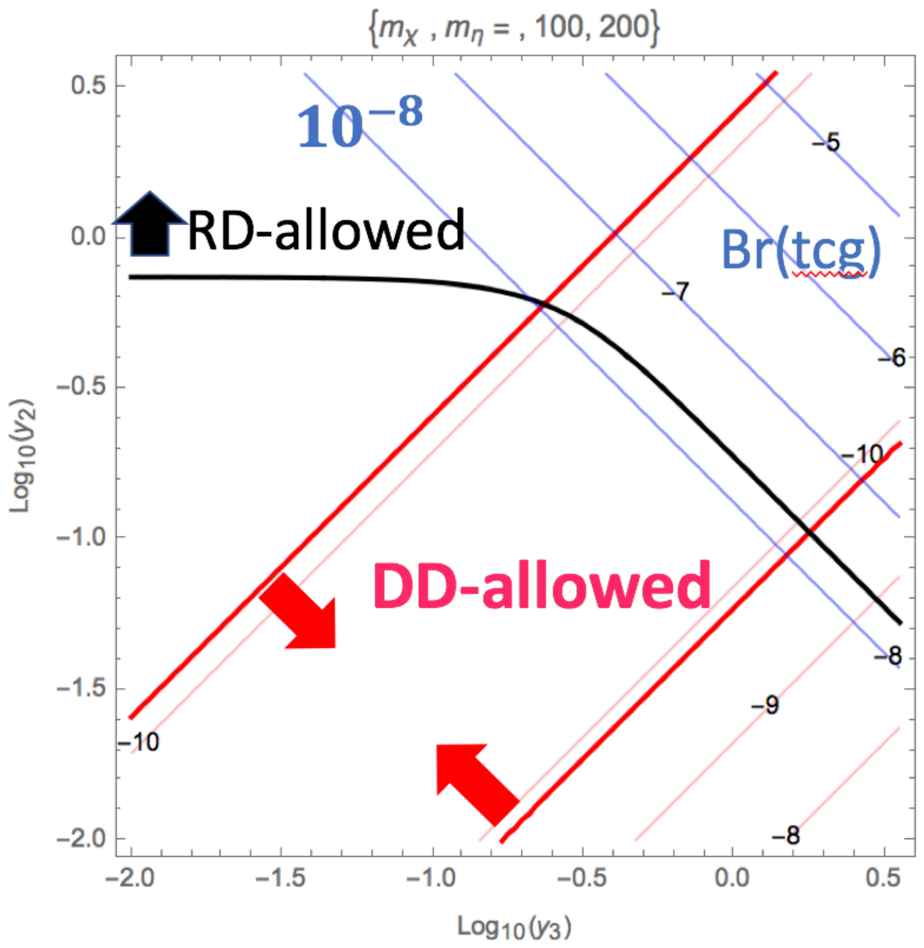
- $\sim 10^{-4}$ passing perturb.
- $\sim 10^{-4}$ passing perturb., DD, part of DM (can be diff.)
- $\sim 10^{-8}$ passing perturb., DD, full of DM

Quick comparison

$\chi\chi \to c\bar{c}$

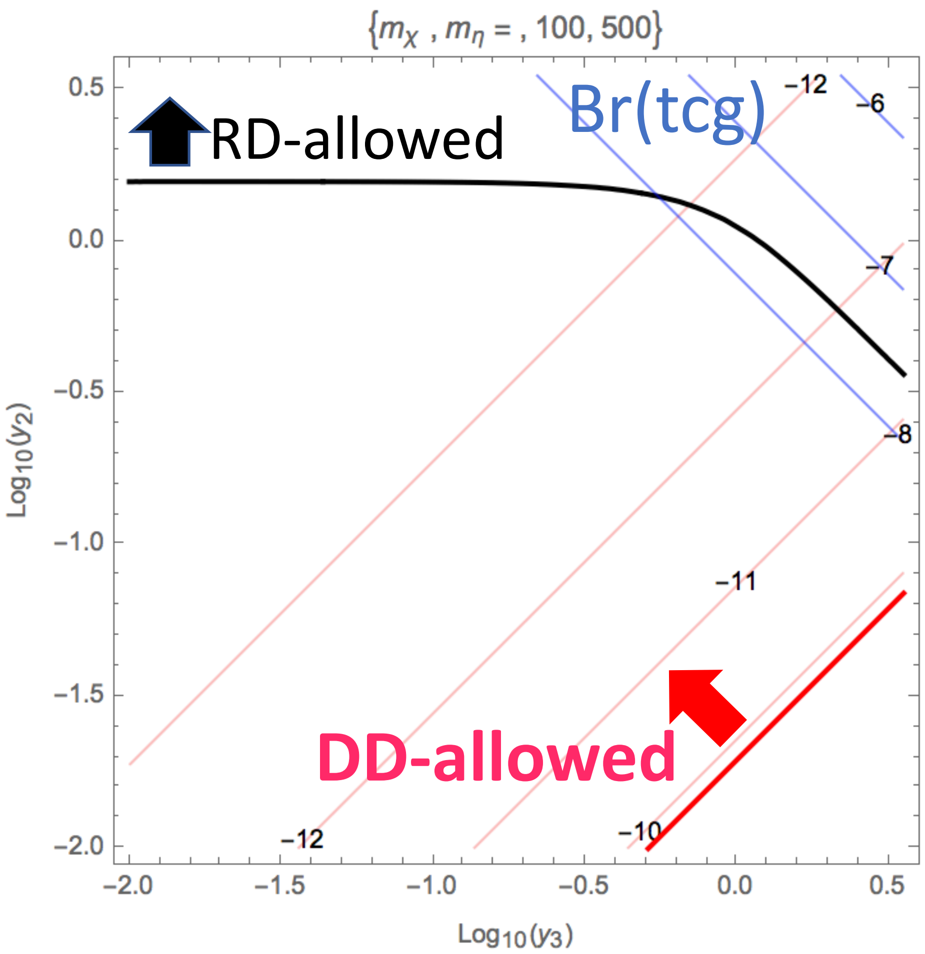


$\chi\chi \to c\bar{c}, t\bar{c}, c\bar{t}$



$\chi\chi \rightarrow c\bar{c}, t\bar{c}, c\bar{t}$ heavier mediator

$\{m_\chi, m_\eta\} = \{100,\ 500\}$ GeV



$$m_\chi,\ m_\eta,\ \sigma^{SI}_{exp.}(m_\chi) = 100,\quad 500 \quad (\text{GeV}),\quad 1.38922\times10^{-10} \quad (\text{pb})$$

$$\Omega_\chi h^2 = \frac{0.737857}{1.\ y2^4 + 3.67172\, y2^2\, y3^2}$$

$$\sigma^{SI}_{the.} = \frac{\Omega_\chi h^2}{\Omega_{DM} h^2}\ \sigma^{SI}_{\chi-p} = \frac{1.69583\times10^{-12}\left(0.+1.\ y2^2+0.336656\, y3^2\right)^2}{1.\ y2^4+3.67172\, y2^2\, y3^2},$$

$$Br(t\to c\ g) = 5.78191\times10^{-12} + 9.72813\times10^{-13}\, y2\, y3 + 1.65686\times10^{-8}\, y2^2\, y3^2$$

$$Br(t\to c\ \gamma) = 5.35038\times10^{-14} - 1.82911\times10^{-14}\, y2\, y3 + 3.64705\times10^{-10}\, y2^2\, y3^2$$

$$Br(t\to c\ Z) = 1.22242\times10^{-14} - 2.69563\times10^{-14}\, y2\, y3 + 3.83247\times10^{-11}\, y2^2\, y3^2$$

- DD-allowed region changes for different mass spectrum
- Stronger bounds on χ-p scattering rate when allowing other DM components to generate DD signal

$$\chi\chi \to c\bar{c}, t\bar{c}, c\bar{t}, t\bar{t}$$

$$\{m_\chi, m_\eta\} = \{200,\ 300\}\ \text{GeV}$$

Top quark y_3 leads in RD while suppressed in DD

$$m_\chi,\ m_\eta,\ \sigma^{SI}_{exp.}(m_\chi) = 200,\quad 300\quad (\text{GeV}),\quad 2.58092\times10^{-10}\quad (\text{pb})$$

$$\Omega_\chi h^2 = \frac{0.0744905}{1.\,y2^4 + 14.9773\,y2^2\,y3^2 + 15.4163\,y3^4}$$

$$\sigma^{SI}_{the.} = \frac{\Omega_\chi h^2}{\Omega_{DM} h^2}\sigma^{SI}_{\chi-p} = \frac{2.87941\times10^{-10}\left(0. + 1.\,y2^2 + (0.120686 + 0.\,i)\,y3^2\right)^2}{1.\,y2^4 + 14.9773\,y2^2\,y3^2 + 15.4163\,y3^4},$$

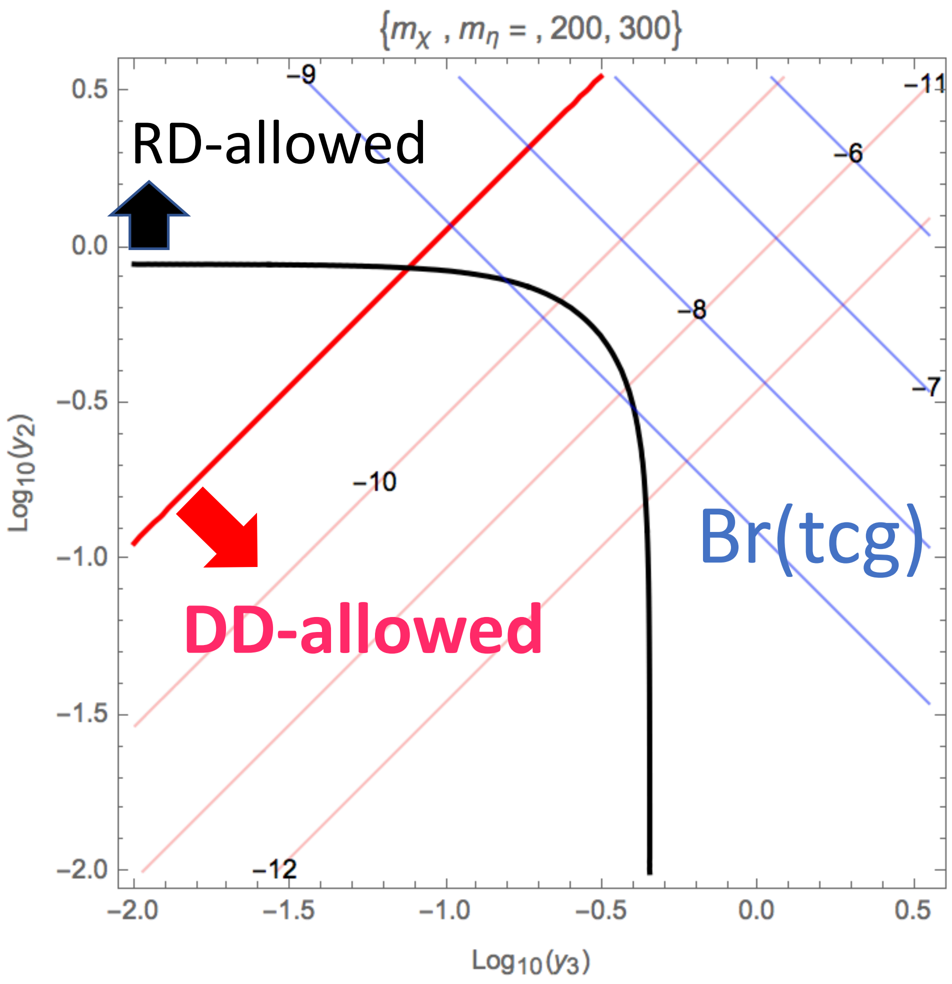
$$Br(t\text{->}c\ g) = 5.78191\times10^{-12} + 1.90517\times10^{-12}\,y2\,y3 + 6.641\times10^{-8}\,y2^2\,y3^2$$

$$Br(t\text{->}c\ \gamma) = 5.35038\times10^{-14} - 3.5939\times10^{-14}\,y2\,y3 + 1.46181\times10^{-9}\,y2^2\,y3^2$$

$$Br(t\text{->}c\ Z) = 1.22242\times10^{-14} - 5.33448\times10^{-14}\,y2\,y3 + 1.35084\times10^{-10}\,y2^2\,y3^2$$

$\chi\chi \to c\bar{c}, t\bar{c}, c\bar{t}, t\bar{t}$

$\{m_\chi, m_\eta\} = \{200,\ 300\}$ GeV



$$m_\chi,\ m_\eta,\ \sigma^{SI}_{exp.}(m_\chi) = 200,\quad 300 \quad (\text{GeV}),\quad 2.58092\times10^{-10} \quad (\text{pb})$$

$$\Omega_\chi h^2 = \frac{0.0744905}{1.\ y2^4 + 14.9773\ y2^2\ y3^2 + 15.4163\ y3^4}$$

$$\sigma^{SI}_{the.} = \frac{\Omega_\chi h^2}{\Omega_{DM} h^2}\ \sigma^{SI}_{\chi-p} = \frac{2.87941\times10^{-10}\left(0.+1.\ y2^2 + (0.120686 + 0.\ i)\ y3^2\right)^2}{1.\ y2^4 + 14.9773\ y2^2\ y3^2 + 15.4163\ y3^4},$$

$$Br(t\to c\ g) = 5.78191\times10^{-12} + 1.90517\times10^{-12}\ y2\ y3 + 6.641\times10^{-8}\ y2^2\ y3^2$$

$$Br(t\to c\ \gamma) = 5.35038\times10^{-14} - 3.5939\times10^{-14}\ y2\ y3 + 1.46181\times10^{-9}\ y2^2\ y3^2$$

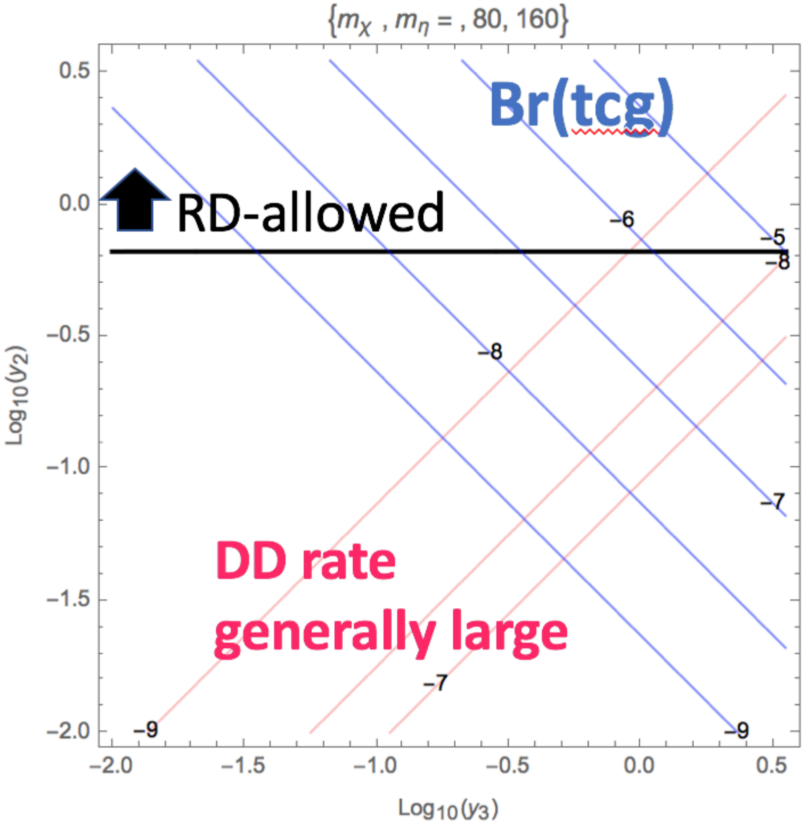
$$Br(t\to c\ Z) = 1.22242\times10^{-14} - 5.33448\times10^{-14}\ y2\ y3 + 1.35084\times10^{-10}\ y2^2\ y3^2$$

Top quark sector coupling y_3 receives stronger bound from RD but weaker from DD

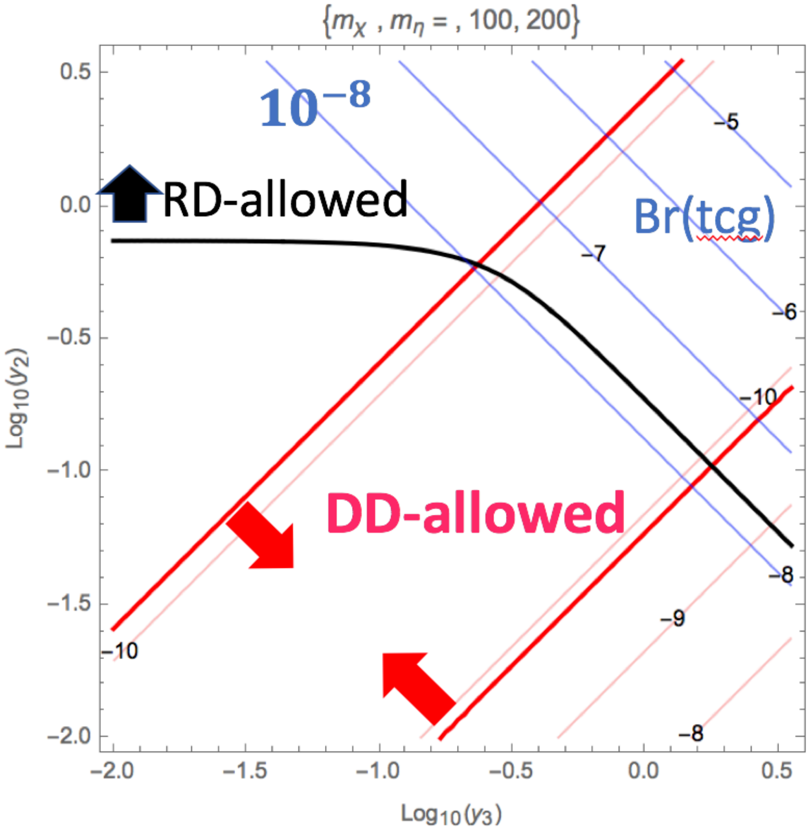
(for chosen mass spectrum)

Comparison

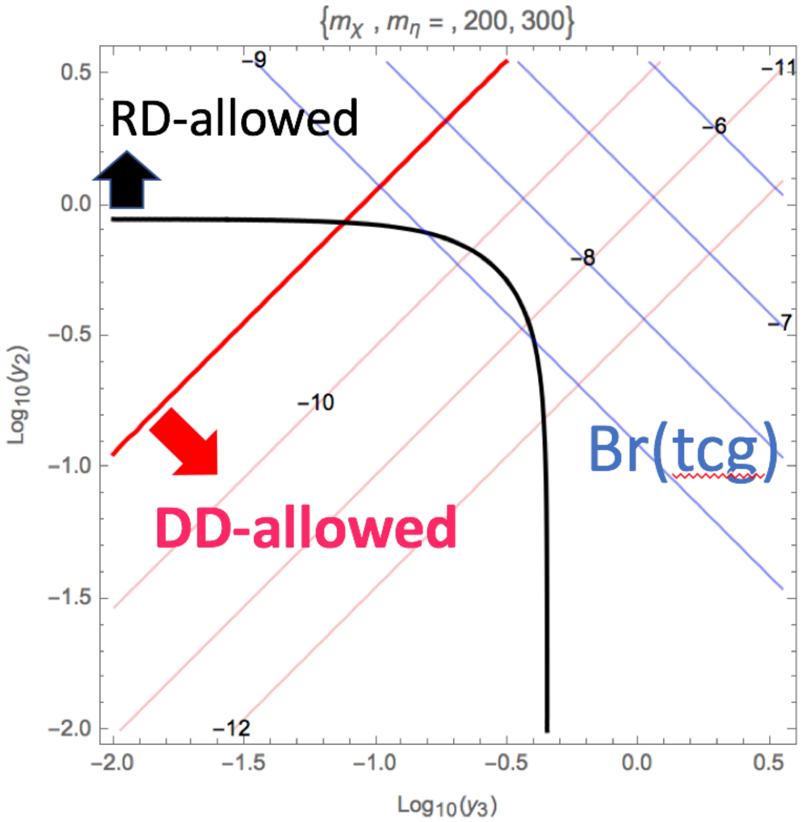
$\chi\chi \to c\bar{c}$



$\chi\chi \to c\bar{c}, t\bar{c}, c\bar{t}$



$\chi\chi \to c\bar{c}, t\bar{c}, c\bar{t}, t\bar{t}$



On-going processes

- collider signals are generally strong
  - RD requires not small couplings
  - mediator can easily decay inside detector
  - y_2, y_3 determined $Br(\eta \to \chi + t/c)$

- Indirect detection from comic-rays
  - charged rays may be as powerful as gamma-ray signal

- effects from mediator-Higgs quartic coupling $\lambda_{\eta H}$

- NLO effects in DM annihilation may alter the observation

Summary

- Absence of DM direct search signal may imply heavy quark-flavored nature of DM-SM interactions

simplified SUSY case

- We revisit the Majorana DM χ with a colorful mediator
  - loop effects leads in direct detections

- We allow χ to annihilate sufficiently, i.e. not being the whole DM
  - scaled DM-nucleon scattering rate present rich behaviors

- Other signals and joint constraints are under analysis

Thank you for your attention