imagine the impossible

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Scalar dark matter in heavy quark sector

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Collaboration with

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1606.00072 [JHEP10(2016)117]

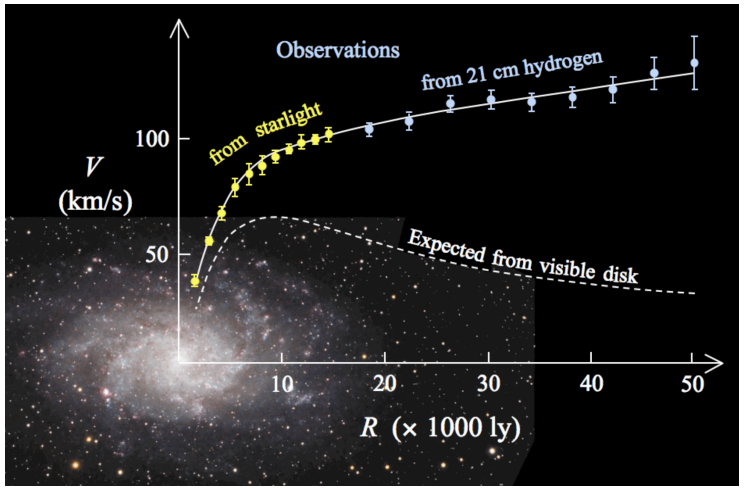
1709.00697 [JCAP07(2018)008]

"Beyond the BSM"
(The 4th Kavli IPMU-Durham IPPP-KEK-KIAS workshop)
Gumma, Japan, Oct 3rd, 2018

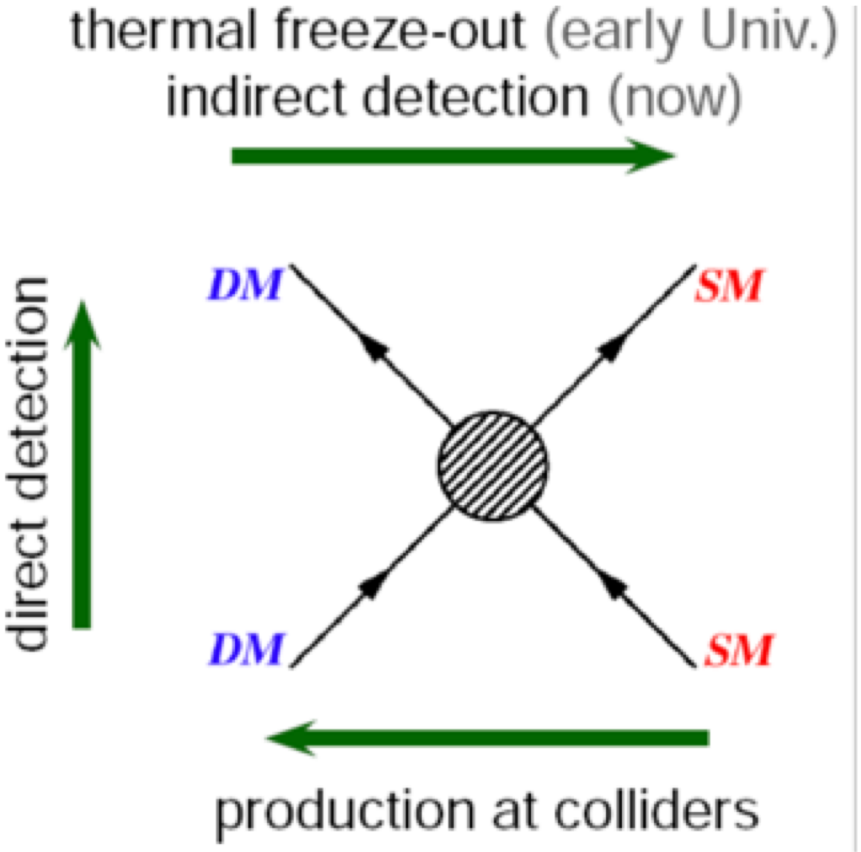
Outline

- DM hints and detections
- Vector-like portal for DM-SM interaction
  - SM sector: $\{u_R, c_R, t_R\}$ as our choice
- Phenomenology
- Summary

DM hints and detections



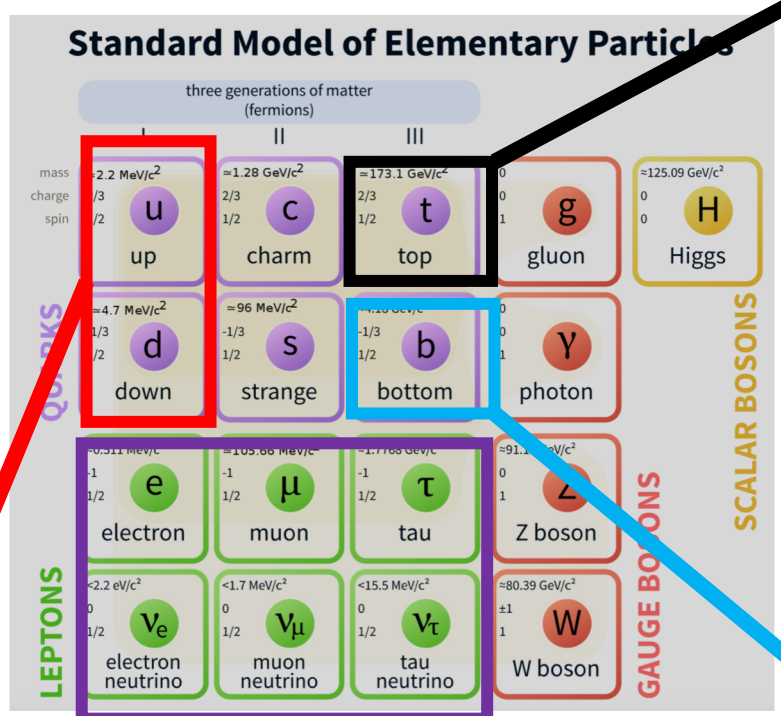
https://en.wikipedia.org



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

(DM)-(SM)-(Med.) Interaction

- Simplified model
- Renormalizable
- Gauge invariant



1606.00072, Baek, Ko, PW
Top-philic Scalar Dark Matter with a Vector-like Fermionic Top Partner

1501.02202, Kilic, Klimek, Yu.
Signatures of Top Flavored Dark Matter

1404.1918, Gomez et al,
Dark Matter on Top

1511.04452, Giacchino *et al*,
Signatures from scalar dark matter with a vector-like quark mediator

1308.0612, Bai, Berger.
Fermion portal dark matter

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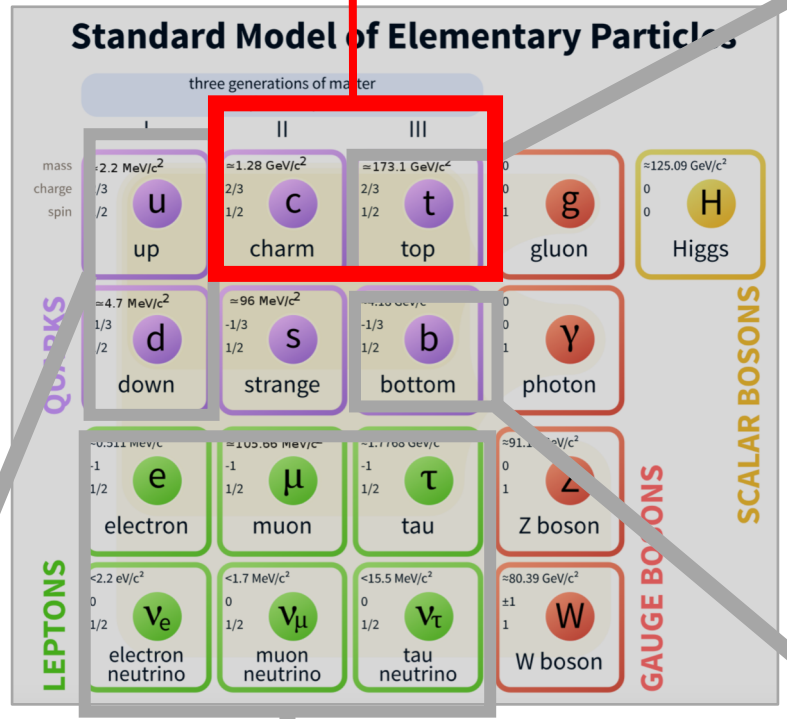
1411.1407, Kile, Kobach, Soni,
Lepton-Flavored Dark Matter

1612.01643, Abe et al,
Dark matter physics, flavor physics and LHC constraints in the dark matter model with a bottom partner

Our focus: Heavy quarks



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1st gen. is strongly constrained

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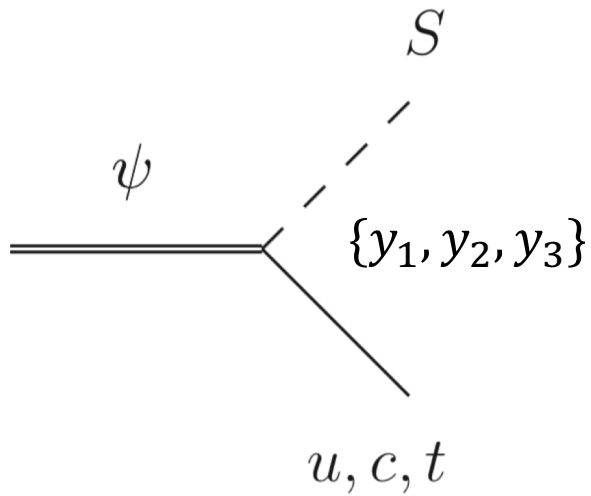
Model set-up

- DM: real scalar S

- Vector-like (VL) fermion ψ, $m_\psi > m_S$
  - (ψ, U_i) same quantum number
  - no chiral anomaly

- Z_2 parity: S, ψ are odd
  - no mixing $(S, H), (\psi, U_i)$
  - $Br\left(\psi \to S U_i^{(*)}\right) = 100\%$
  - free from LHC limits on VL (T, B)



$$
\begin{aligned}
\mathcal{L}_{\text{new}} &= \mathcal{L}_{\text{fermion}} + \mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{Yukawa}}, \\
\mathcal{L}_{\text{fermion}} &= \bar{\psi}(i\not{D} - m_\psi)\psi, \\
\mathcal{L}_{\text{scalar}} &= \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}m_S^2 S^2 - \frac{1}{4!}\lambda_S S^4 - \frac{1}{2}\lambda_{SH} S^2 H^2, \\
\mathcal{L}_{\text{Yukawa}} &= -y_1 S\overline{\psi_L} u_R - y_2 S\overline{\psi_L} c_R - y_3 S\overline{\psi_L} t_R + h.c.,
\end{aligned}
$$

We consider $y_2, y_3 \gg y_1$, Heavy quark-philic

Model set-up

$$\mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_L W_\mu^+ \gamma^\mu d_L^i] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{T}_L Z_\mu \gamma^\mu u_L^i] \right.$$
$$\left. - \sqrt{\frac{\zeta_i \xi_H^T}{\Gamma_H^0}} \frac{M}{v} [\bar{T}_R H u_L^i] - \sqrt{\frac{\zeta_3 \xi_H^T}{\Gamma_H^0}} \frac{m_t}{v} [\bar{T}_L H t_R] \right\}$$

Buchkremera et al, 13'
Model Independent Framework for Searches of Top Partners

- Z_2 parity: S, ψ are odd
  - no mixing $(S, H), (\psi, U_i)$
  - $Br\left(\psi \to S U_i^{(*)}\right) = 100\%$
  - free from LHC limits on VL (T, B)

$$\begin{aligned}
\mathcal{L}_{\text{new}} &= \mathcal{L}_{\text{fermion}} + \mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{Yukawa}}, \\
\mathcal{L}_{\text{fermion}} &= \bar{\psi}(i\not{D} - m_\psi)\psi, \\
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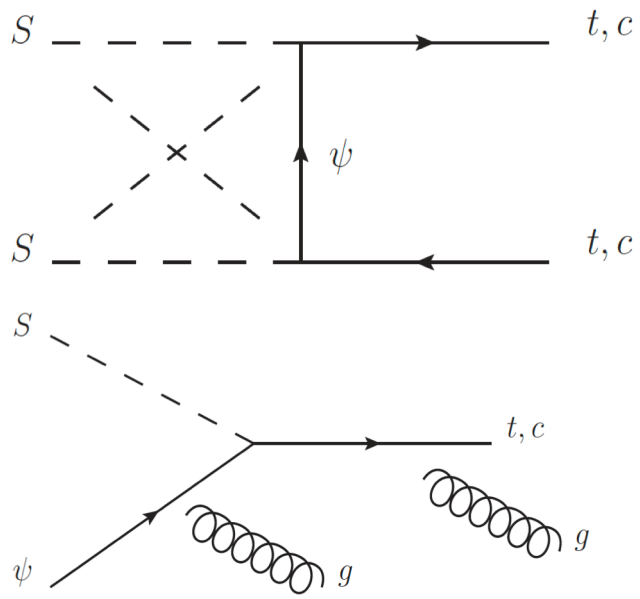
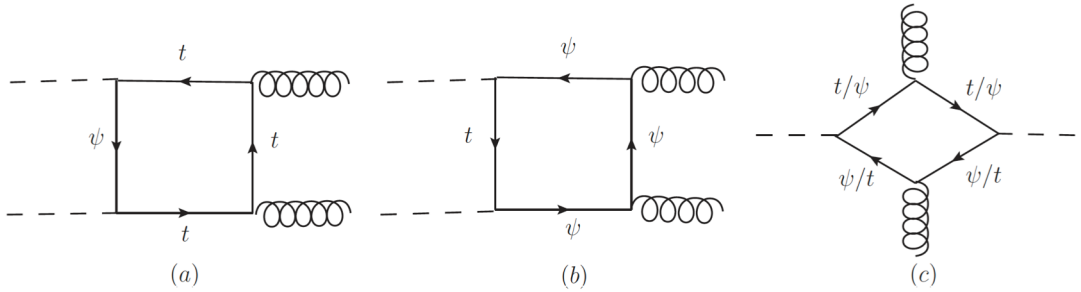
\mathcal{L}_{\text{Yukawa}} &= -y_1 S \overline{\psi_L} u_R - y_2 S \overline{\psi_L} c_R - y_3 S \overline{\psi_L} t_R + h.c.,
\end{aligned}$$

We consider $y_2, y_3 \gg y_1$, Heavy quark-philic

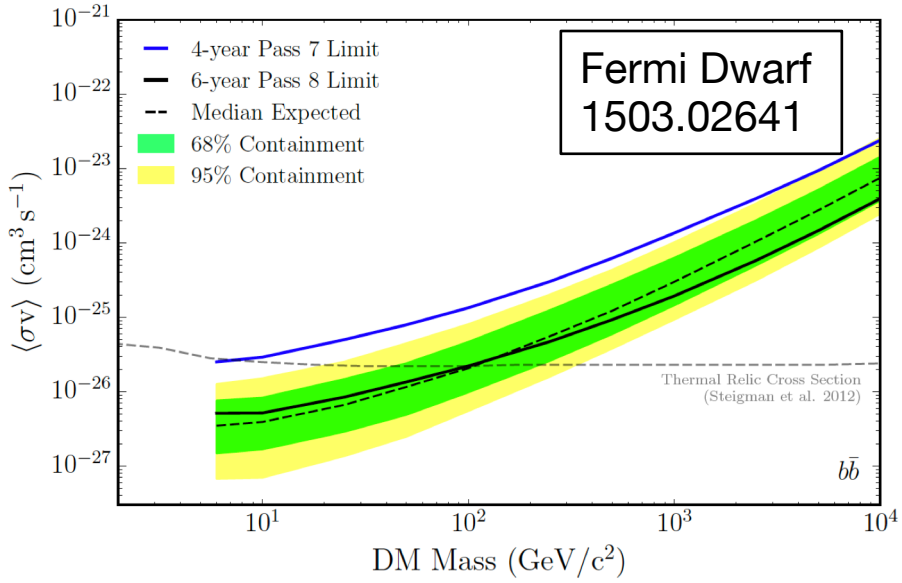
DM Annihilations: Thermal Relic, Indirect Detection





Nojiri et al, 93'; Hisano et al, 10'; Colucci et al, 18'

see Y-F Zhou's talk for charged CR

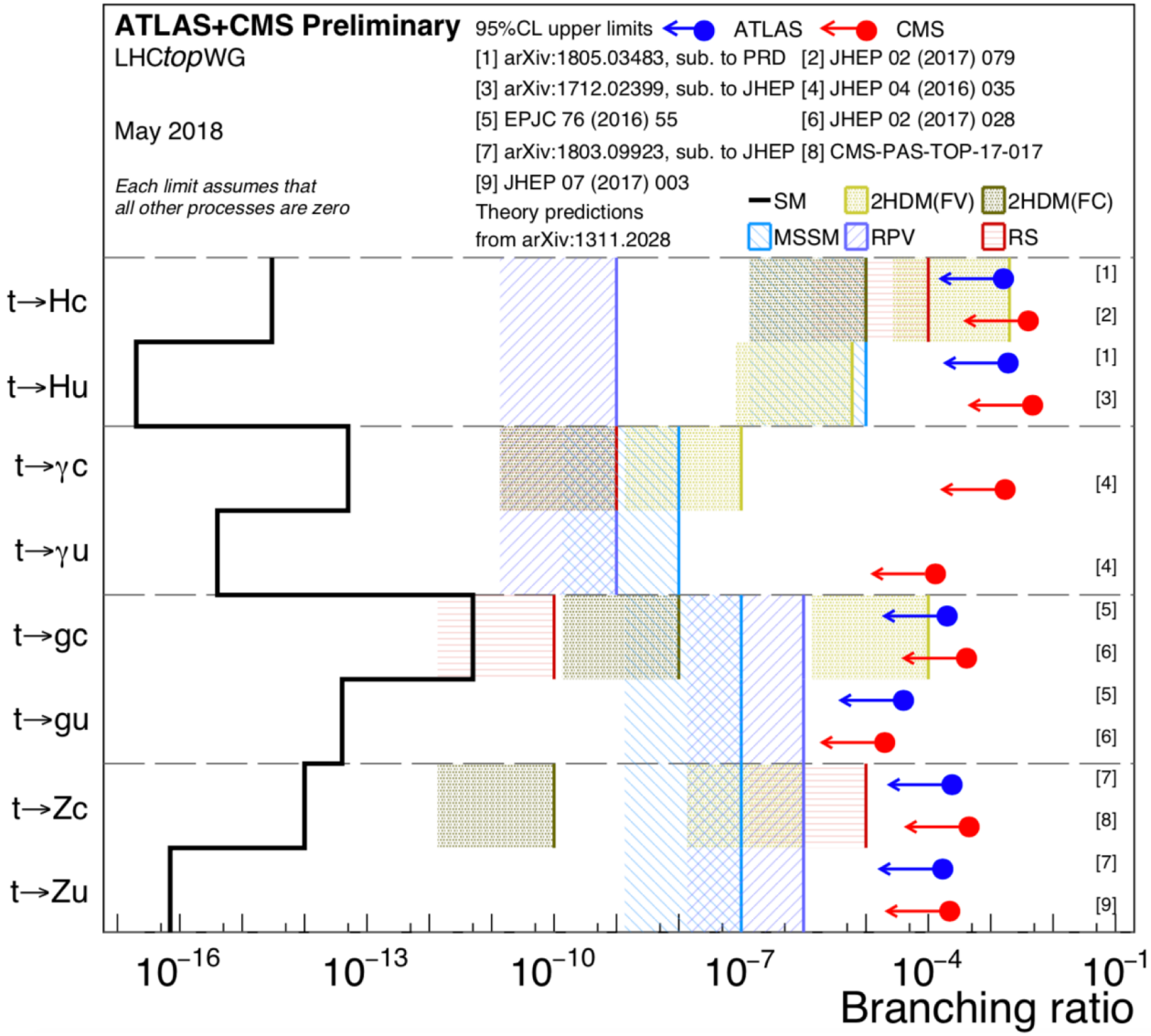


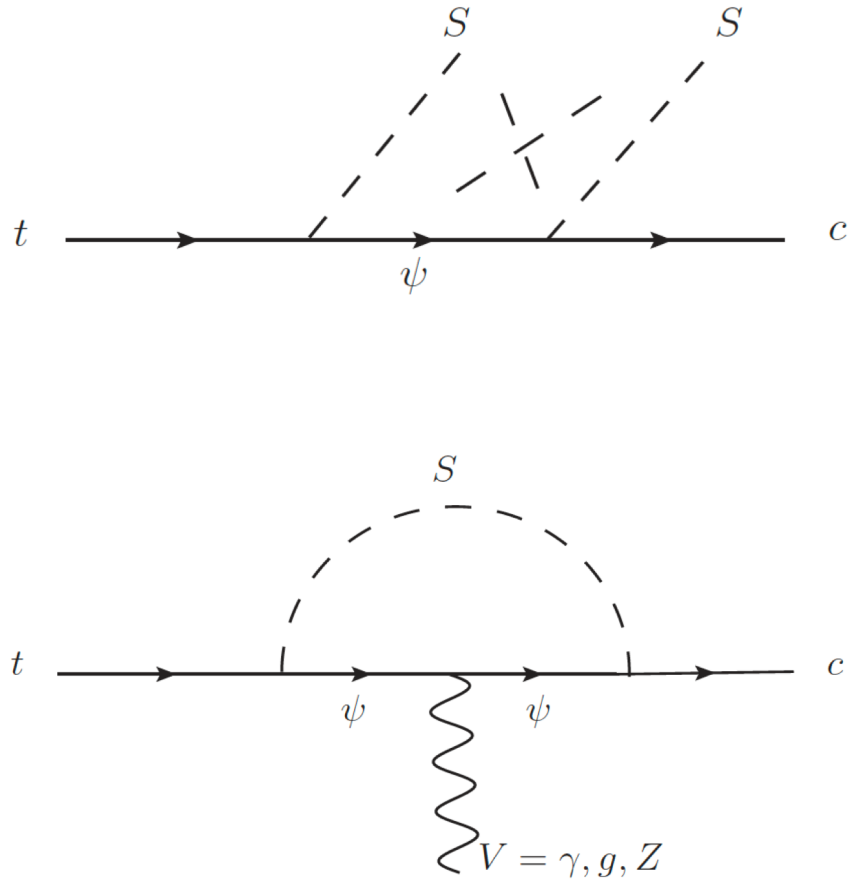
$$N_\gamma^{exp} = 2N_{\gamma,b}(m_S) \times \sigma v_{b\bar{b}}(m_S),$$

Giacchino *et al*, 15'

$$\begin{aligned} N_\gamma^{th} &= 2N_{\gamma,t}(m_S) \times \sigma v(SS \to t\bar{t})_s \\ &+ 2N_{\gamma,c}(m_S) \times \sigma v(SS \to c\bar{c})_s \\ &+ \Big(N_{\gamma,t}(E_t) + N_{\gamma,c}(E_c)\Big) \times \sigma v(SS \to t\bar{c} + c\bar{t})_s \\ &+ 2N_{\gamma,g}(m_S) \times \sigma v(SS \to gg)_s \end{aligned}$$

Top FCNC, exp. limit $< 10^{-(4\sim5)}$



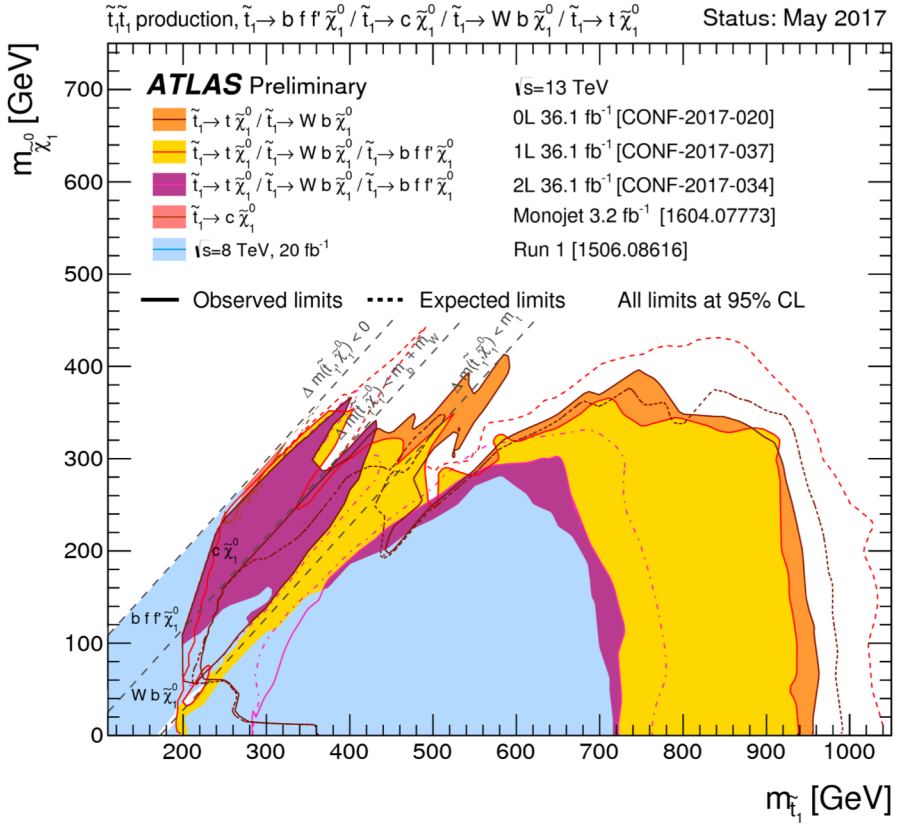


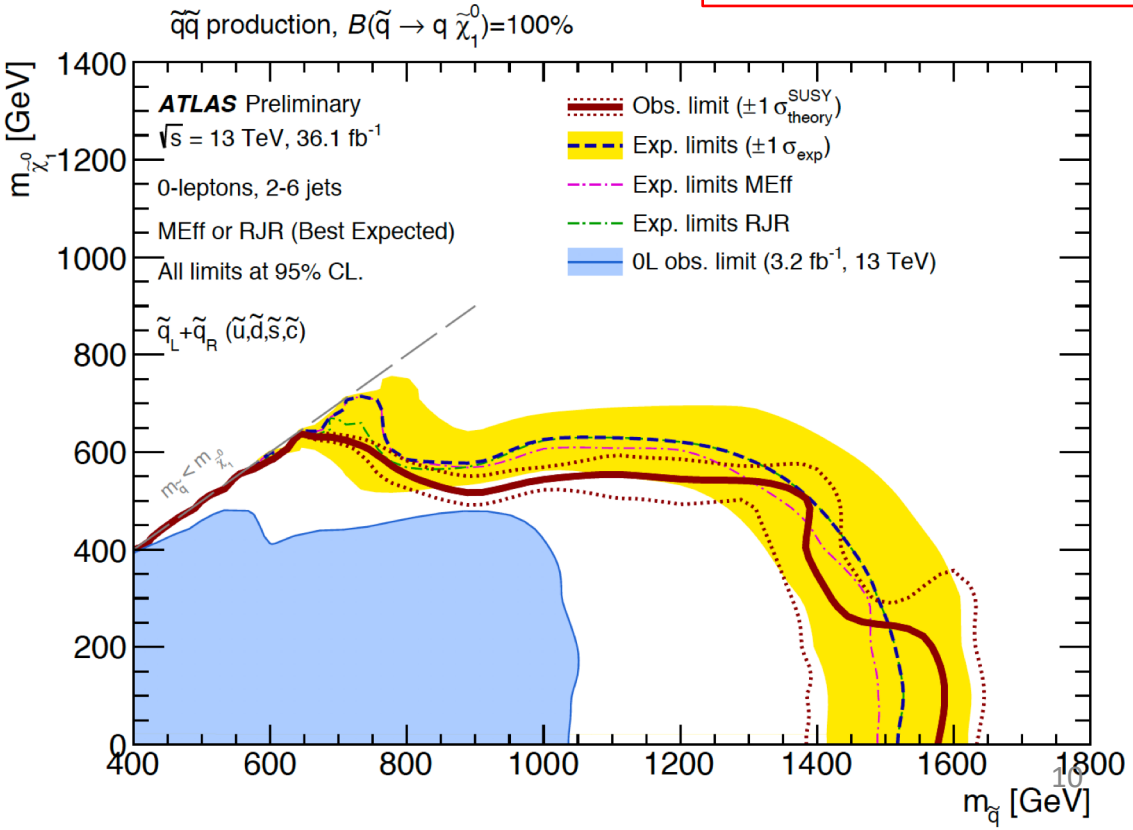
courtesy to Taejeong Kim

Collider signals (ATLAS 36 fb^{-1} @ 13 TeV)

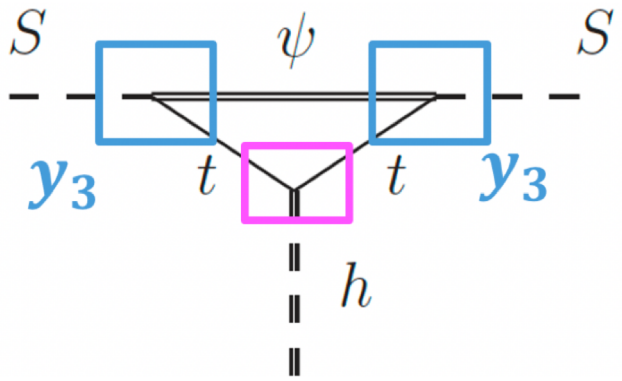
- $pp \to \psi\bar{\psi} \to SS + t/c + t/c,$ i.e. $E_t^{miss} + t\bar{t}, jj, tj$
- ~ SUSY squark searches (3rd , 1st & 2nd gen.)

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





DM-nucleon scattering



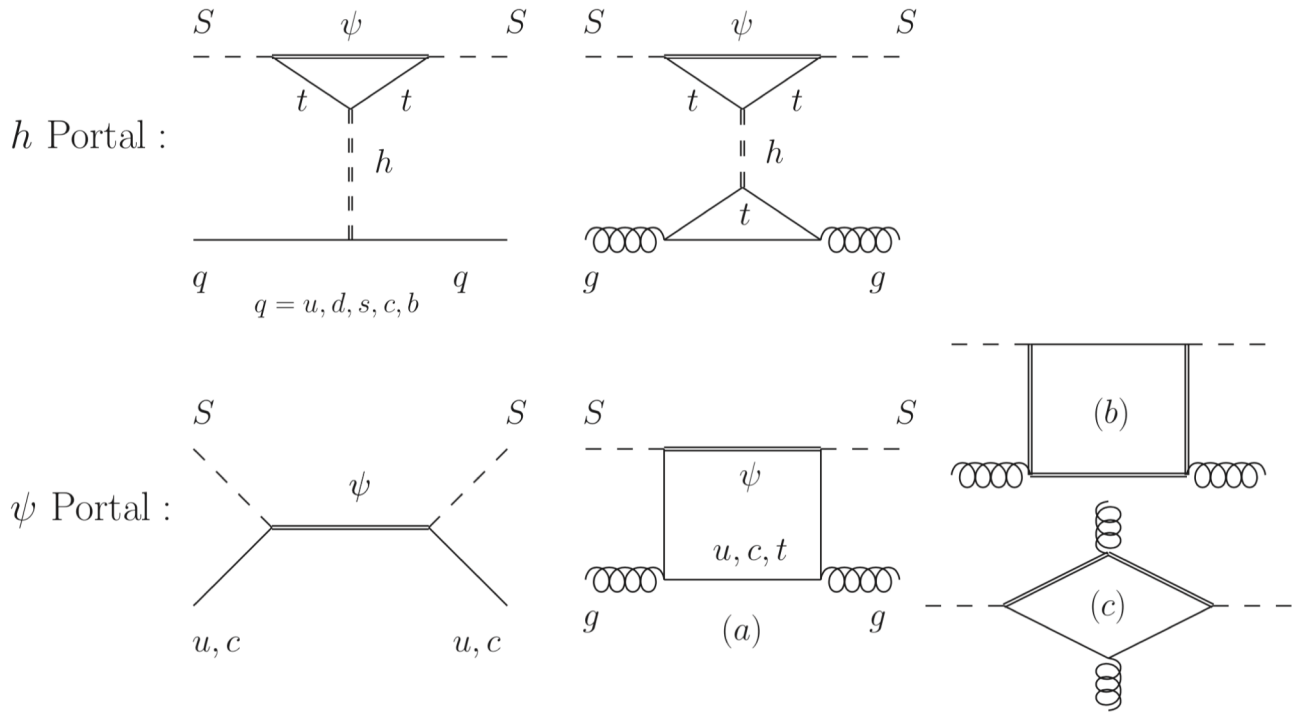
- Corrections to H.P. from VL portal
- heavy particles $\{\psi, t, h\}$ are integrated out at m_Z
- Down to ~ 1 GeV, RGE & {c,b} thrsh. effects included

- $\mu_{EFT} \sim m_Z$

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

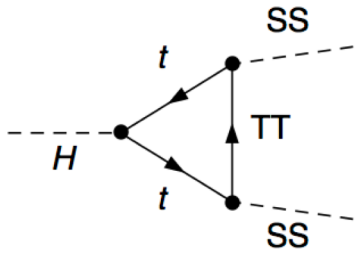
- RGE
- Quark thresholds
- $\mu_{had} \sim 1$ GeV

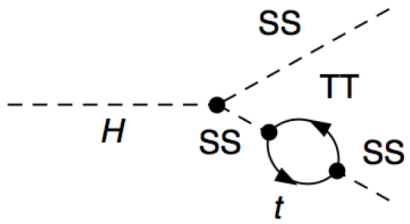
$$\mathcal{L}_{\text{SI}}^{(N)} = f_N \phi^2 \overline{N} N \ ,$$

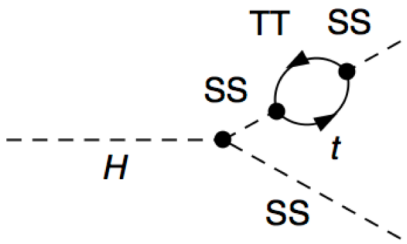


Interplay: VLP & H.P.

$$\lambda_{SH}^{\text{ren.}} = \lambda_{SH}\Big(1 + Fin.[\frac{1}{2}\delta Z_h + \delta Z_S + \delta v]\Big) + Fin.[\lambda_{SH}^{\text{1PI}}]$$







+ inverse loop rotations

$$\delta Z_S^{\text{new}} = -3\,y_3^2\frac{1}{16\pi^2}\Big(m_t^2\,B_0 + m_S^2\,B_1 + A_0(m_\psi^2)\Big)$$

$$\lambda_{SH}^{\text{1PI}} = -y_3^2\,y_t\frac{m_t}{\sqrt{2}}\frac{1}{16\pi^2}\Big(24(B_0 + m_h^2\,C_1) + 6(m_h^2 + 4m_t^2)C_0 + 16(m_h^2 + 4m_S^2)C_2\Big)$$

$$B_i \equiv B_i(m_S^2; m_t^2, m_\psi^2),$$
$$C_i \equiv C_i(m_h^2, m_S^2, m_S^2; m_t^2, m_t^2, m_\psi^2),$$

In the numerical calculations we impose modified minimal subtraction ($\overline{\text{MS}}$) scheme by choosing $\delta\lambda_{SH} = (...)\Delta$ to eliminate all $\bar{\Delta} = 1/\epsilon - \gamma_E + \ln 4\pi$ in $\lambda_{SH}^{\text{ren.}}$.

- Case-I:

$$\lambda_{SH} = 0,$$
$$\lambda_{SH}^{\text{ren.}} = \text{Fin.}\left[\lambda_{SH}^{\text{1PI}}\right].$$

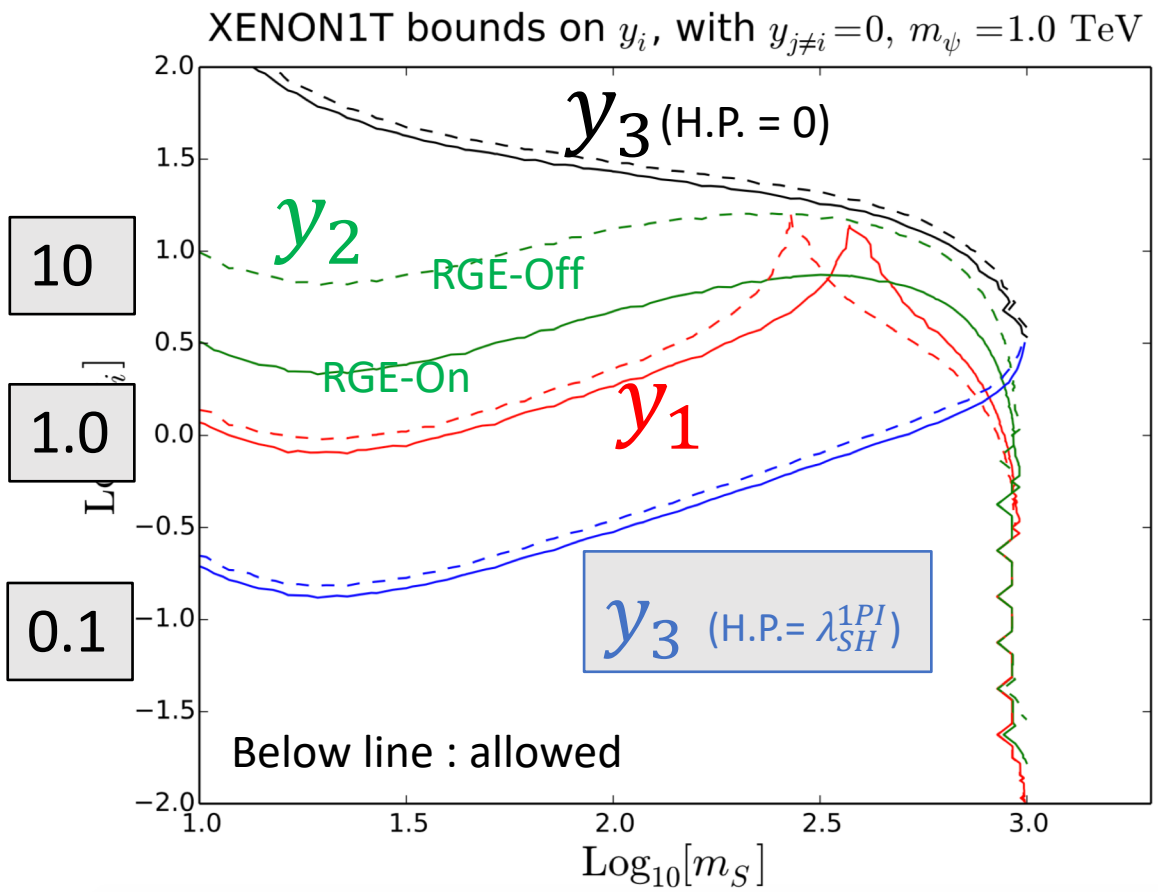
- Case-II:

$$\lambda_{SH} = -\frac{\text{Fin.}\left[\lambda_{SH}^{\text{1PI}}\right]}{1 + \text{Fin.}\left[\frac{1}{2}\delta Z_h + \delta Z_S + \delta v\right]},$$
$$\lambda_{SH}^{\text{ren.}} = 0.$$

Interplay: VLP & H.P.

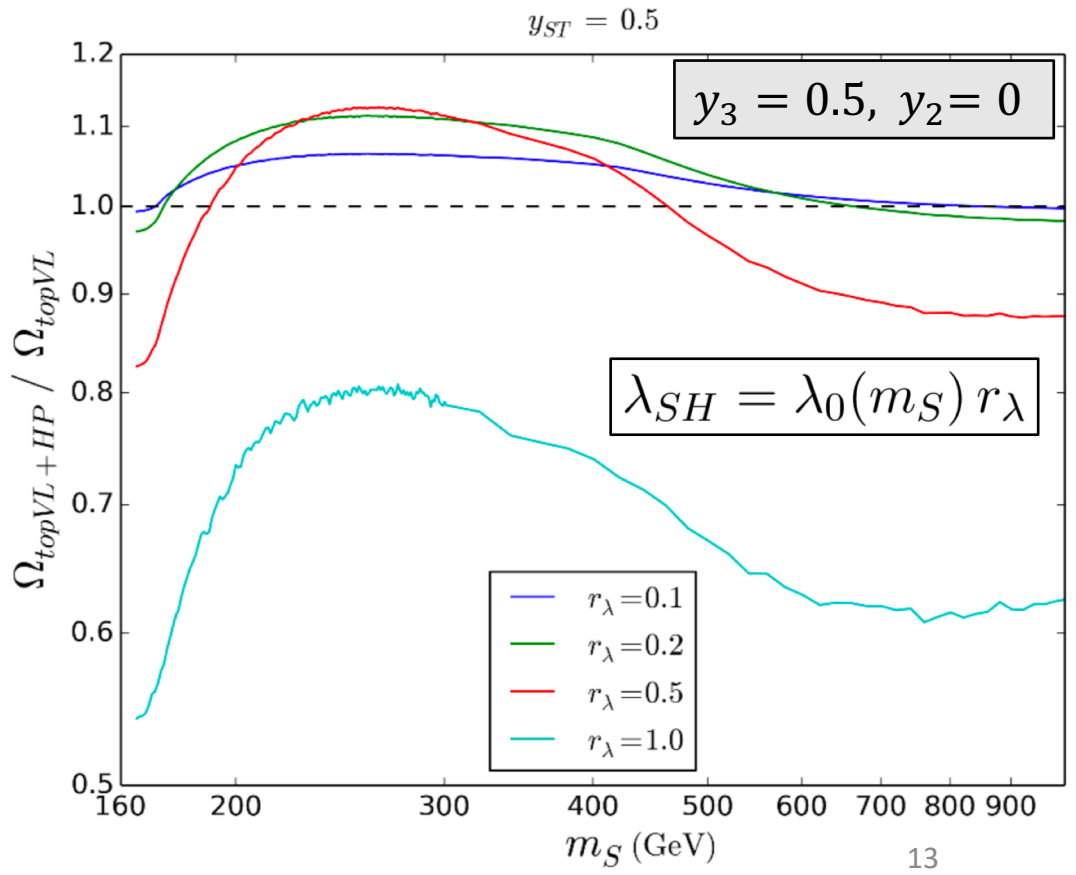
1709.00697
Baek, Ko, PW

XENON1T limits on $y_{1,2,3}$



$$\frac{\Omega_{\mathrm{DM}}h^2\ (\mathrm{VLP}+\mathrm{HP})}{\Omega_{DM}h^2\ (\mathrm{VLP})}$$

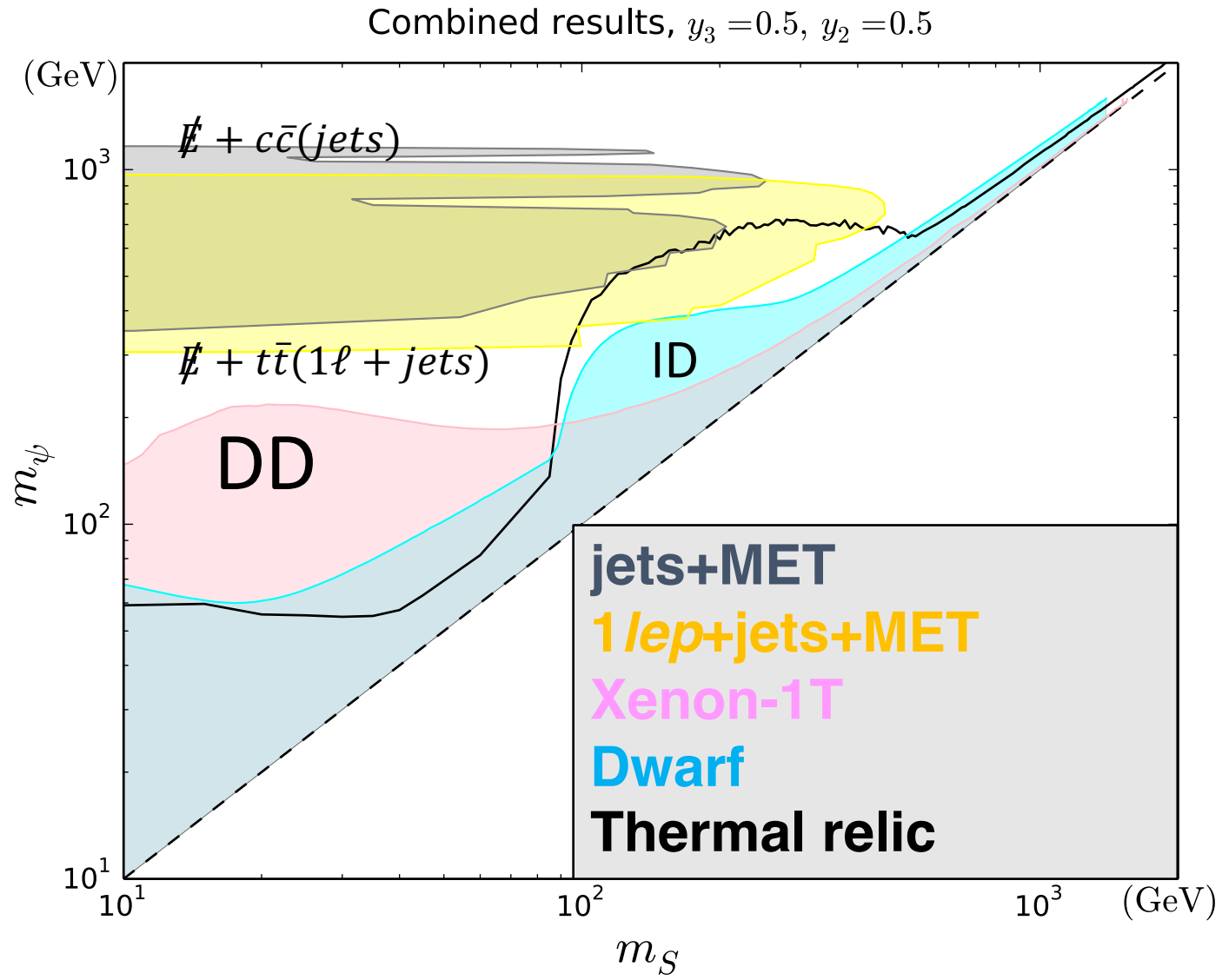
1606.00072
Baek, Ko, PW



Combined results (color regions: excluded)

$y_3 = 0.5$

$\boldsymbol{y_2 = 0.5}$

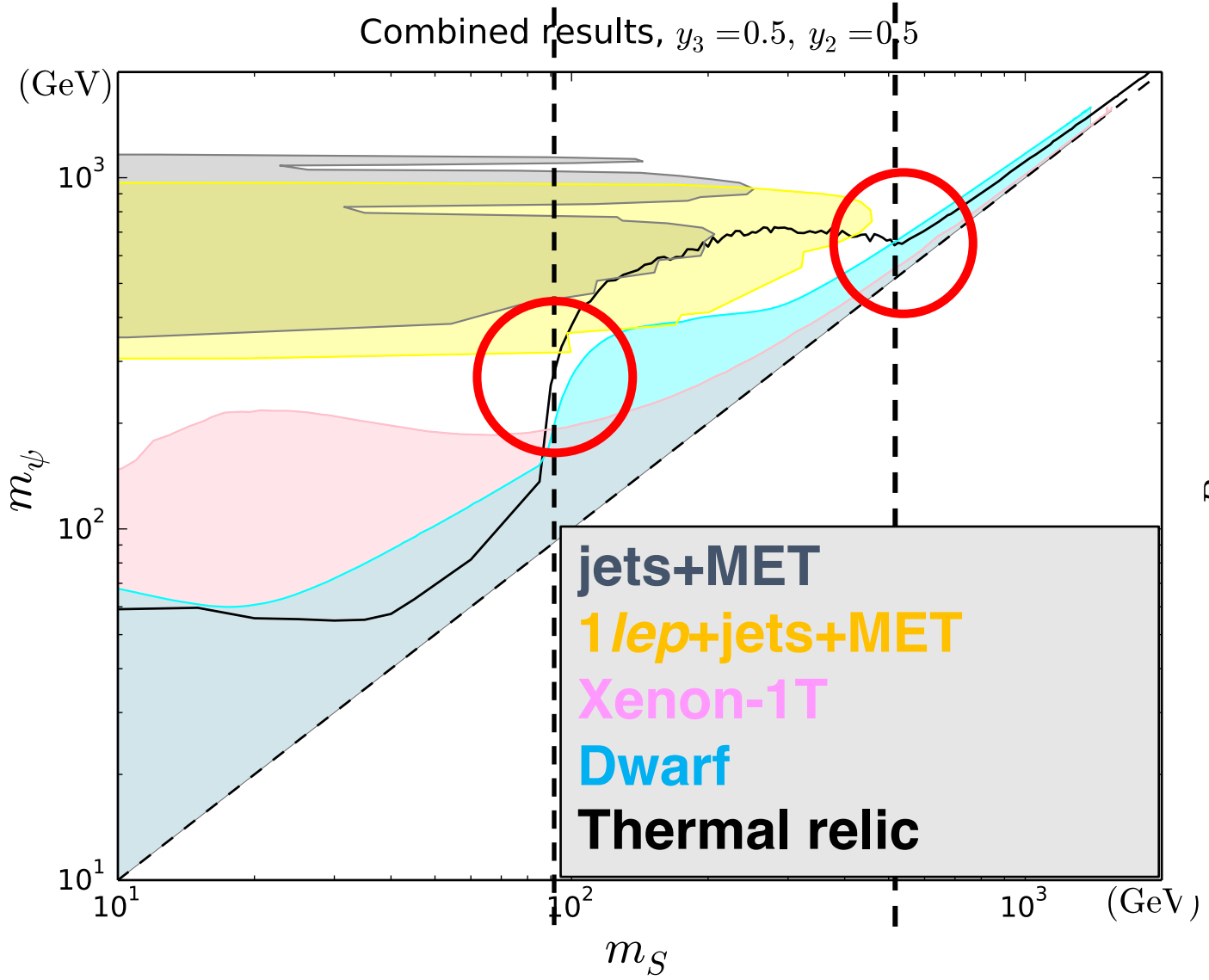


$y_3 = 0.5$

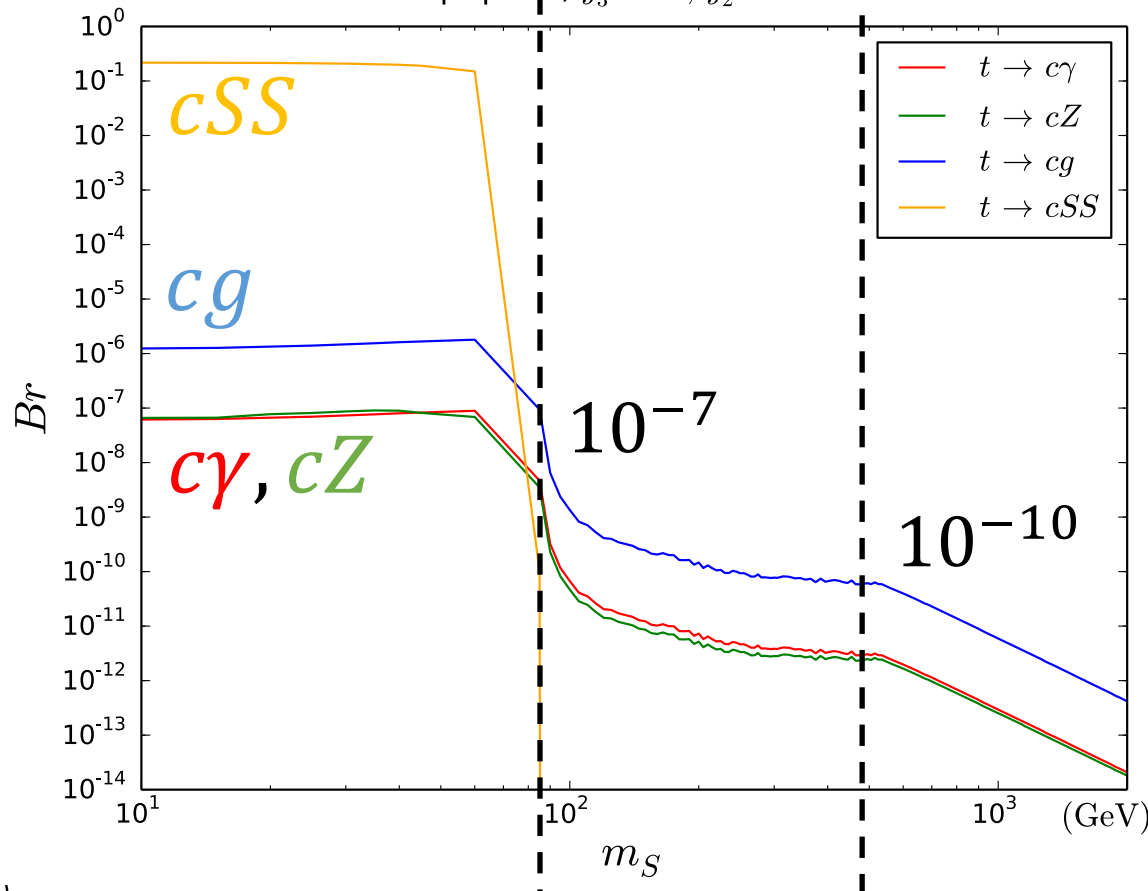
$m_S \sim \frac{m_t}{2}$

$m_S \sim 500$ GeV

$y_2 = 0.5$



Br^t_{FCNC}

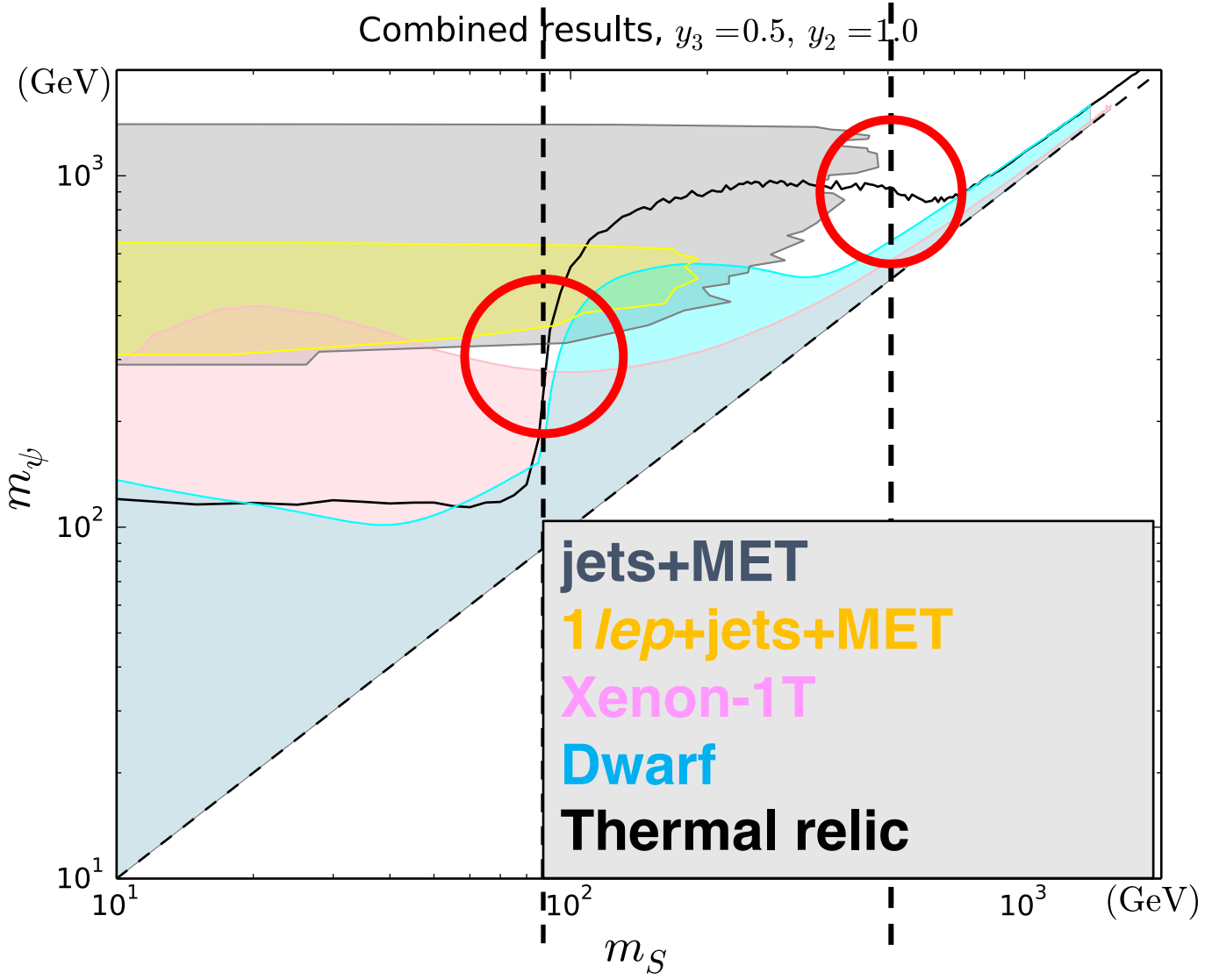


$y_3 = 0.5$

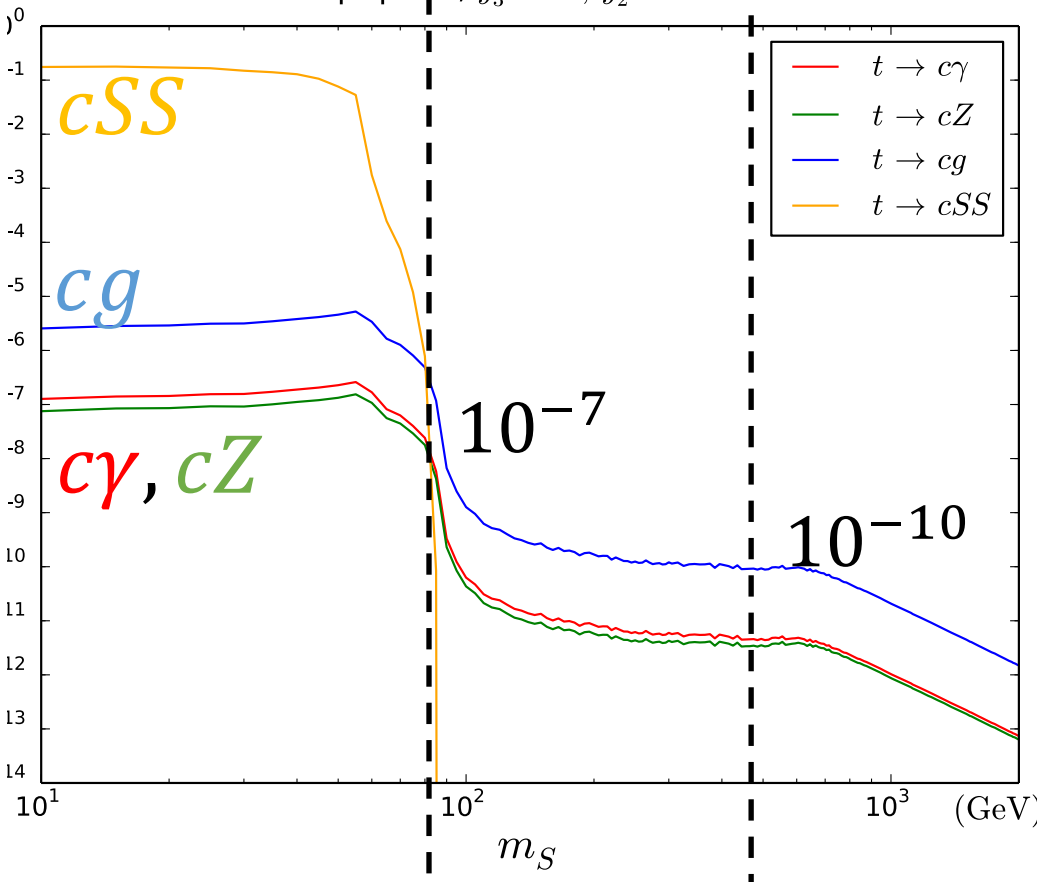
$m_S \sim \frac{m_t}{2}$

$m_S \sim 500$ GeV

$y_2 = 1.0$



Br^t_{FCNC}



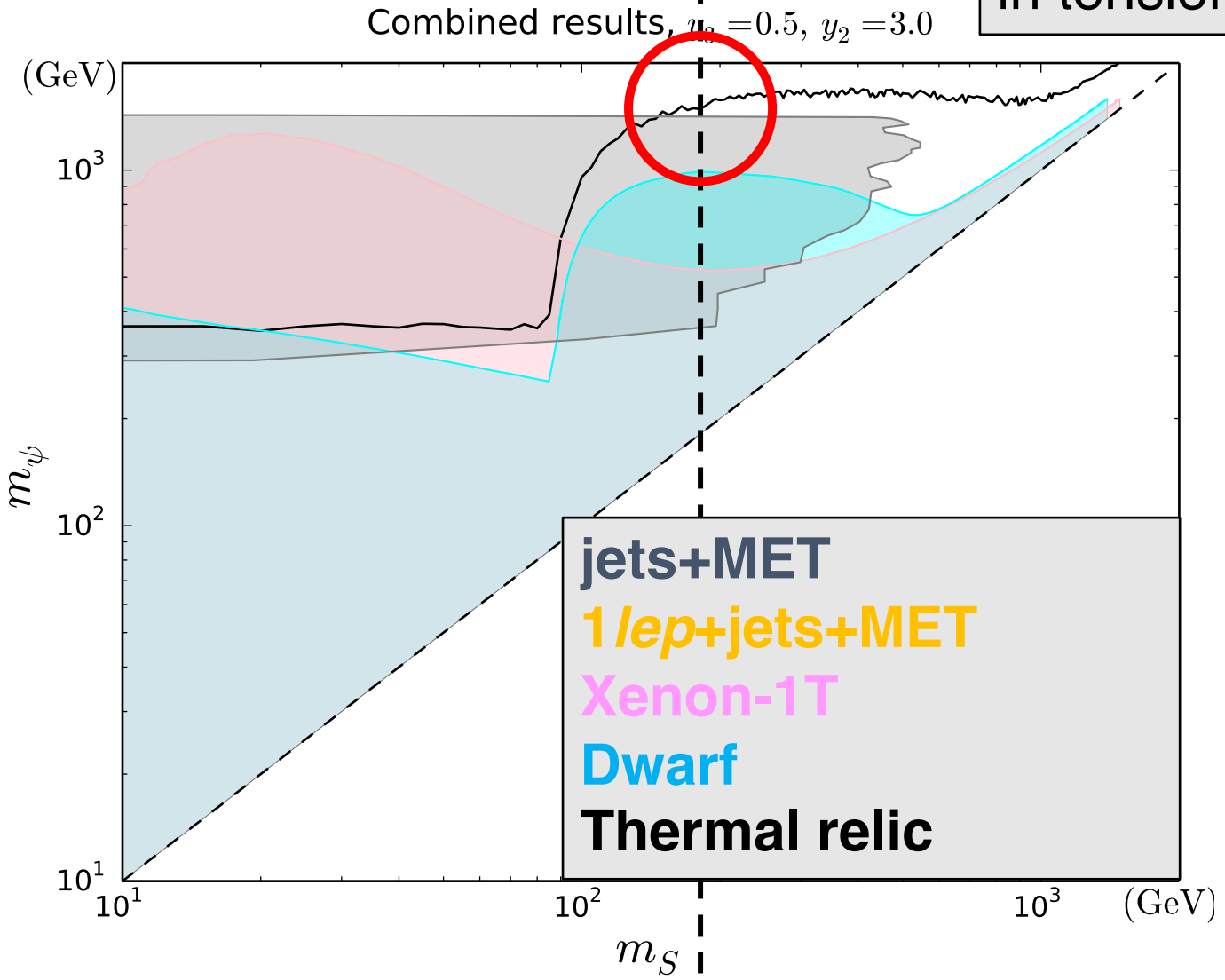
$y_3 = 0.5$

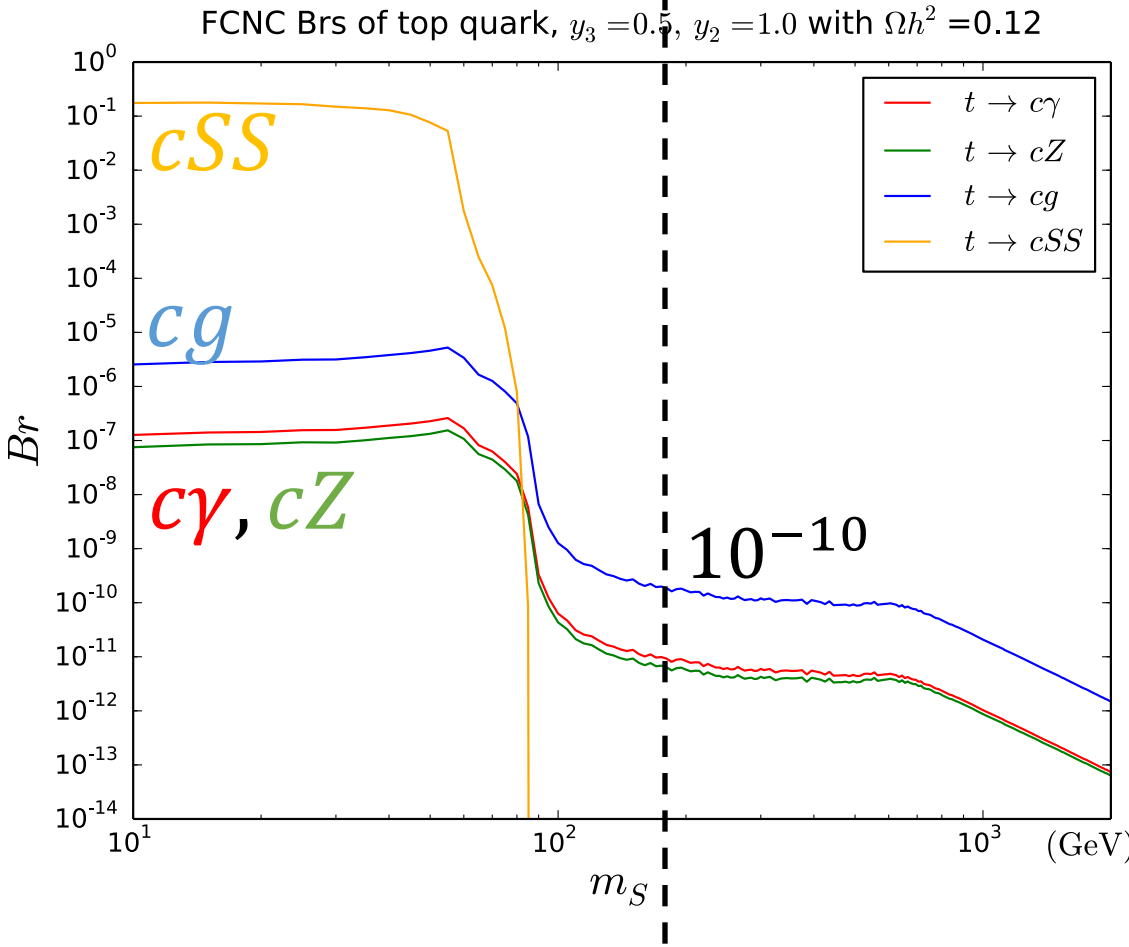
$m_S \sim m_t$

$m_S \sim m_t$

$y_2 = 3.0$

Generally, thermal $m_S < m_t$ in tension with XENON-1T





Summary

- We studied a real scalar DM S, coup. to $\{c_R, t_R\}$ via a vector-like fermion ψ.

- charm sector dominates in direct detection
  - for $m_S < \frac{m_t}{2}$, $\quad y_2 = 1\ (3)$ excludes $m_\psi < 400$ (1000) GeV
  - for $y_{2,3} \sim O(1)$, thermal $m_S < m_t$ in tension with XENON-1T

- loop correction to H.P. λ_{SH} from VL portal
  - y_3 can adjust H.P. strength

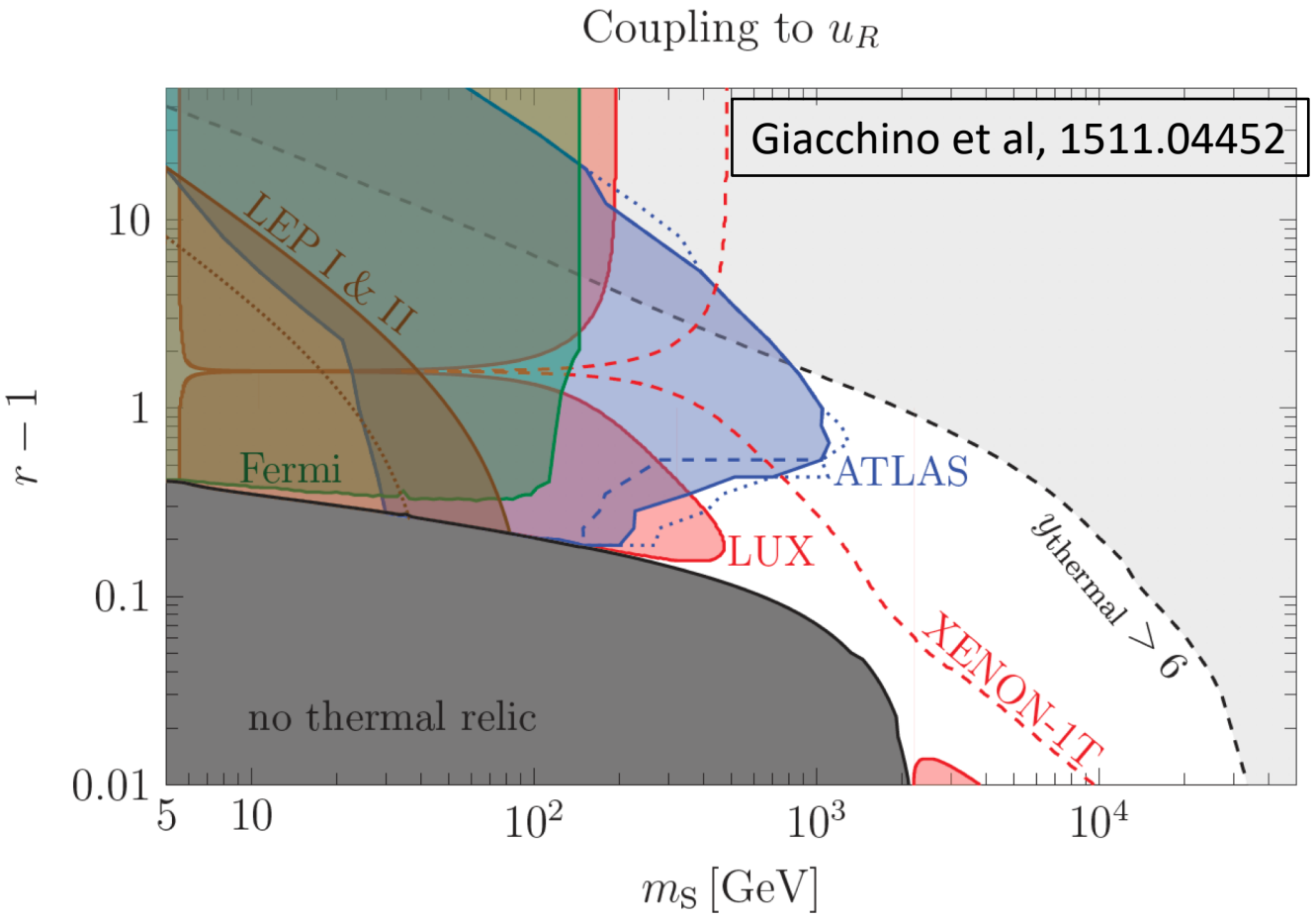
- top FCNC Brs ~ 10^{-7}, below current limits $\sim 10^{-(4\sim5)}$
  - future top measurements are valuable

Thank you for your attention

Back up

Other scenarios

$y_1 \gg y_2, y_3$: light quark-philic



$y_3 \gg y_1, y_2$: top-philic