Heavy Quark Flavored Scalar Dark Matter

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based on arXiv: 1606.00072 [JHEP10(2016)117] and 1709.00697

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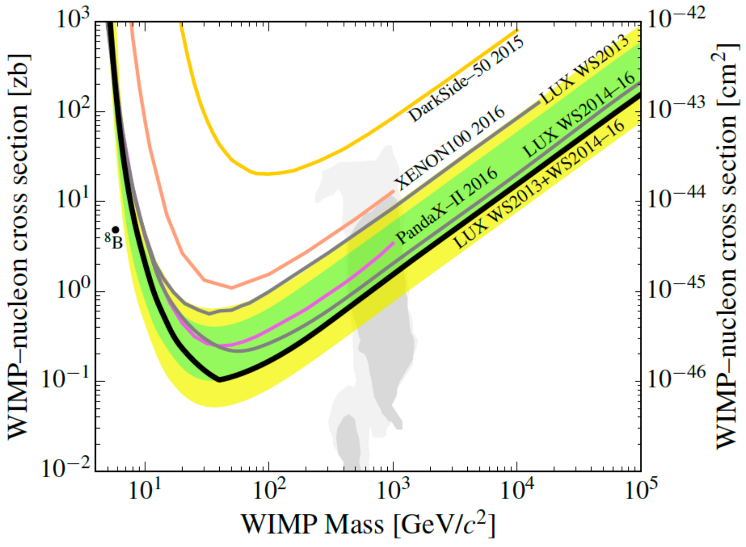
Outline

- Motivation
- Model
- DM couples to three flavors
  - Direct detection
    - interplay between H.P. and VLP
    - RGE, threshold matching
- DM couples to heavy flavors
  - Thermal relic
  - Direct/Indirect detection
  - Top FCNC
  - Collider Signals
- Summary

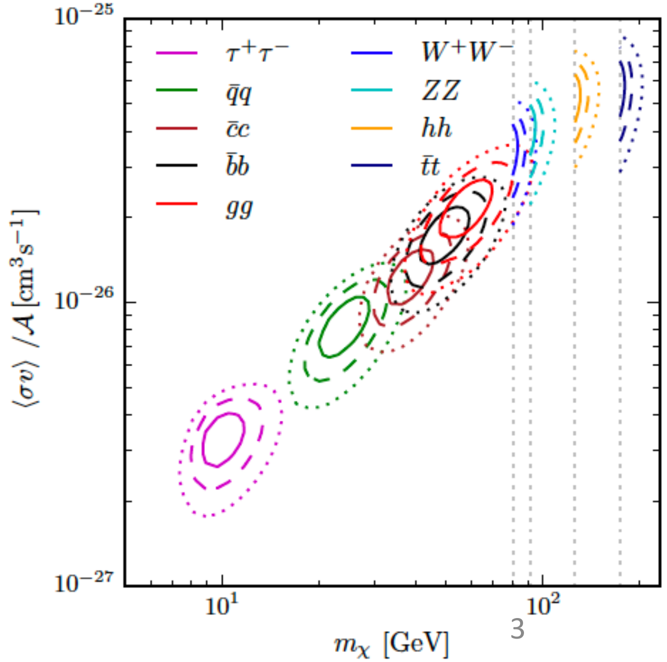
Why Flavored DM?

- Main components in (p, n): ***gluons*** & ***light quarks***
- No confirmed DM direct detection signal
  - constrained coupling of DM to ***gluons*** & ***light quarks***
  - blind spot: cancellations in scattering amplitude
- Favored channels when fitting astro- anomalies
  - $b\bar{b}, \tau\tau$ are favored, up to astro-uncertainties [Hooper et al]
- Theoretical model building [Agrawal, Kilic et al]
  - flavor symmetry in dark sector, MFV…

[LUX, 1608.07648]



[F. Calore et al, 1411.4647]



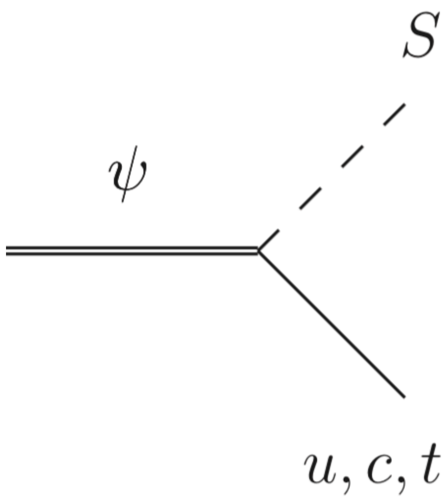
In this work

- we consider a real scalar DM, coupling to $\{U_i = u_R, c_R, t_R\}$ via a vector-like fermion portal ψ
- three DM-U_i-ψ couplings $\{y_1, y_2, y_3\}$ reflecting flavor structure, receiving DD constraints with different strengths.
- vector-like fermion portal ψ (**<u>VLP</u>**) can radiatively generate Higgs portal (**<u>HP</u>**)
- both twist-0 (scalar-type) and twist-2 operators are considered
- RGE effects and heavy quark threshold matching are addressed

The model

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

- 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 to stabilize DM: S, ψ are odd
  - no mass mixing $(S, H), (\psi, U_i)$
  - $Br\left(\psi \to SU_i^{(*)}\right) = 100\%$
  - LHC searches for VL (T, B) do not apply



DM-nucleon scattering: General

[Hisano et al, 1502.02244]

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

↓

- RGE

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

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

↓

- Quark thresholds

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

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

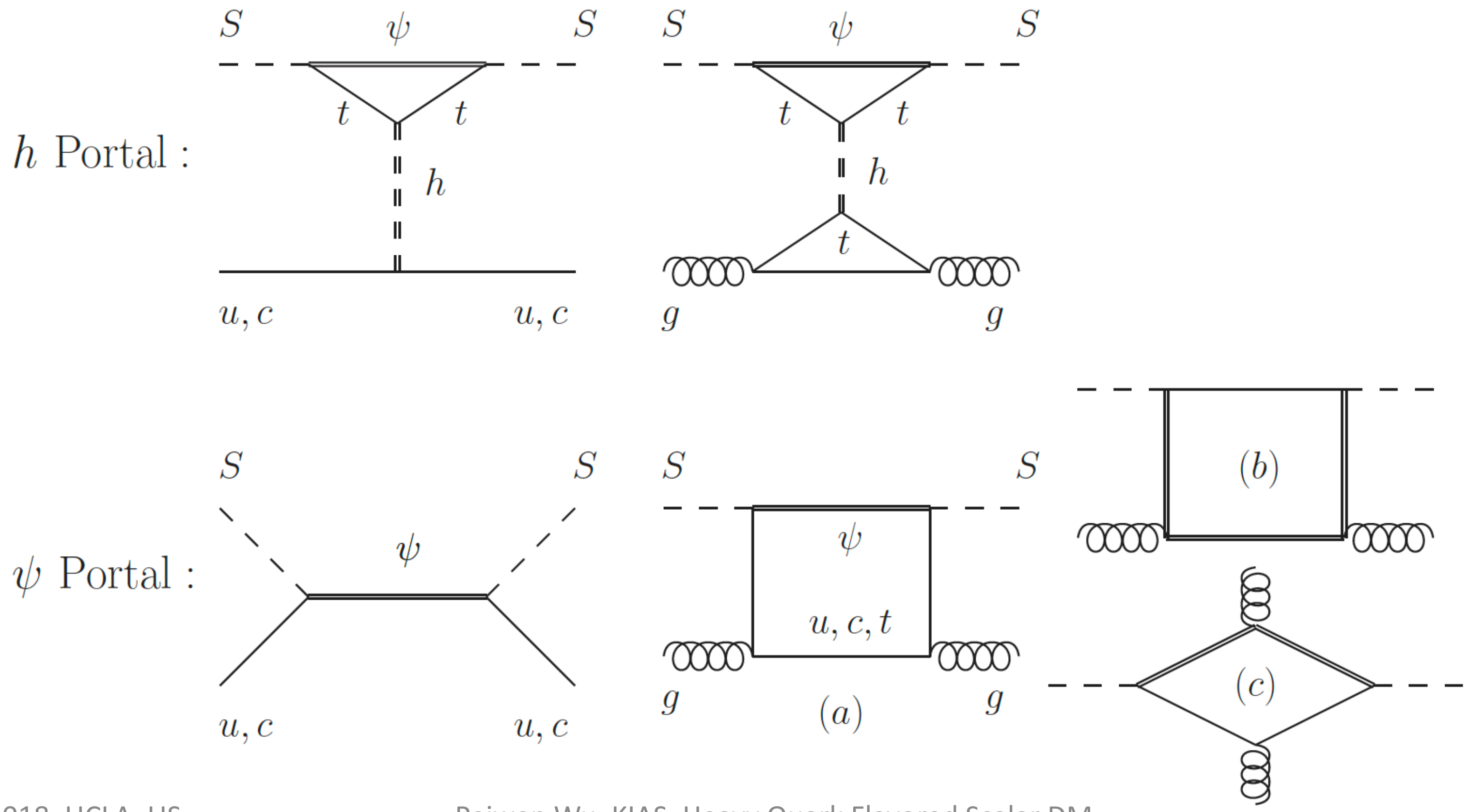
↓

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

$$\mathcal{L}_{\mathrm{SI}}^{(N)} = f_N \phi^2 \overline{N} N \,, \quad \sigma = \frac{1}{\pi}\left(\frac{M_T}{M + M_T}\right)^2 |n_p f_p + n_n f_n|^2$$

DM-nucleon scattering: This model

- Both HP and VLP contribute, we consider amplitudes up to $O(y_i^2)$
- active *d.o.fs* depend on μ_{EFT}, we compare $\mu_{EFT} \sim m_Z$ with $\mu_{EFT} \sim \mu_{had}$



DM-nucleon scattering: This model

- We include both twist-0 (scalar-type) and twist-2 operators
  - destructive interferences between twist-***2 up*** quark with twist-***0 gluon***
  - twist-2 gluon Wilson at $O(y_i^2)$ coefficient suppressed by additional α_s/π

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

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

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

$$q(2;\mu) = \int_0^1 dx\ x\ q(x,\mu) \ , \quad \bar{q}(2;\mu) = \int_0^1 dx\ x\ \bar{q}(x,\mu) \ , \quad g(2;\mu) = \int_0^1 dx\ x\ g(x,\mu)$$

$$\mathcal{O}_S^q \equiv S^2 m_q \bar{q} q \ ,$$

$$\mathcal{O}_S^g \equiv S^2 \frac{\alpha_s}{\pi} G^{A\mu\nu} G_{\mu\nu}^A \ ,$$

$$\mathcal{O}_{T_2}^q \equiv \frac{1}{m_S^2} S i\partial^\mu i\partial^\nu S \mathcal{O}_{\mu\nu}^q$$

$$\mathcal{O}_{T_2}^g \equiv \frac{1}{m_S^2} S i\partial^\mu i\partial^\nu S \mathcal{O}_{\mu\nu}^g$$

$$\mathcal{O}_{\mu\nu}^q \equiv \frac{1}{2}\bar{q} i \left(D_\mu \gamma_\nu + D_\nu \gamma_\mu - \frac{1}{2} g_{\mu\nu} \not{D} \right) q \ ,$$

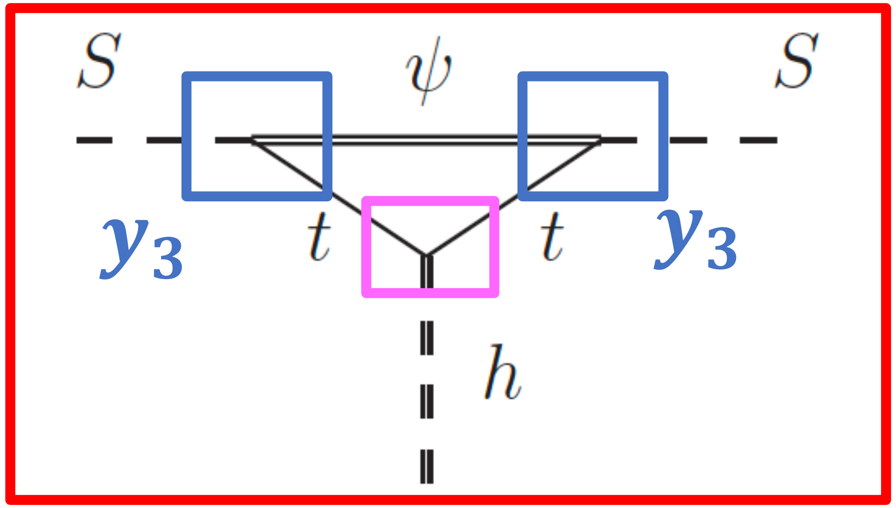
$$\mathcal{O}_{\mu\nu}^g \equiv G_\mu^{A\rho} G_{\nu\rho}^A - \frac{1}{4} g_{\mu\nu} G_{\rho\sigma}^A G^{A\rho\sigma} \ .$$

Higgs Portal at $O(y_i^2)$: only generate twist-0

- radiative corrections from vector-like ψ portal, mainly top quark $y_3^2 y_t$

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}m_S^2 S^2 - \frac{1}{4!}\lambda_S S^4 - \frac{1}{2}\lambda_{SH} S^2 H^2,$$

$$\mathcal{L}_{\rm Yukawa} = -y_1 S\overline{\psi_L}u_R - y_2 S\overline{\psi_L}c_R - y_3 S\overline{\psi_L}t_R + h.c.,$$



$$\lambda_{SH}^{\rm 1PI} = \sum_{k=1,2,3} (-8) y_3^2 N_c \left(\frac{m_{U_k}}{v}\right)^2 \frac{1}{16\pi^2}\Big(4C_{00} + m_S^2(C_{11}+C_{22}) - 2m_S^2 C_{12}\Big),$$

$$C_{ij} \equiv C_{ij}(m_S^2, 0, m_S^2; m_\psi^2, m_{U_k}^2, m_{U_k}^2),$$

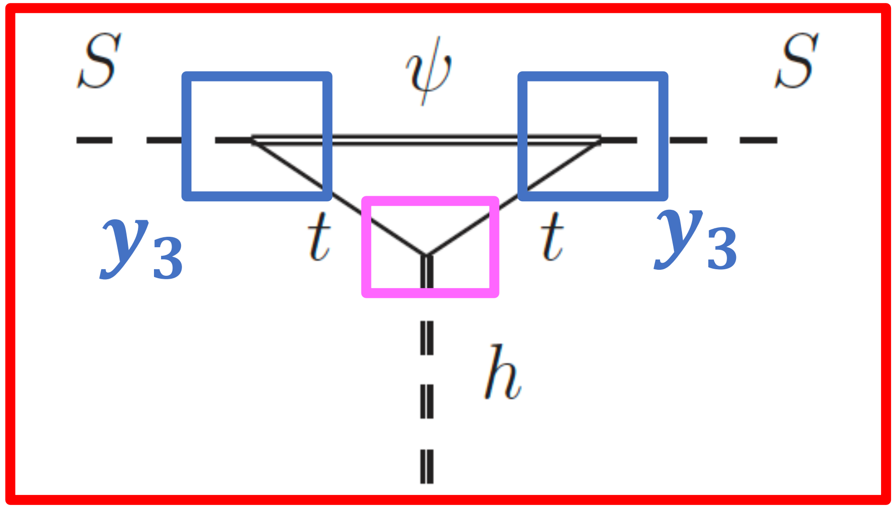
After proper renormalization

$$\lambda_{SH}^{\rm ren.} = \lambda_{SH} + \delta\lambda_{SH} + \lambda_{SH}^{\rm 1PI} + \lambda_{SH}\left(\frac{1}{2}\delta Z_h + \delta Z_S + \delta v\right)$$

Higgs Portal at $O(y_i^2)$: only generate twist-0

- radiative corrections from vector-like ψ portal, mainly top quark $y_3^2 y_t$

$$C_{S,\mathrm{HP}}^{u,c} = \frac{\lambda_{SH}^{\mathrm{ren.}}}{m_h^2}, \qquad C_{S,\mathrm{HP}}^{g} = -\frac{\lambda_{SH}^{\mathrm{ren.}}}{12 m_h^2},$$



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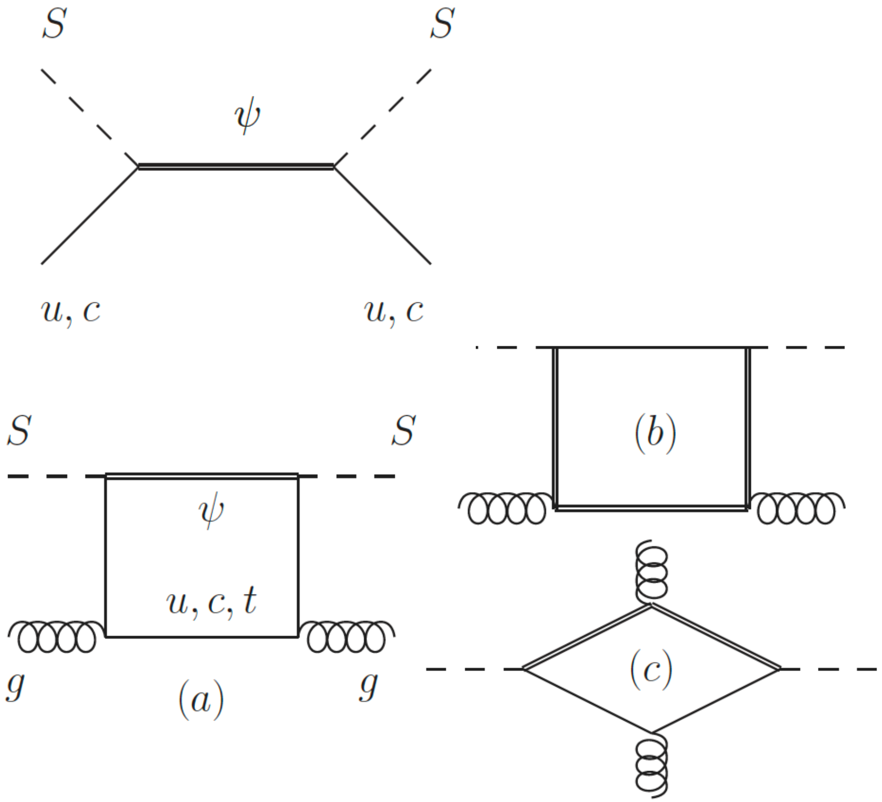
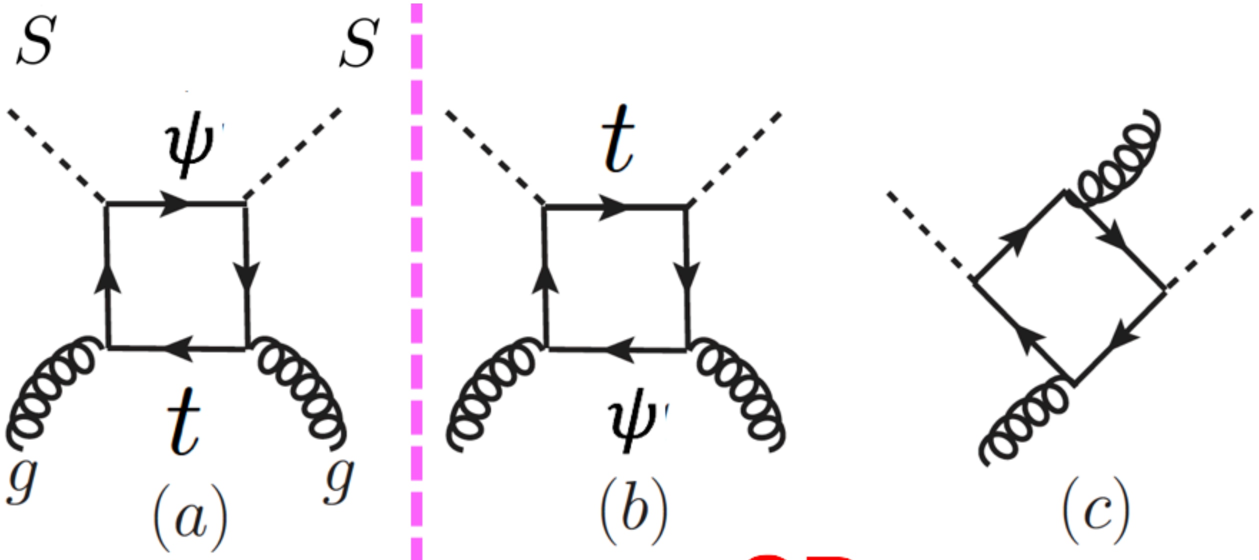
After proper renormalization

$$\lambda_{SH}^{\mathrm{ren.}} = \lambda_{SH} + \delta\lambda_{SH} + \lambda_{SH}^{\mathrm{1PI}} + \lambda_{SH}\left(\frac{1}{2}\delta Z_h + \delta Z_S + \delta v\right)$$

Vector-like ψ portal at $O(y_i^2)$: both twist-0/2

- DM-gluon loop coupling: **Short** / **Long** **Distances** are distinguished



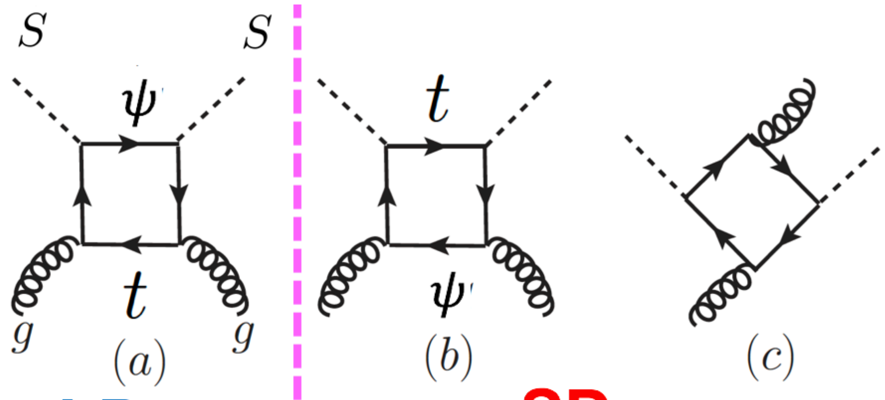


LD~m_t

SD~m_ψ

Vector-like ψ portal at $O(y_i^2)$: both twist-0/2

- Asumming $\mu_{EFT} \sim m_Z$
  - top, fully integrated out, generates $\{O_S^g\}$
  - up/charm, active *d.o.f*, generates $\{O_S^g, O_{S/T_2}^{u,c}\}$



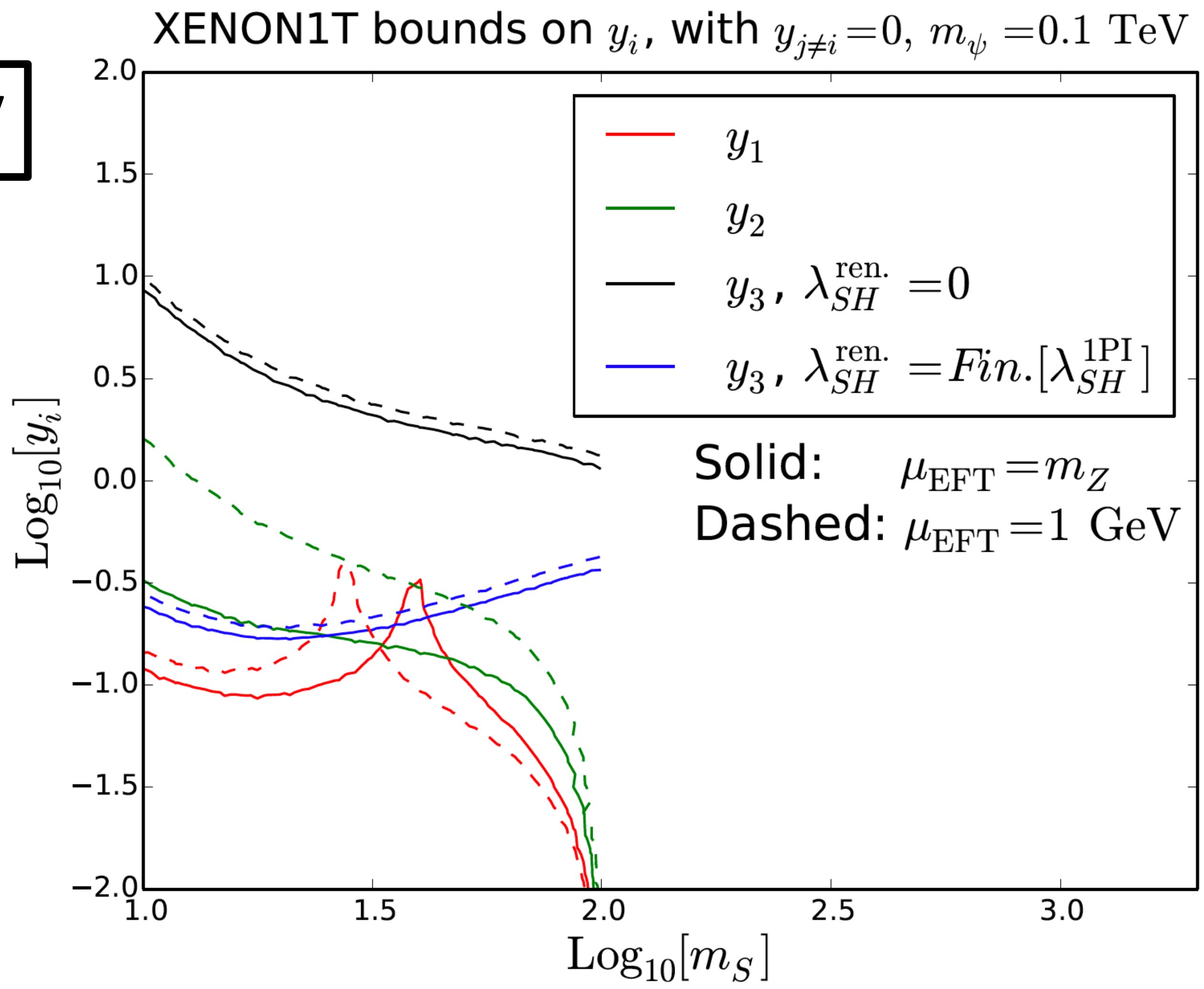
$$C^g_{S,\mathrm{VLP}} = C^g_{S,\mathrm{VLP}}\Big|_t^{\mathrm{LD+SD}} + C^g_{S,\mathrm{VLP}}\Big|_{u,c}^{\mathrm{SD}} ,$$

$$C^g_{S,\mathrm{VLP}}\Big|_t^{\mathrm{LD+SD}} = \frac{1}{4}\frac{y_3^2}{2}\left(f_+^{(a)} + f_+^{(b)} + f_+^{(c)}\right)(m_S; m_t, m_\psi) ,$$

$$C^g_{S,\mathrm{VLP}}\Big|_{u,c}^{\mathrm{SD}} = \frac{1}{4}\frac{y_{1,2}^2}{2}\left(f_+^{(b)} + f_+^{(c)}\right)(m_S; m_{u,c}, m_\psi) ,$$

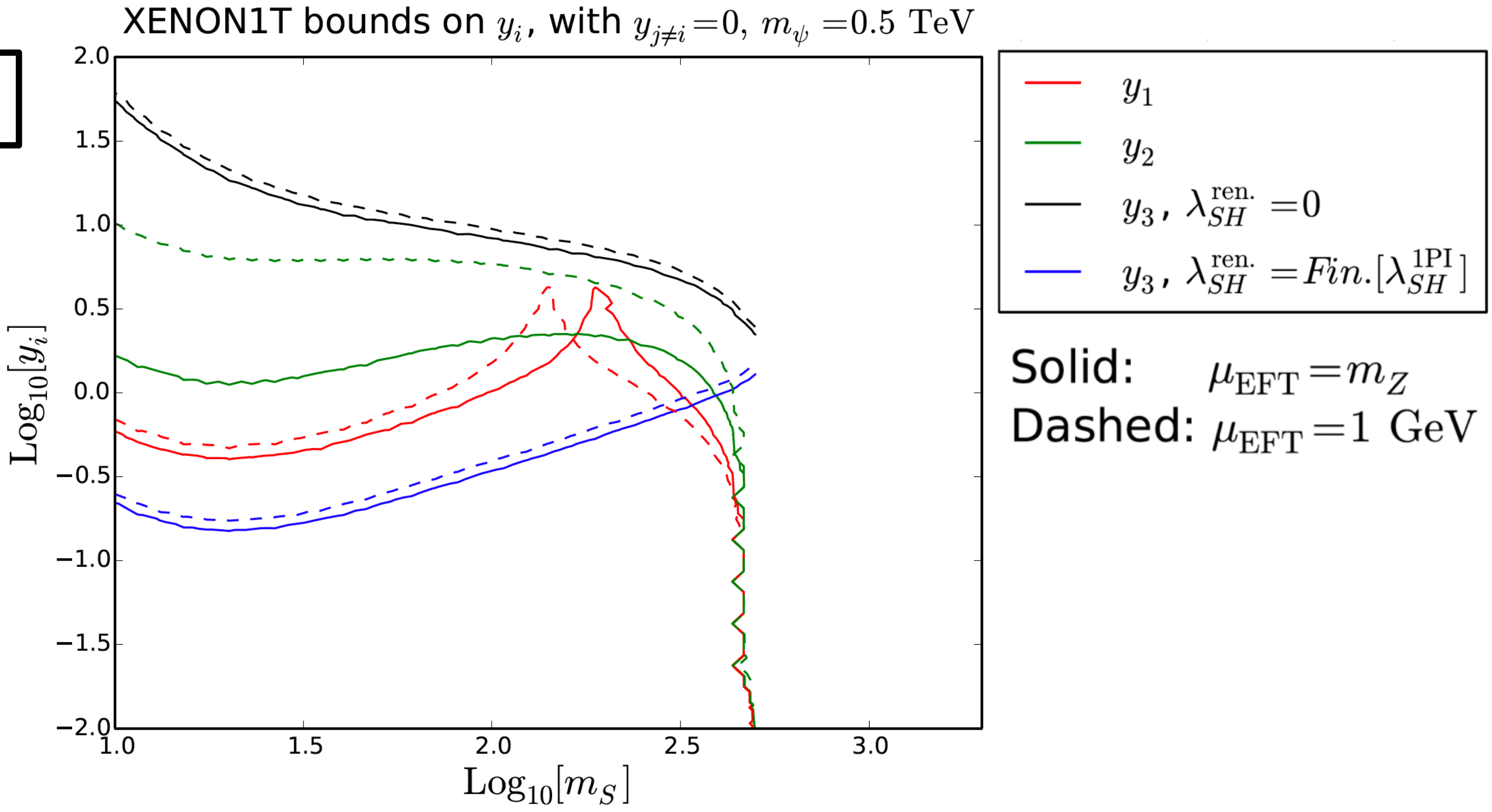
XENON1T bounds on separate $\{y_1, y_2, y_3\}$

$m_\psi = 0.1$ TeV



XENON1T bounds on separate $\{y_1, y_2, y_3\}$

$m_\psi = 0.5$ TeV

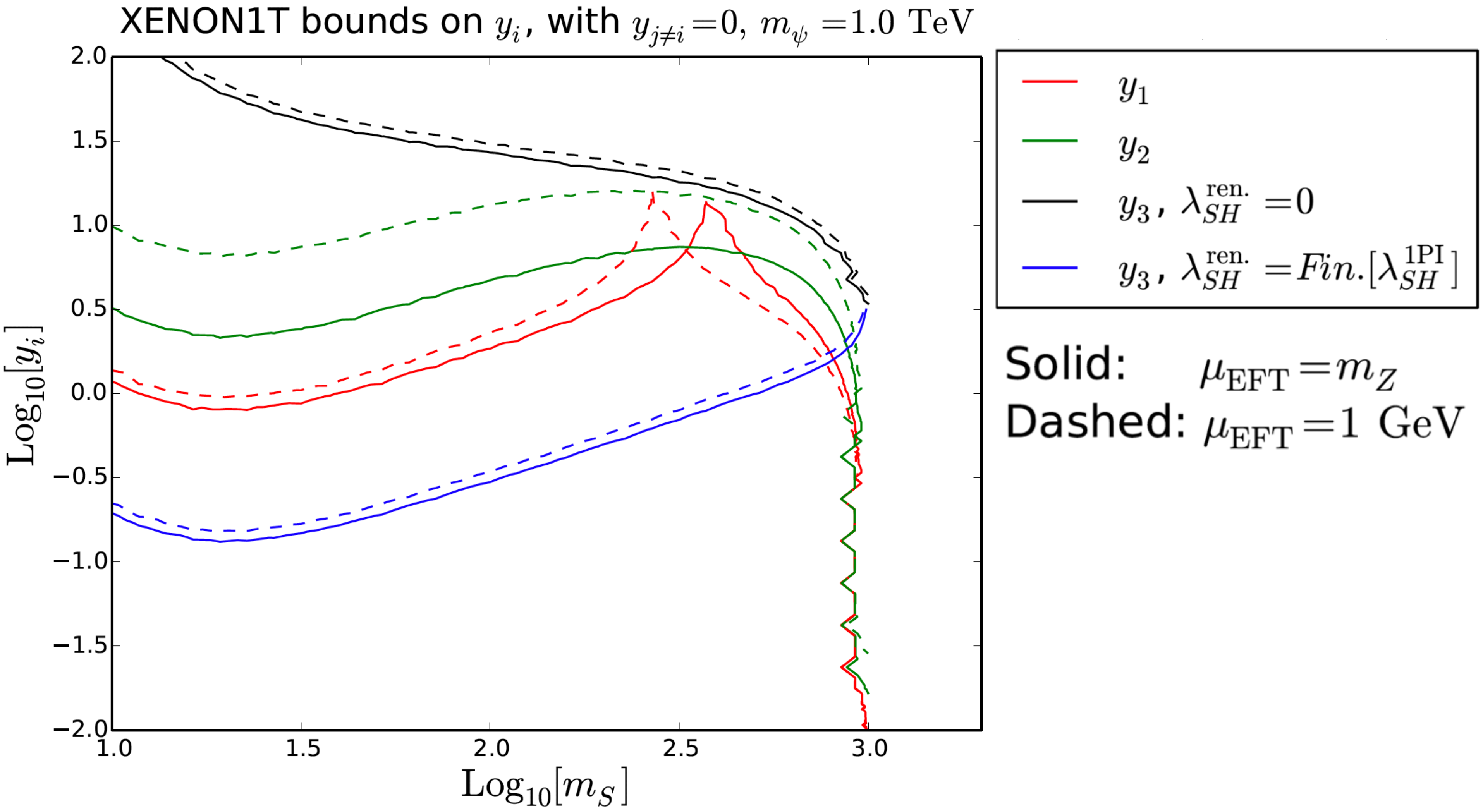


Solid: $\mu_{\mathrm{EFT}}=m_Z$

Dashed: $\mu_{\mathrm{EFT}}=1$ GeV

XENON1T bounds on separate $\{y_1, y_2, y_3\}$

m_ψ = 1 TeV



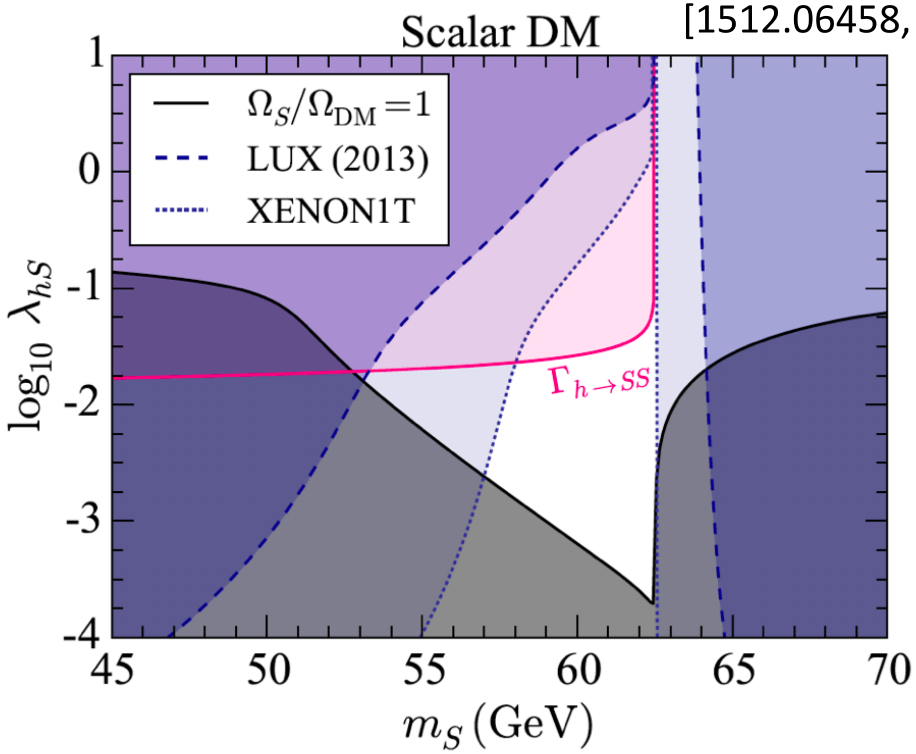
Solid: $\mu_{\mathrm{EFT}}=m_Z$

Dashed: $\mu_{\mathrm{EFT}}=1$ GeV

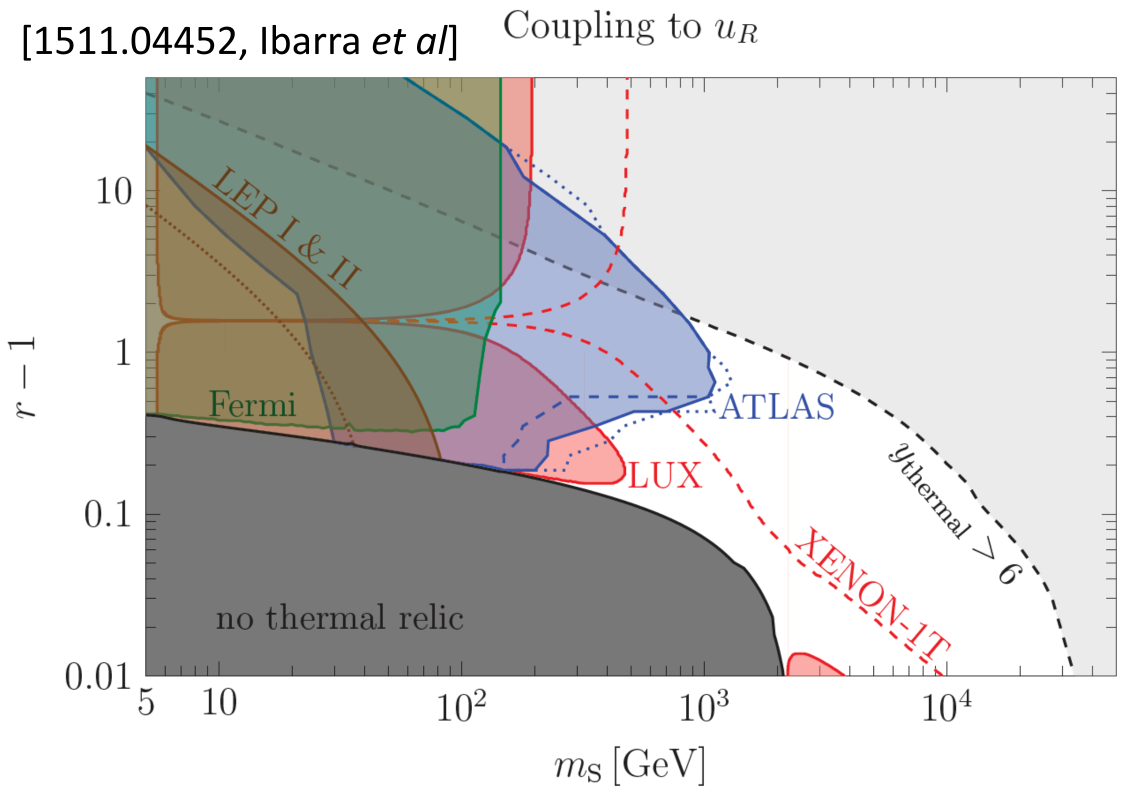
Bounds on y_1 and H.P. are strong

- Both are well studied and strongly constrained

[1512.06458, Beniwal *et al*]



[1511.04452, Ibarra *et al*]



VLP through heavy quark flavors

- By setting y_1 and Higgs portal $\lambda_{SH}^{ren.}$ to be negligibly small, we focus on DM-charm/top interactions $\{y_2, y_3\}$ to explore surviving status.

$$\mathcal{L} \supset -y_2 S \overline{\psi_L} c_R - y_3 S \overline{\psi_L} t_R + h.c.$$

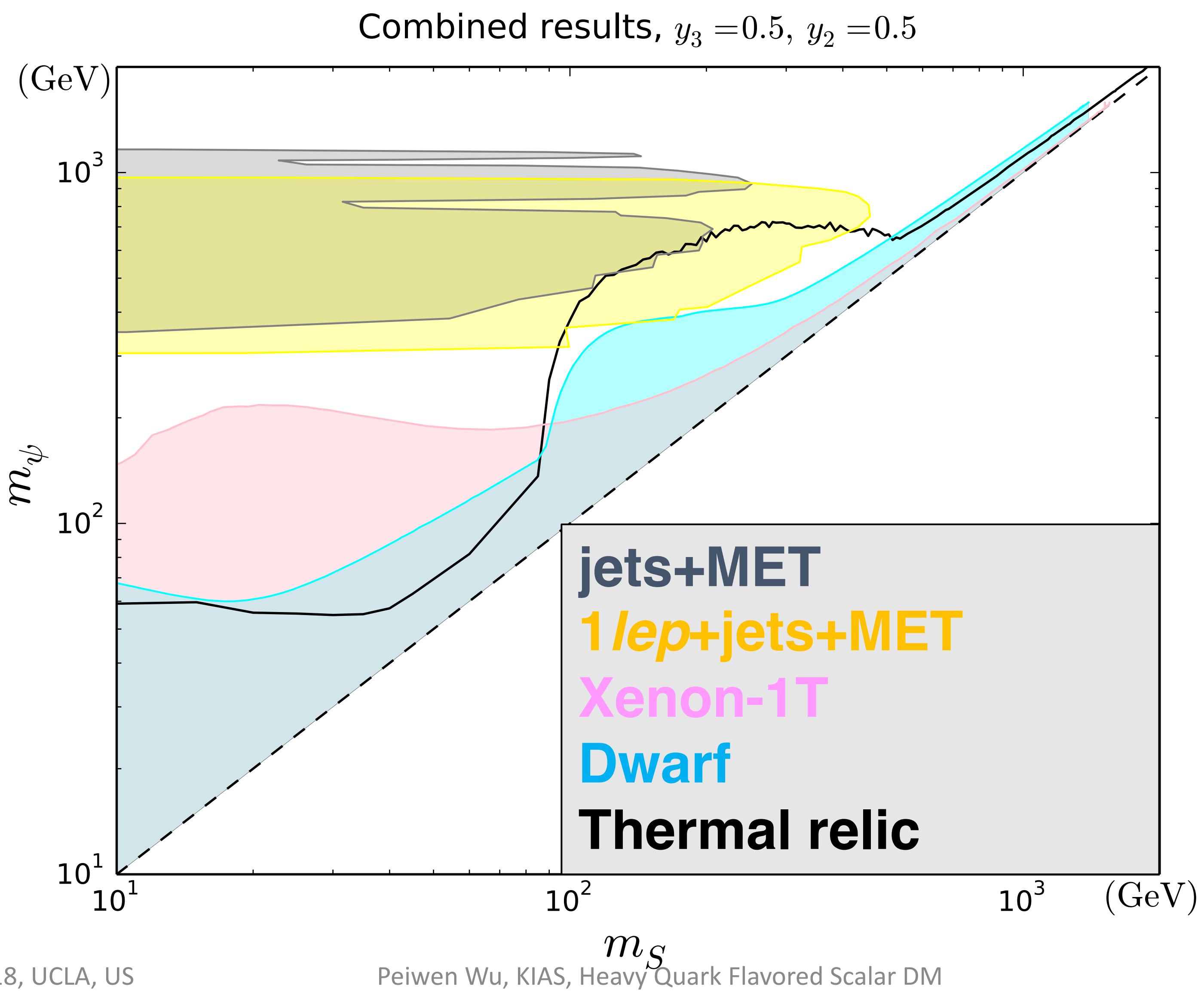
- This can be realized in the framework of Minimal Flavor Violation.

  [1109.3516, Agraval *et al*; 1501.02202, Kilic *et al*]

Combined results

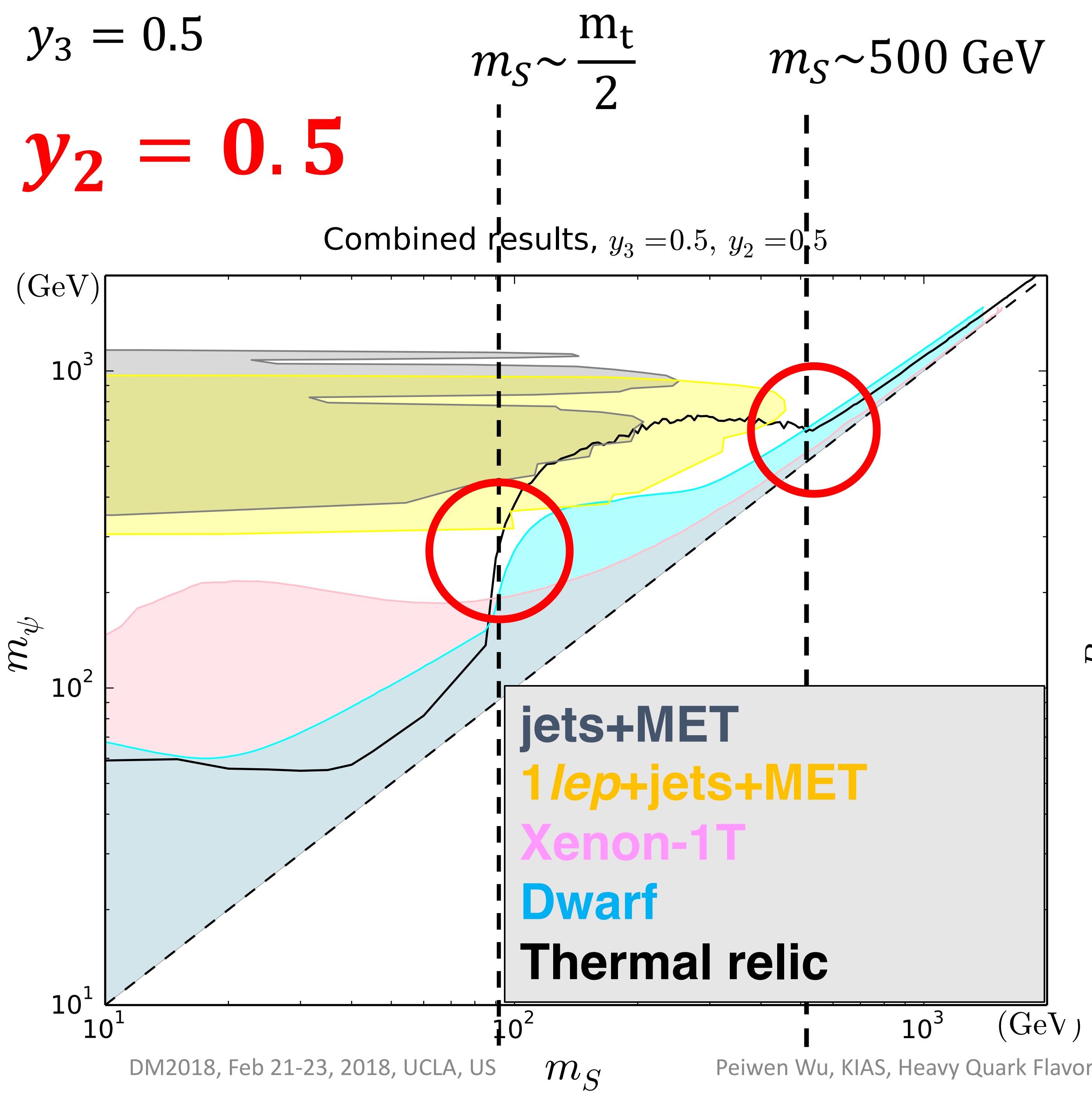
$y_3 = 0.5$

$y_2 = 0.5$

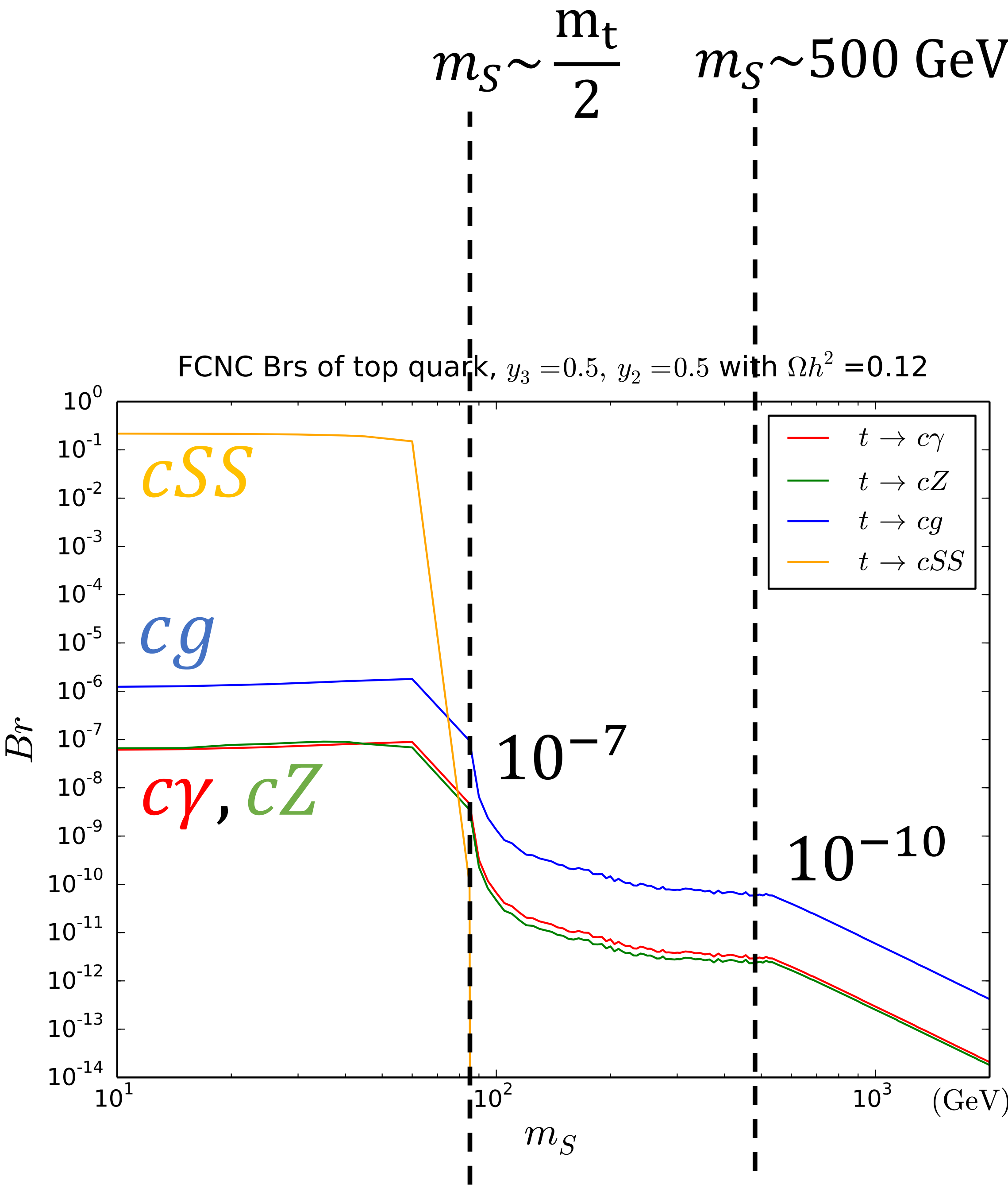


$y_3 = 0.5$

$y_2 = 0.5$



$m_S \sim \frac{m_t}{2}$
$m_S \sim 500$ GeV
Combined results, $y_3 = 0.5$, $y_2 = 0.5$
(GeV)
m_ψ
m_S
jets+MET
1*lep*+jets+MET
Xenon-1T
Dwarf
Thermal relic

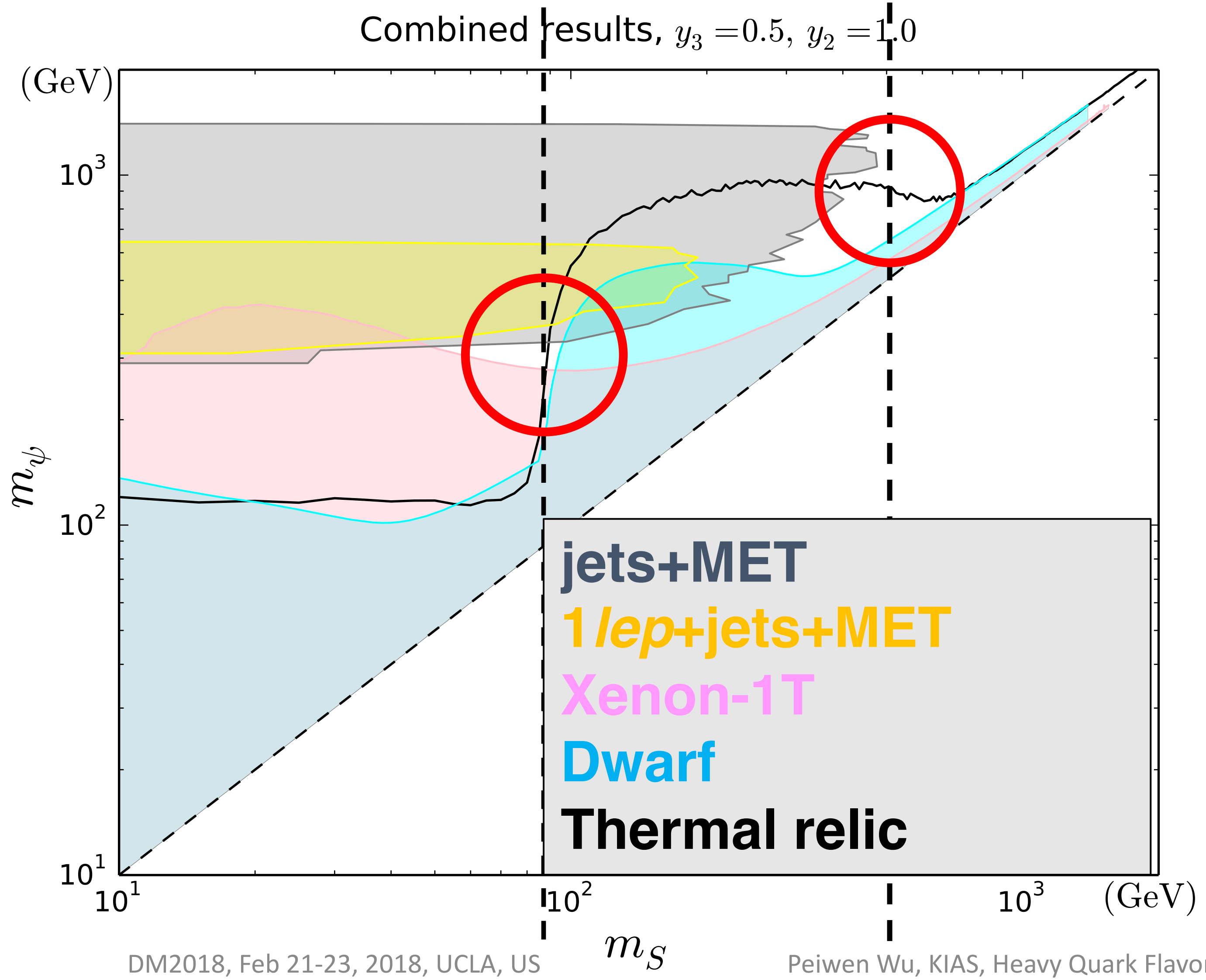


$m_S \sim \frac{m_t}{2}$
$m_S \sim 500$ GeV
FCNC Brs of top quark, $y_3 = 0.5$, $y_2 = 0.5$ with $\Omega h^2 = 0.12$
Br
m_S
(GeV)
$t \to c\gamma$
$t \to cZ$
$t \to cg$
$t \to cSS$
cSS
cg
$c\gamma$, cZ
10^{-7}
10^{-10}

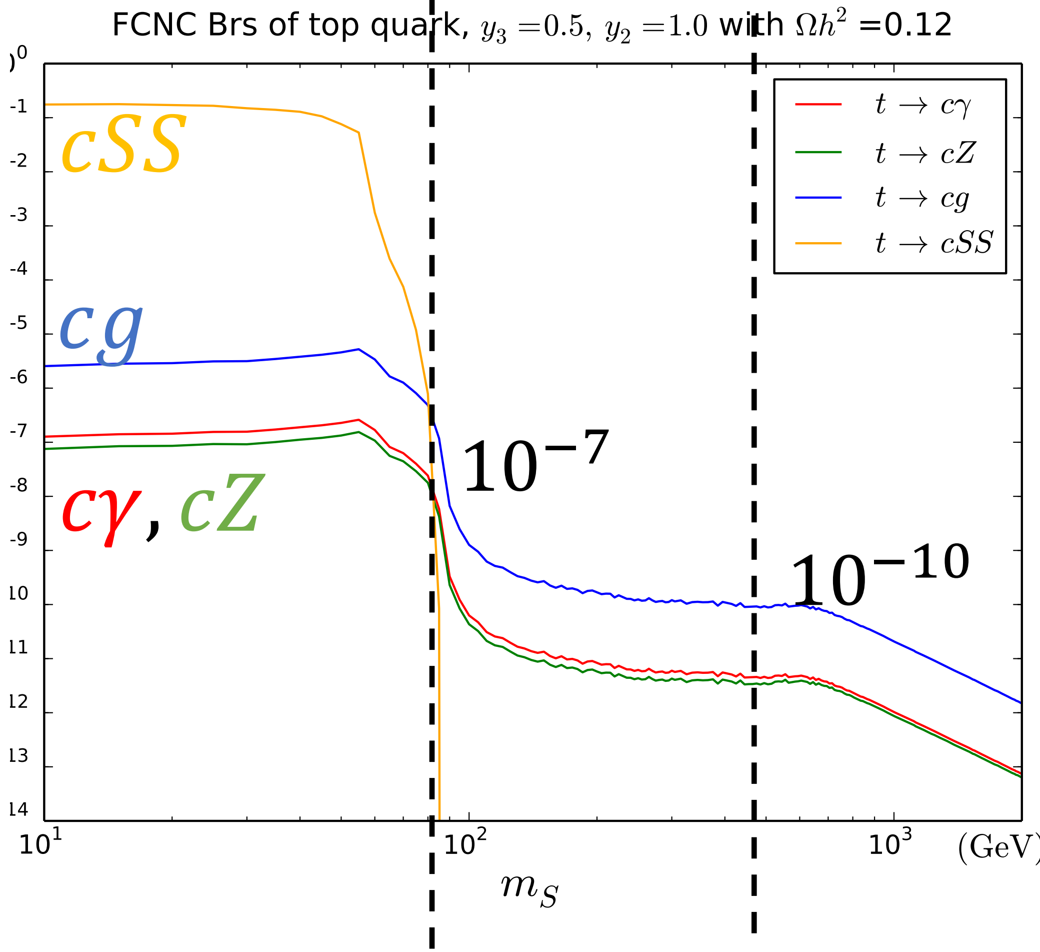
$y_3 = 0.5$

$\mathbf{y_2 = 1.0}$

$m_S \sim \frac{m_t}{2}$ $m_S \sim 500$ GeV



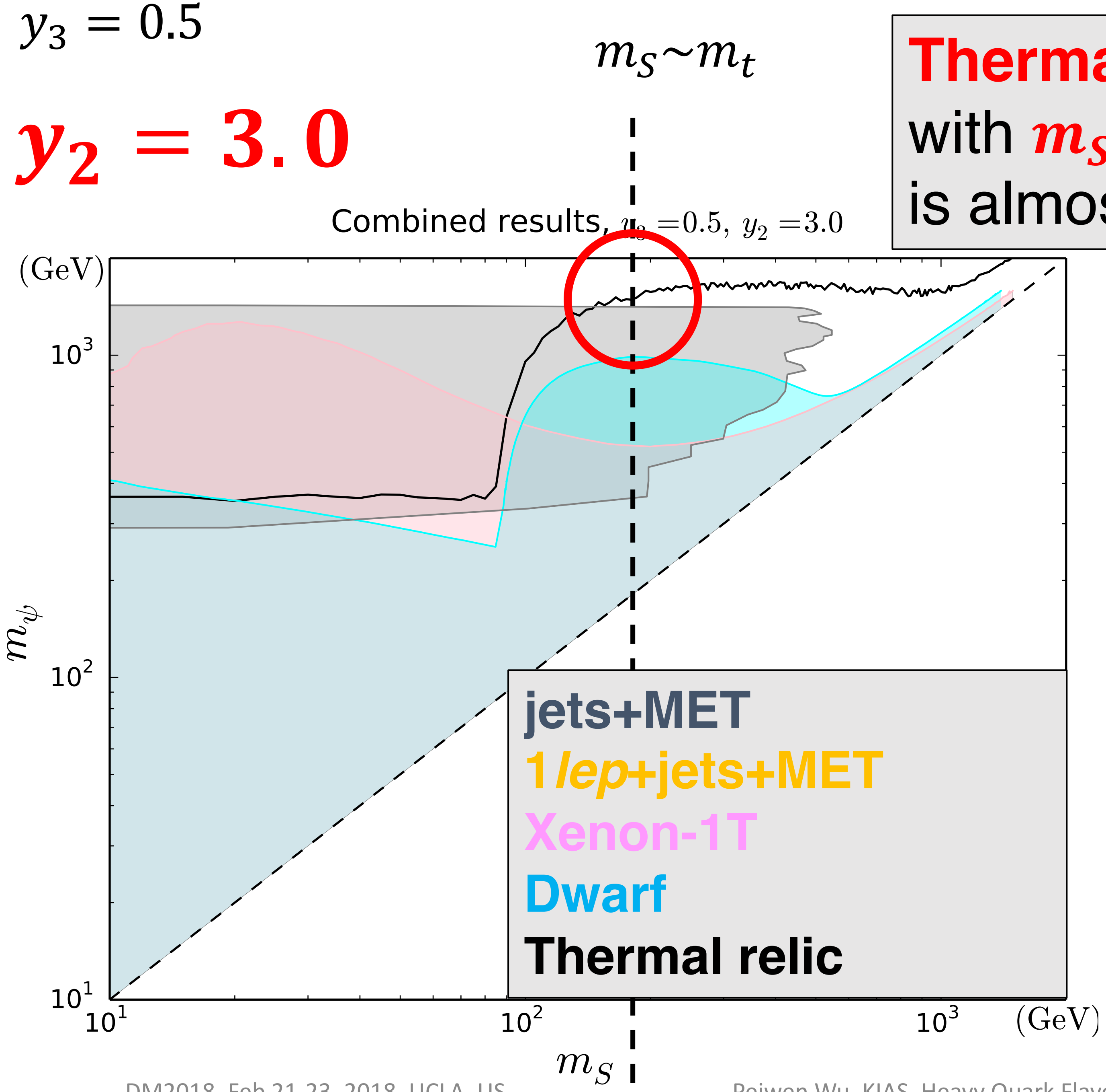
$m_S \sim \frac{m_t}{2}$ $m_S \sim 500$ GeV

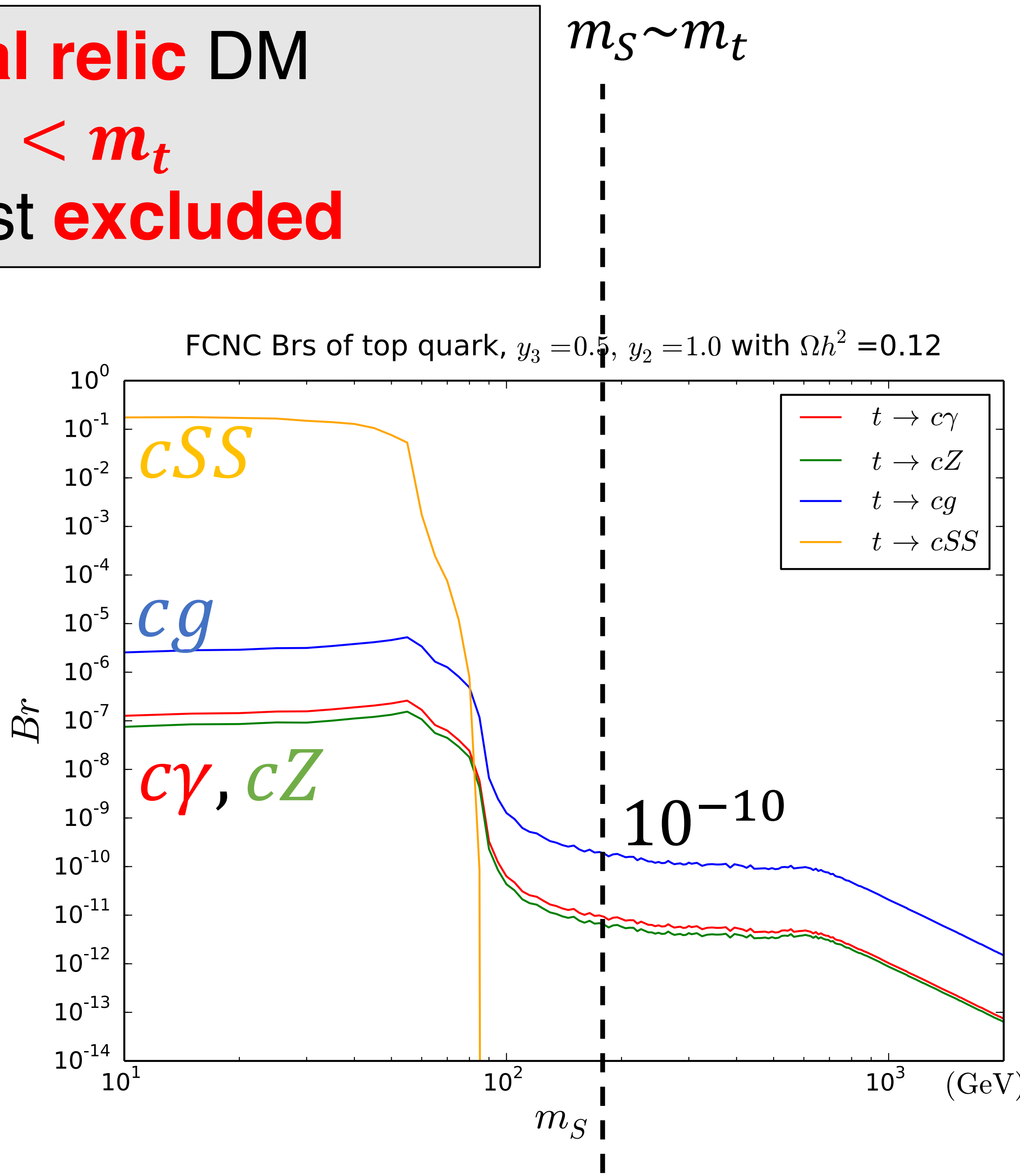


$y_3 = 0.5$

$y_2 = 3.0$

Thermal relic DM with $m_S < m_t$ is almost **excluded**





Summary

- No confirmed DD signal, DM may couple weakly to gluons & light quarks.

- we consider a real scalar DM, coupling to $\{U_i = u_R, c_R, t_R\}$ via a vector-like fermion portal ψ. XENON1T constraints on $\{y_1, y_2, y_3\}$ through pure VLP are in descending order, which may imply flavor structure in DM sector.

- RGE effects and heavy quark threshold matching can be significant for $\{y_1, y_2\}$. Radiative HP constraints on $\{y_3\}$ can be strong.

- For exclusive DM couplings to heavy quarks $\{c, t\}$ with $y_2, y_3 \sim O(1)$, thermal relic DM with $m_S < m_t$ is almost excluded, surviving top FCNC Brs < 10^{-7} still allowed in current bounds.

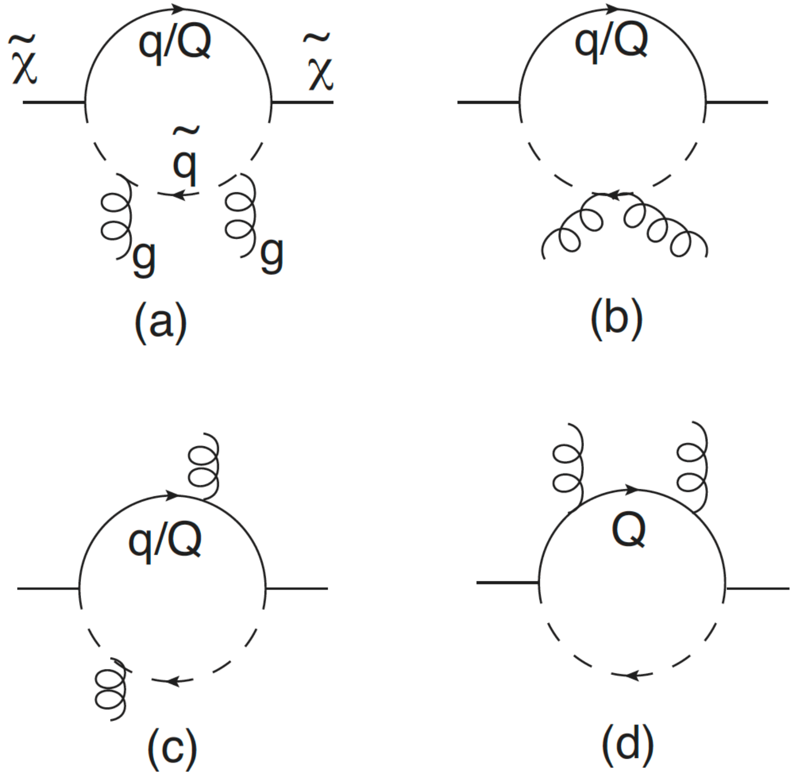
Thank you for your attention

Back up slides

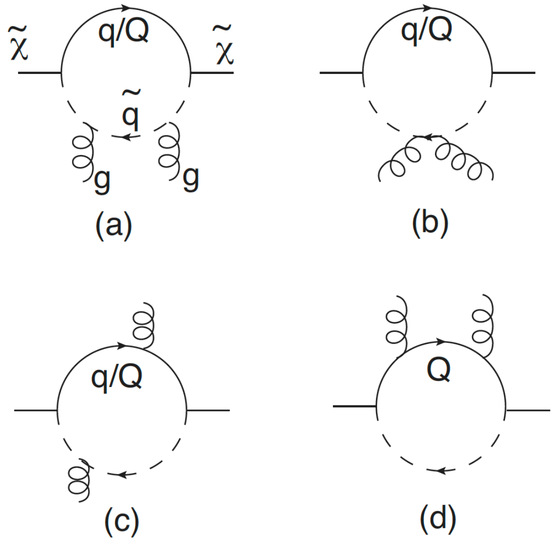
Short / Long distance decomposition (SD / LD)

- Two mass scales in DM-gluon loop: m_{quark} (LD) and $m_{\tilde{q}}$ (SD)
- loop momentum integral separated into:

$$f_G|_q = f_G|_q^{\mathrm{LD}} + f_G|_q^{\mathrm{SD}}$$



SUSY case $\mathcal{O}_S^g \equiv \frac{\alpha_s}{\pi}\overline{\widetilde{\chi}^0}\widetilde{\chi}^0 G^A_{\mu\nu}G^{A\mu\nu}$



$$\mathcal{L} = \bar{q}(a_q + b_q\gamma_5)\tilde{\chi}\tilde{q} + \text{h.c.}$$

$$f_G = \sum_{q=\text{all}} f_G^{\text{SD}}|_q + \sum_{Q=c,b,t} f_G^{\text{LD}}|_Q$$

$$f_G^{\text{SD}}|_q = \frac{\alpha_s}{4\pi}\left(\frac{a_q^2+b_q^2}{4}Mf_+^s + \frac{a_q^2-b_q^2}{4}m_q f_-^s\right)$$

$$f_G^{\text{LD}}|_q = \frac{\alpha_s}{4\pi}\left(\frac{a_q^2+b_q^2}{4}Mf_+^l + \frac{a_q^2-b_q^2}{4}m_q f_-^l\right)$$

$$f_+^s = m_{\tilde{q}}^2\,(B_0^{(1,4)} + B_1^{(1,4)})\,,$$

$$f_-^s = m_{\tilde{q}}^2\,B_0^{(1,4)}\,,$$

$$f_+^l = m_q^2\,(B_0^{(4,1)} + B_1^{(4,1)})\,,$$

$$f_-^l = B_0^{(3,1)} + m_q^2\,B_0^{(4,1)}\,,$$

$$\int \frac{d^4q}{i\pi^2}\frac{1}{((p+q)^2 - m_q^2)^n(q^2 - m_{\tilde{q}}^2)^m} \equiv B_0^{(n,m)},$$

$$\int \frac{d^4q}{i\pi^2}\frac{q_\mu}{((p+q)^2 - m_q^2)^n(q^2 - m_{\tilde{q}}^2)^m} \equiv p_\mu B_1^{(n,m)}$$

SD is characterized by $q_{loop} \sim m_{\tilde{q}}$

LD is characterized by $q_{loop} \sim m_q$

higher energy ➡ shorter distance