Dark matter as the trigger of flavor changing neutral current decays of the top quark

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In collaboration with S. Kanemura (arXiv: 2402.08652)

Why $t \to qX$ is extremely small in the SM?

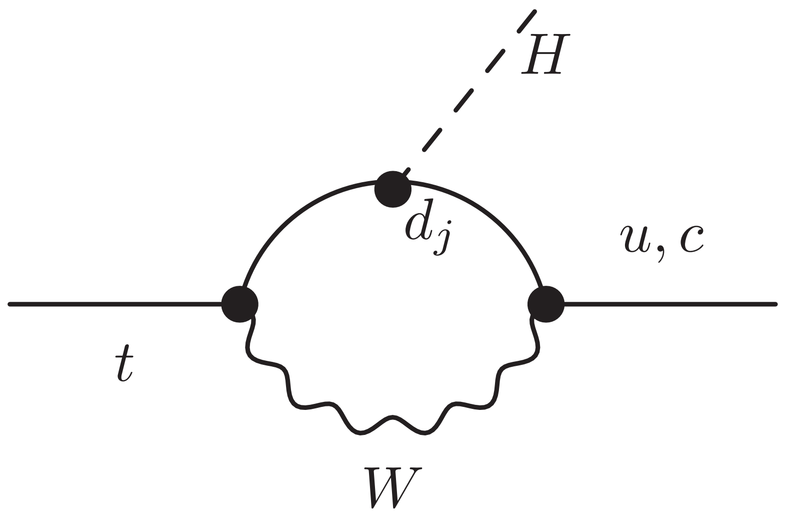
Let us take for example the Yukawa Lagrangian in the SM

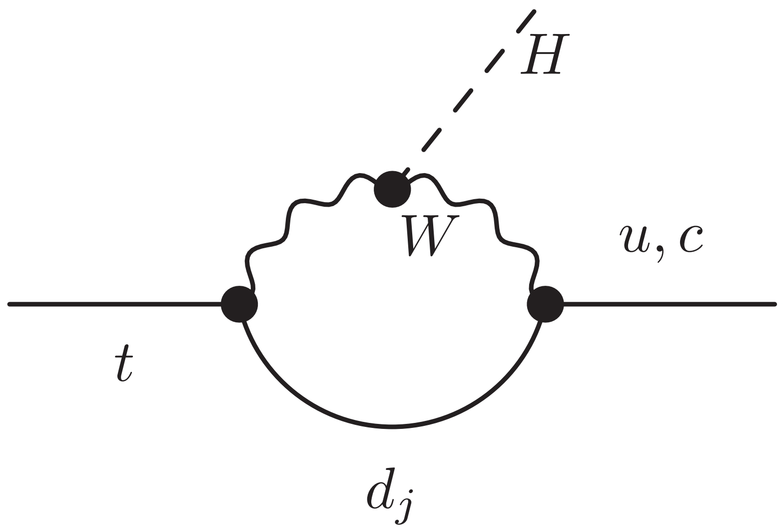
$$-\mathscr{L} \supset Y^d_{ij}\bar{Q}_{L,i}\Phi d_{R,j} + Y^u_{ij}\bar{Q}_{L,i}\tilde{\Phi} u_{R,j} + \mathrm{h.c.}$$

$$\Longrightarrow -\mathscr{L} \supset m^i_u \bar{u}_{L,i} u_{R,i}\left(1 + \frac{H}{v}\right) + m^i_d \bar{d}_{L,i} d_{R,i}\left(1 + \frac{H}{v}\right) + \mathrm{h.c.}$$

The tree-level Yukawa Higgs couplings to quarks is diagonal in flavour $\Longrightarrow i\mathscr{M}(t \to cH) = 0$

What about the one-loop order?





Small because:

- Unitarity of the CKM matrix
- Small mass differences between the quarks running the loops.

$t \to qX$ in the SM: Theory predictions

The rates of $t \to qX$ in the SM have been calculated nearly 33 years ago — G. Eilam, J. L. Hewett, A.Soni, PRD44 (1991) 1473-1484 —.

Updates from the Top Quark Working Group Report (arXiv: 1311.2028)

$$\text{BR}(t \to Zc) = 1 \times 10^{-14}$$

$$\text{BR}(t \to Zu) = 7 \times 10^{-17}$$

$$\text{BR}(t \to gc) = 5 \times 10^{-12}$$

$$\text{BR}(t \to gu) = 4 \times 10^{-14}$$

$$\text{BR}(t \to \gamma c) = 5 \times 10^{-14}$$

$$\text{BR}(t \to \gamma u) = 4 \times 10^{-16}$$

$$\text{BR}(t \to Hc) = 3 \times 10^{-15}$$

$$\text{BR}(t \to Hu) = 2 \times 10^{-17}$$

Very small rates!!!

$t \to qX$ in the SM: unlikely to be observed?

Take the $t \to Hc$ for example and assume $pp \to t(\to bW)\ \bar{t}(\to Hc)$:

LHC

$$\sigma(pp \to t\bar{t} \to bWHc) = 2\sigma(pp \to t\bar{t}) \times \mathrm{BR}(t \to cH) \times \mathrm{BR}(t \to bW)$$
$$= 2 \times 833.9 \times 10^3 \times 10^{-14} \approx 5 \times 10^{-9}\ \mathrm{fb}$$

FCC

$$\sigma(pp \to t\bar{t} \to bWHc) = 2 \times 3 \times 10^{-15} \times 34.6 \times 10^6 = 2.06 \times 10^{-7}\ \mathrm{fb}$$

Assume $H \to b\bar{b}$, $t \to \ell\nu b$ and $A \times \epsilon = 50\,\%$, we need

$\int \mathrm{d}t\ \mathscr{L} \geq 3.5 \times 10^9\ (5 \times 10^7)\ \mathrm{fb}^{-1}$ to observe one top FCNC event at the LHC (FCC)

In terms of years, we need about one million years if the LHC collect $3\ \mathrm{ab}^{-1}$ of data each year NONSTOP!!

Observation of top quark FCNC phenomena is a clear sign of new physics

$t \to qX$ in beyond-the-SM theories

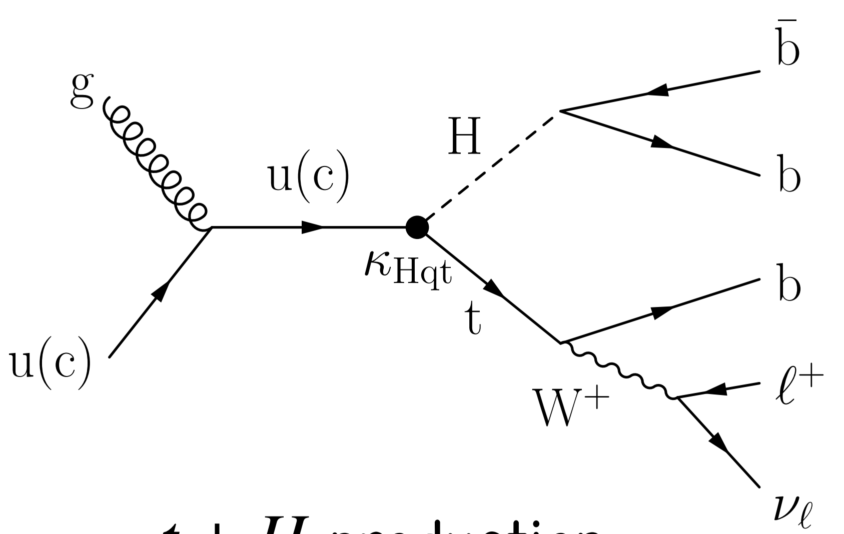
Various models beyond the SM predict reasonably large rates for $t \to qX$ transitions:

- Flavor conserving (FC) 2HDM (Santi Bejar, hep-ph/0606138)
- Flavor violating (FV) 2HDM (J.A. Aguilar-Saavedra, hep-ph/0409342; David Atwood et al., hep-ph/9609279)
- The MSSM (J.J. Cao et al., hep-ph/0702264)
- The MSSM with R-parity violation (Jin Min Yang et al., hep-ph/9705341; G. Eilam et al., hep-ph/0102037).
- Warped extra dimensional models (Kaustubh Agashe et al., hep-ph/0606293; Kaustubh Agashe et al., 0906.1542)

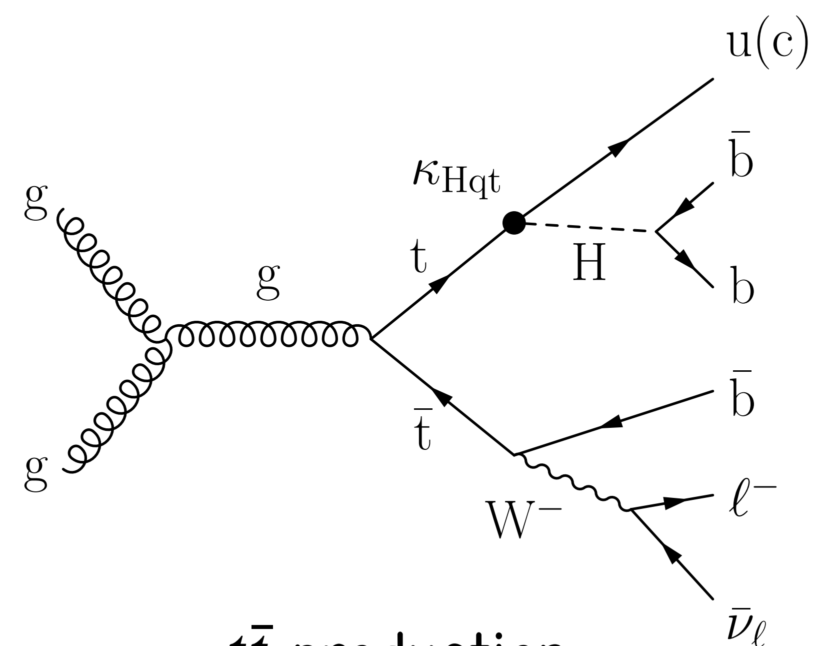
Process	2HDM (FC)	2HDM (FV)	MSSM	RPV–MSSM	RS
$\mathrm{BR}(t \to Zc) \leq$	10^{-10}	10^{-6}	10^{-7}	10^{-6}	10^{-5}
$\mathrm{BR}(t \to Zu) \leq$	–	–	10^{-7}	10^{-6}	–
$\mathrm{BR}(t \to gc) \leq$	10^{-8}	10^{-4}	10^{-7}	10^{-6}	10^{-10}
$\mathrm{BR}(t \to gu) \leq$	–	–	10^{-7}	10^{-6}	–
$\mathrm{BR}(t \to \gamma c) \leq$	10^{-9}	10^{-7}	10^{-8}	10^{-9}	10^{-9}
$\mathrm{BR}(t \to \gamma u) \leq$	–	–	10^{-8}	10^{-9}	–
$\mathrm{BR}(t \to Hc) \leq$	10^{-5}	2×10^{-3}	10^{-5}	10^{-9}	10^{-4}
$\mathrm{BR}(t \to Hu) \leq$	–	6×10^{-6}	10^{-5}	10^{-9}	–

Searches for top quark FCNCs at the LHC

Let us take the example of $t \to u(c)\ H$ (CMS-TOP-19-002)

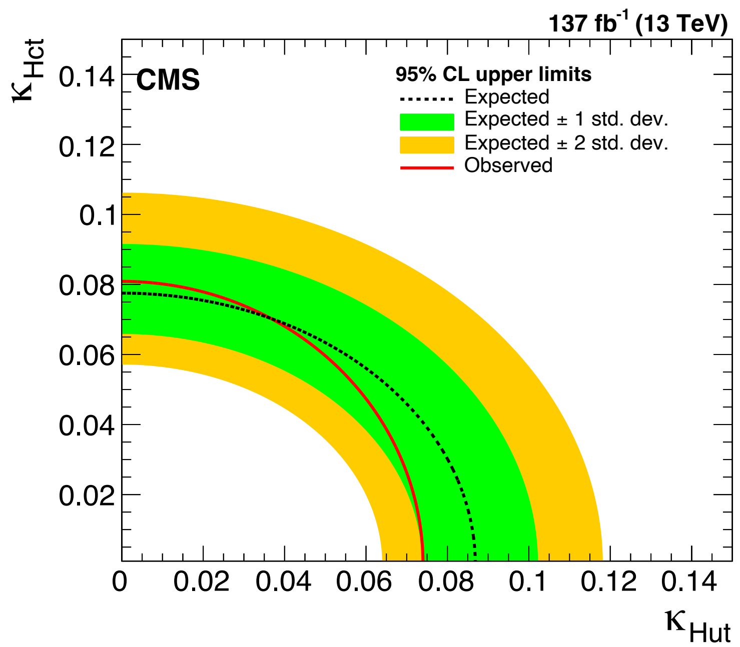


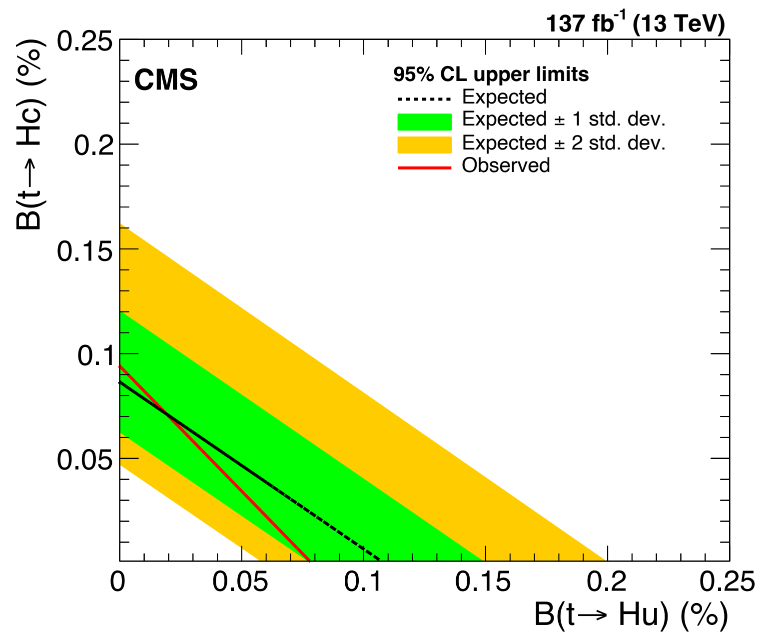
$t + H$ production



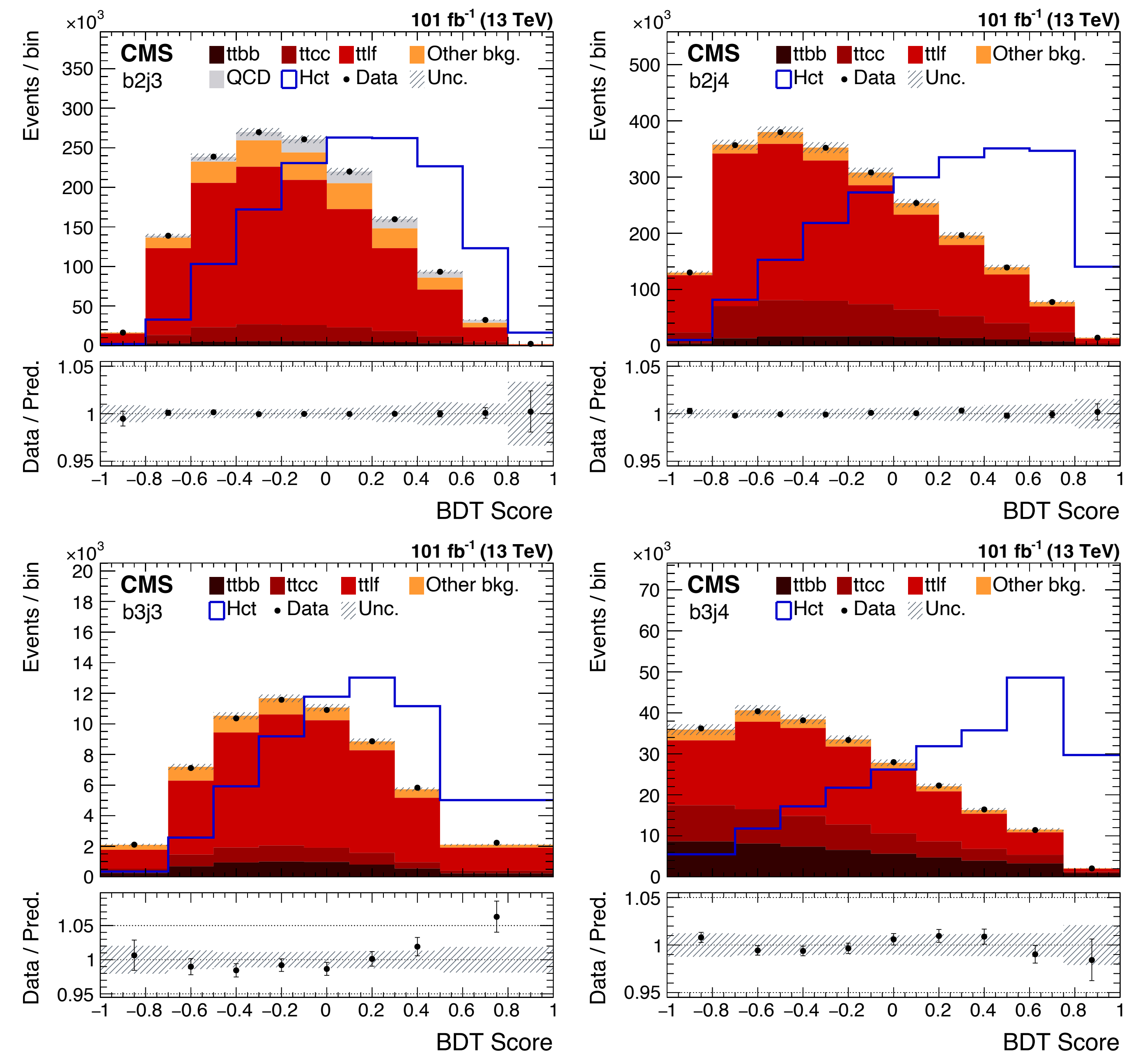
$t\bar{t}$ production

$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2}} \bar{t}\, \kappa_{\rm Hqt} (f^{\rm L}_{\rm Hq} P_{\rm L} + f^{\rm R}_{\rm Hq} P_{\rm R}) {\rm qH} + {\rm h.c.}$$

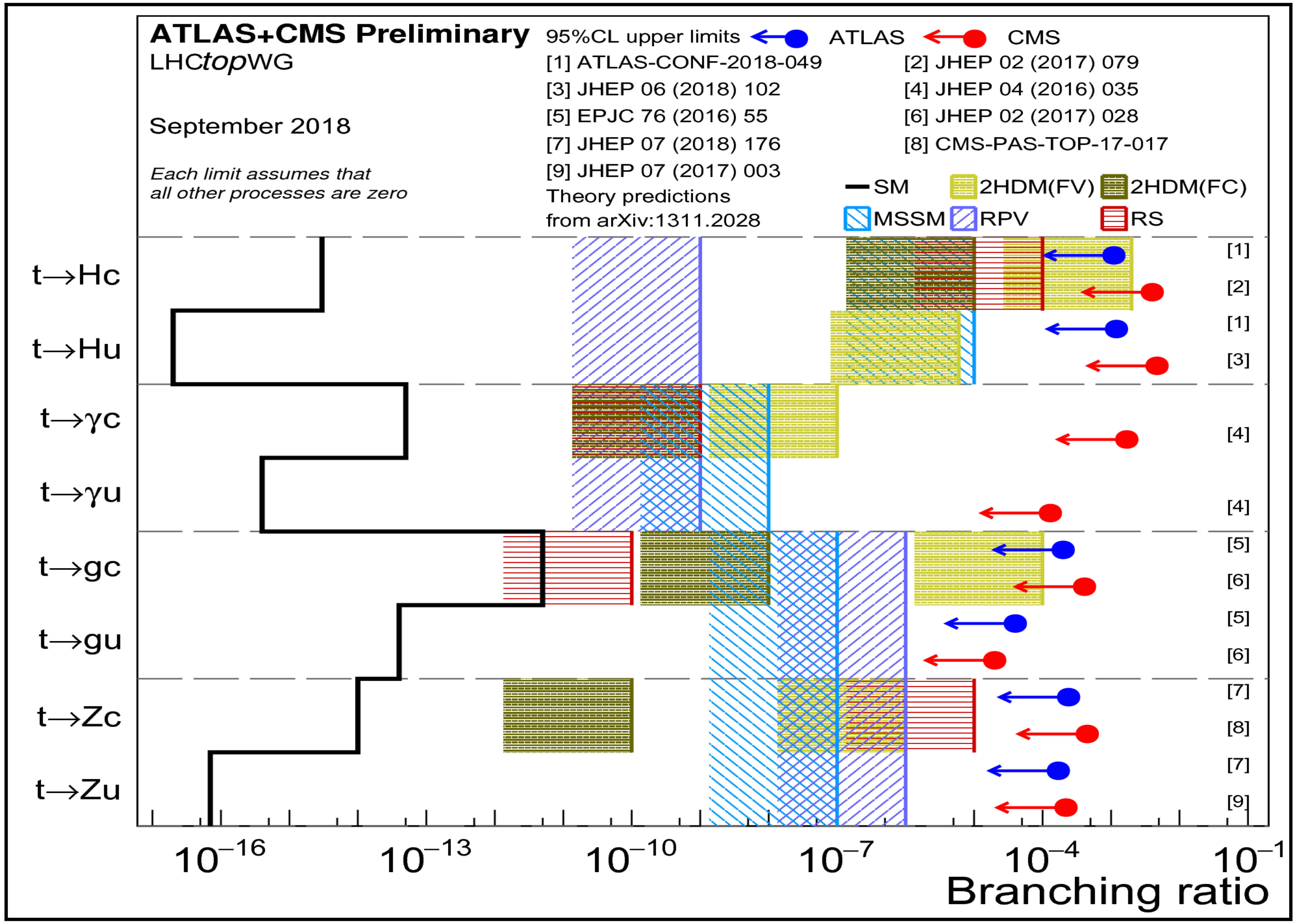




Major backgrounds: $t\bar{t}b\bar{b}; t\bar{t}c\bar{c}; t\bar{t} + \text{LF}$



Searches for top quark FCNC decays at the LHC



Direct connection between DM and top FCNCs?

- Theoretically it is possible to have a DM that couples solely to the quark sector of the SM.

- In this case the mediator must have a color charge and therefore interacts via QCD with gluons.

  These models are called t-channel models (C. Arina et al., 2010.07559, 2307.10367)

- In all these studies, the mediator is assumed to couple to one generation only!

  $\Longrightarrow$ Avoiding constraints from flavor physics especially FCNC decays.

- What if the mediator couples to all the quark generations (minimal)

  $\Longrightarrow$ The presence of DM and mediator will generate FCNC processes at the one-loop order.

- Depending on the spin of the mediator and DM, there are six minimal models for $SU(2)_L$ singlet mediators and six models for $SU(2)_L$ doublets!

The model

We extend the SM with two $SU(2)_L$ singlets: a colored scalar (S) and a right-handed fermion (χ)

$$S: \quad (\mathbf{3}, \mathbf{1})_{+2/3}, \quad \chi: \quad (\mathbf{1}, \mathbf{1})_0$$

Both χ and S are odd under an ad-hoc Z_2 symmetry while all the SM particles are even.

The interaction of χ to quarks resembles that of squark-quark-neutralino in supersymmetric models.

The right-handed fermion (χ) is a suitable DM candidate if $M_\chi < M_S$.

The model

Lagrangian

$$\mathcal{L} \supset \mathcal{L}_{\rm S} + \mathcal{L}_\chi - V(S, \Phi)$$

$\mathcal{L}_{\rm S}$, $\mathcal{L}_\chi$ → S and χ

$V(S, \Phi)$ → Scalar potential

$$\mathcal{L}_S + \mathcal{L}_\chi \equiv i\bar{\chi}\not{\partial}\chi^c + \frac{1}{2}M_\chi\bar{\chi}\chi^c + (\mathcal{D}_\mu S)^\dagger(\mathcal{D}^\mu S) + \left(Y_q \bar{q}_R^c \chi S + \text{h.c.}\right)$$

→ Relevant for DM annihilation, DM and S production at colliders

$$V(S, \Phi) = -m_{11}^2|\Phi^\dagger\Phi| + m_{22}^2|S^\dagger S| + \lambda_1|\Phi^\dagger\Phi|^2 + \lambda_2|S^\dagger S|^2 + \lambda_3|S^\dagger S||\Phi^\dagger\Phi|$$

→ Relevant for DM co-annihilation, Higgs decays.

The decays of the mediator

The mediator decays solely into a quark and DM (dominates over the 3-body decays)

$$\Gamma(S \to q\chi) \equiv \frac{Y_q^2 M_S}{16\pi}\left(1 - \frac{M_\chi^2 + m_q^2}{M_S^2}\right)\sqrt{\lambda\left(1, \frac{M_\chi^2}{M_S^2}, \frac{m_q^2}{M_S^2}\right)}$$

$$\approx \frac{Y_q^2 M_S}{16\pi}\left(1 - \frac{M_\chi^2}{M_S^2}\right)^2, \qquad m_q \ll M_S$$

Some comments:

- **For $\Delta \equiv M_S - M_\chi < m_t$, the mediator decays solely to light quarks with equal branching ratios if $Y_u = Y_c$.**
- **For $\Delta > m_t$ the decay into top quarks opens up with branching ratio going from a few % to $1/3$ or even more depending on the couplings (Y_u, Y_c, Y_t) and the mediator mass.**

The model

After electroweak symmetry breaking, one lefts with three extra states: $S, S^\dagger, \chi$.

Parameters:

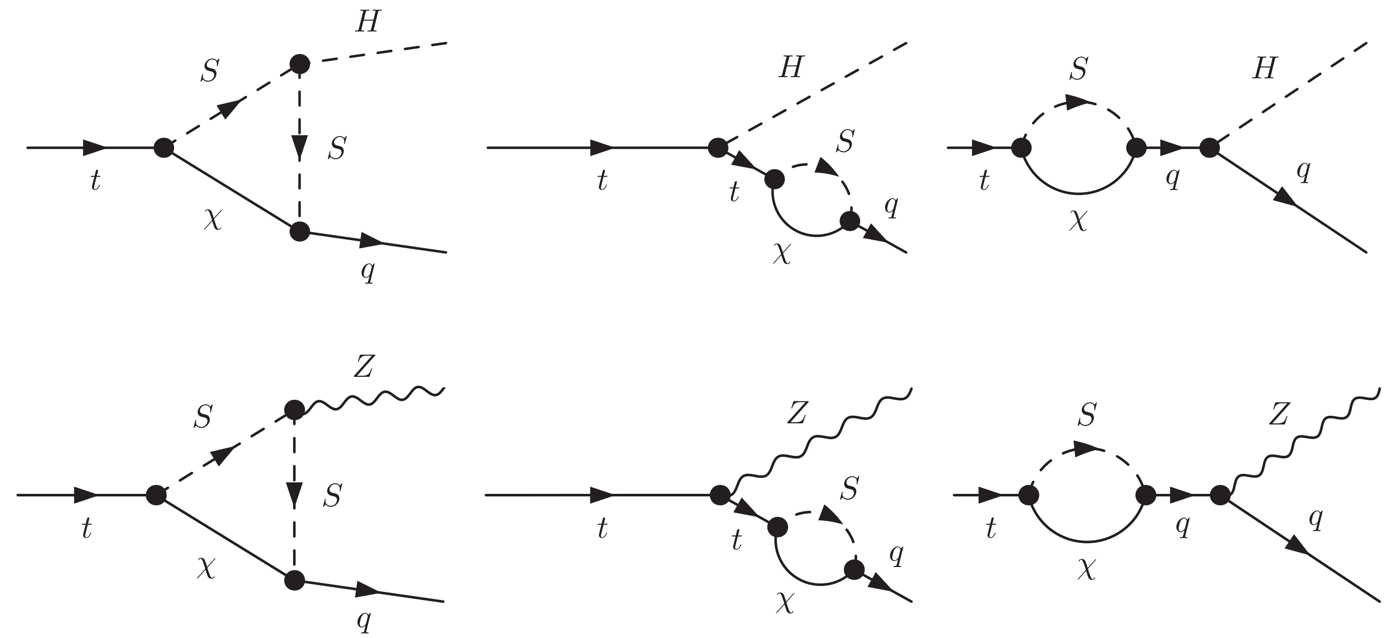
- Two masses: M_S and M_χ
- Two quartic couplings: λ_2 and λ_3.
- Three dark-matter couplings: Y_u, Y_c and Y_t

Parameter ranges:

- $M_\chi \in [20,\ 2000]$ GeV
- $\Delta \equiv M_S - M_\chi = 100,\ 300,\ 500$ GeV
- $Y_q Y_t = 0.5,\ 1,\ 3.$
- $\lambda_2 = 1$
- $\lambda_3 = -1,\ 0,\ 1,\ 3$ (for illustration).

Top quark FCNC decays

In this work, we consider two FCNC decays of the top quark: $t \to qH$ and $t \to qZ$



The effective Lagrangian can be written as

$$-\mathcal{L}_{\rm eff} = \bar{t}\gamma^\mu (f^L_{tqZ} P_L + f^R_{tqZ} P_R) q Z_\mu + \bar{t} p^\mu (g^L_{tqZ} P_L + g^R_{tqZ} P_R) q Z_\mu$$
$$+ \bar{t}(f^L_{tqH} P_L + f^R_{tqH} P_R) q H + \text{h.c.},$$

$f^{L,R}_{tqX}; g^{L,R}_{tqZ}$ are the form factors calculable at the one-loop order.

Top quark FCNC decays

For $t \to qH$, we have

$$f^L_{tqH} = \frac{Y_q Y_t m_t}{16\pi^2}\left(3\lambda_3 v C_1 + \frac{m_q^2}{v(m_t^2 - m_q^2)}\left(B_{1,t} - B_{1,q}\right)\right)$$
$$f^R_{tqH} = \frac{Y_q Y_t m_q}{16\pi^2}\left(3\lambda_3 v C_2 + \frac{m_t^2}{v(m_t^2 - m_q^2)}\left(B_{1,t} - B_{1,q}\right)\right)$$

For $Y_q = Y_t$, $f^L_{tqH} \gg f^R_{tqH}$

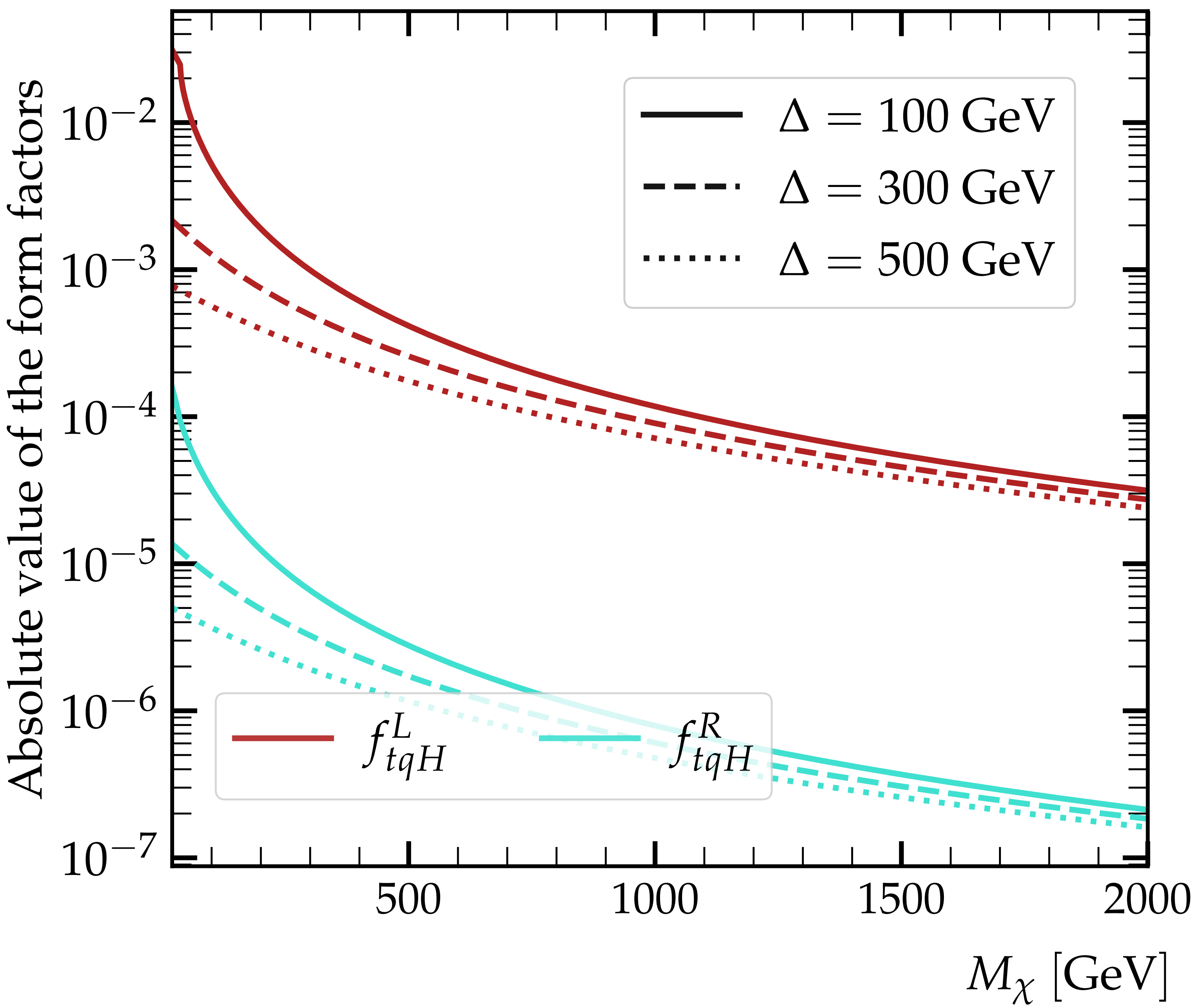
For $t \to qZ$, we have

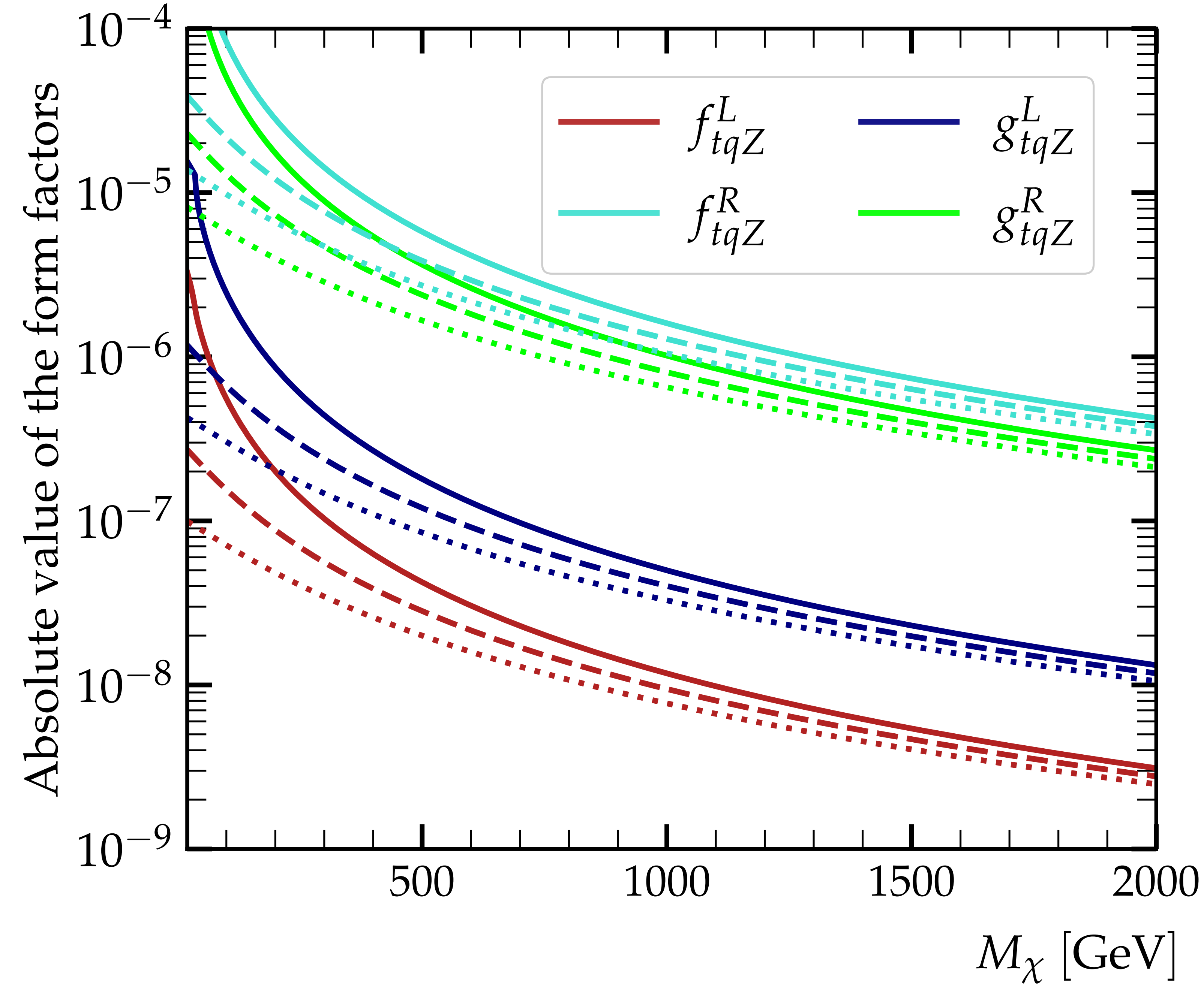
$$f^L_{tqZ} = \frac{g_1 m_q m_t (3c_W^2 - s_W^2)}{96 s_W \pi^2}\frac{Y_q Y_t}{(m_t^2 - m_q^2)}\left(B_{1,t} - B_{1,q}\right),$$
$$f^R_{tqZ} = -\frac{g_1 s_W Y_q Y_t}{24\pi^2}\left(2C_{00} + \frac{1}{m_t^2 - m_q^2}(m_t^2 B_{1,t} - m_q^2 B_{1,q})\right)$$
$$g^L_{tqZ} = \frac{g_1 s_W Y_q Y_t m_t}{12\pi^2}\left(C_1 + C_{11} + C_{12}\right),$$
$$g^R_{tqZ} = \frac{g_1 s_W Y_q Y_t m_q}{12\pi^2}\left(C_2 + C_{12} + C_{22}\right),$$

$f^R_{tqZ} \simeq g^L_{tqZ} \gg g^R_{tqZ} > f^L_{tqZ}$

$C_{i,ij}$, B_i are Passarino-Veltman functions

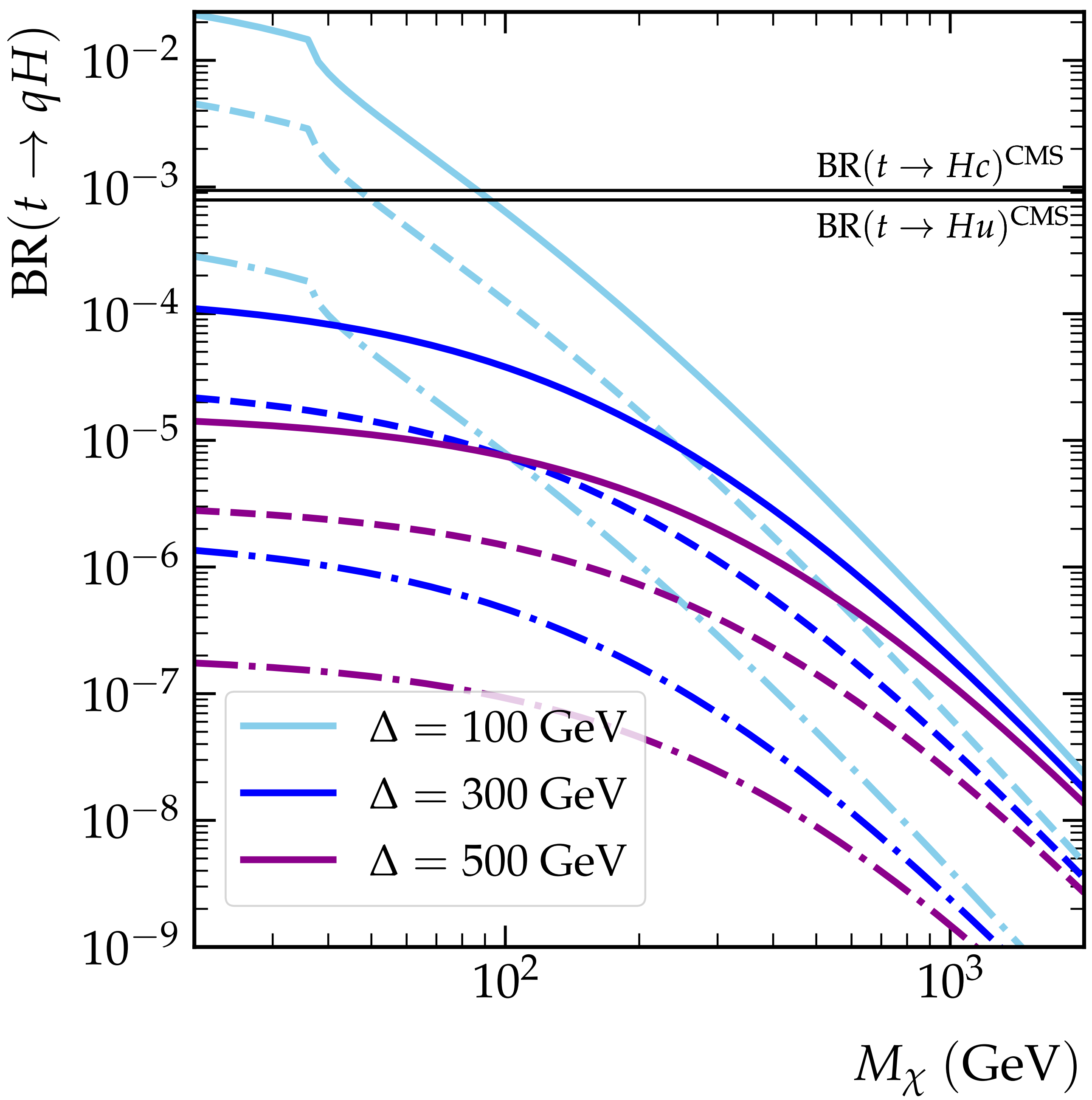
Top quark FCNC decays

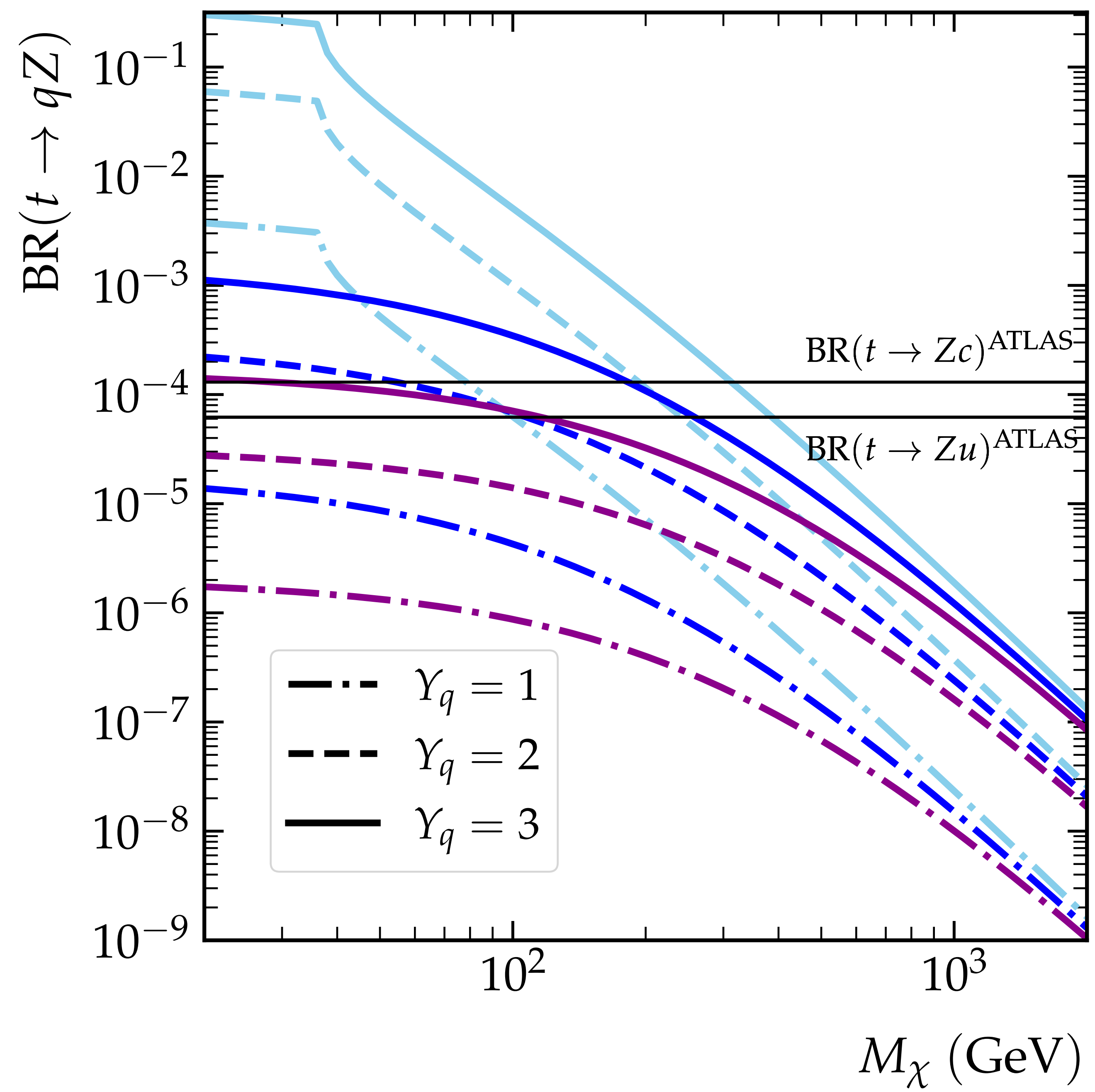




$$q = c; Y_c = Y_t = 1$$

Top quark FCNC decays





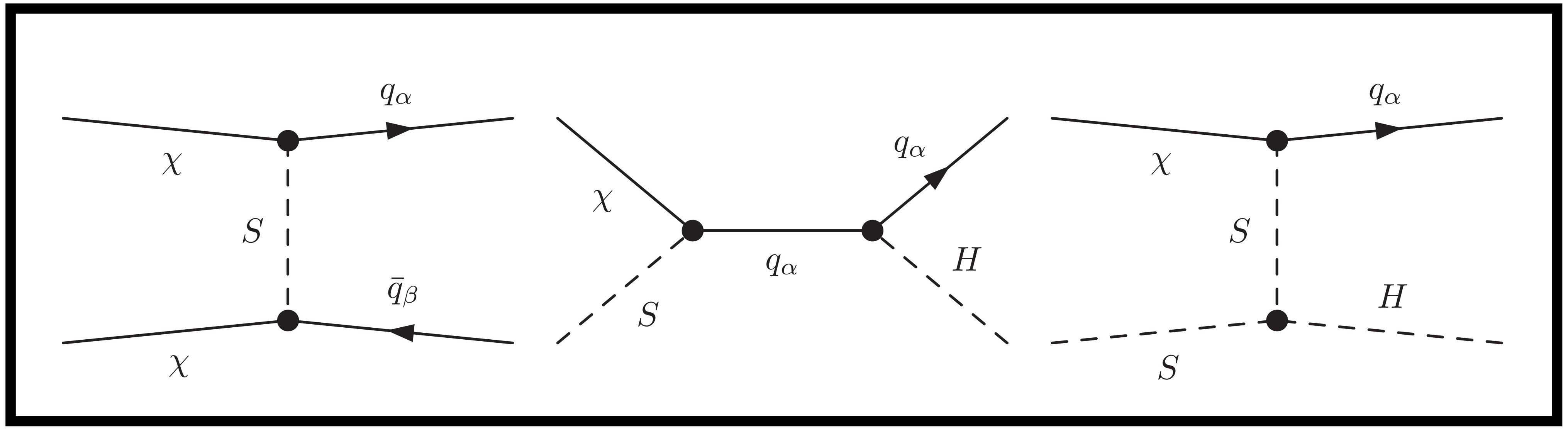
$$\mathrm{BR}(t \to qX) \equiv \frac{\Gamma(t \to qX)}{\Gamma(t \to bW)_{\mathrm{NNLO}}}$$

$$r \equiv \frac{\mathrm{BR}(t \to qZ)}{\mathrm{BR}(t \to qH)} \equiv \frac{1}{\lambda_3^2}\mathcal{O}(10)$$

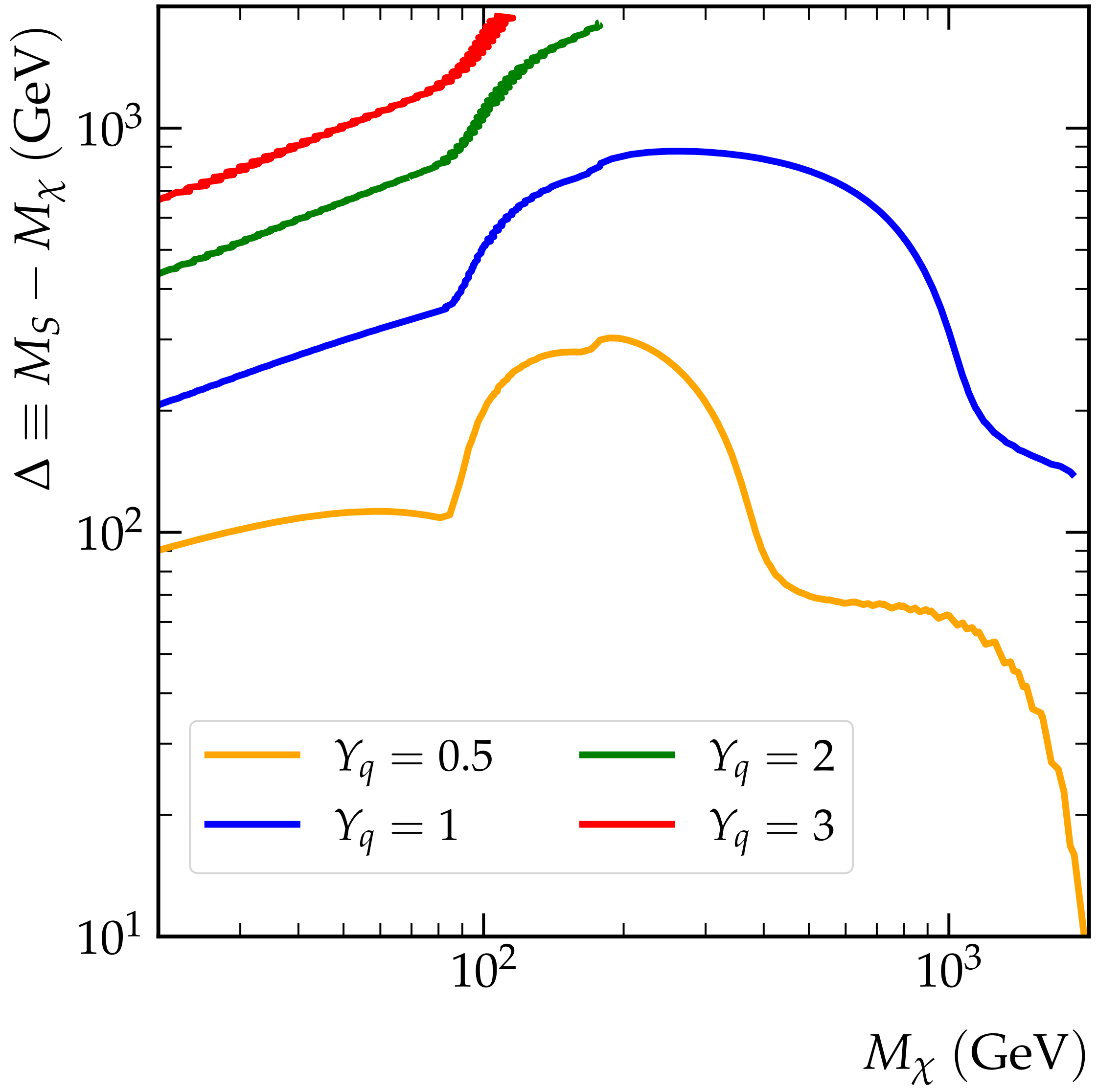
Dark matter relic density

The relic density of the χ is generated through the standard freeze-out mechanism.

$$\chi\chi \to q_\alpha \bar{q}_\beta \qquad \chi S \to q_\alpha \gamma/Z/H/g \quad (\text{for } \Delta/M_\chi < 0.1)$$



Annihilation **Co-annihilation**



Collider bounds: monojet

The most important bound from the LHC comes from the search of new physics in events with at least one jet plus missing energy

We use the most recent search of DM in the mono-jet channel by the ATLAS collaboration (ATLAS-EXOT-2018-06).

139 1/fb of data collected between 2015 and 2018.

26 signal regions depending on $E_T^{\rm miss}$

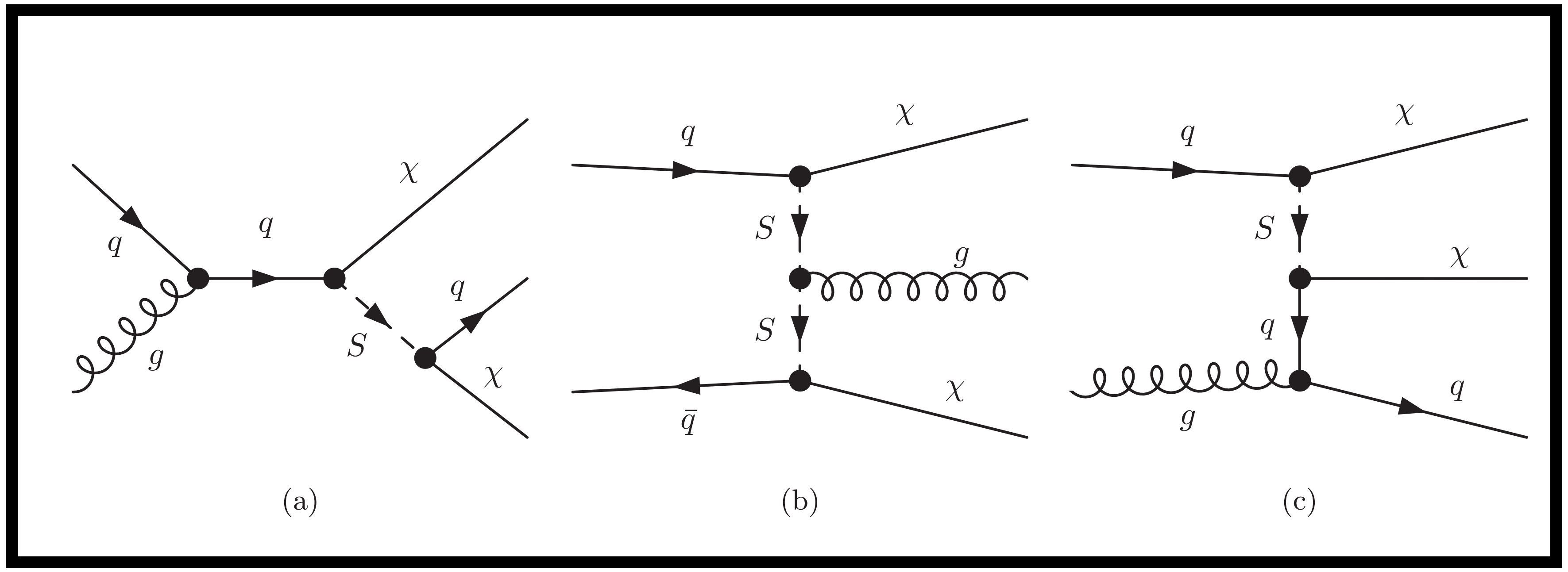
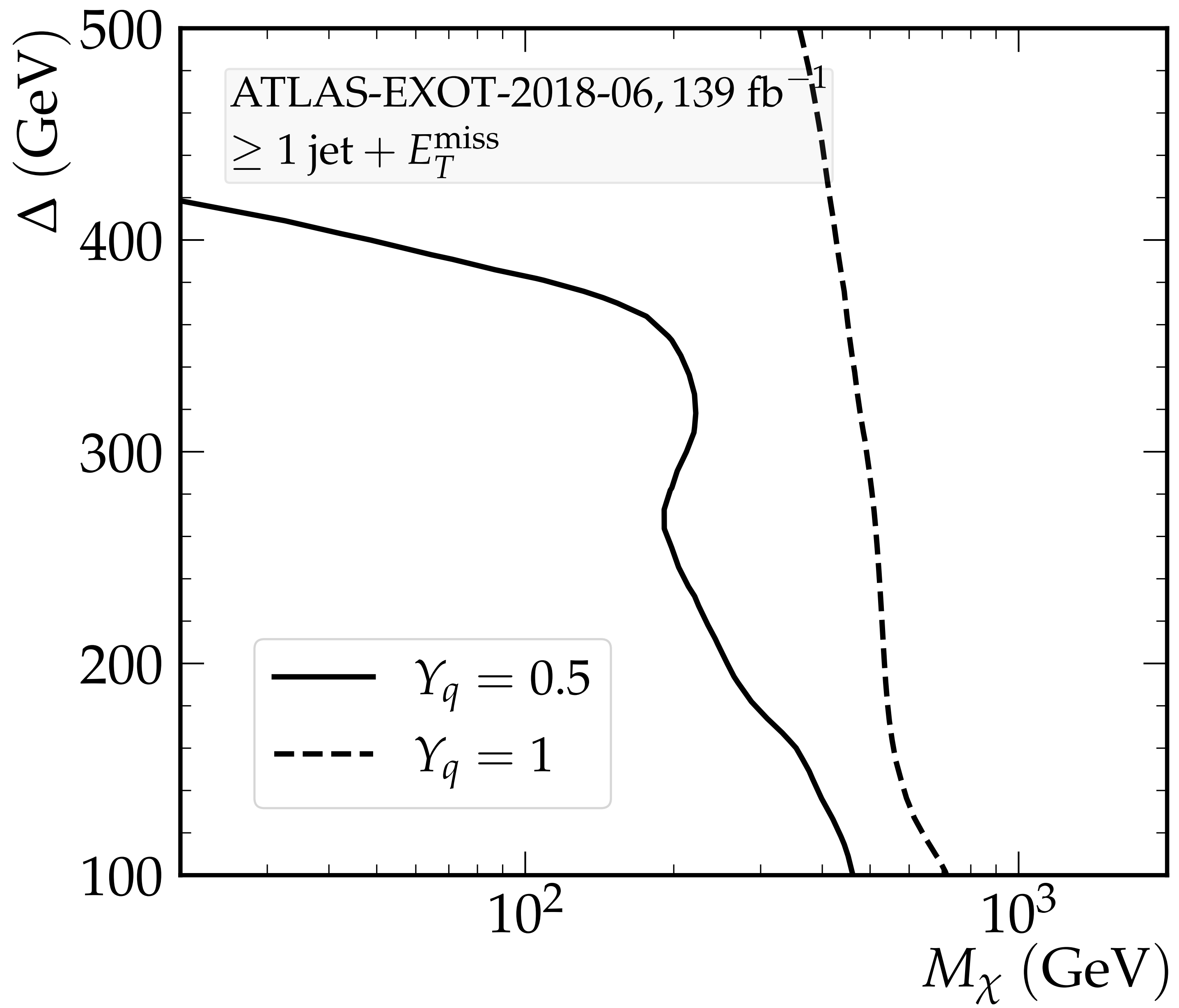


Table 1: Intervals and labels of the $E_{\rm T}^{\rm miss}$ bins used for the signal region. Details are given in the text.

Exclusive (EM)	EM0	EM1	EM2	EM3	EM4	EM5	EM6
$E_{\rm T}^{\rm miss}$ [GeV]	200–250	250–300	300–350	350–400	400–500	500–600	600–700
	EM7	EM8	EM9	EM10	EM11	EM12	
	700–800	800–900	900–1000	1000–1100	1100–1200	>1200	
Inclusive (IM)	IM0	IM1	IM2	IM3	IM4	IM5	IM6
$E_{\rm T}^{\rm miss}$ [GeV]	>200	>250	>300	>350	>400	>500	>600
	IM7	IM8	IM9	IM10	IM11	IM12	
	>700	>800	>900	>1000	>1100	>1200	

Collider bounds: monojet

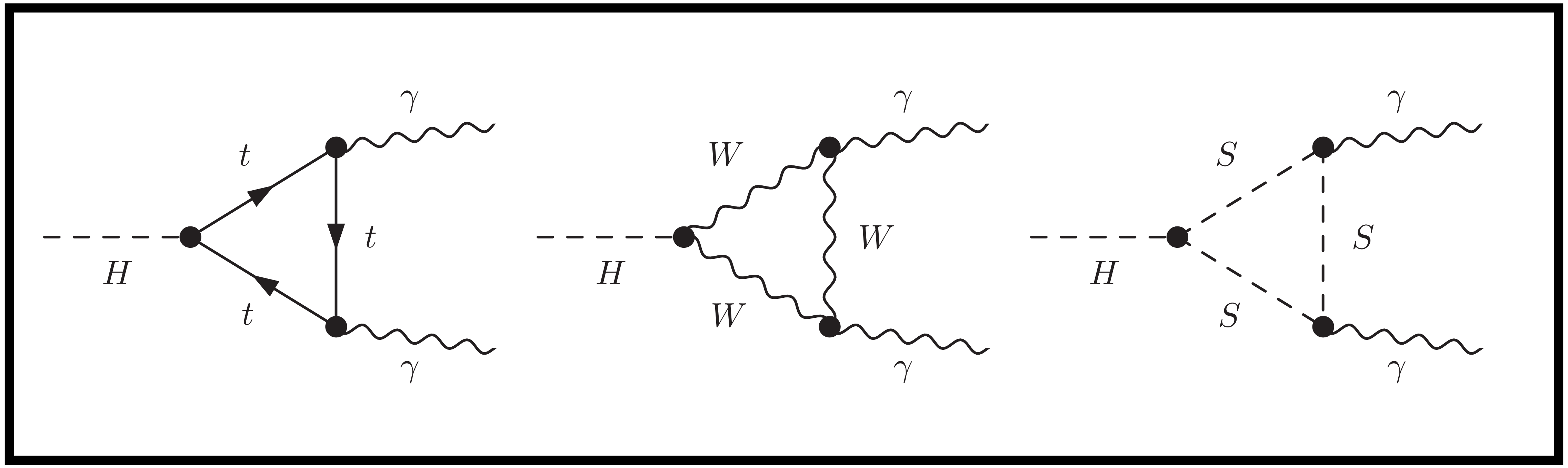
Bounds were obtained by using an implementation of the search in the MadAnalysis 5 framework



Impact on SM Higgs couplings

What about the impact on the SM Higgs Boson measurements (production and decay)?

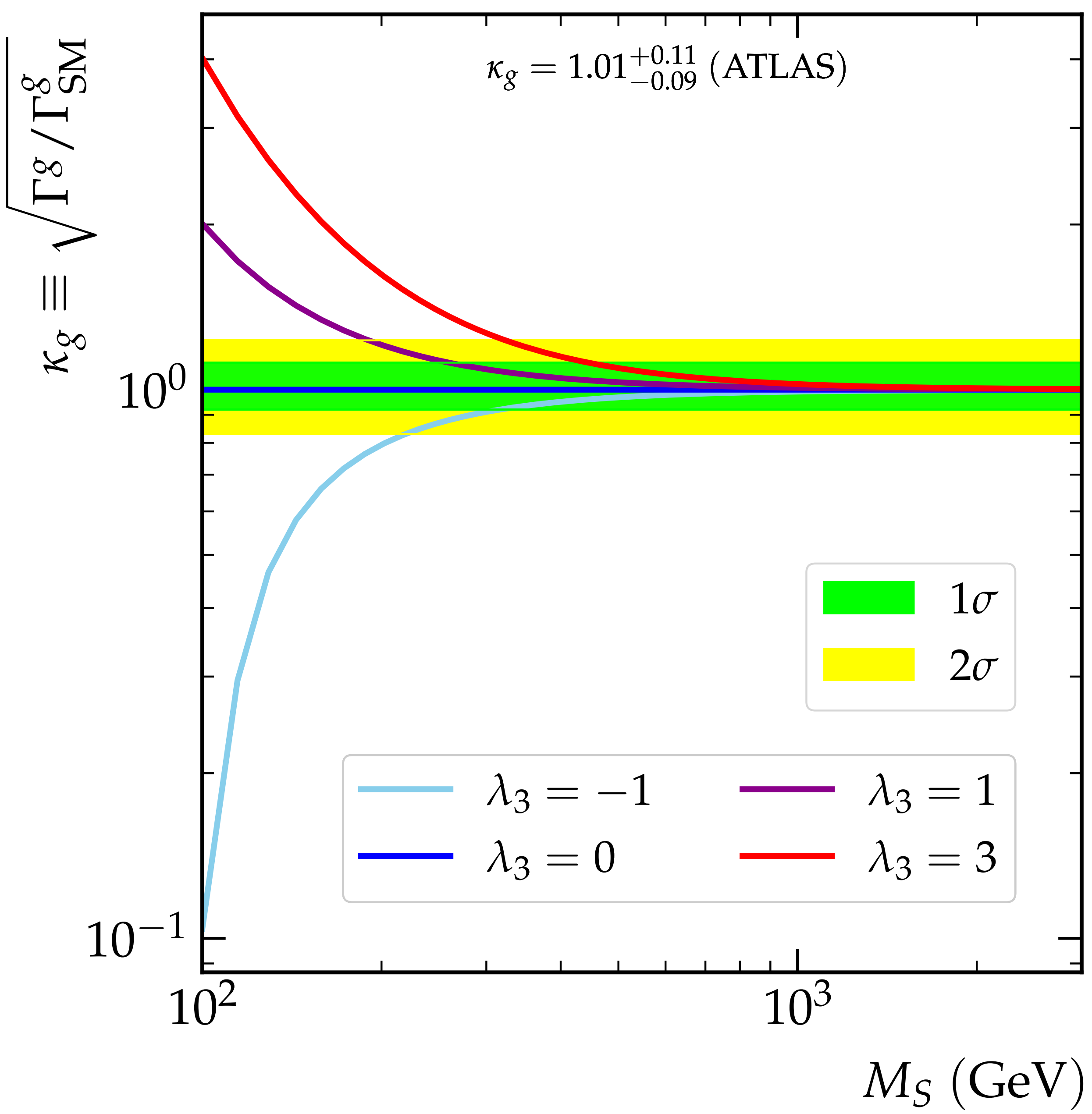
Consider for example the partial width of $H \to \gamma\gamma$ $\kappa_X = \sqrt{\Gamma_X/\Gamma_X^{\rm SM}}$ (good measure)

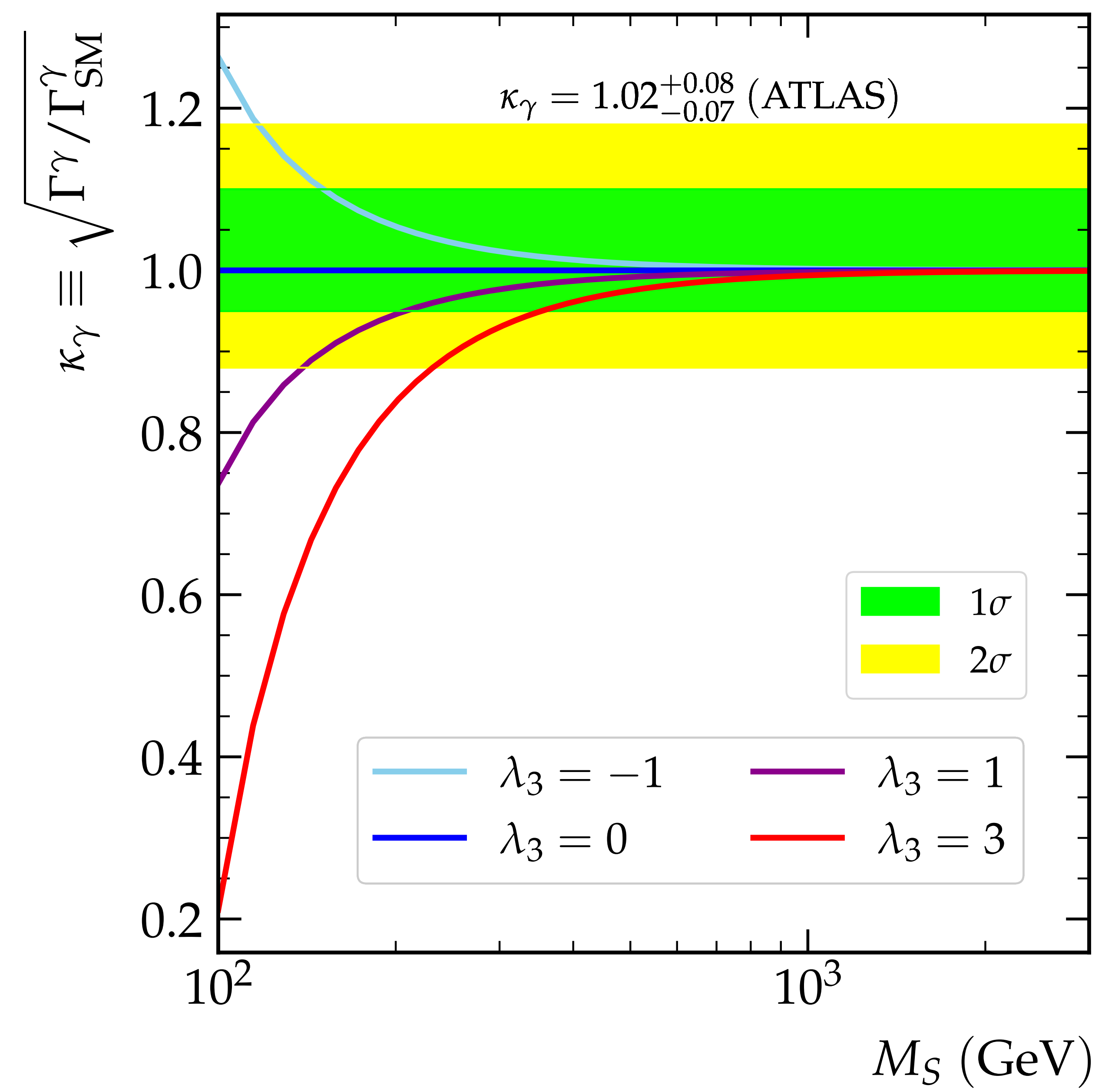


$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha_{\rm EM}^2 m_H^3}{128\sqrt{2}\pi^3} \left| \sum_f Q_f^2 N_{cf} A_{1/2}(\tau_f) + A_1(\tau_W) + N_{cS} Q_S^2 \frac{\lambda_3 v^2}{2M_S^2} A_0(\tau_S) \right|^2$$

$$\Gamma(H \to gg) = \frac{G_F \alpha_s^2 m_H^3}{64\sqrt{2}\pi^3} \left| \sum_f A_{1/2}(\tau_f) + \frac{\lambda_3 v^2}{2M_S^2} A_0(\tau_S) \right|^2$$

Impact on SM Higgs couplings

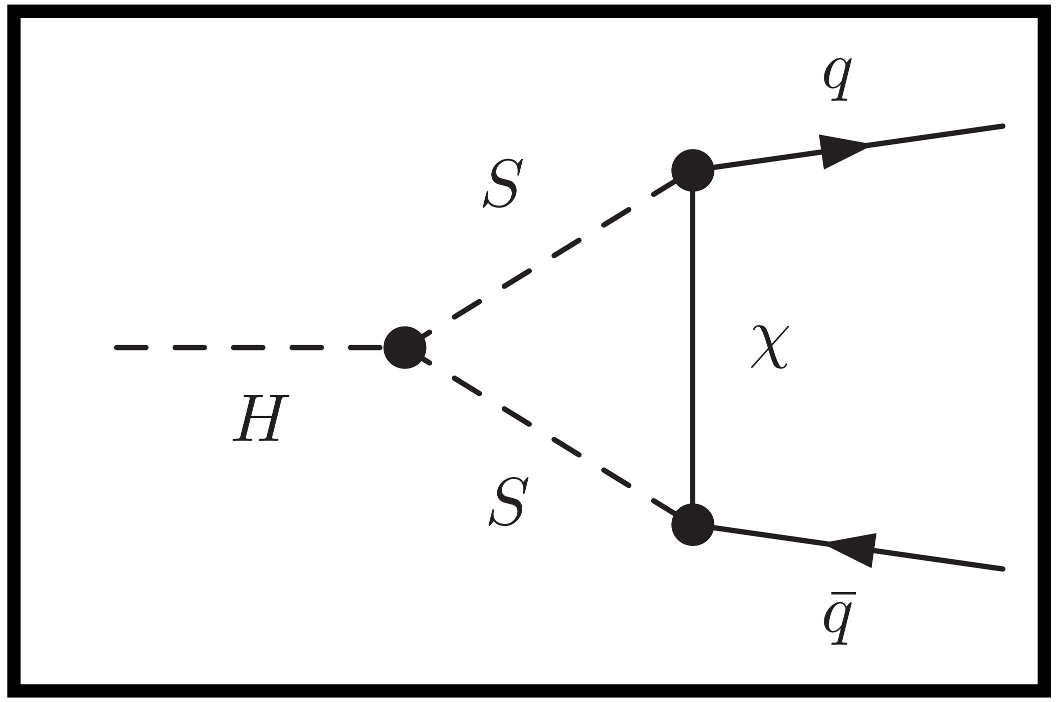




κ_γ and κ_g are anticorrelated in our model

Impact on SM Higgs couplings

What about the decays of the SM Higgs into quarks?



$$\propto Y_q^2 \lambda_3 m_q$$

$$\Gamma(H \to q\bar{q}) = \Gamma(H \to q\bar{q})_{\rm N3LO} + \Delta\Gamma(H \to q\bar{q})_{\rm NP}$$

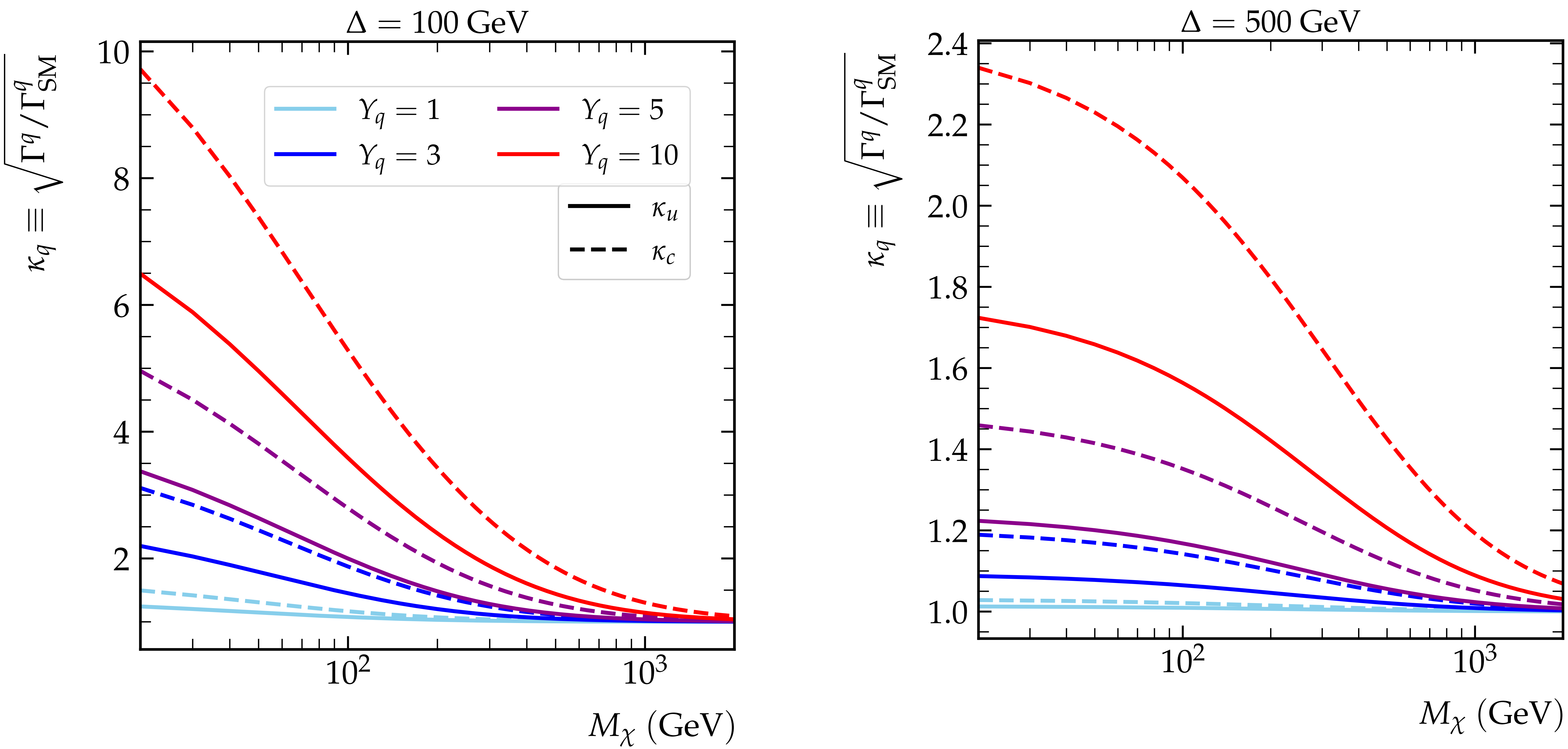
$$\Delta\Gamma(H \to q\bar{q})_{\rm NP} = \frac{6 m_H m_q}{16\pi v}\Big[\mathrm{Re}(f_L) + \mathrm{Re}(f_R)\Big]$$

$$f_L = \frac{3\lambda_3 m_q v Y_q^2}{16\pi^2} C_2(m_q^2, m_H^2, m_q^2, M_\chi^2, M_S^2, M_S^2)$$

$$f_R = \frac{3\lambda_3 m_q v Y_q^2}{16\pi^2} C_1(m_q^2, m_H^2, m_q^2, M_\chi^2, M_S^2, M_S^2)$$

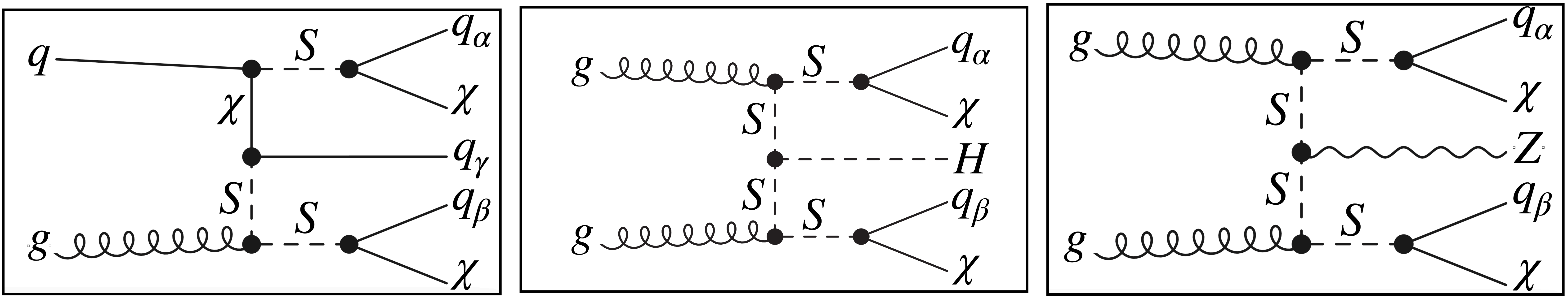
Corrections must be small!!

Impact on SM Higgs couplings



Corrections are small for moderate values of Y_q (percent level)

Future prospects at colliders



$\propto Y_{q_\alpha} Y_{q_\beta} Y_{q_\gamma}$

$\propto Y_{q_\alpha} Y_{q_\beta} \lambda_3$

$\propto Y_{q_\alpha} Y_{q_\beta}$

Correlate FCNC and DM for $q_\alpha q_\beta \equiv t\bar{c} + \mathrm{h.c.}$

Benchmark points

Benchmark point	Quantity	BP1	BP2	BP3	BP4
Parameters	Y_u	0.4	0.4	0.0	0.4
	Y_c	0.4	0.8	1.0	1.0
	Y_t	0.4	1.2	2.0	0.8
	λ_3	2.0	2.0	4.0	4.0
	M_χ (GeV)	500	200	100	600
	Δ (GeV)	57	650	500	250
Branching ratios					
$\text{BR}(S \to q\chi)$	$\text{BR}(S \to u\chi)$	0.5	0.076	0.0	0.101
	$\text{BR}(S \to c\chi)$	0.5	0.303	0.231	0.632
	$\text{BR}(S \to t\chi)$	0.0	0.621	0.769	0.267
	Γ_S/M_S	1.18×10^{-4}	3.64×10^{-2}	8.31×10^{-2}	7.92×10^{-3}
$\text{BR}(t \to qX)$	$\text{BR}(t \to cH)$	1.02×10^{-8}	7.92×10^{-8}	5.91×10^{-6}	1.43×10^{-7}
	$\text{BR}(t \to uH)$	1.02×10^{-8}	1.97×10^{-8}	0.0	2.29×10^{-8}
	$\text{BR}(t \to cZ)$	1.50×10^{-8}	1.79×10^{-7}	3.49×10^{-6}	5.92×10^{-8}
	$\text{BR}(t \to uZ)$	1.50×10^{-8}	4.48×10^{-8}	0.0	9.48×10^{-9}
Dark matter	$\Omega_\chi h^2$	0.118	6.42×10^{-2}	8.58×10^{-2}	1.05×10^{-1}
	σ_{SI}^p (pb)	4.74×10^{-11}	3.51×10^{-14}	4.57×10^{-13}	2.97×10^{-12}

Benchmark points

Production cross sections [fb]					
13.6 TeV	$S\chi$	61.1	32.3	78.9	13.4
	$SS^\dagger$	155.8	11.9	106.0	11.6
	$SS + \text{h.c.}$	17.9	1.45	0.48	5.47
	$\chi\chi H$	3.36×10^{-4}	1.06×10^{-3}	1.43×10^{-2}	4.94×10^{-4}
	$\chi\chi Z$	1.82×10^{-3}	1.25×10^{-2}	1.48×10^{-2}	2.08×10^{-3}
	$\chi S H$	5.35×10^{-2}	1.54×10^{-2}	1.77×10^{-1}	3.02×10^{-2}
	$\chi S Z$	4.44×10^{-2}	2.27×10^{-2}	3.88×10^{-2}	1.12×10^{-2}
	$SS^\dagger j$	219.8	16.4	145.9	16.3
	$SS^\dagger \gamma$	1.02	0.11	0.74	0.11
	$SS^\dagger t$	8.21×10^{-2}	0.14	1.01	4.50×10^{-2}
	$SS^\dagger H$	0.48	2.56×10^{-2}	1.22	0.10
	$SS^\dagger Z$	0.24	2.85×10^{-2}	0.18	2.86×10^{-2}
100 TeV	$S\chi$	3.41×10^3	2.32×10^3	6.53×10^3	1.57×10^3
	$SS^\dagger$	28.82×10^3	4.63×10^3	21.36×10^3	4.61×10^3
	$SS + \text{h.c.}$	225.4	49.4	53.9	230.6
	$\chi\chi H$	1.61×10^{-2}	4.04×10^{-2}	8.12×10^{-1}	4.69×10^{-2}
	$\chi\chi Z$	9.91×10^{-2}	5.03×10^{-1}	8.84×10^{-1}	2.04×10^{-1}
	$\chi S H$	4.32	1.63	22.2	5.06
	$\chi S Z$	4.24	2.27	5.35	2.26
	$SS^\dagger j$	58.65×10^3	10.36×10^3	43.92×10^3	10.32×10^3
	$SS^\dagger \gamma$	138.0	24.8	89.1	27.5
	$SS^\dagger t$	13.8	66.5	373.1	22.5
	$SS^\dagger H$	128.5	14.5	357.8	58.4
	$SS^\dagger Z$	26.5	6.66	21.6	6.70

Conclusions

- We suggested a new mechanism for the generation of quark flavour violation at the one-loop order.
- The model is a minimal realization of this mechanism that extends the SM with two $SU(2)_L$ singlet: a colored scalar mediator and a right-handed fermion.
- Decent rates for top quark FCNC decays are predicted while not being in conflict with current LHC data.
- More work is needed to pin down the connection between the two sectors at hadron colliders.