t-channel dark matter, flavour anomalies and top flavour-changing neutral currents

Adil Jueid
Institute for Basic Science

Roadmap of Dark Matter models for Run 3
13-17 May 2024

Based on:

2402.08652 w/ Shinya Kanemura

2111.08027 w/ G. Belanger, A. Bharucha, B. Fuks, A. Goudelis, J. Heisig, A. Lessa, K. A. Mohan, G. Polesello, P. Pani, A. Pukhov, D. Sengupta, J. Zurita

1. Top flavour-changing neutral currents

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

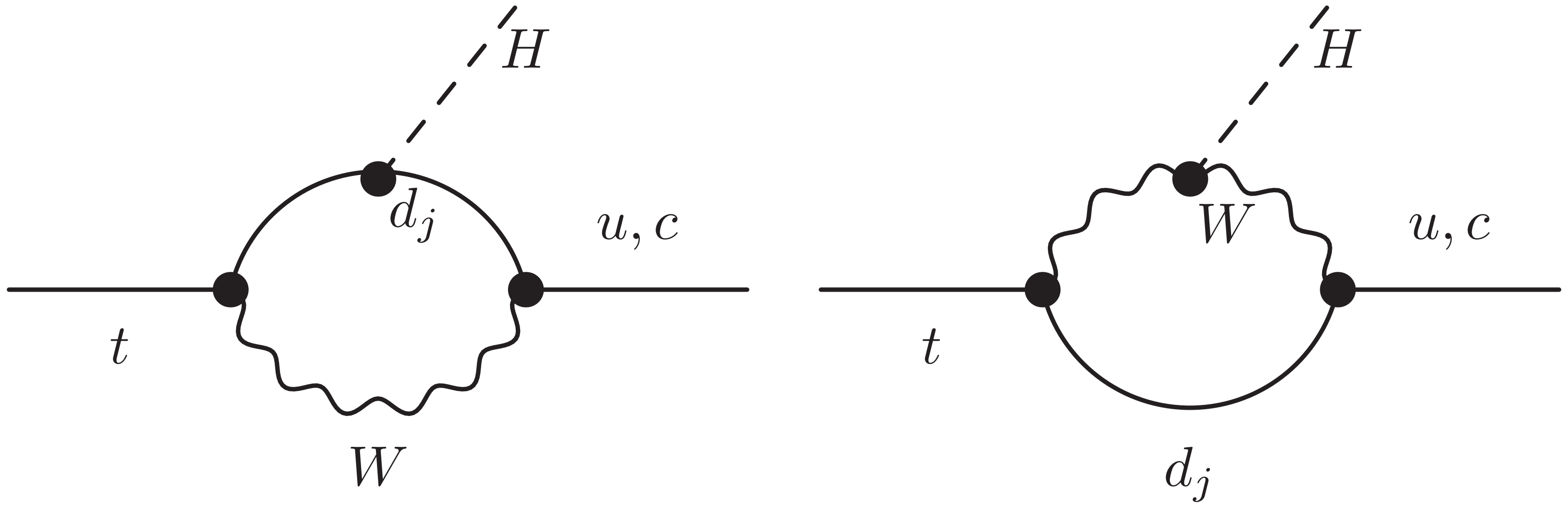
Let us take for example the Yukawa Lagrangian in the SM

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

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

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.

$t \to qX$: 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) $\Longrightarrow$ Too small to be observed even at HL-LHC or FCC-hh!!

Beyond the SM predictions?

- **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}	–

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)

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

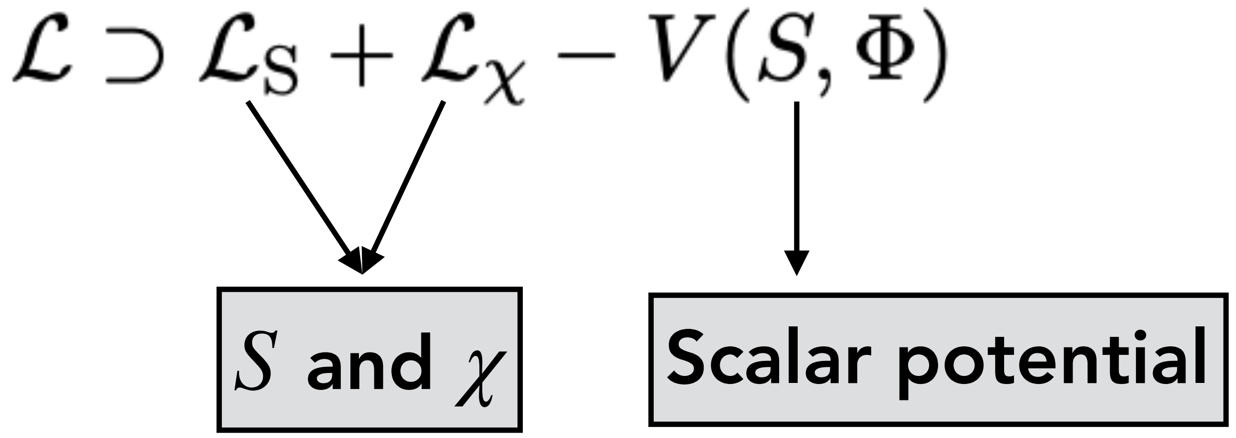
Both χ and S are odd under an ad-hoc Z_2 symmetry while all the SM particles are even.

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



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

S and χ

Scalar potential

$$\mathcal{L}_S + \mathcal{L}_\chi \equiv i\bar{\chi}\partial\!\!\!/\chi^c + \frac{1}{2}M_\chi\bar{\chi}\chi^c + (\mathcal{D}_\mu S)^\dagger(\mathcal{D}^\mu S) + \left(Y_q \bar{q}_R^c \chi S + \text{h.c.}\right)$$

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 model

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

Parameters:

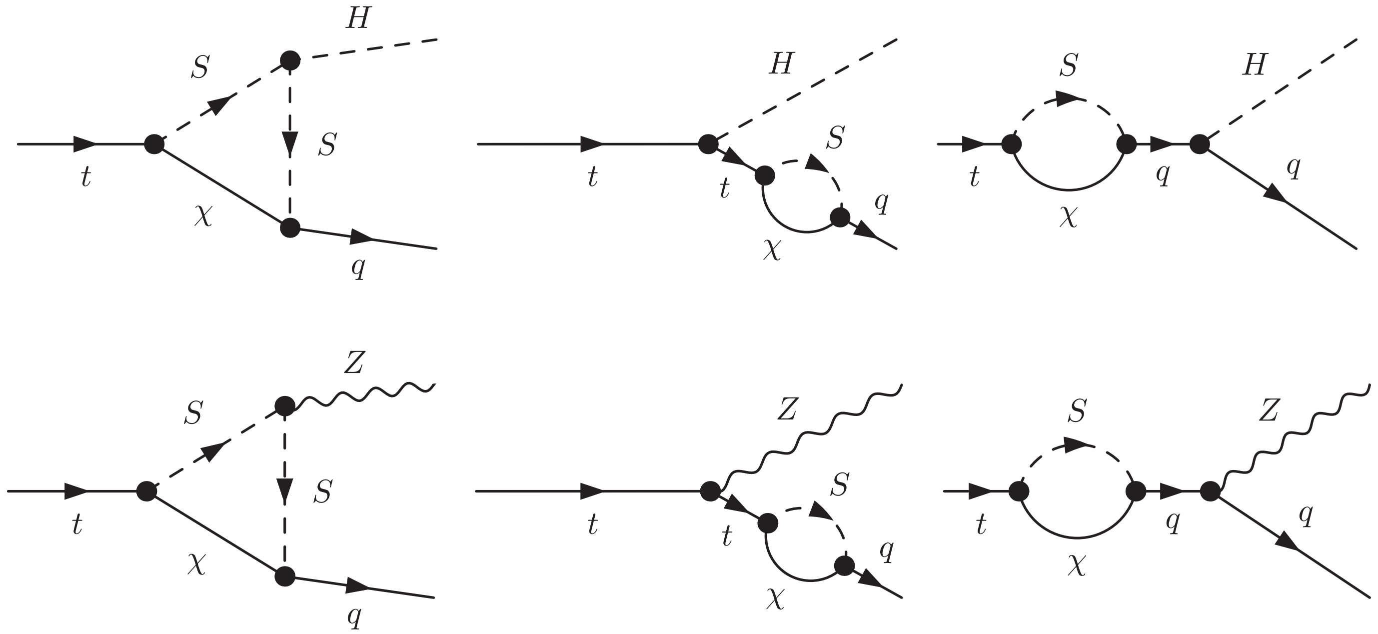
- Two masses: M_S and M_χ
- Two quartic couplings: λ_2 and λ_3.
- Three dark-matter couplings: Y_u, Y_c and Y_t

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 $t \to qZ$

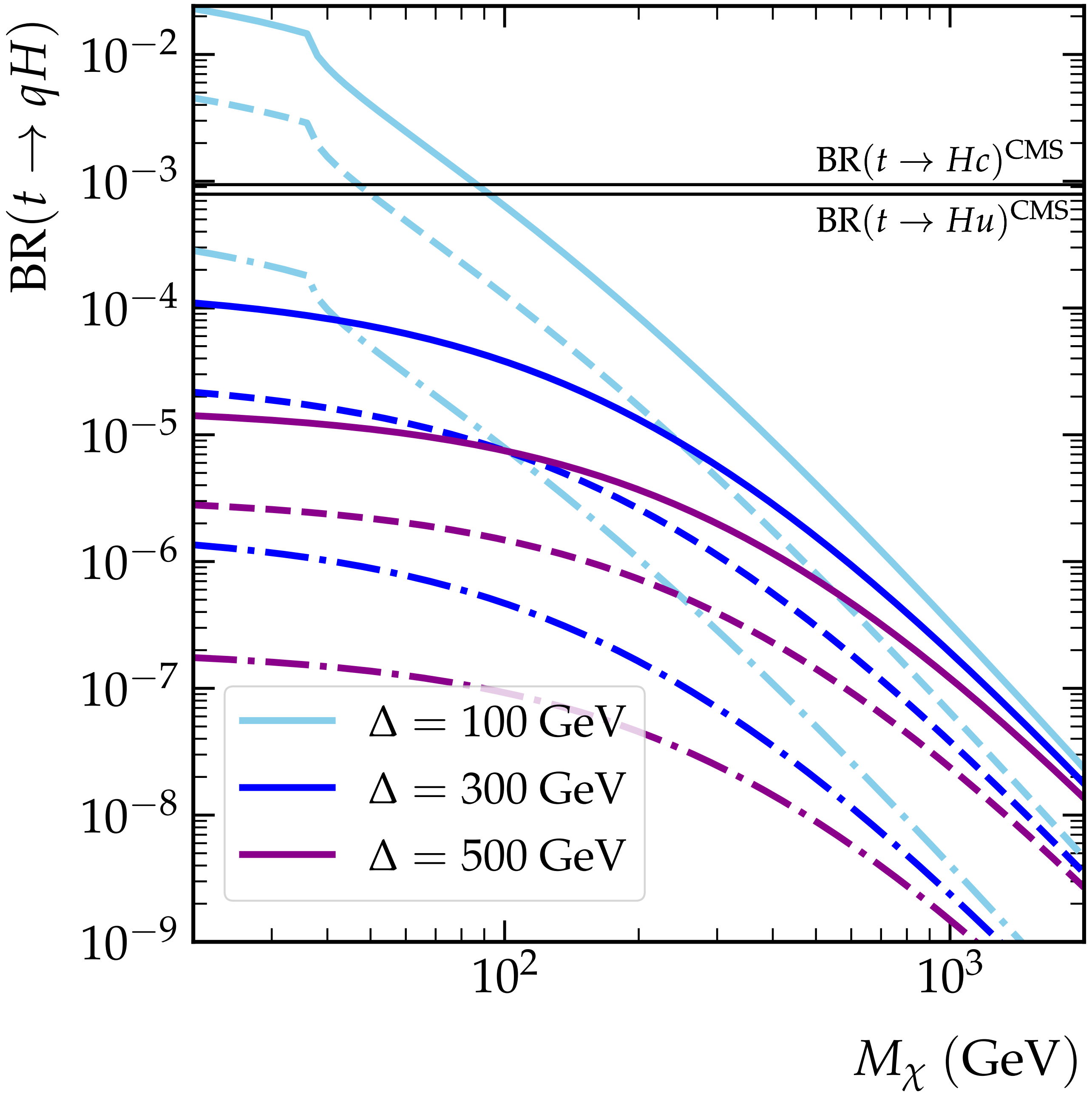


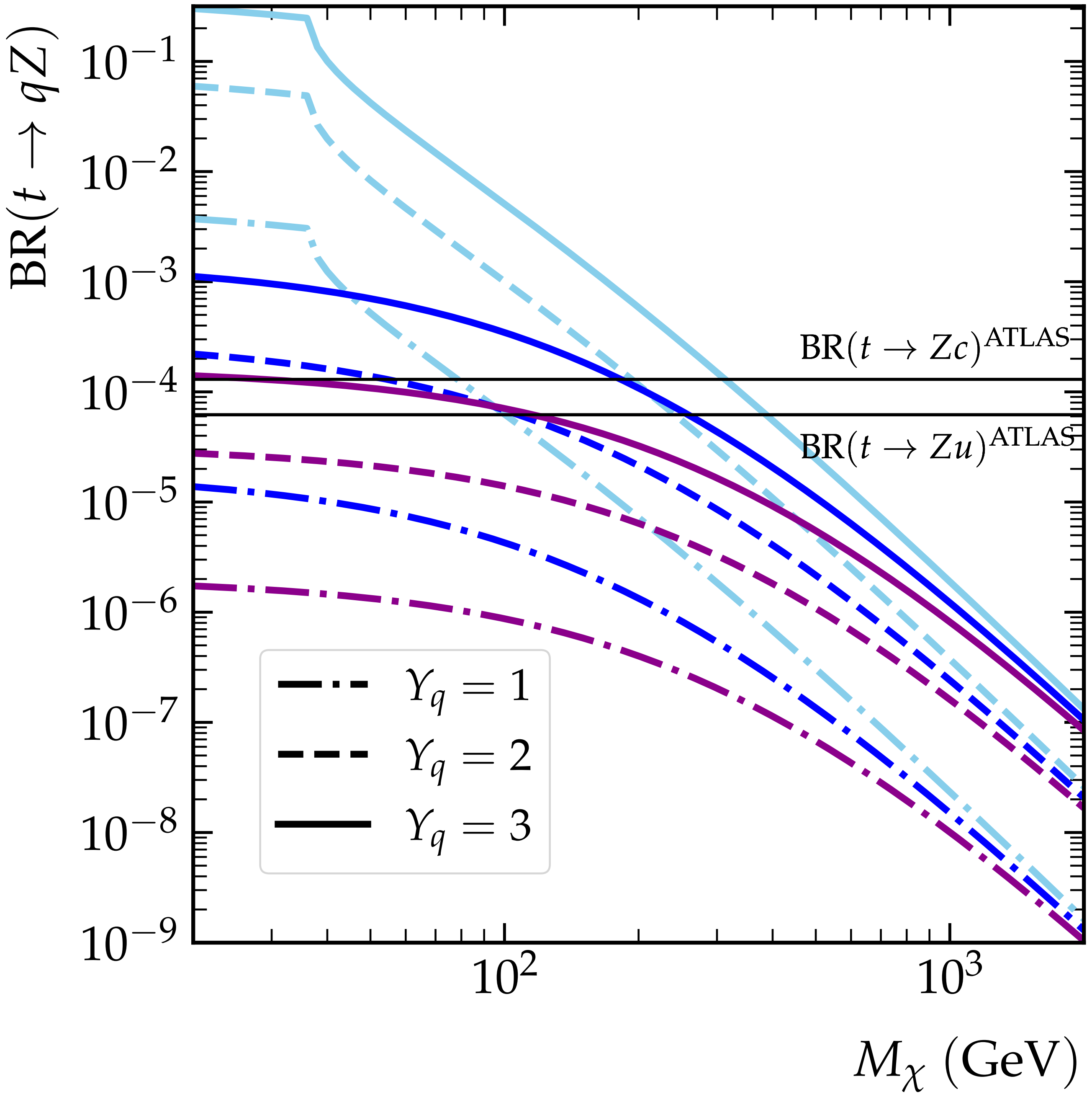
The effective Lagrangian can be written as

$$\begin{aligned} -\mathcal{L}_{\rm eff} &= \bar{t}\gamma^\mu(f^L_{tqZ}P_L + f^R_{tqZ}P_R)qZ_\mu + \bar{t}p^\mu(g^L_{tqZ}P_L + g^R_{tqZ}P_R)qZ_\mu \\ &+ \bar{t}(f^L_{tqH}P_L + f^R_{tqH}P_R)qH + \text{h.c.}, \end{aligned}$$

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

Top quark FCNC decays





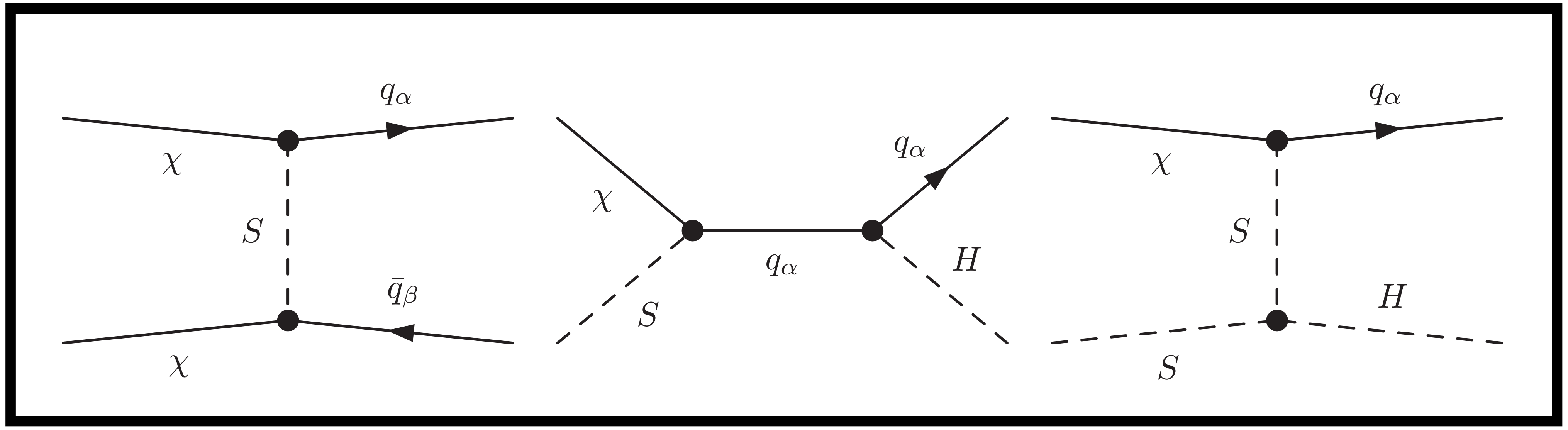
$$\mathrm{BR}(t \to qX) \equiv \frac{\Gamma(t \to qX)}{\Gamma(t \to bW)_{\mathrm{NNLO}}}$$

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

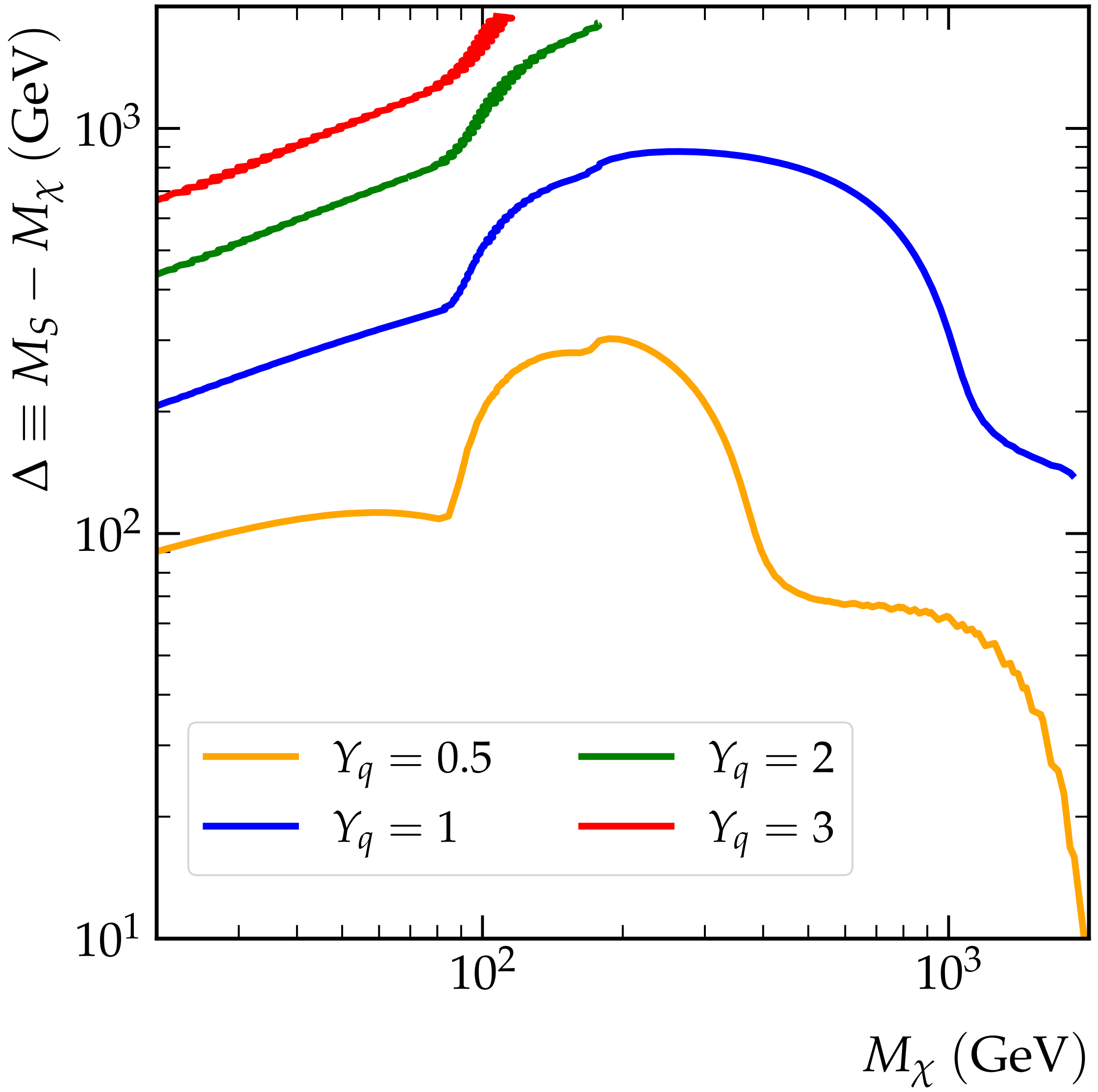
Dark matter relic density

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

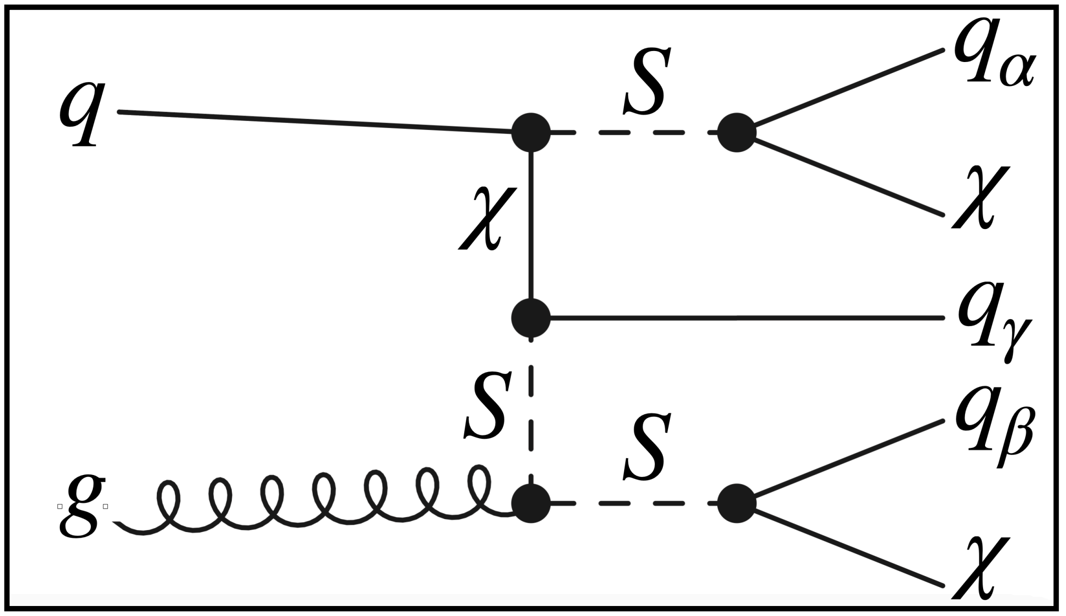
$$\chi\chi \to q_\alpha \bar{q}_\beta \qquad\qquad \chi S \to q_\alpha \gamma/Z/H/g \quad \text{(for } \Delta/M_\chi < 0.1\text{)}$$

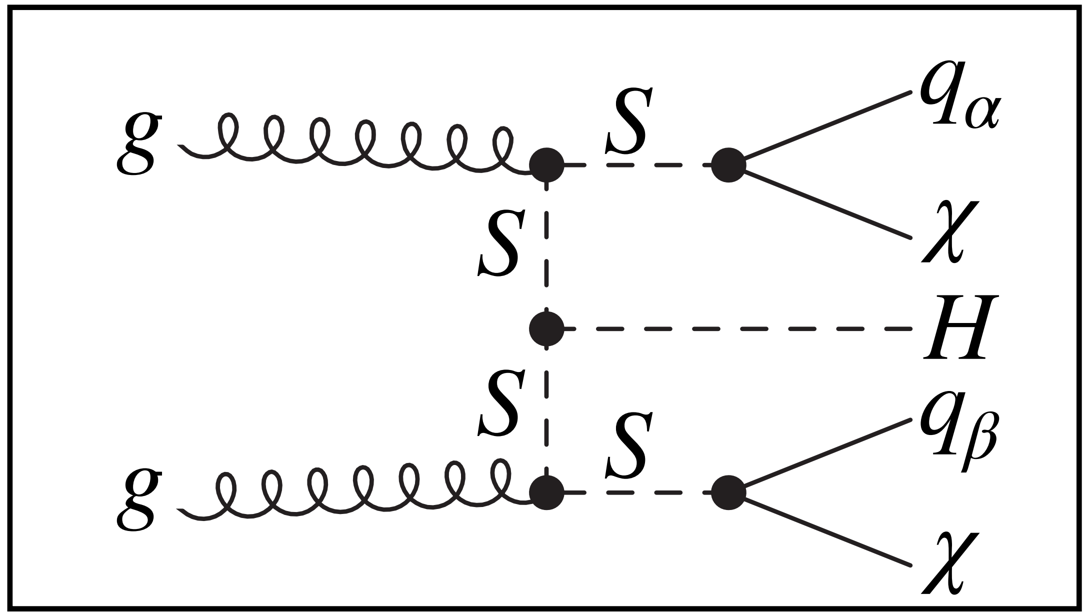


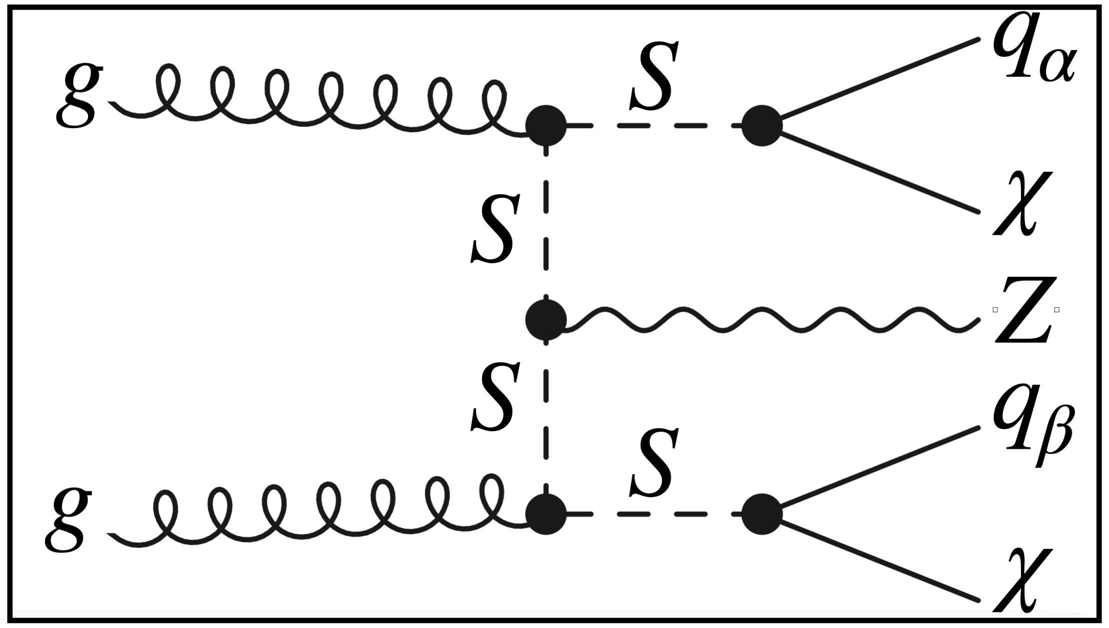
Annihilation **Co-annihilation**



Future prospects at colliders







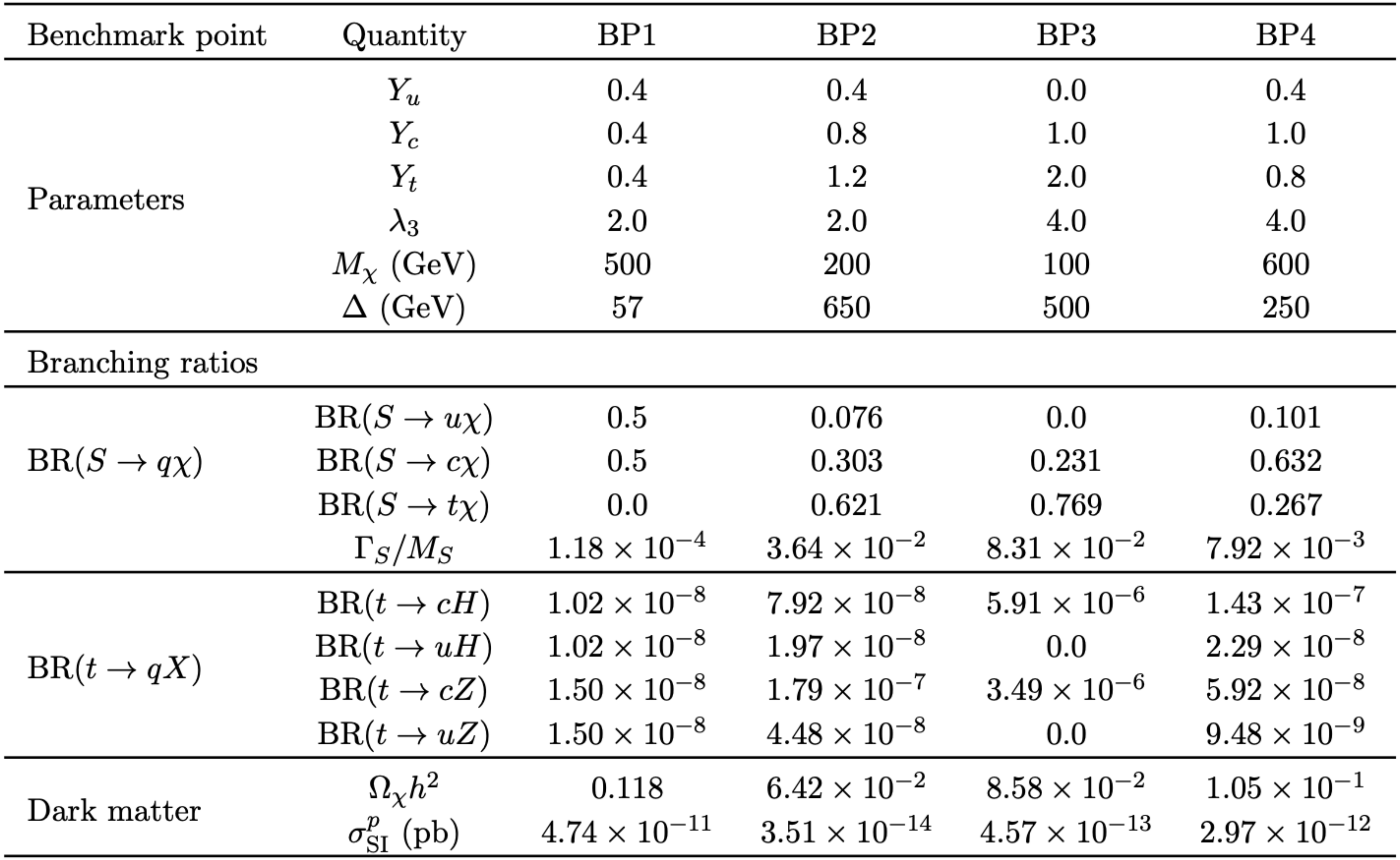
$$\propto Y_{q_\alpha} Y_{q_\beta} Y_{q_\gamma}$$

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

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

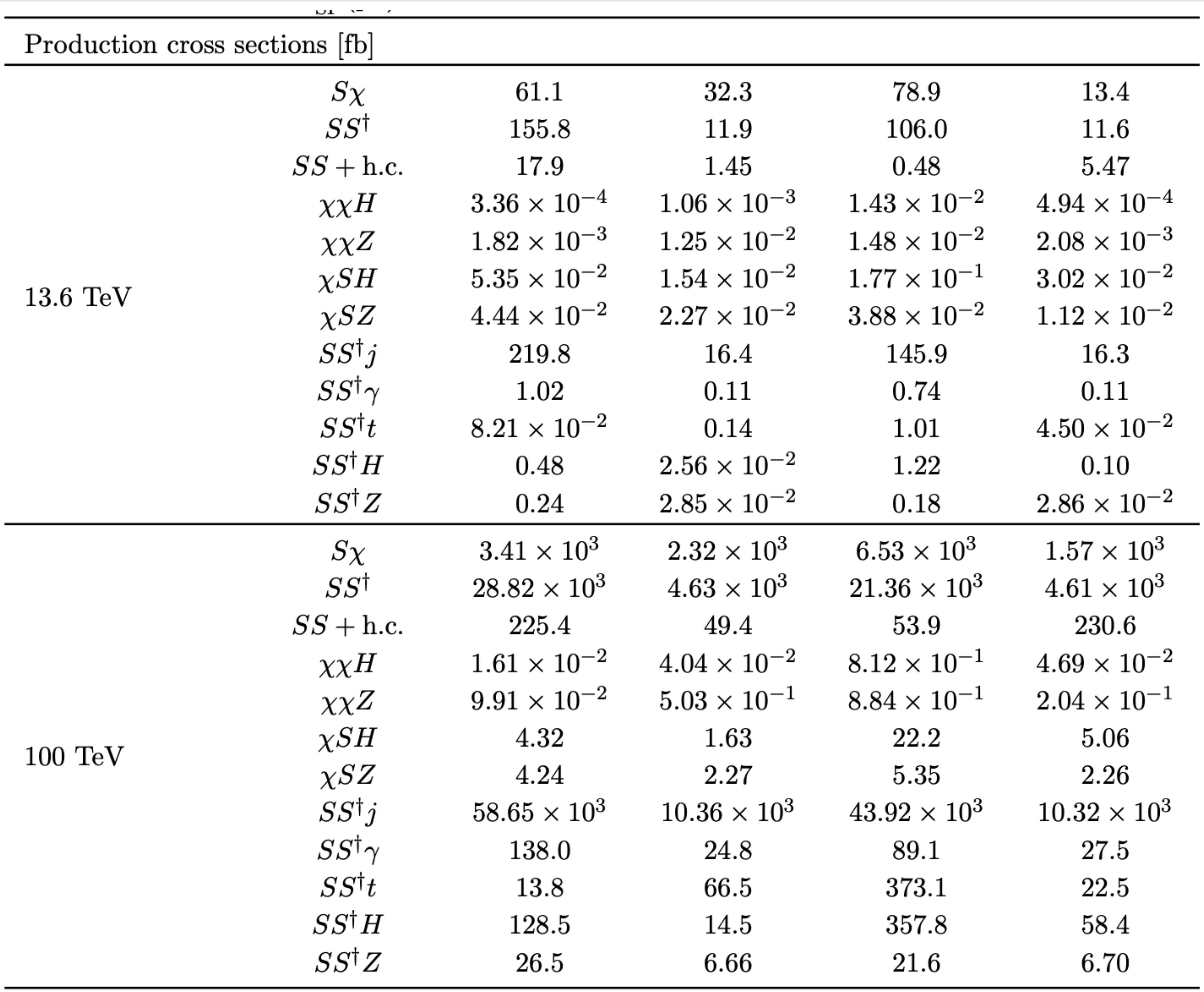
Correlate FCNC and DM for $q_\alpha q_\beta \equiv t\bar{c} + \mathrm{h.c.}$

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					
$\mathrm{BR}(S \to q\chi)$	$\mathrm{BR}(S \to u\chi)$	0.5	0.076	0.0	0.101
	$\mathrm{BR}(S \to c\chi)$	0.5	0.303	0.231	0.632
	$\mathrm{BR}(S \to t\chi)$	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}
$\mathrm{BR}(t \to qX)$	$\mathrm{BR}(t \to cH)$	1.02×10^{-8}	7.92×10^{-8}	5.91×10^{-6}	1.43×10^{-7}
	$\mathrm{BR}(t \to uH)$	1.02×10^{-8}	1.97×10^{-8}	0.0	2.29×10^{-8}
	$\mathrm{BR}(t \to cZ)$	1.50×10^{-8}	1.79×10^{-7}	3.49×10^{-6}	5.92×10^{-8}
	$\mathrm{BR}(t \to uZ)$	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

2. Flavour anomalies

Flavour anomalies

- There are strong hints for the breakdown of the lepton flavour universality in the heavy meson decays…. UPDATE: They are going away!

$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$

$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathrm{BR}(B \to D^{(*)}\ell\nu_\ell)}$$

- To address both the anomalies two species of Leptoquarks are usually introduced

  R_2 models — $(\mathbf{3},\mathbf{2})_{7/6}$ with couplings to taus and electrons (O. Popov, M. Schmidt, G.White, 1905.06339)

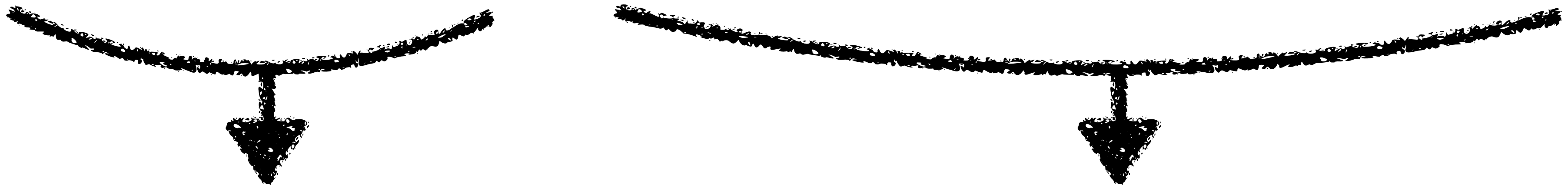
  Two-leptoquark model inspired by GUT: R_2 and S_3. The two Leptoquarks couple to muons and taus (D. Becerivic et al. 1806.05689)

  The singlet-triplet model: S_1 and S_3. Can also addresses the muon anomalous magnetic moment (A. Crivellin, D. Muller, F. Saturnino, 1912.04224)

A simultaneous solution to $R_{D^{(*)}}$ and DM

- **We minimally extend the Standard Model with three extra states: a scalar Leptoquark singlet (S_1), a colored Dirac fermion (χ_1) and a Majorana fermion (χ_0)**

$$S_1 : \ (\mathbf{3}, \mathbf{1})_{-1/3}, \quad \chi_1 : (\mathbf{3}, \mathbf{1})_{-1/3}, \quad \chi_0 : \ (\mathbf{1}, \mathbf{1})_0$$



Even under Z_2

Odd under Z_2

- **The most general Lagrangian is thus given by**

$$\mathscr{L} \supset \mathscr{L}_{\rm kin} + \left[\lambda_{\rm R} \overline{u}_R^c \ell_R S_1^\dagger + \lambda_{\rm L} \overline{Q_L^c} \cdot L_L S_1^\dagger + y_\chi \overline{\chi}_1 \chi_0 S_1 + \mathrm{h.c.}\right]$$

Link to the FR model file: https://feynrules.irmp.ucl.ac.be/wiki/LQDM

Benchmark slopes and benchmark scenarios

- The results shown in the previous slide are displayed in the plane defined by

$$\tilde{\lambda}_L \equiv (\lambda_L)_{33}(\mathrm{TeV}/M_{S_1}) \text{ and } \tilde{\lambda}_R \equiv (\lambda_R)_{23} \; (\mathrm{TeV}/M_{S_1})$$

- A choice of $\tilde{\lambda}_L$ and $\tilde{\lambda}_R$ defines a benchmark slope (BS) while adding the LQ mass define the benchmark scenario (BS)

BS1a

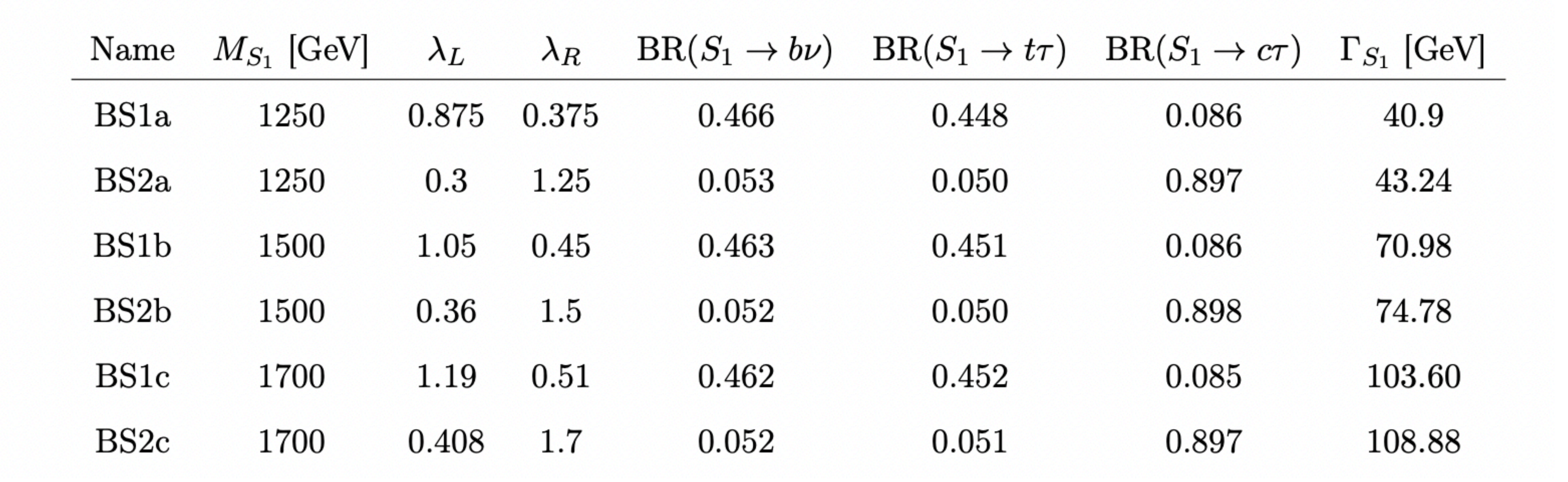
Latin character defines the benchmark scenario

Arab numeral defines the benchmark slope

Two benchmark slopes are defined throughout this study:

- **BS1:** $(\tilde{\lambda}_L, \tilde{\lambda}_R) = (0.7,\ 0.3)$
- **BS2:** $(\tilde{\lambda}_L, \tilde{\lambda}_R) = (0.24,\ 1.0)$

Benchmark slopes and benchmark scenarios



Name	M_{S_1} [GeV]	λ_L	λ_R	$\mathrm{BR}(S_1 \to b\nu)$	$\mathrm{BR}(S_1 \to t\tau)$	$\mathrm{BR}(S_1 \to c\tau)$	Γ_{S_1} [GeV]
BS1a	1250	0.875	0.375	0.466	0.448	0.086	40.9
BS2a	1250	0.3	1.25	0.053	0.050	0.897	43.24
BS1b	1500	1.05	0.45	0.463	0.451	0.086	70.98
BS2b	1500	0.36	1.5	0.052	0.050	0.898	74.78
BS1c	1700	1.19	0.51	0.462	0.452	0.085	103.60
BS2c	1700	0.408	1.7	0.052	0.051	0.897	108.88

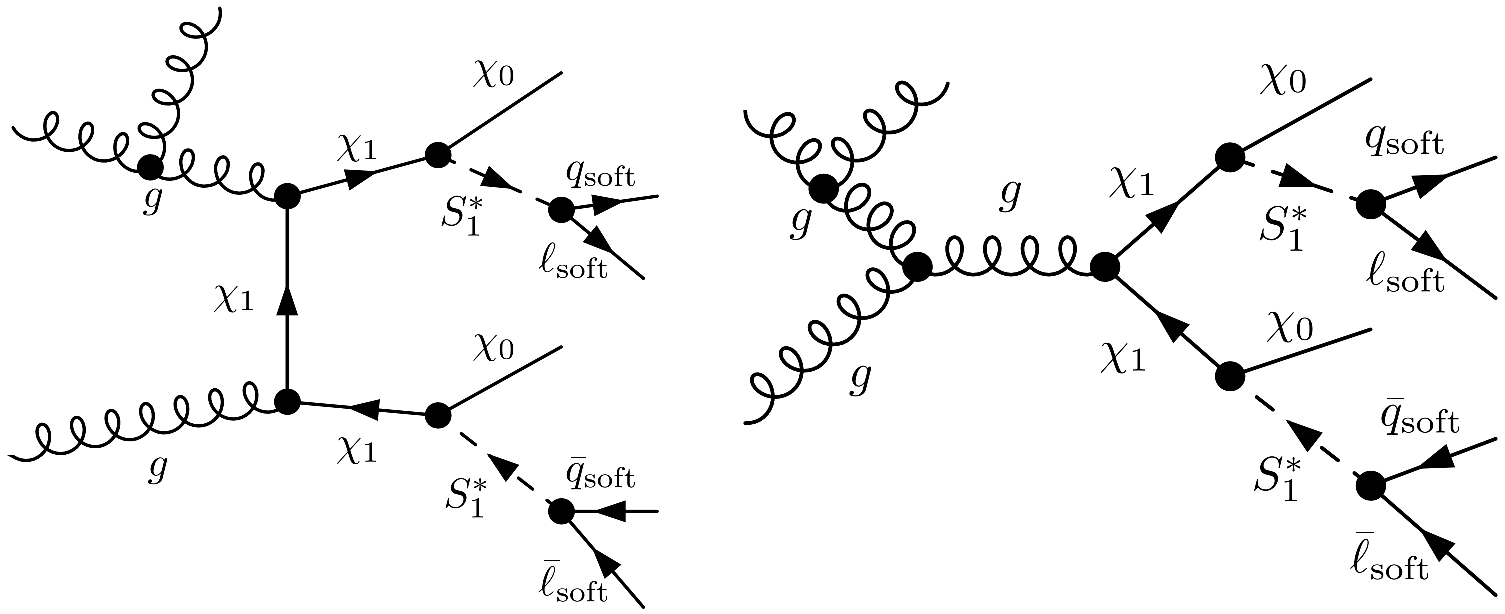
Some characteristics of the Benchmark scenarios being used for $y_\chi = 0$

LHC constraints: Introduction

In this model, we have three major classes of LHC constraints:

- Missing energy searches: In this case, a pair of χ_1 particles are produced and then decays into $\ell q \chi_0$. Depending on the mass splitting, one can have various signatures: mono-jet, soft-lepton, multijet+MET, tautau+MET
- Leptoquark searches: This case has two sub-categories which are either through leptoquark pair production (lead to two quarks+two leptons) or single leptoquark production (leads to one lepton and two quarks).
- Resonant leptoquark plus MET: This can be relevant in case of leptoquark pair production with one leptoquark decays to quark and lepton and the other one invisibly.

LHC constraints: MET searches



Search	arXiv	$\mathcal{L}$ [fb^{-1}]	BS1	BS2
CMS b/c + MET	1707.07274 [45]	35.9	✓	X
ATLAS $b\bar b$+MET	2101.12527 [46]	139	✓	X
CMS $\ell_{\rm soft}$ + MET	1801.01846 [47]	35.9	X	✓
ATLAS mono-jet	2102.10874 [48]	139	✓	✓
ATLAS $\tau^+\tau^-$+MET	1911.06660 [49]	139	X	✓
ATLAS multi-jet	2010.14293 [50]	139	X	✓

$$pp \to \bar\chi_1\chi_1 \to (\chi_0\ell q)\ (\chi_0\bar\ell\bar q)$$

$m_b < \Delta < m_t$

Main decays of χ_1:

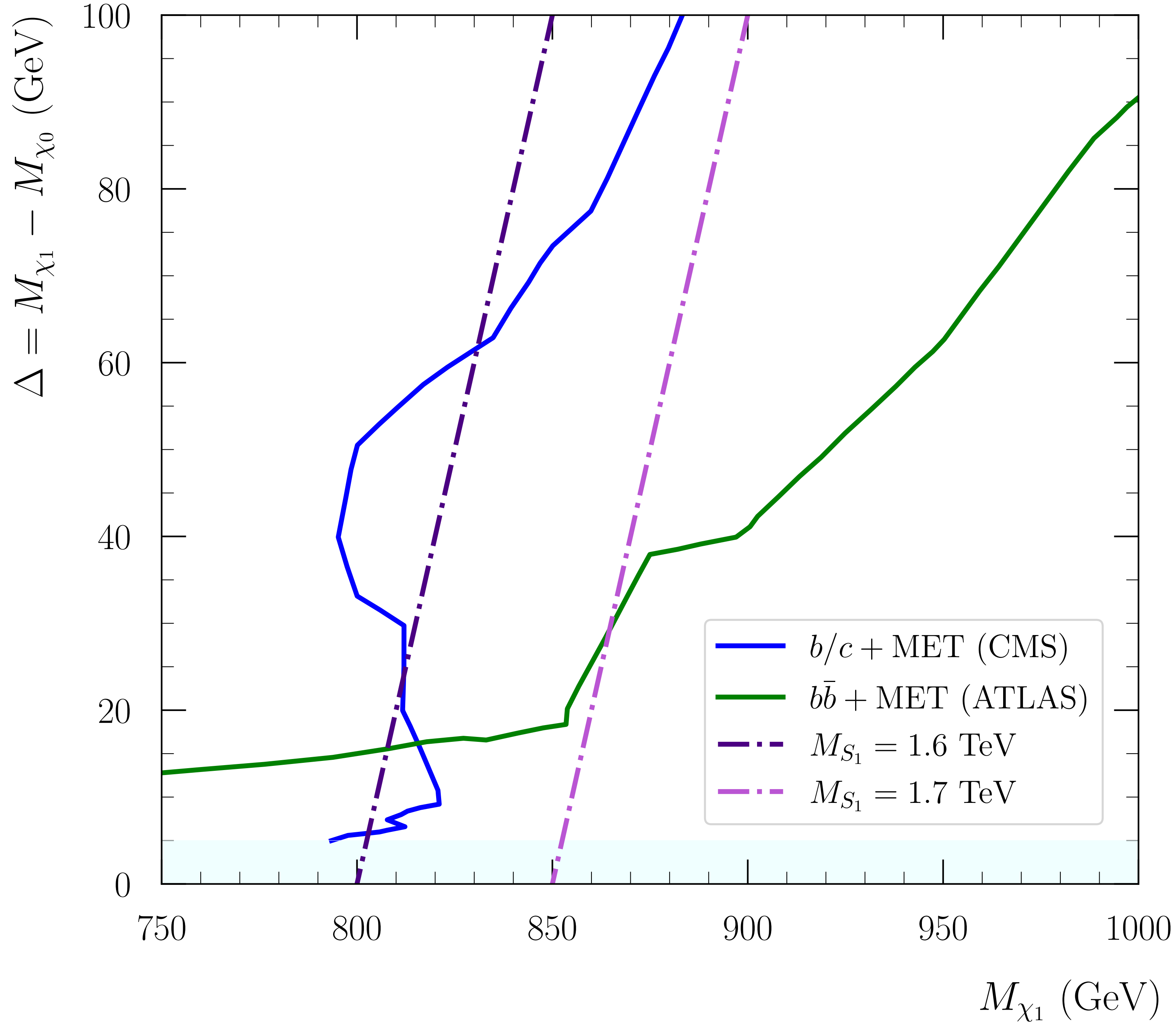
- $\chi_1 \to b\nu\chi_0$ (BS1)
- $\chi_1 \to c\tau\chi_0$ (BS2)

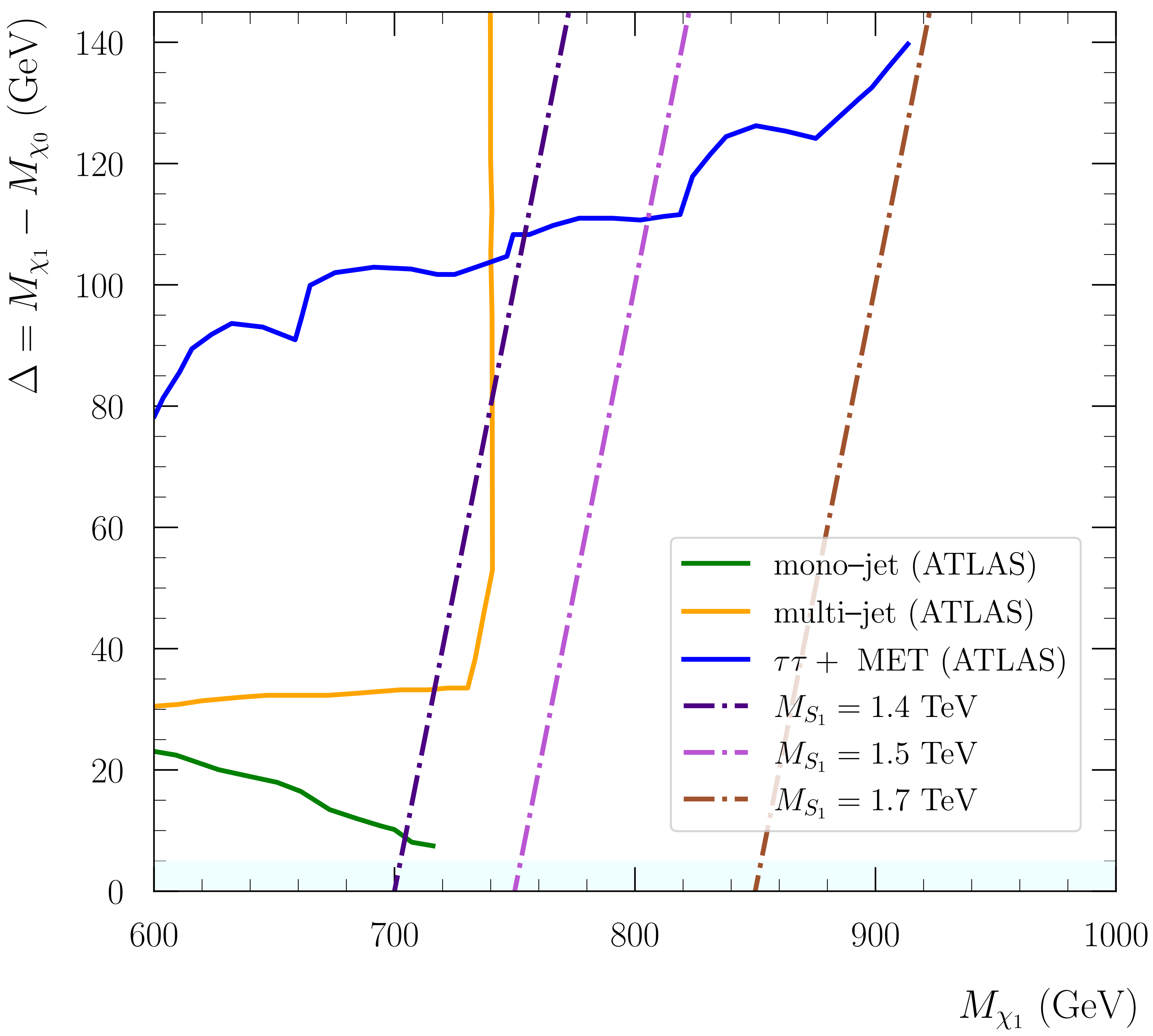
$\Delta < m_b$

χ_1 is long-lived particle and decays exclusively into

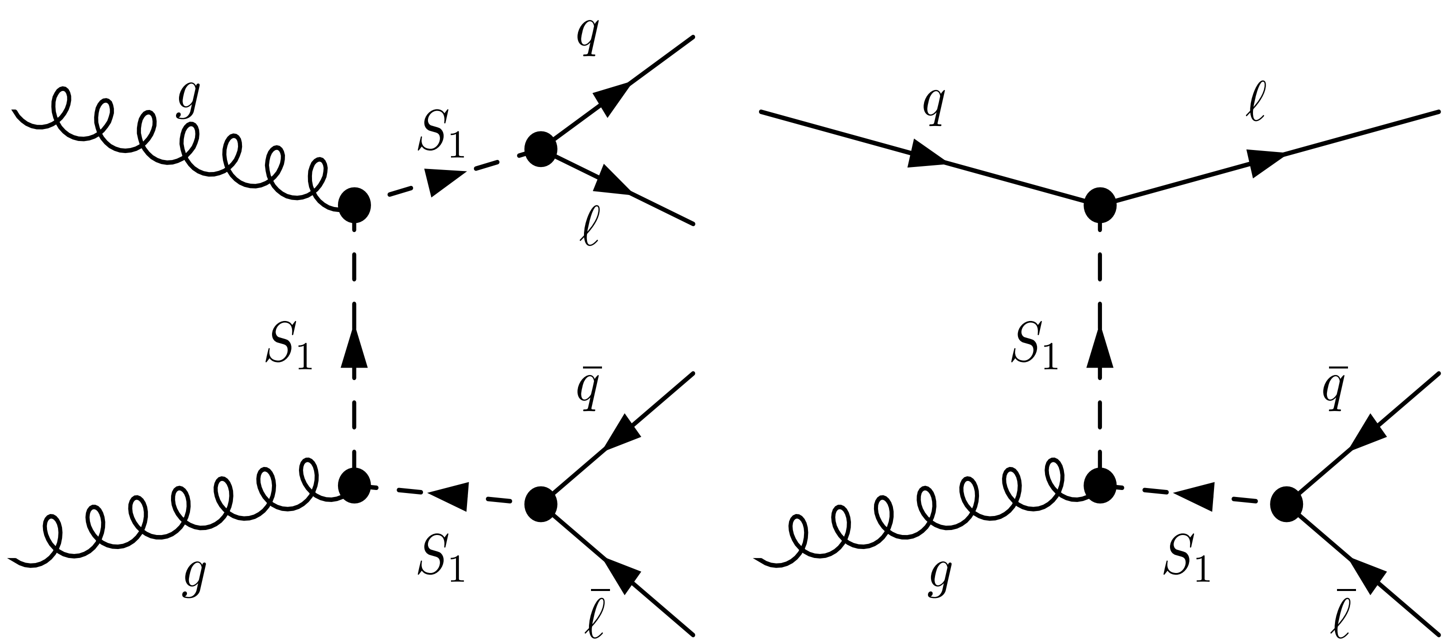
- $\chi_1 \to c\tau\chi_0$

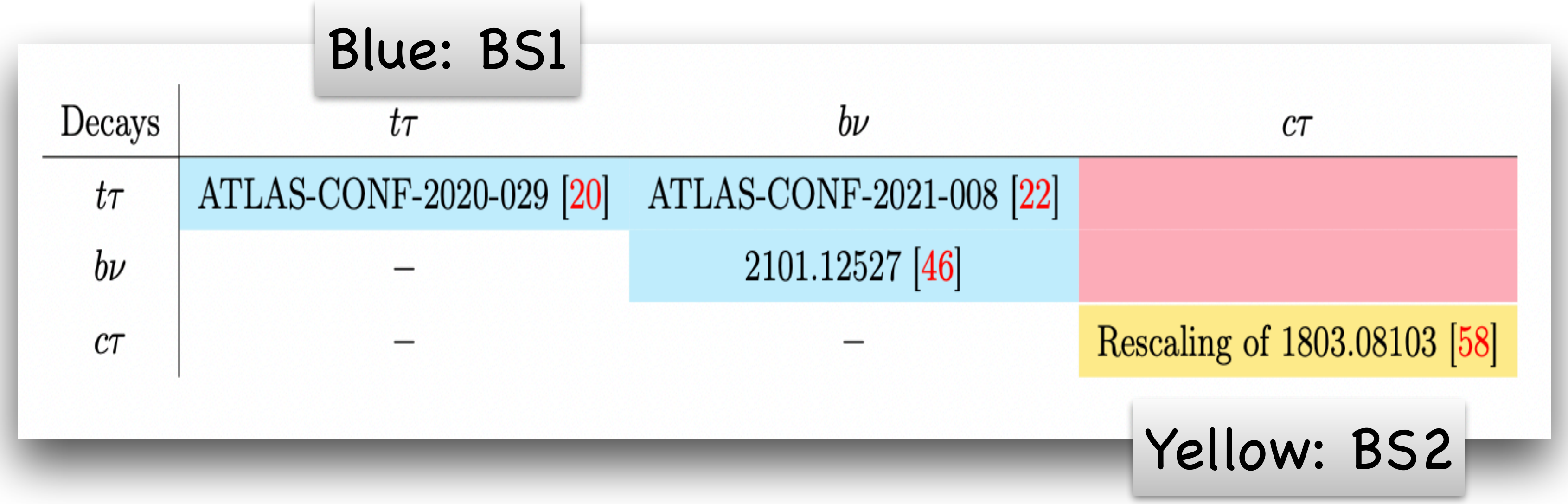
LHC constraints: MET searches





LHC constraints: Leptoquark searches

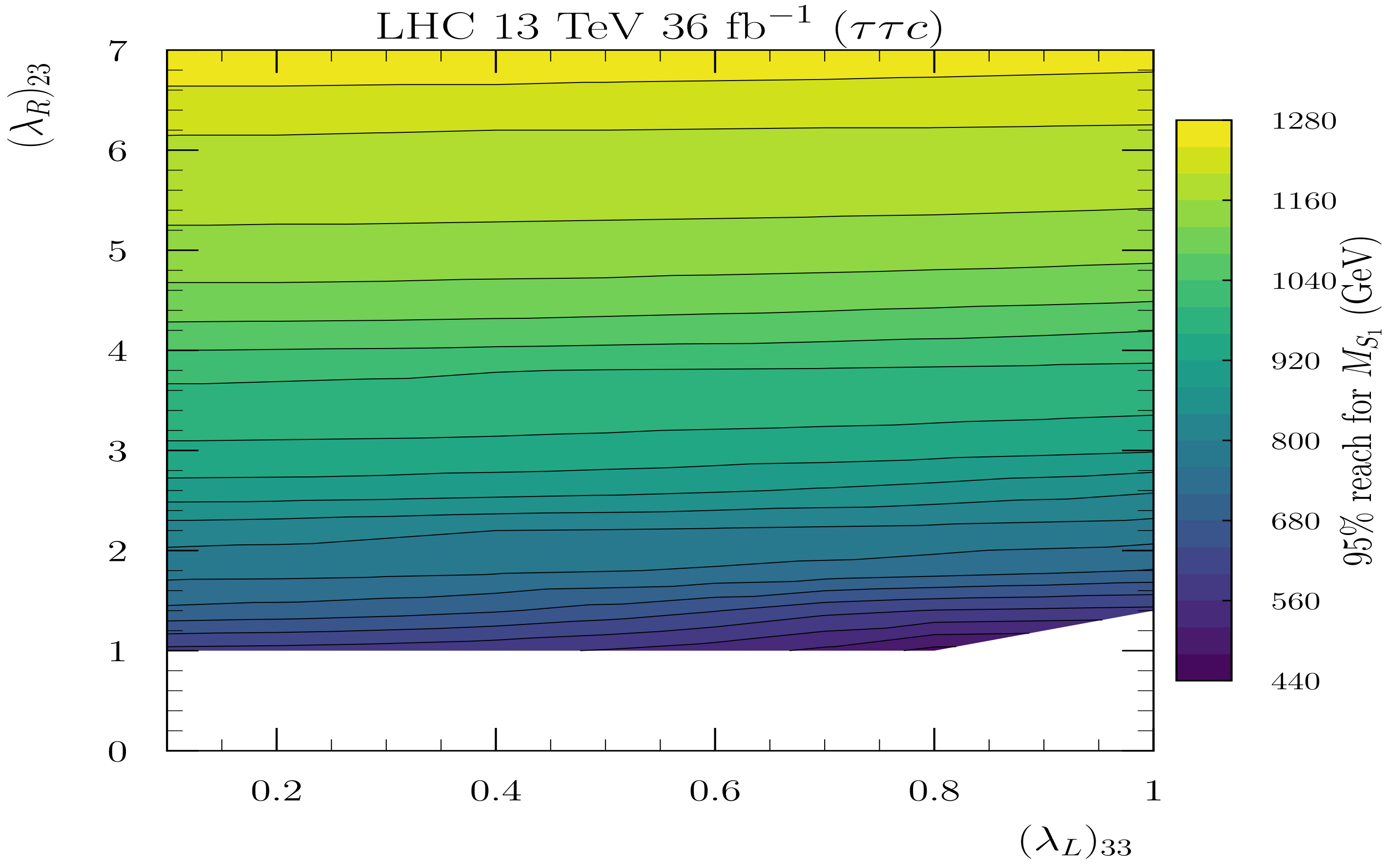


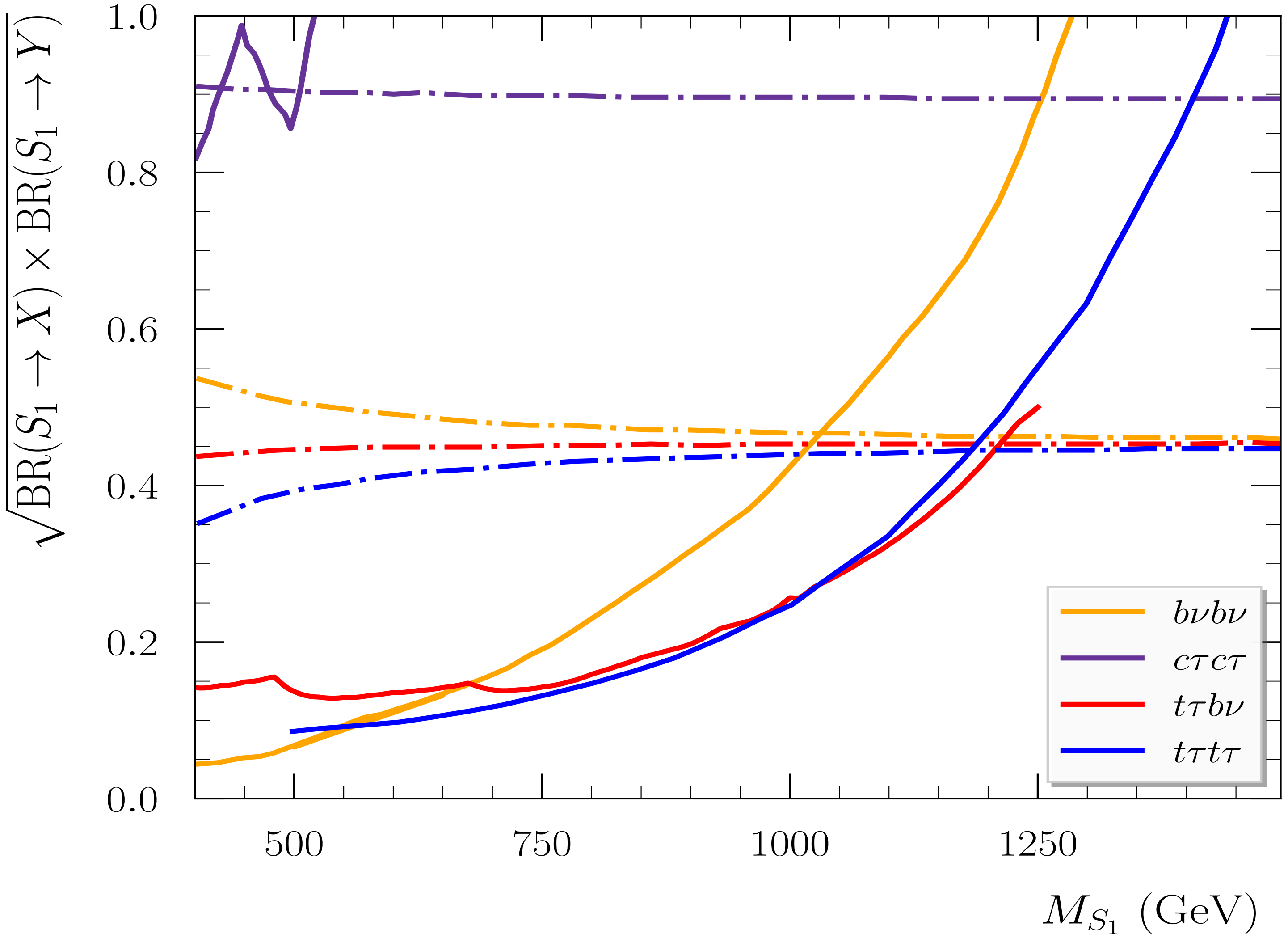


Blue: BS1

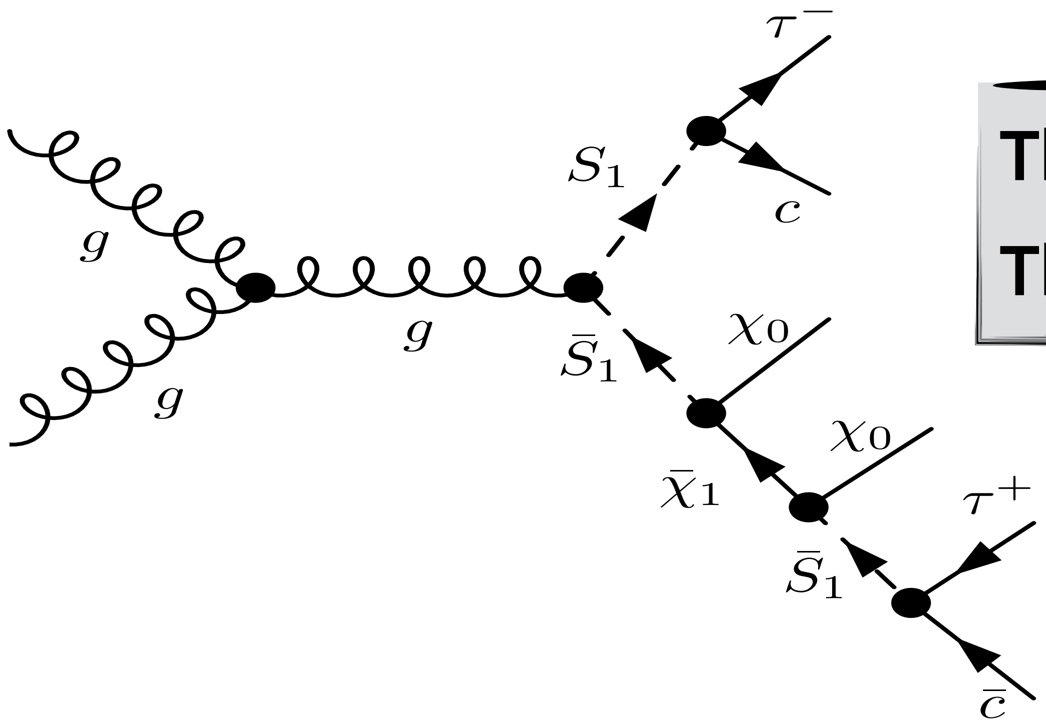
Decays	$t\tau$	$b\nu$	$c\tau$
$t\tau$	ATLAS-CONF-2020-029 [20]	ATLAS-CONF-2021-008 [22]	
$b\nu$	–	2101.12527 [46]	
$c\tau$	–	–	Rescaling of 1803.08103 [58]

Yellow: BS2





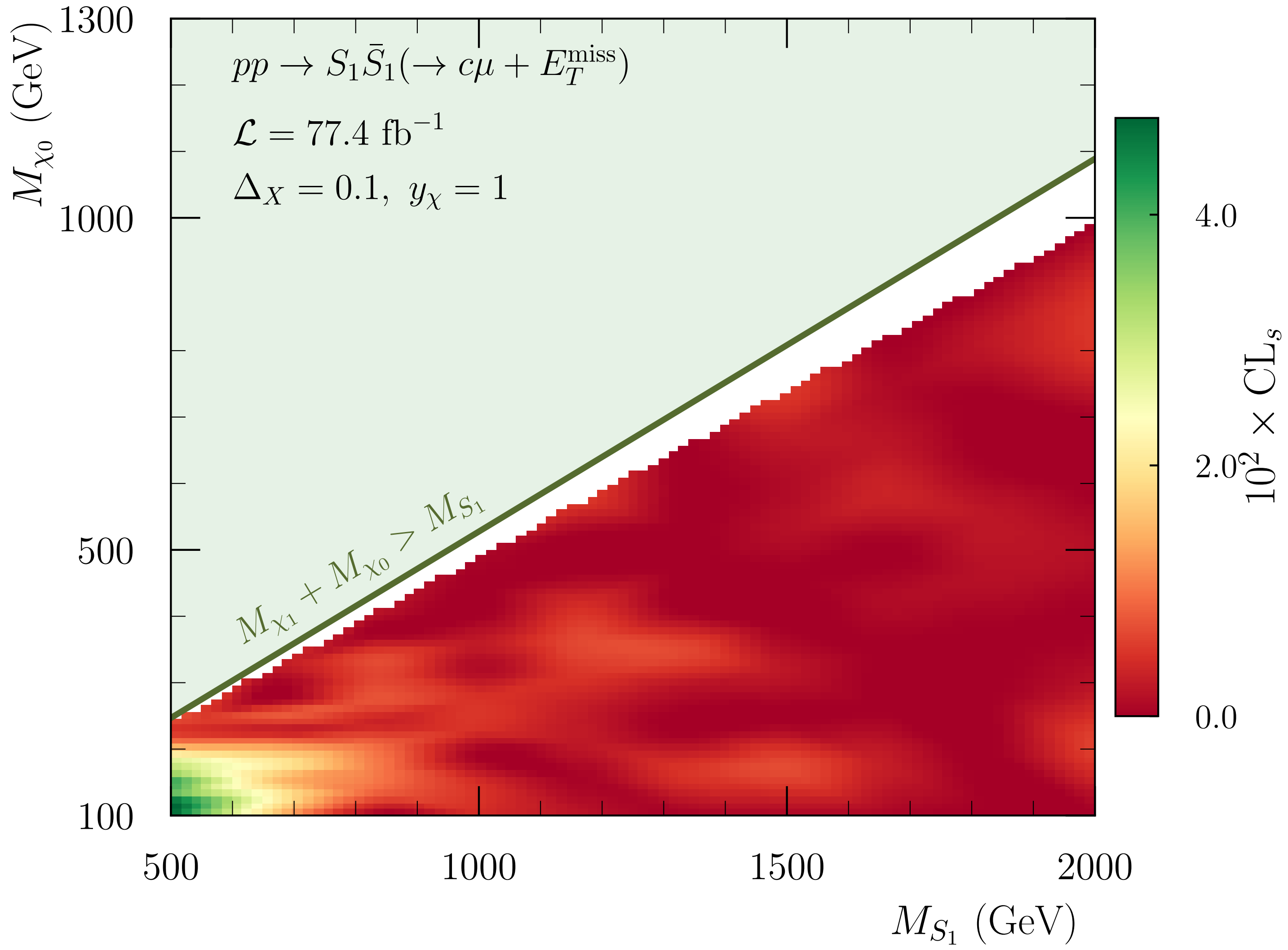
LHC constraints: Resonant Leptoquark plus MET searches



There is only one search which targets $c\mu + E_T^{\rm miss}$ (BS2)

The implementation of this analysis exists in MA5 (B. Fuks, AJ, 2021)

- **BS2 scenario is sensitive to the bounds reported on by the CMS search.**
- **All the muons in this case are coming from leptonically decaying tau leptons.**
- **Low sensitivity because of the small branching ratios $\Longrightarrow$ the resulting muons are soft.**



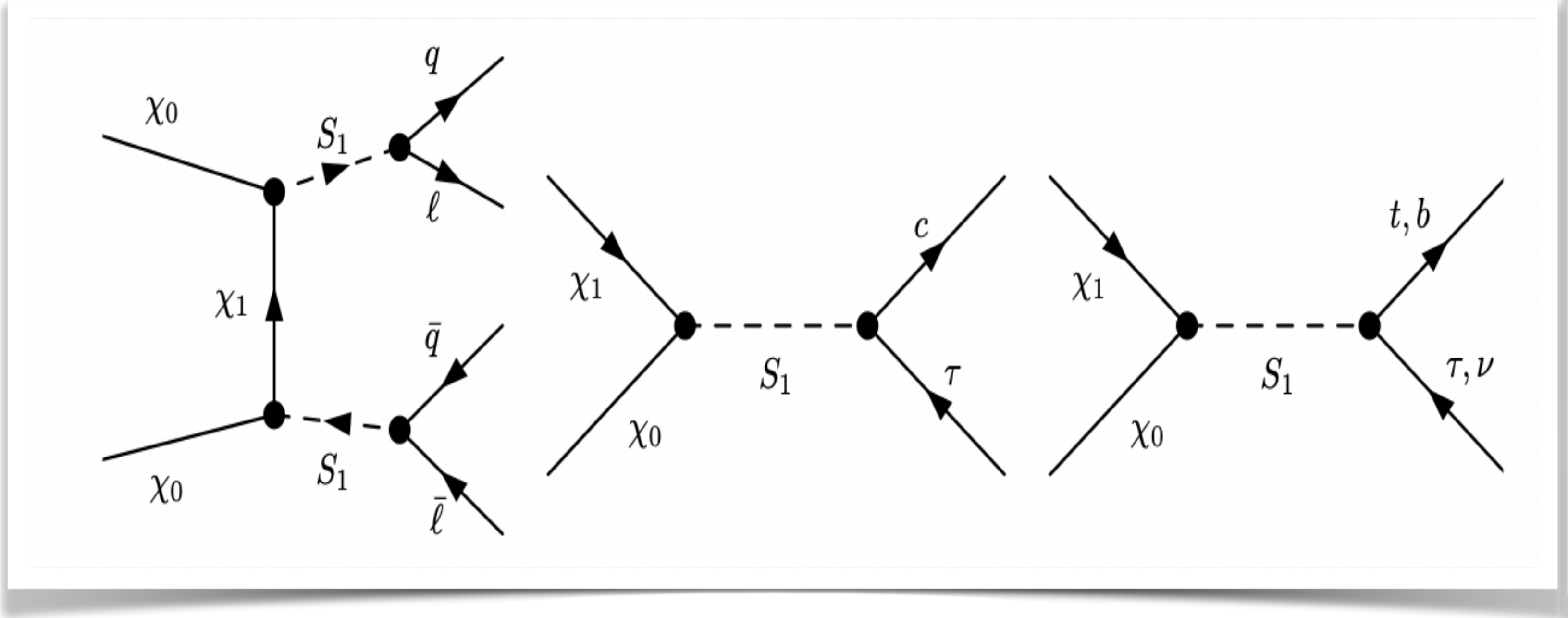
Dark matter relic density

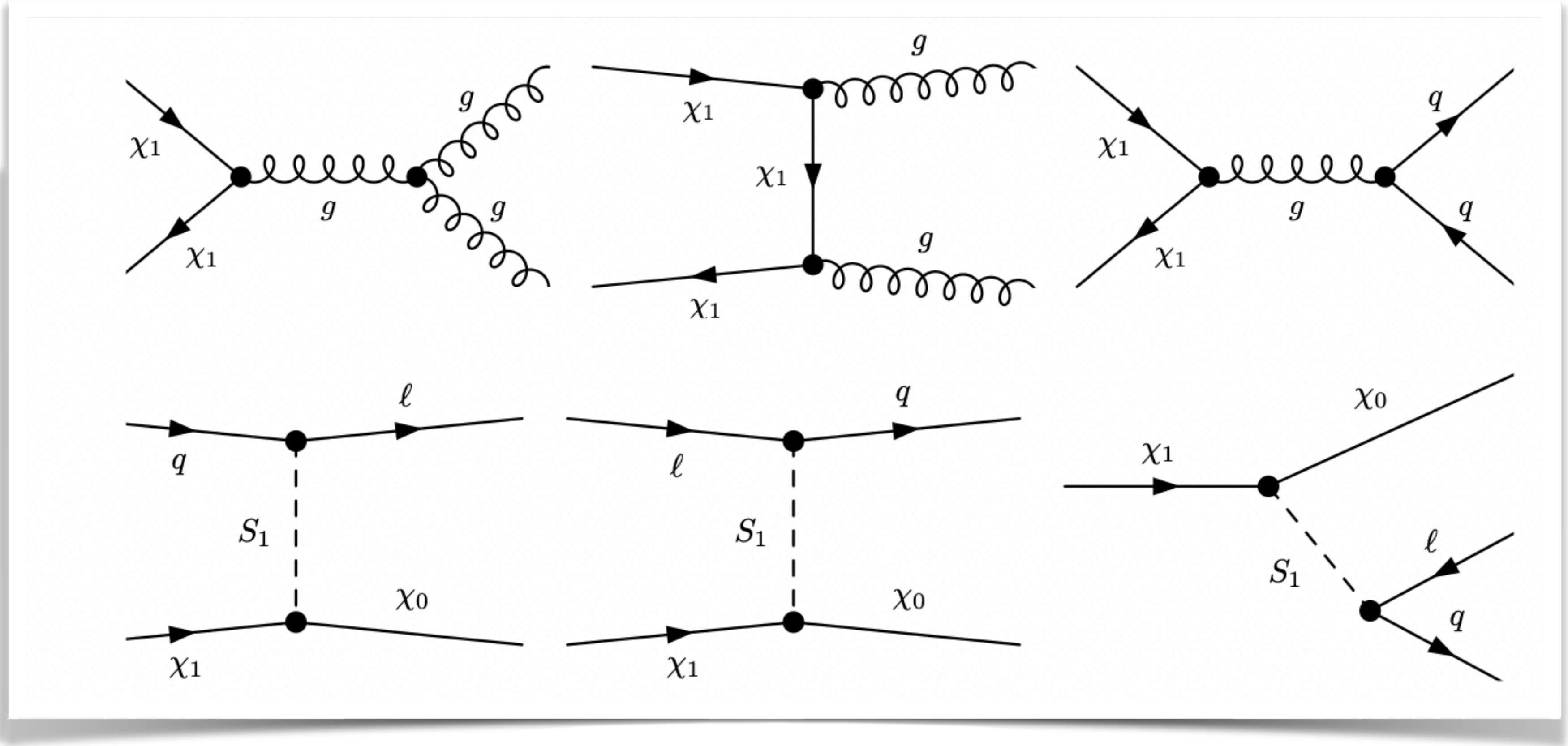
- The relic density of χ_0 can be produced in three different scenarios:

  Conversion-driven freeze-out (CDFO): interaction in the dark sector (requires very small mass-splitting and small couplings).

  Freeze-out with co-annihilation: Small mass splitting between χ_0 and χ_1.

  Freeze-out with annihilation: No requirements (lead to four body final states…)

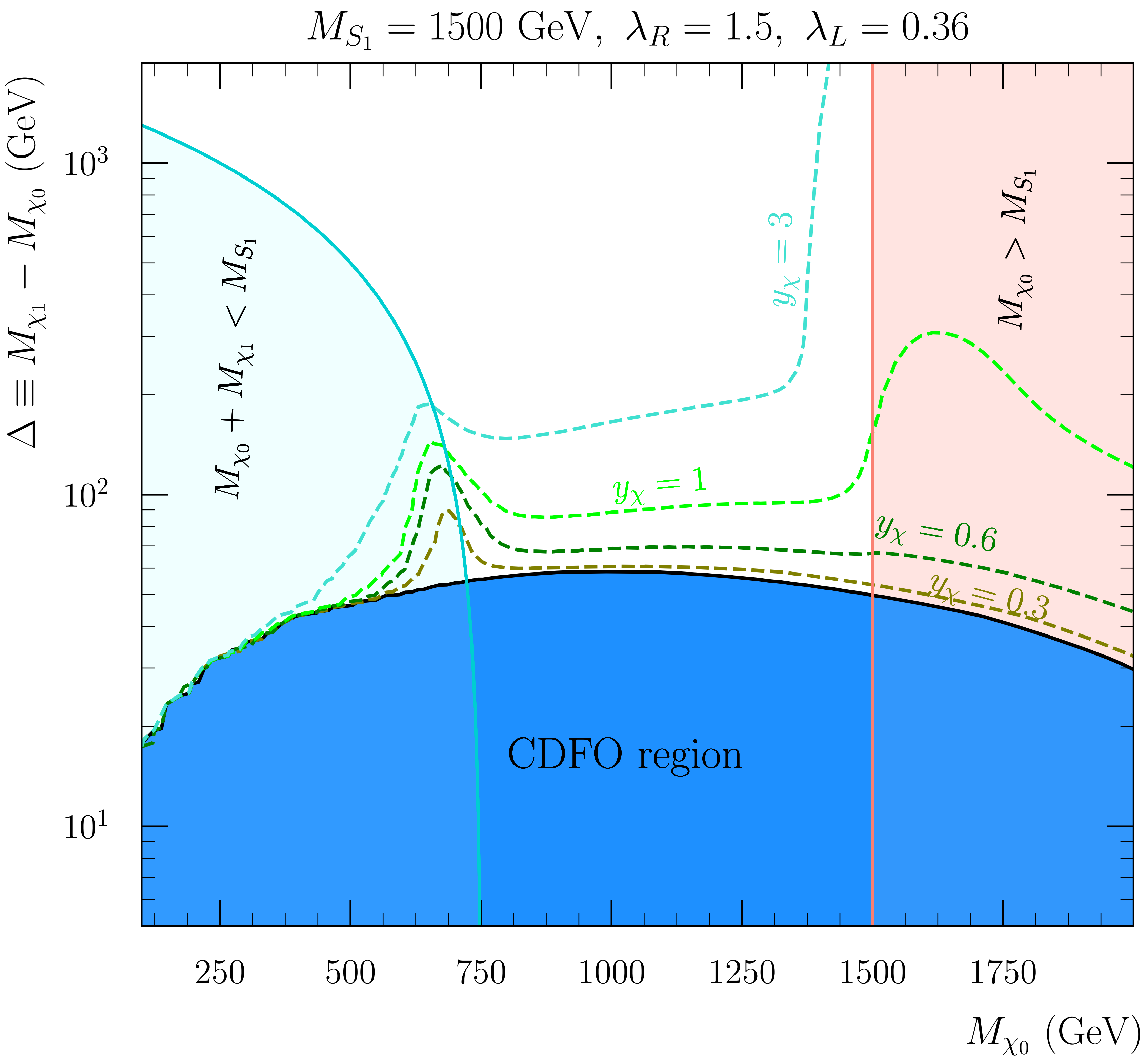




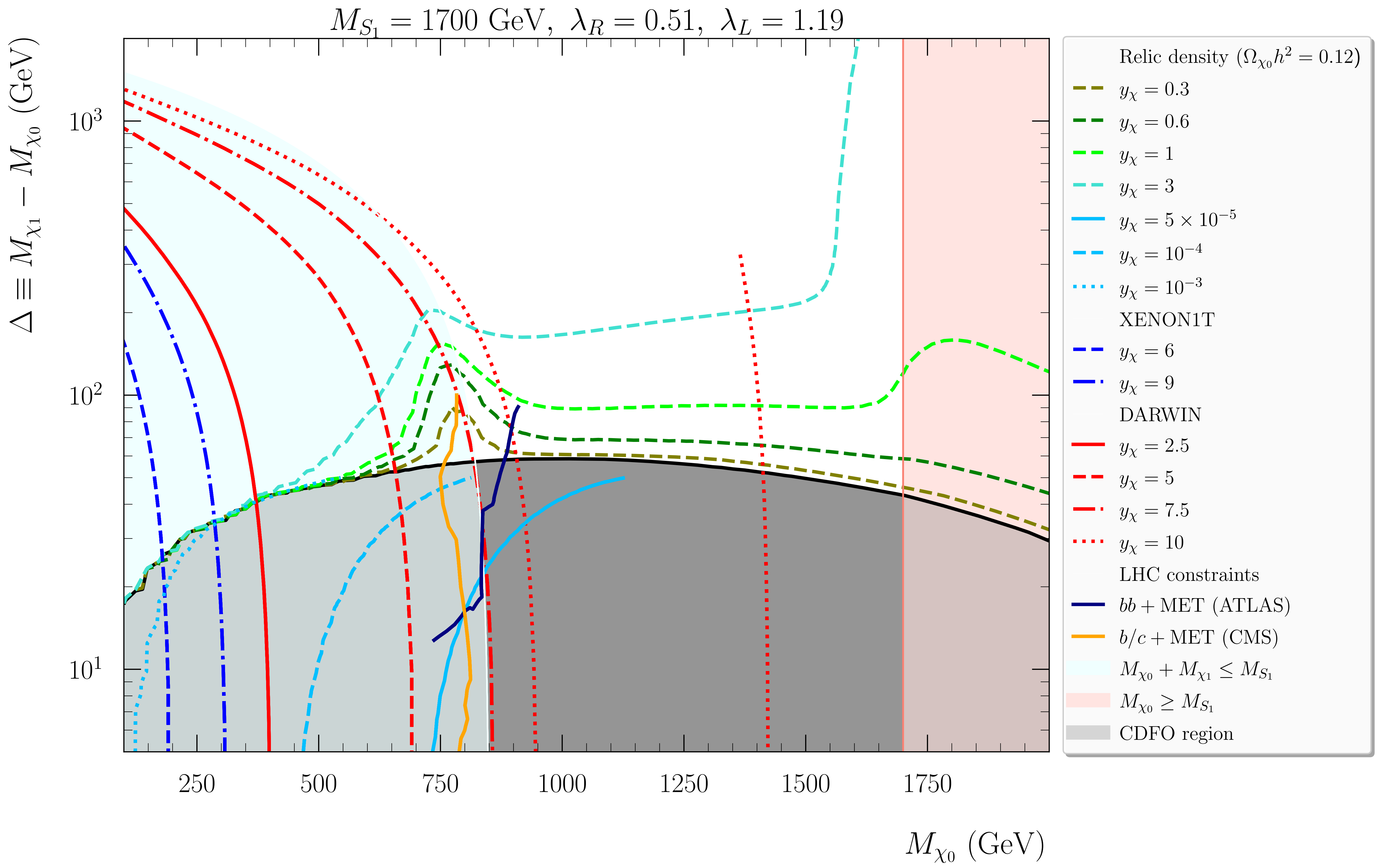
Freeze out

Conversion-driven freeze-out (CDFO)

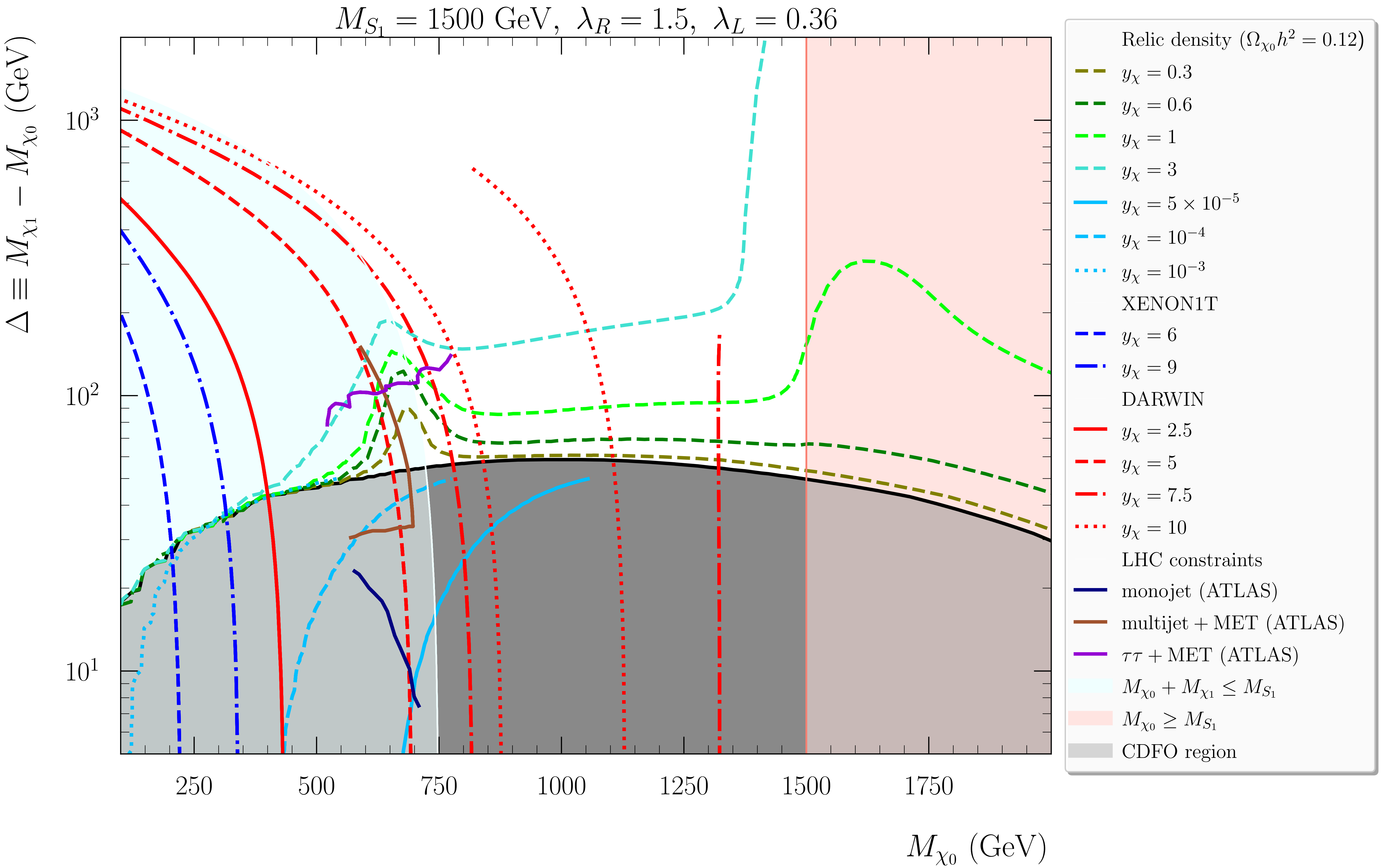
Dark matter relic density



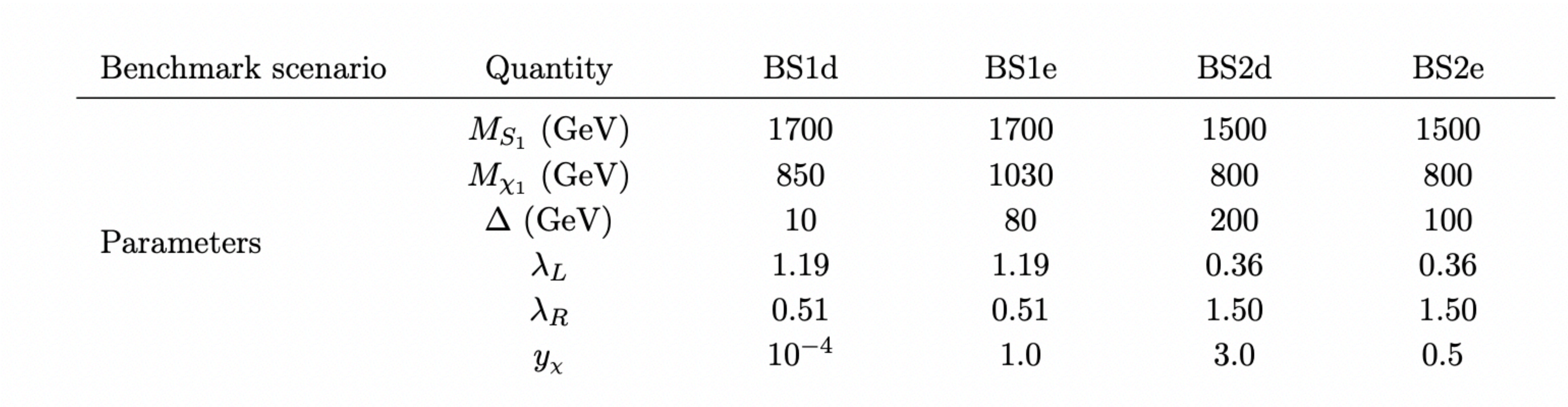
The money plot (BS1)



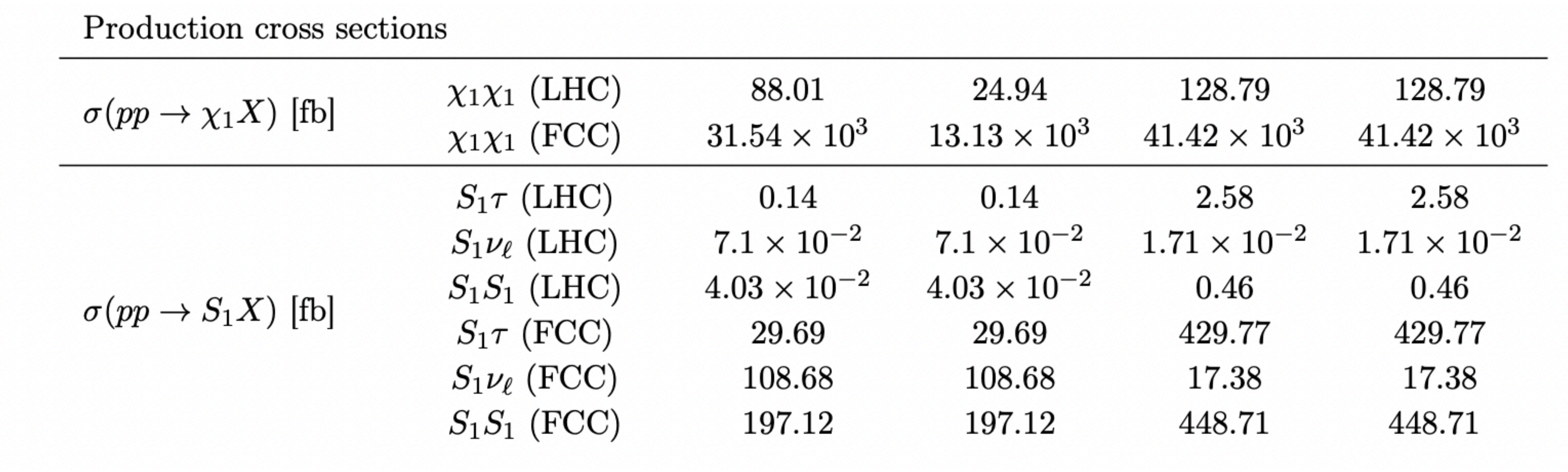
The money plot (BS2)



Benchmark scenarios for future searches



Benchmark scenario	Quantity	BS1d	BS1e	BS2d	BS2e
Parameters	M_{S_1} (GeV)	1700	1700	1500	1500
	M_{χ_1} (GeV)	850	1030	800	800
	Δ (GeV)	10	80	200	100
	λ_L	1.19	1.19	0.36	0.36
	λ_R	0.51	0.51	1.50	1.50
	y_χ	10^{-4}	1.0	3.0	0.5



Production cross sections					
$\sigma(pp \to \chi_1 X)$ [fb]	$\chi_1\chi_1$ (LHC)	88.01	24.94	128.79	128.79
	$\chi_1\chi_1$ (FCC)	31.54×10^3	13.13×10^3	41.42×10^3	41.42×10^3
$\sigma(pp \to S_1 X)$ [fb]	$S_1\tau$ (LHC)	0.14	0.14	2.58	2.58
	$S_1\nu_\ell$ (LHC)	7.1×10^{-2}	7.1×10^{-2}	1.71×10^{-2}	1.71×10^{-2}
	S_1S_1 (LHC)	4.03×10^{-2}	4.03×10^{-2}	0.46	0.46
	$S_1\tau$ (FCC)	29.69	29.69	429.77	429.77
	$S_1\nu_\ell$ (FCC)	108.68	108.68	17.38	17.38
	S_1S_1 (FCC)	197.12	197.12	448.71	448.71

Conclusions

- In this talk, I discussed two interesting scenarios for BSM physics:
    - Solution to DM and flavor anomalies
    - DM as trigger of larger top quark FCNC decays

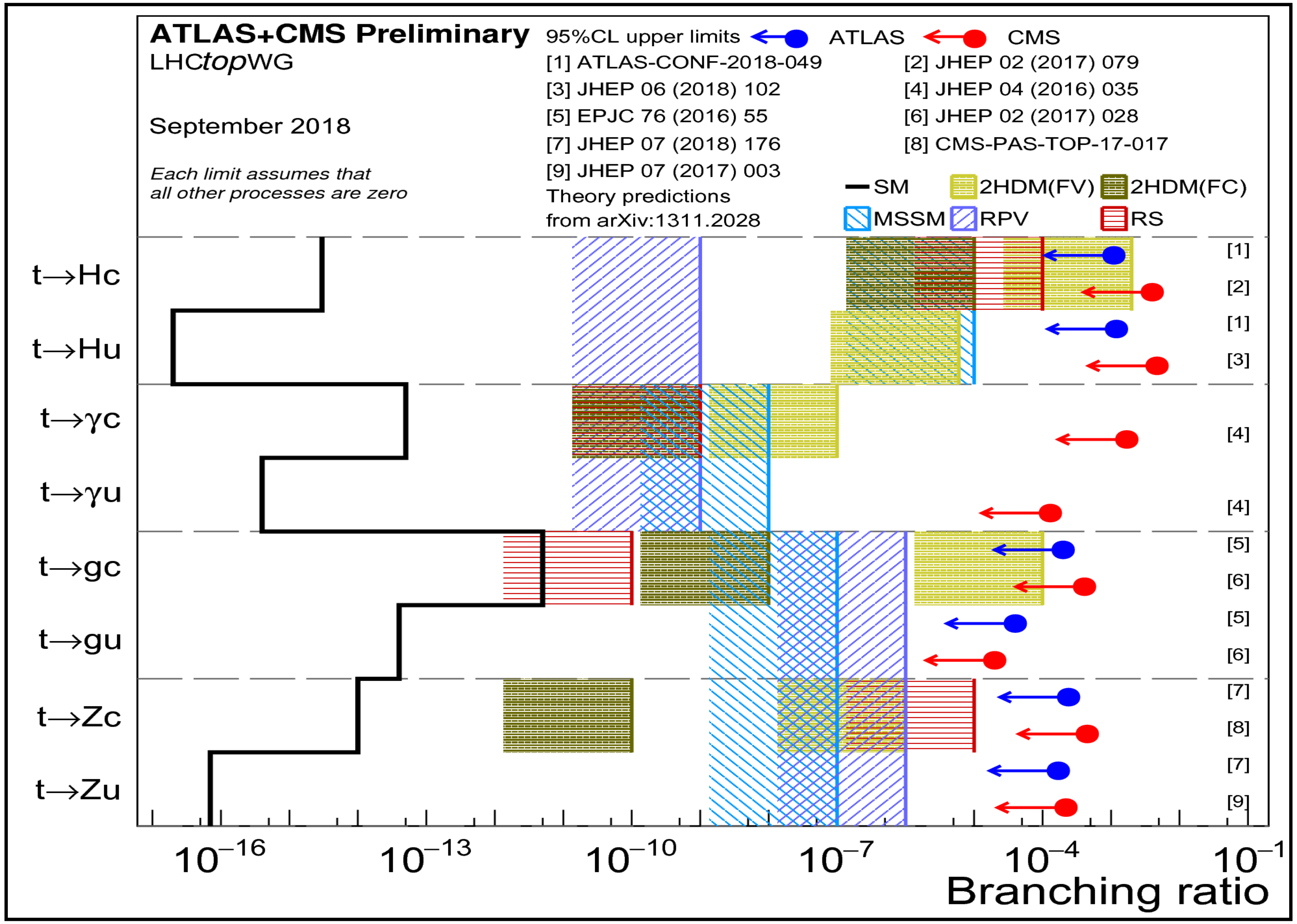
- The two models are minimal extensions of the SM with $SU(2)_L$singlets.

- Decent rates for top quark FCNC decays are predicted while not being in conflict with current LHC data and more work is needed to probe the connection between the two sectors.

- We have found some holes in the ATLAS/CMS searches of leptoquark pairs at the LHC notably the mixed ones: $c\tau t\tau$ and $c\tau b\nu$ and that more work is needed in the resonant LQ plus MET searches.

3. Back-up slides

Searches for top quark FCNC decays at the LHC



The decays of the mediator of top FCNCs

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.**

Top quark FCNC decays

For $t \to qH$, we have

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

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

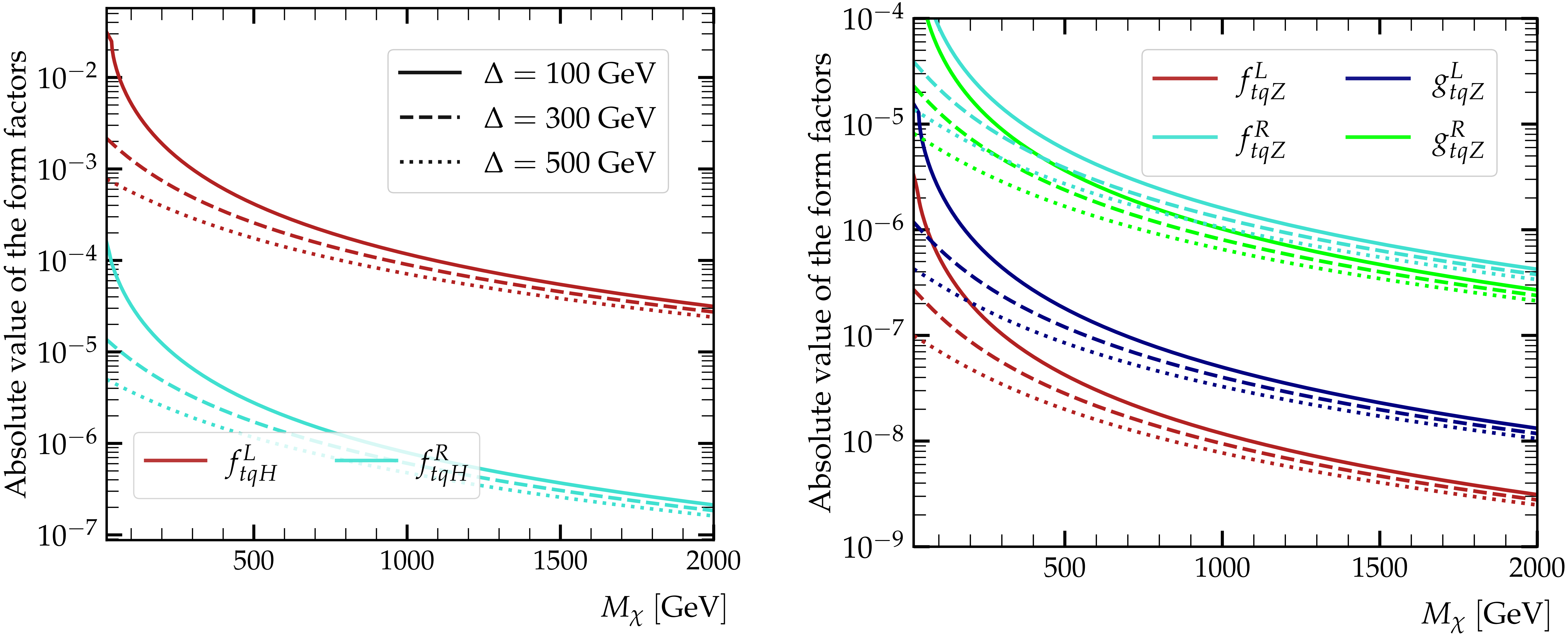
For $t \to qZ$, we have

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

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

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

Top quark FCNC decays



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

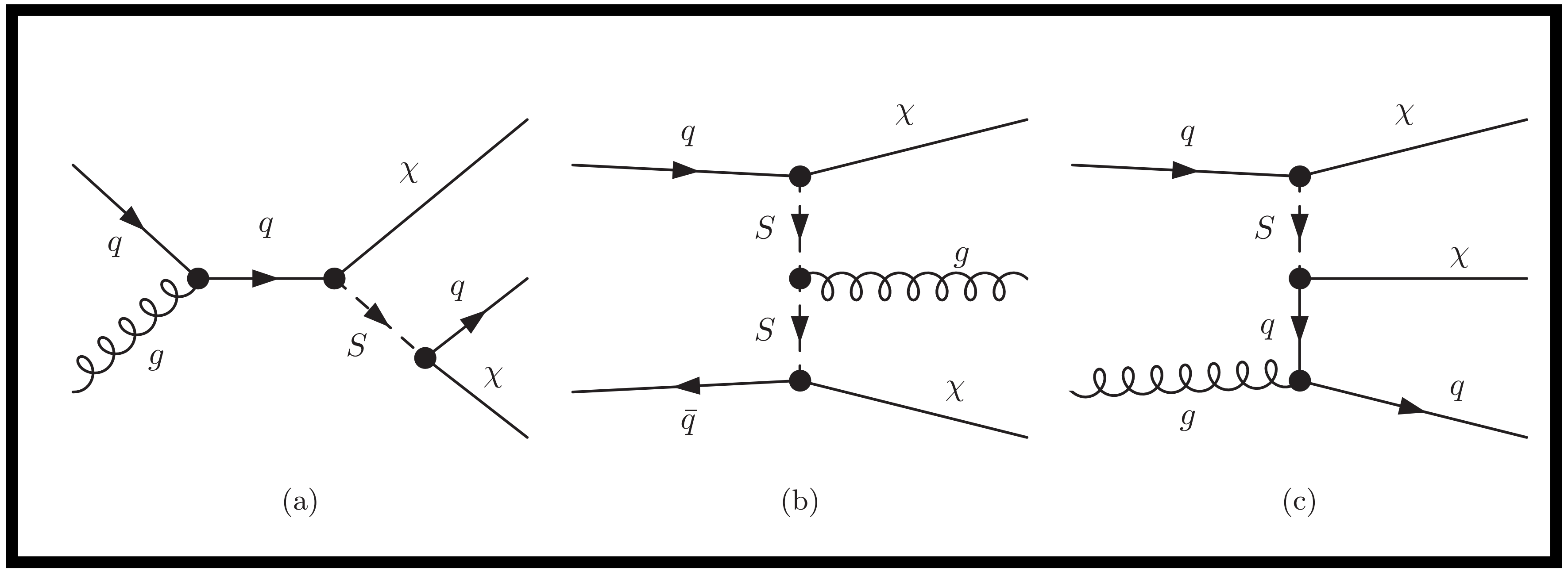
Collider bounds: monojet

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 $E_T^{\rm miss}$



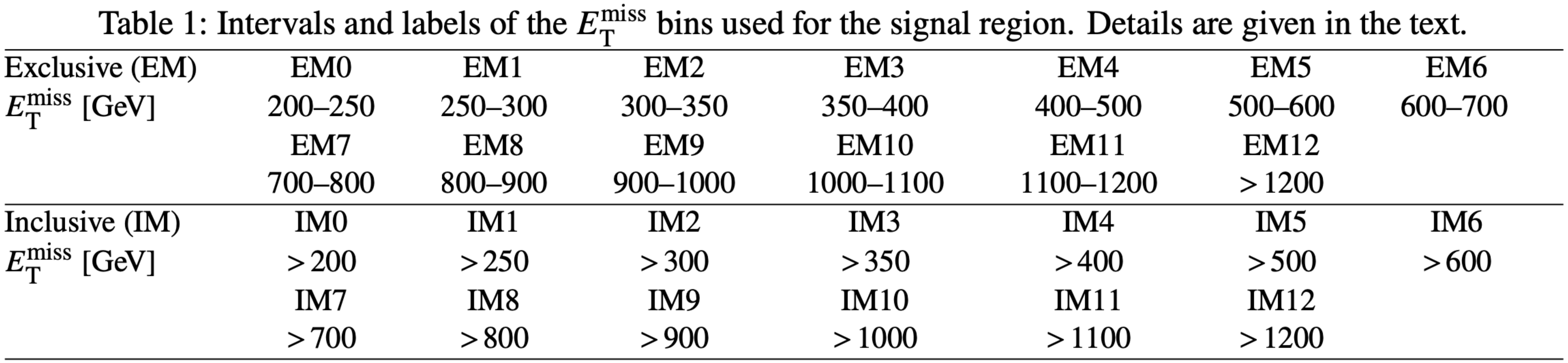
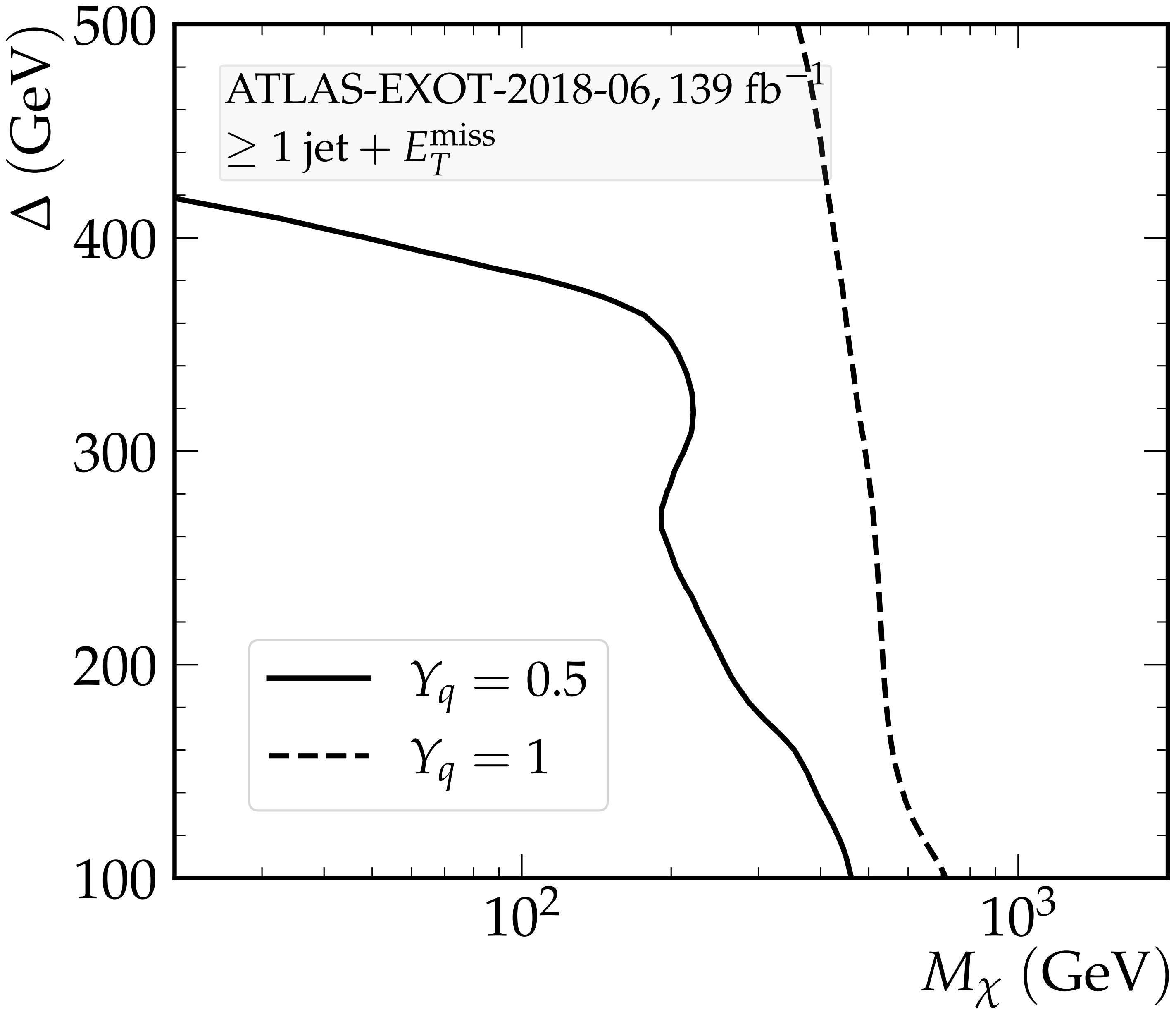


Table 1: Intervals and labels of the $E_{\rm T}^{\rm miss}$ bins used for the signal region. Details are given in the text.

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

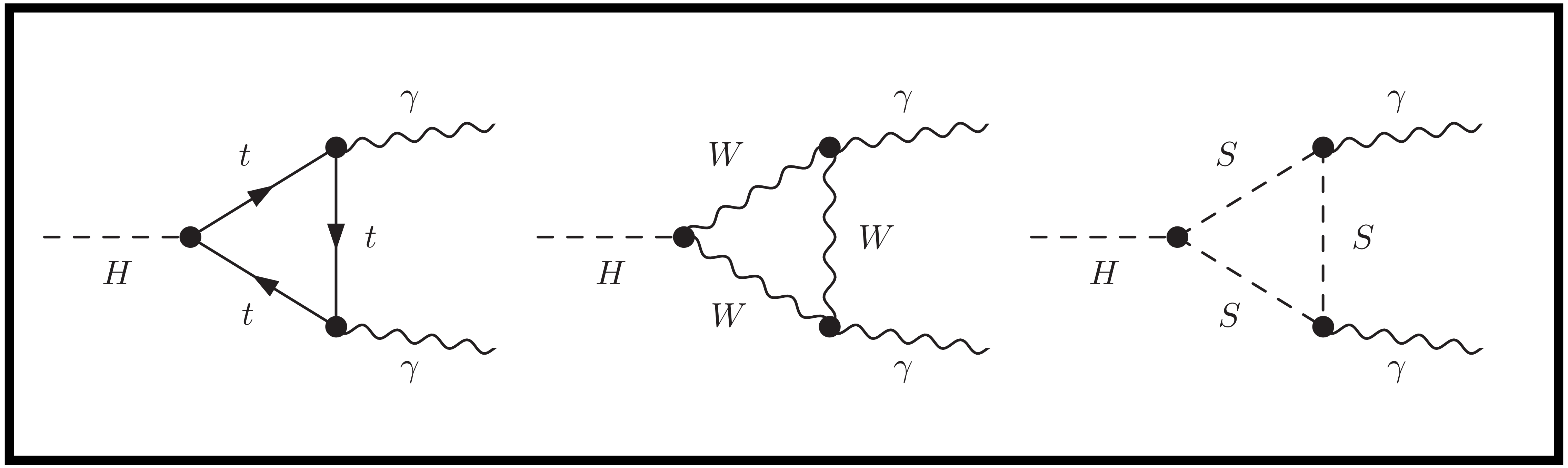


Impact on SM Higgs couplings

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

Consider for example the partial width of $H \to \gamma\gamma$

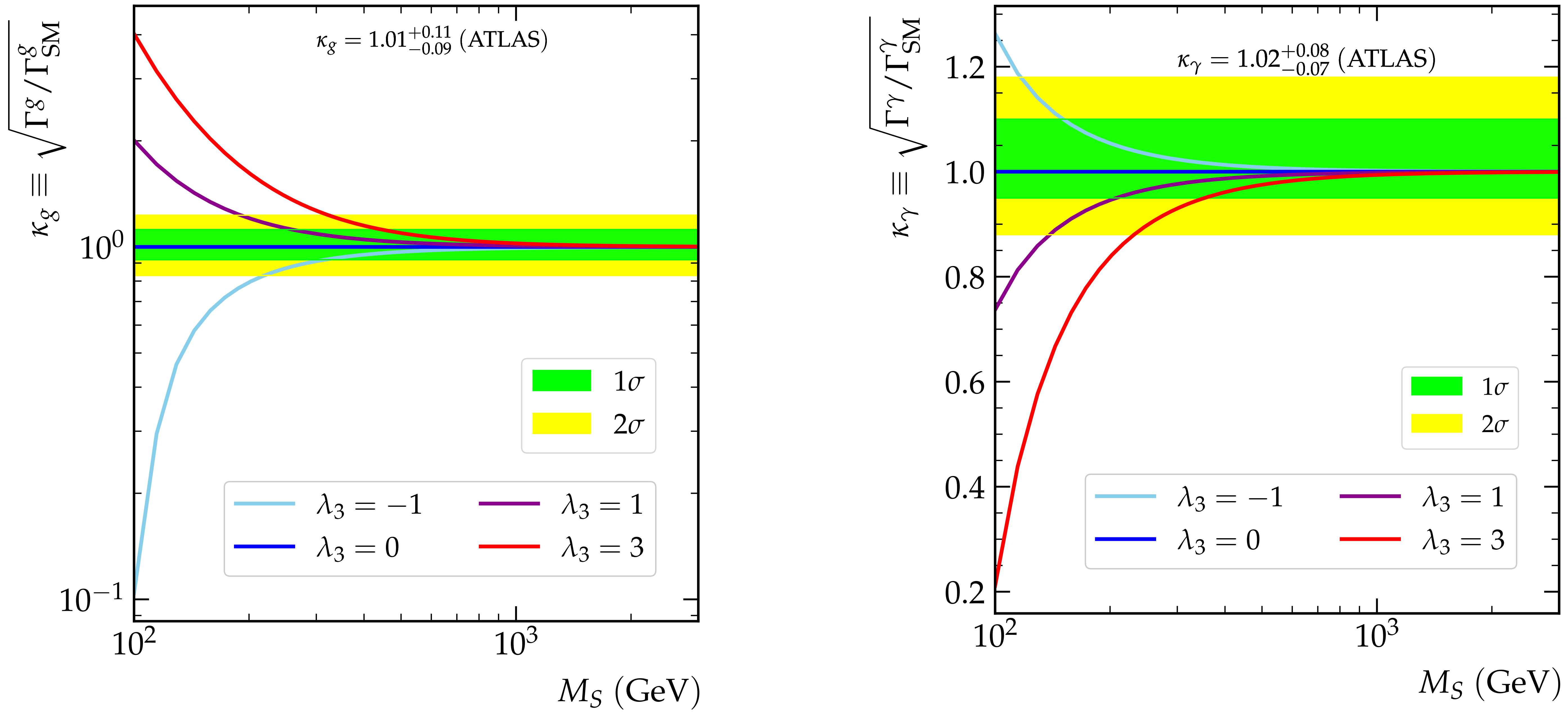
$\kappa_X = \sqrt{\Gamma_X/\Gamma_X^{\rm SM}}$ (good measure)



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

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

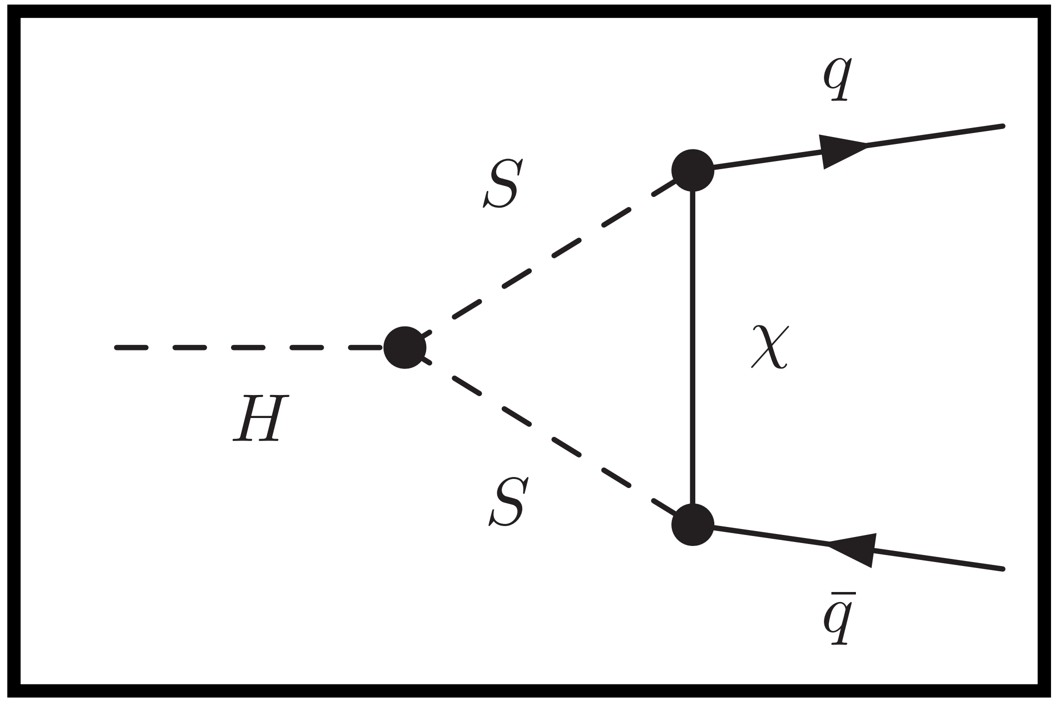
Impact on SM Higgs couplings



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?



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

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

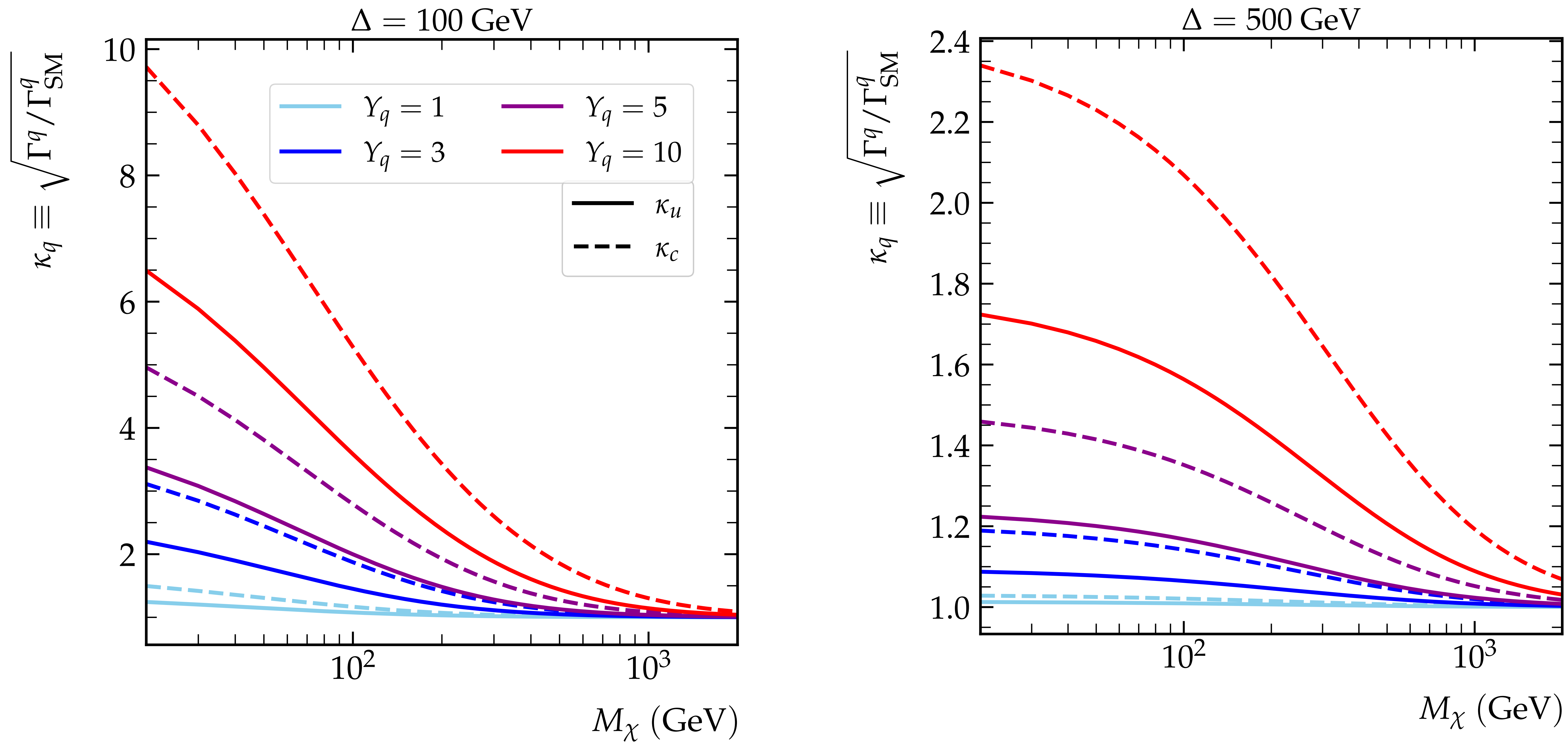
$$\Delta\Gamma(H \to q\bar{q})_{\rm NP} = \frac{6 m_H m_q}{16\pi v}\Big[\mathrm{Re}(f_L) + \mathrm{Re}(f_R)\Big]$$

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

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

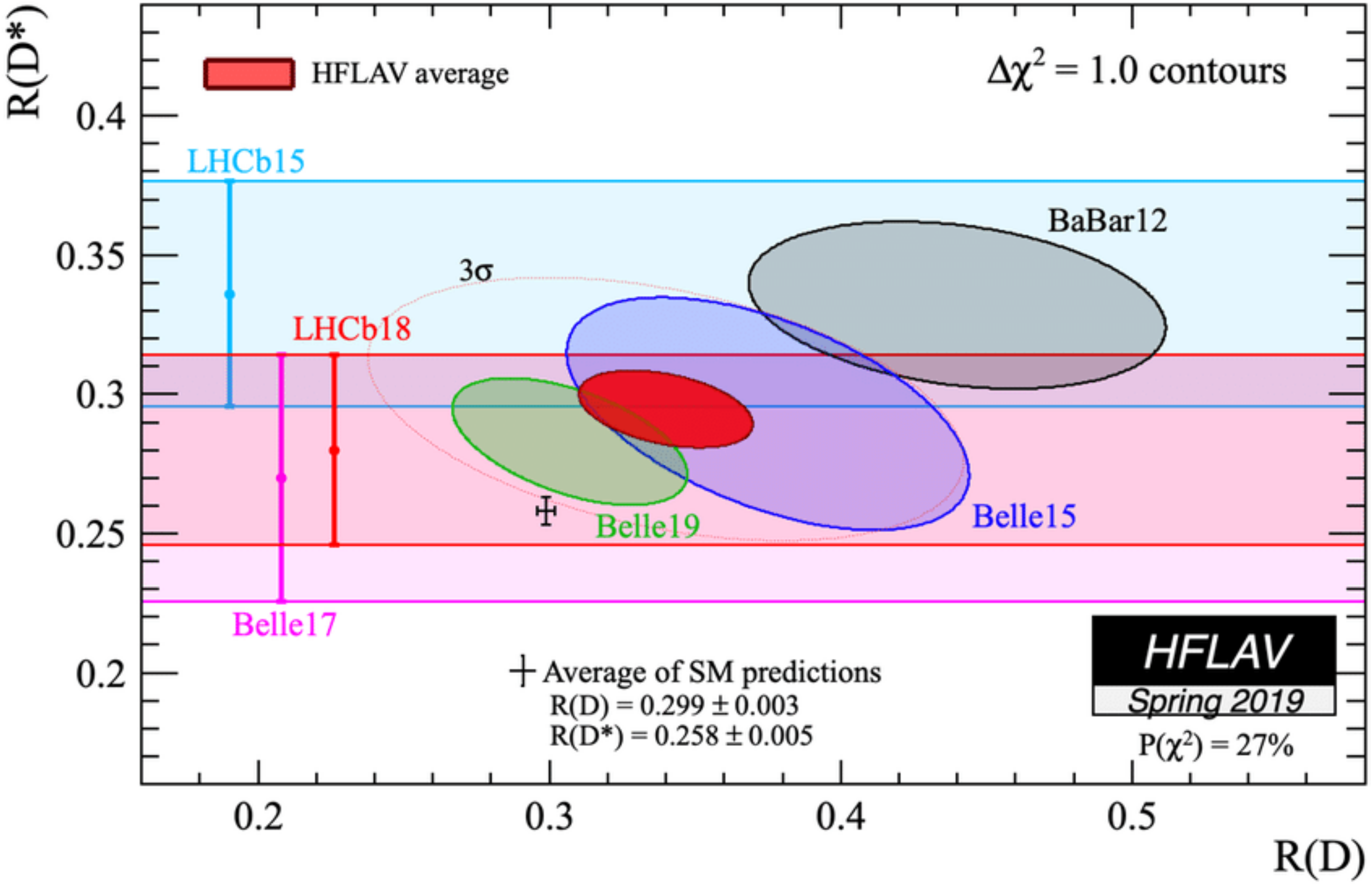
Corrections must be small!!

Impact on SM Higgs couplings



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

Evolution of the flavour anomalies



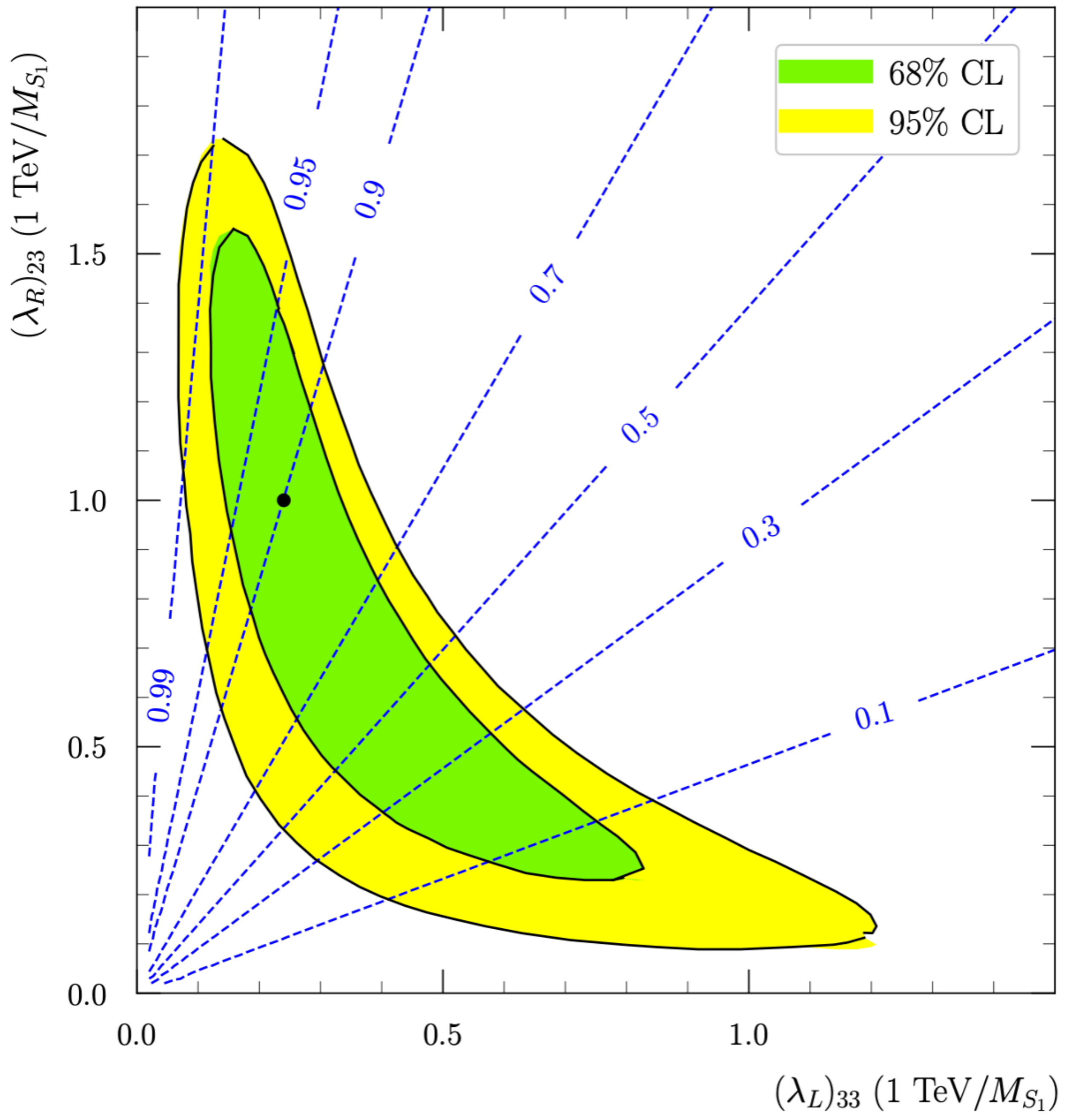
Solutions to the $R_{D^{(*)}}$ anomalies

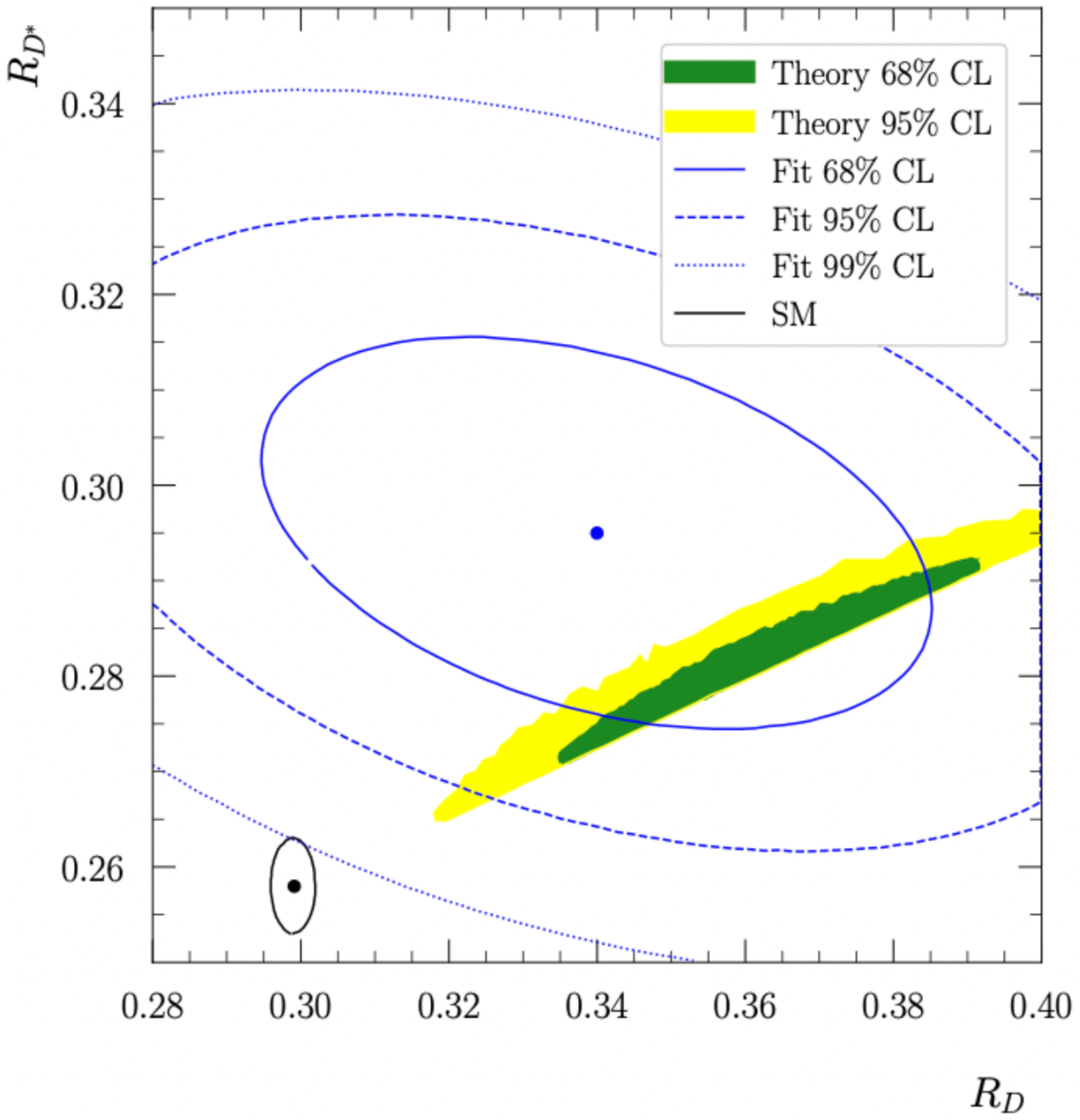
- In principle, only two entries of the $\lambda_{\rm L}$ and $\lambda_{\rm R}$ coupling matrices are enough to address $R_{D^{(*)}}$ anomalies: $(\lambda_L)_{33}$ and $(\lambda_R)_{23}$.

  NOTE 1: $(\lambda_L)_{23} \neq 0$ would give an unacceptable large contribution to $\mathrm{BR}(B \to X_s \nu \bar{\nu})$.
  NOTE 2: $(\lambda_R)_{33} \neq 0$ would require right-handed neutrinos.

- We demand that not only the $R_{D^{(*)}}$ anomalies are addressed but also that experimental measurements do not challenge the theory in a number of observables such as: test of lepton universality in τ decays, $\mathrm{BR}(B_c^+ \to \tau^+ \nu)$ and the tail of the p_T distribution in $pp \to \tau\tau$

Solutions to the $R_{D^{(*)}}$ anomalies





V. Gherardi, D. Marzocca, and E. Venturini, 2008.09548

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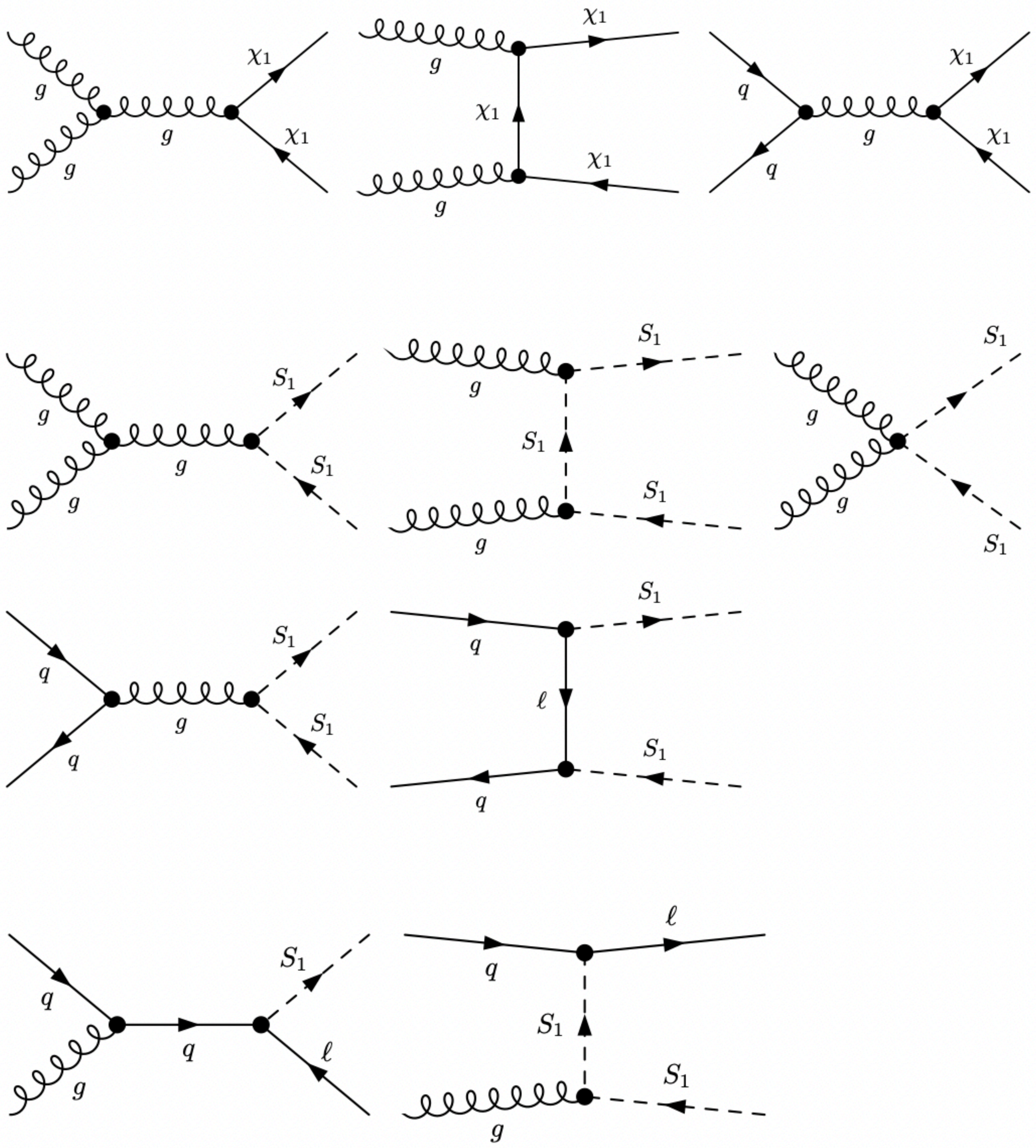
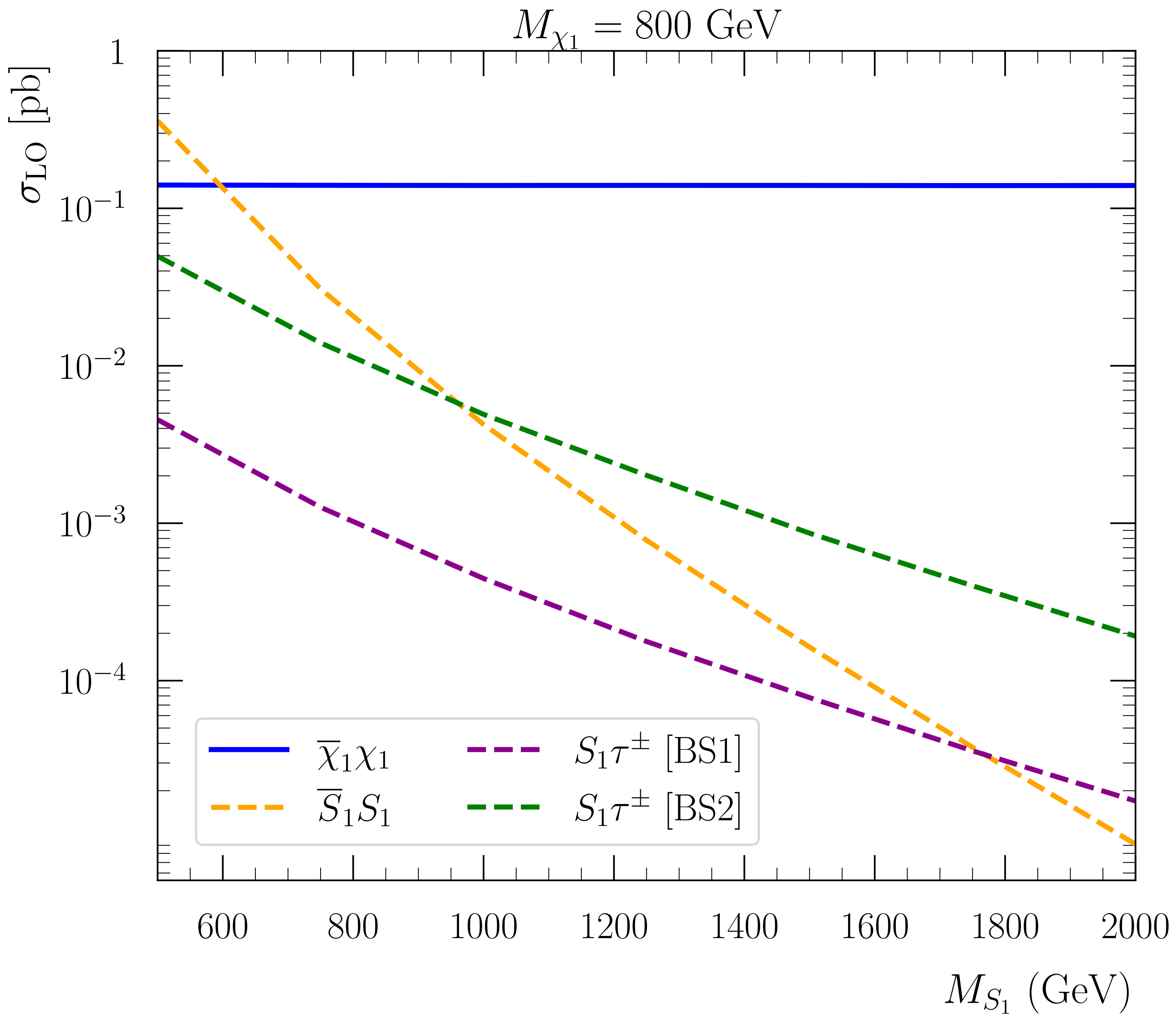
Production rates of LQs and DM

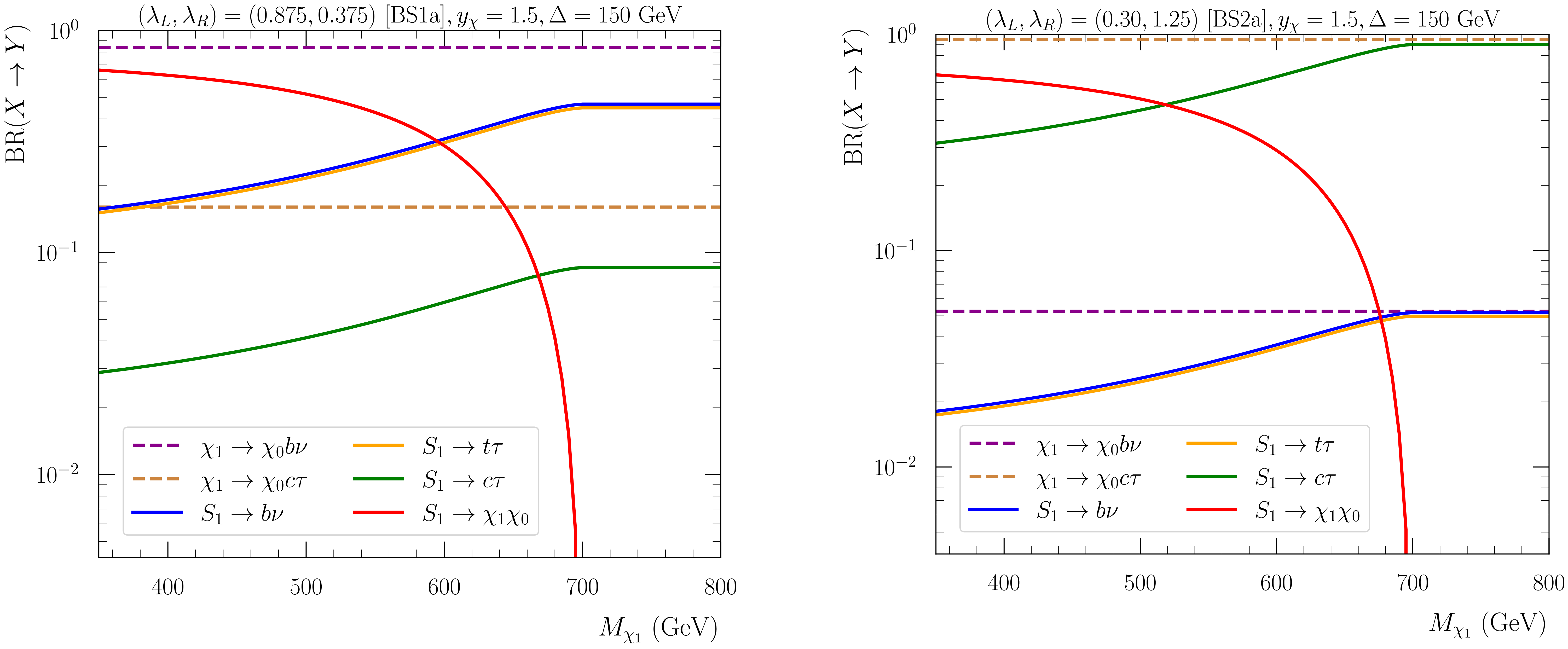




All the constraints are analyzed using LO matrix elements

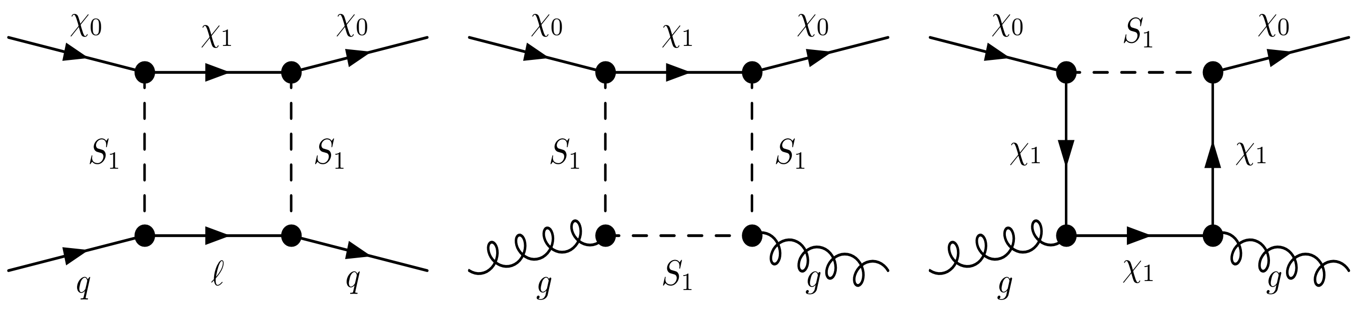
Decay rates of LQs

- The decay rates of the Leptoquark (S_1) depend on the dark coupling (y_χ) as well.
- The decays of the dark colored particle (χ_1) are always three-body!!



Dark matter in the LQ model: Direct detection

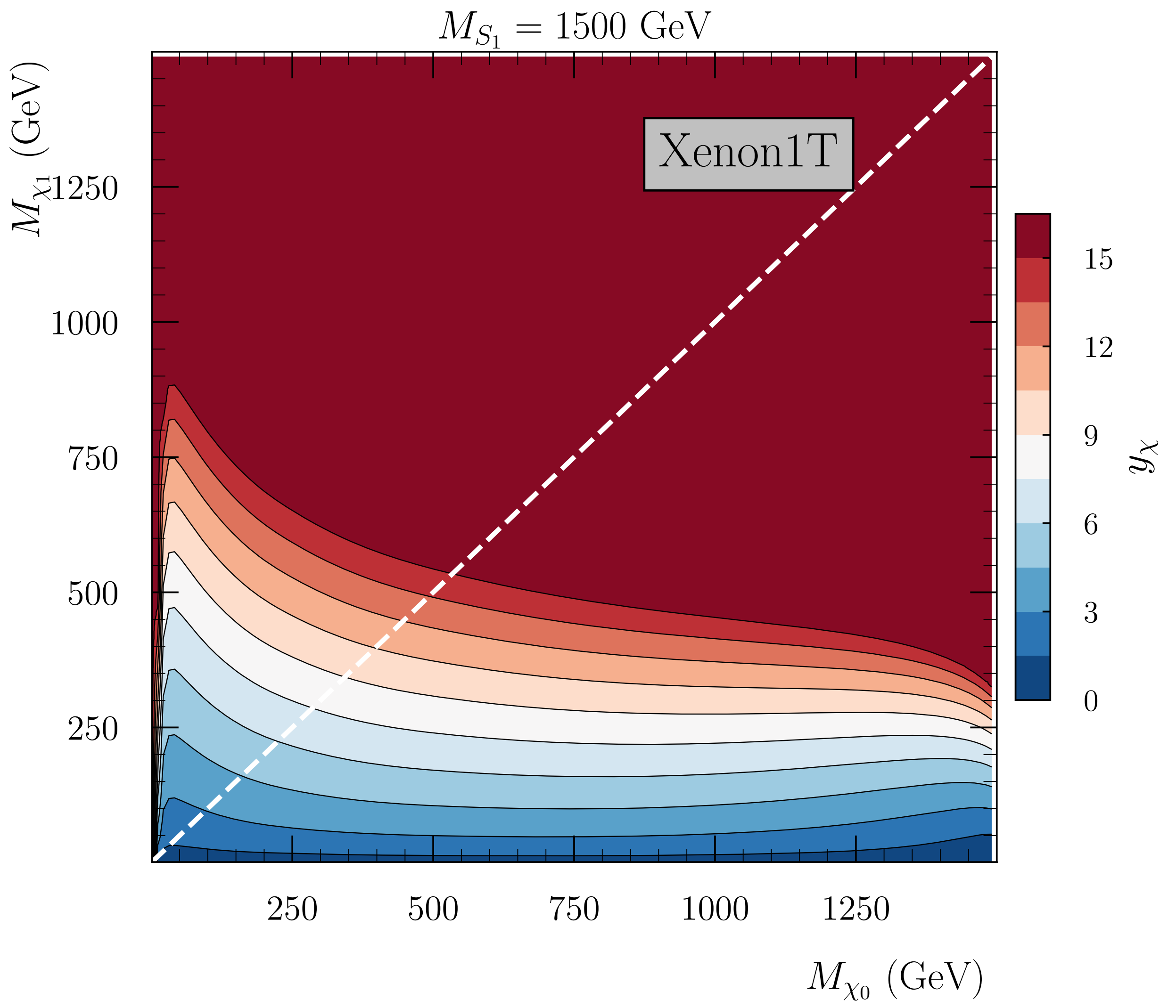
- The spin-independent cross section occurs at the one-loop order

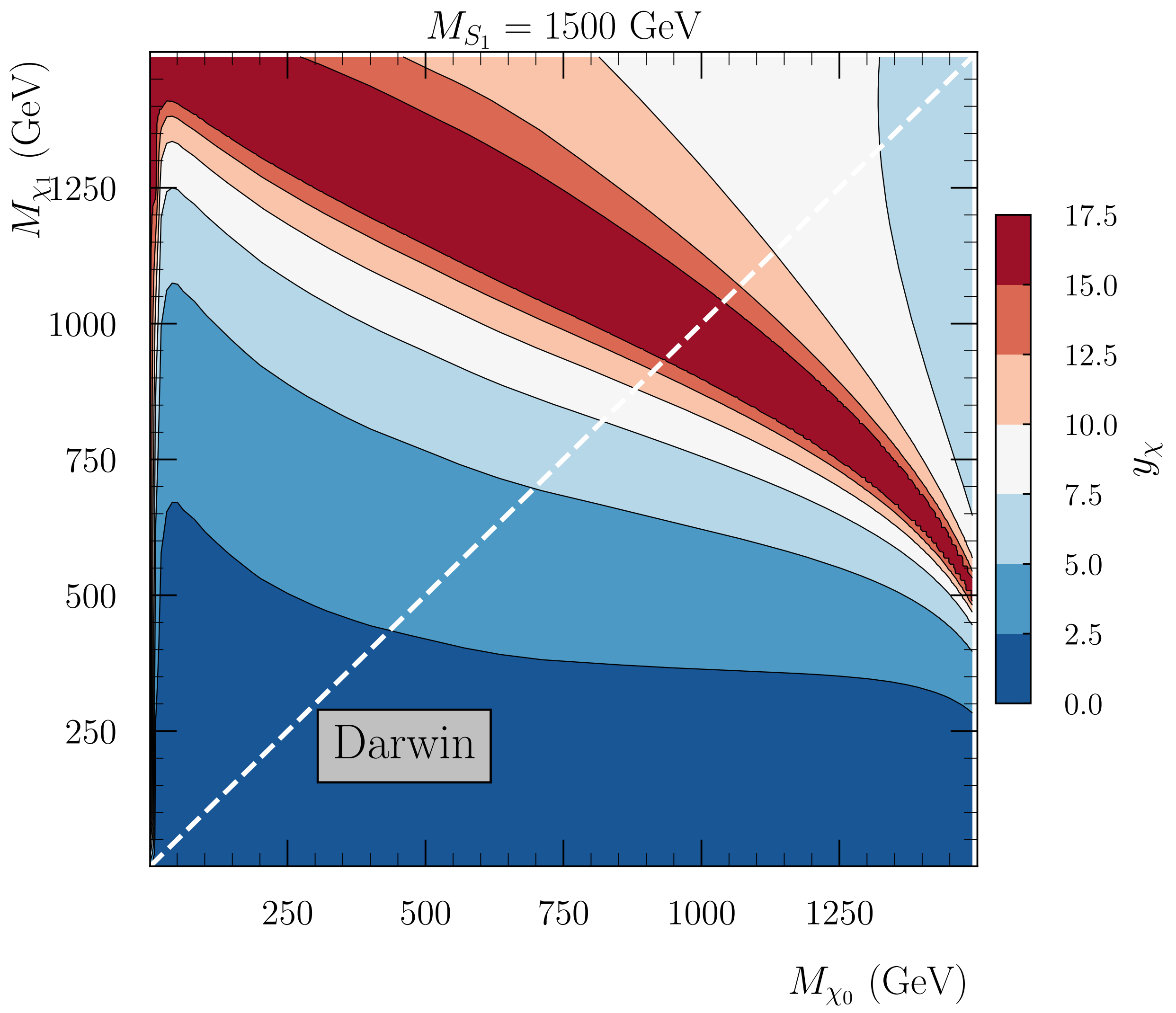


(i) *(ii)* *(iii)*

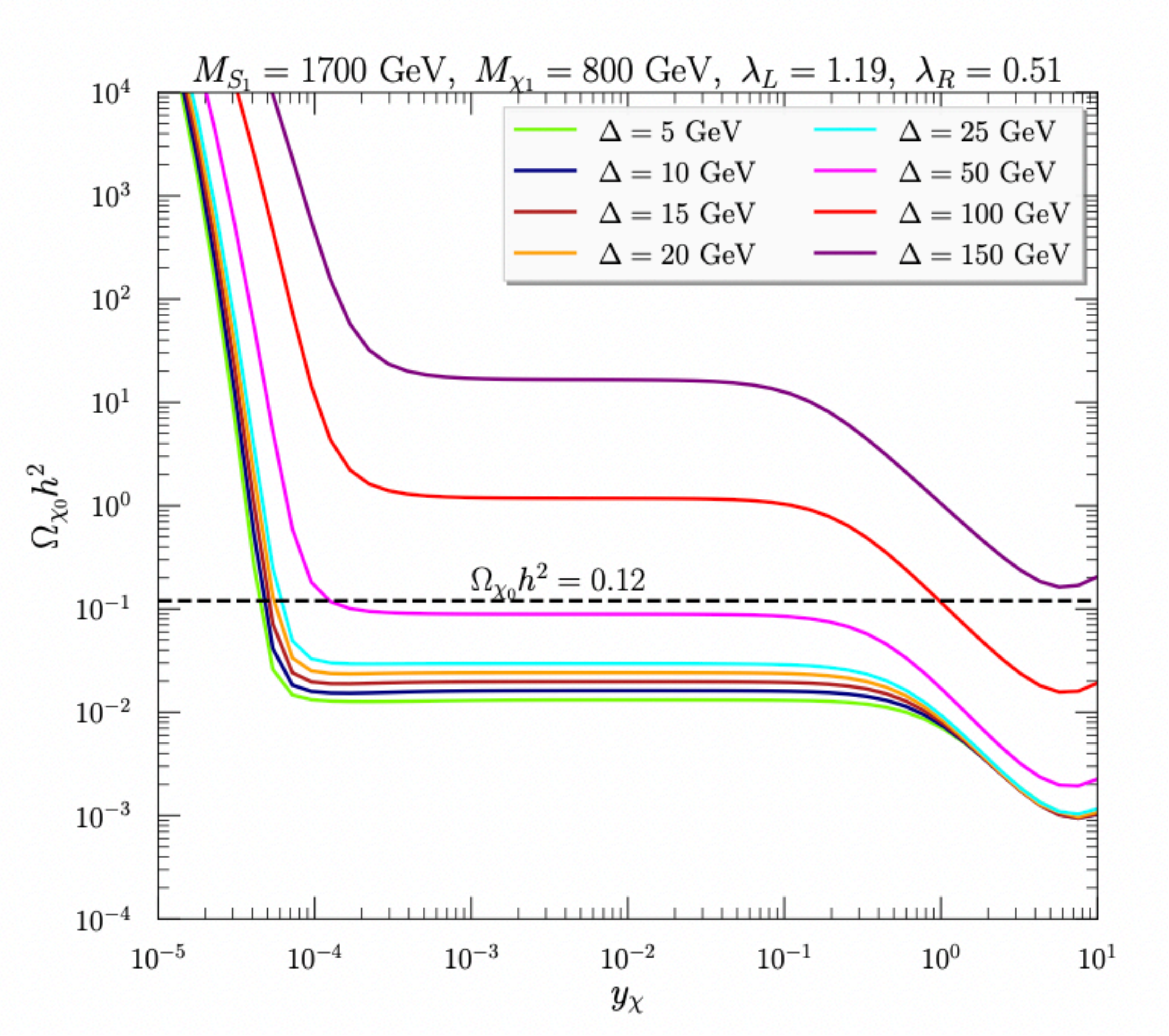
- Contribution of the gluon form factors is dominant

→ The constraints are not sensitive to the BS — either BS1 or BS2 are fine





Dark matter relic density in the LQ model



- Minimum y_χ is required to reach a threshold for the inverse $\chi_0 \to \chi_1$ reaction (depends on the mass splitting).
- A plateau is observed where DM production is dominated by QCD-induced $\chi_1\chi_1 \to \mathrm{SM\ SM}$ co-annihilations.
- Processes such as $\chi_1\chi_0 \to \mathrm{SM\ SM}$ eventually start to contribute more significantly when y_χ increases.
- The relic density is proportional to the mass splitting $\Delta\ (\equiv M_{\chi_1} - M_{\chi_0})$. Therefore, for large values of Δ, the correct relic density is only produced for freeze-out.
- For some threshold of Δ, the relic density cannot be correctly produced (unless $M_{\chi_0} > M_{S_1}$).