Leptoquark manoeuvres in the dark: a simultaneous solution of the dark matter problem and the RD(*) anomalies

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Largely based on:

Leptoquark Manoeuvres in the Dark: a simultaneous solution of the dark matter problem and the R_D anomalies, G. Bélanger, A. Bharucha, B. Fuks, A. Goudelis, J. Heisig, A. Jueid, A. Lessa, K. Mohan, G. Polesello, P. Pani, A. Pukhov, D. Sengupta JZ, arXiv 2111.08027, JHEP 02 (2022) 42

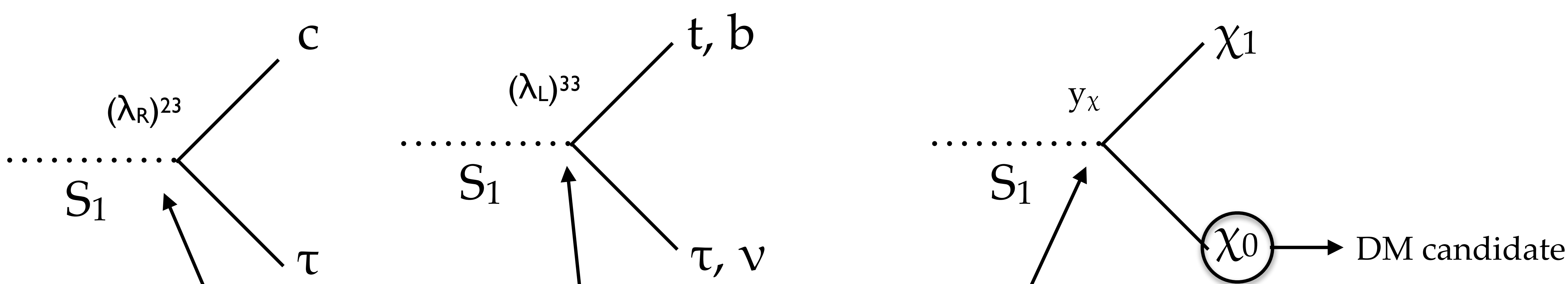
27th International Symposium on Particles, Strings and Cosmology, Heidelberg, 27.05.2022

Outline

- Motivation and model
- Collider phenomenology
  - Missing energy (MET) searches
  - Leptoquark (LQ) searches
  - LQ + MET (CMS only…)
- Dark matter phenomenology (time allowing)
- Conclusion

Motivation

- Two *games in town*: $(g\text{-}2)_\mu$ and $R_{D,K^{(*)}}$. The *flavour anomalies* can be solved with Z' or *leptoquarks* (LQ): scalars | vectors, O(1000) pheno papers don't fit in this marg… line.
- Can these LQ models also account for dark matter? (e.g. 1507.06660, 2005.10117, 2007.11931, 2104.03228)
- Here: we pick a <u>scalar</u> LQ (S_1) with right-handed down-type quark quantum numbers (*right handed squark,* for the SUSY fans)



$$\mathcal{L} \supset \left[\lambda_{\mathbf{R}}\ \bar{u}^c_R\ \ell_R\ S_1^\dagger + \lambda_{\mathbf{L}}\ \bar{Q}^c_L \cdot L_L\ S_1^\dagger + y_\chi \bar{\chi}_1 \chi_0 S_1 + \text{H.c.} \right] .$$

Only 6 params: m_{S_1}, $(\lambda_R)^{23}$, $(\lambda_L)^{33}$, m_{χ_1}, m_{χ_0}, y_χ (sometimes $\Delta = m_{\chi_1} - m_{\chi_0}$)

Flavour structure favoured by global fit of R_{D^*}

UFO model file: https://feynrules.irmp.ucl.ac.be/wiki/LQDM

Flavour side

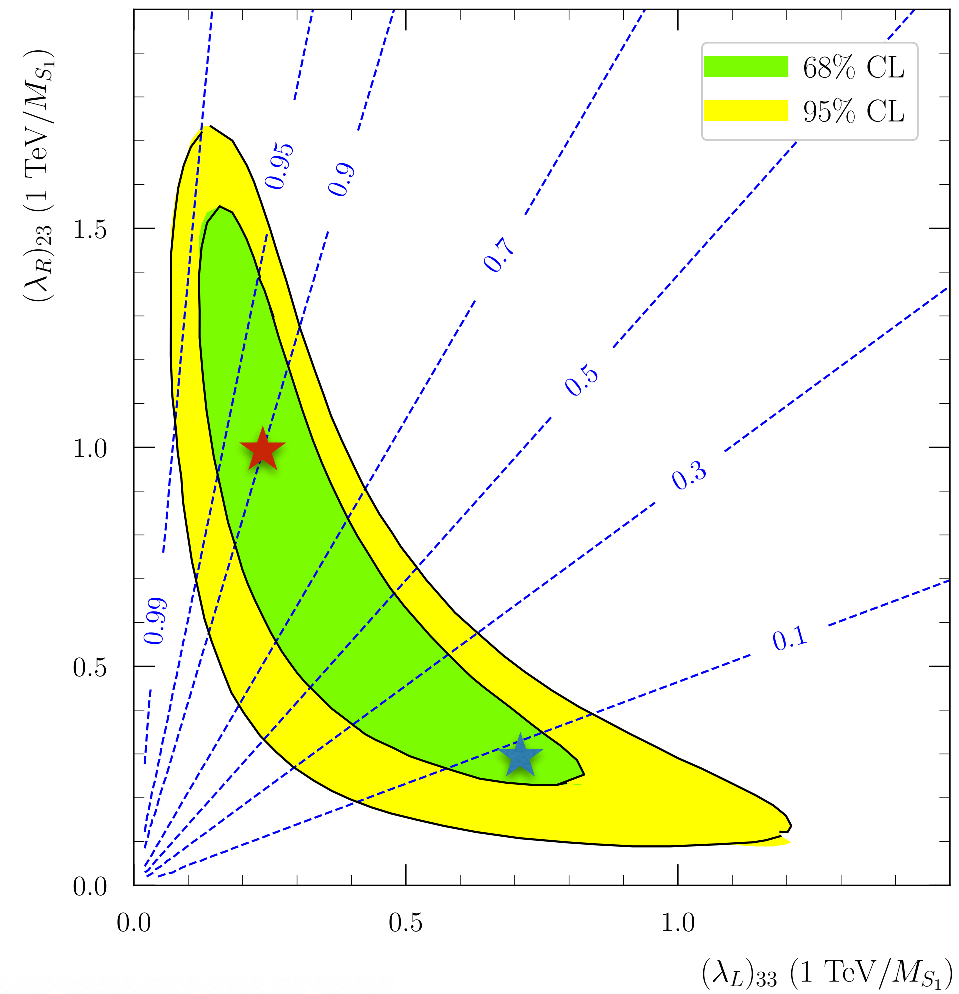
V. Gherardi, D. Marzocca, and E. Venturini, 2008.09548

- Global fit can be expressed in terms of

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

- We define benchmarks BS1=(0.7, 0.3) and BS2=(0.24, 1.0), all in 68 % C.L ellipse.

- These could be taken as the extreme cases where either λ_L or λ_R dominates



Name	M_{S_1} [GeV]	λ_L	λ_R	BR($S_1 \to b\nu$)	BR($S_1 \to t\tau$)	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

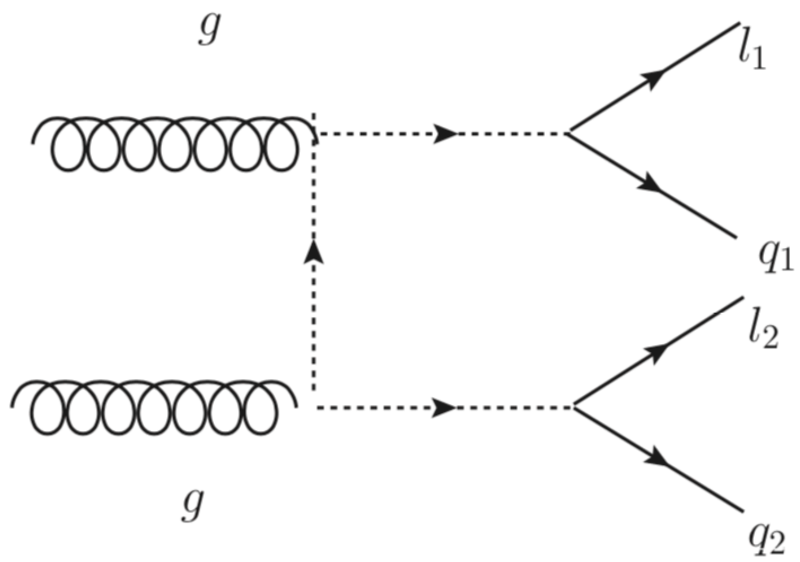
setting yχ=0 (no S1 decays to dark matter)

S1 is not fat (Γ/M ~ 3-6%)

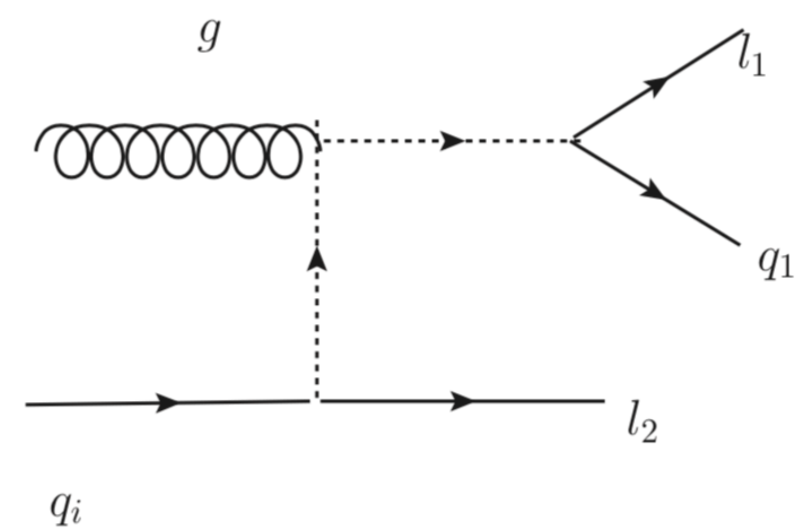
Collider signals

1) LQ searches

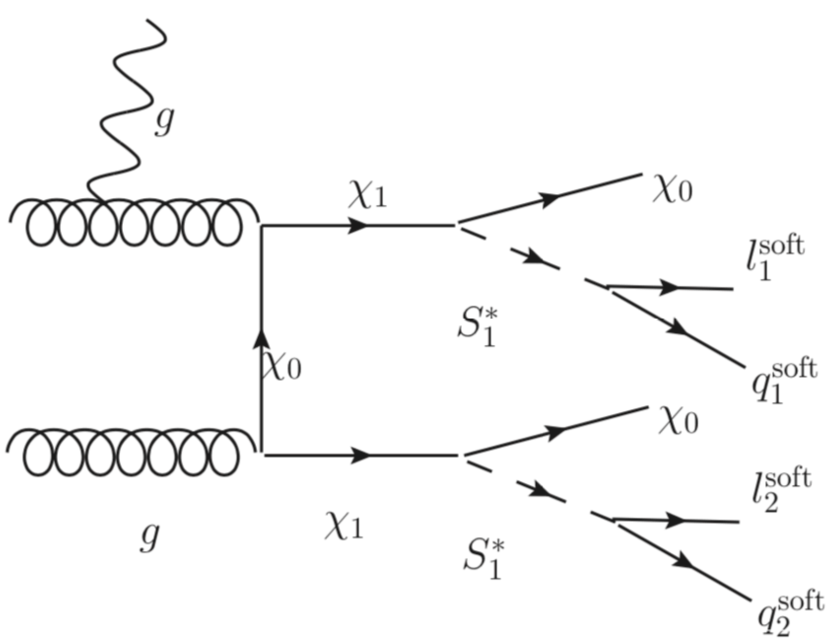
LQ pairs



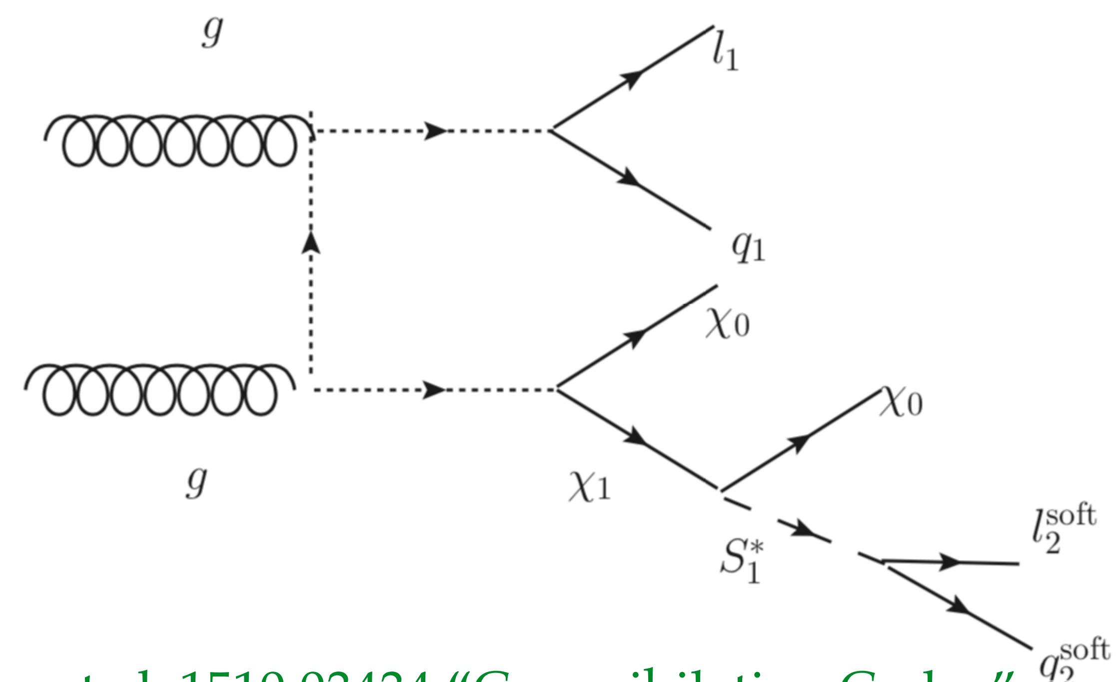
single LQ + lepton



2) MET + j + … +(+soft)



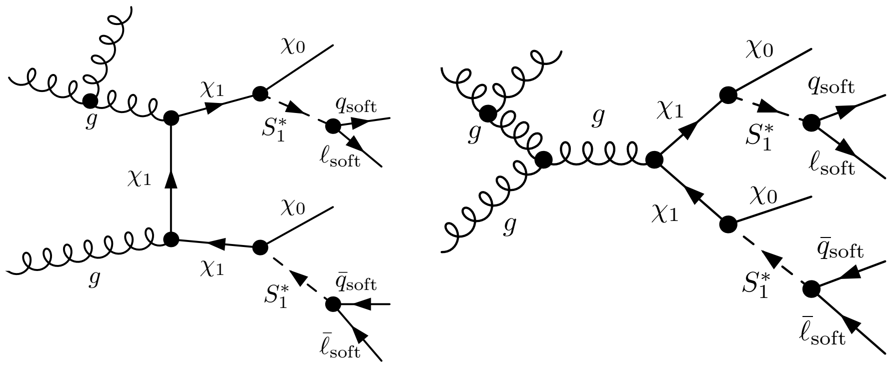
3) MET + LQ_{res} +(soft)



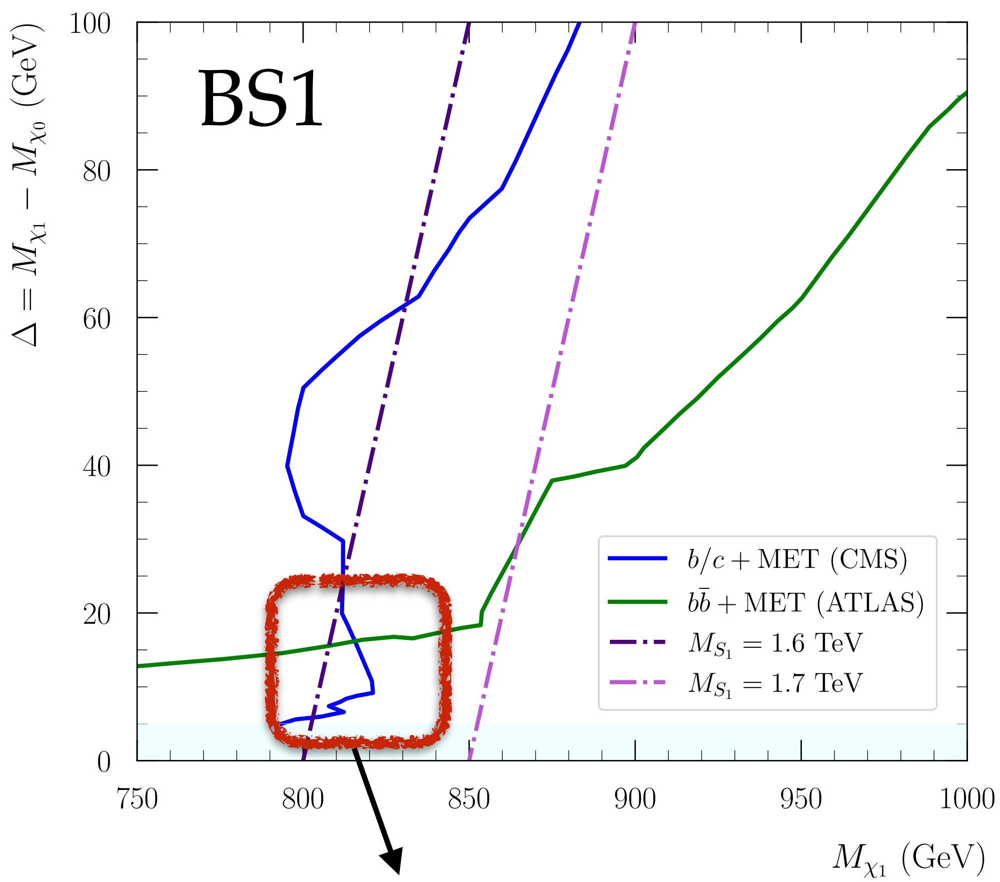
Proposed in Baker et al, 1510.03434 "Coannihilation Codex"

CMS Collaboration, A. M. Sirunyan et al., *Search for dark matter in events with a leptoquark and missing transverse momentum in proton-proton collisions at 13 TeV*, *Phys. Lett.* **B795** (2019) 76–99, [arXiv:1811.10151].

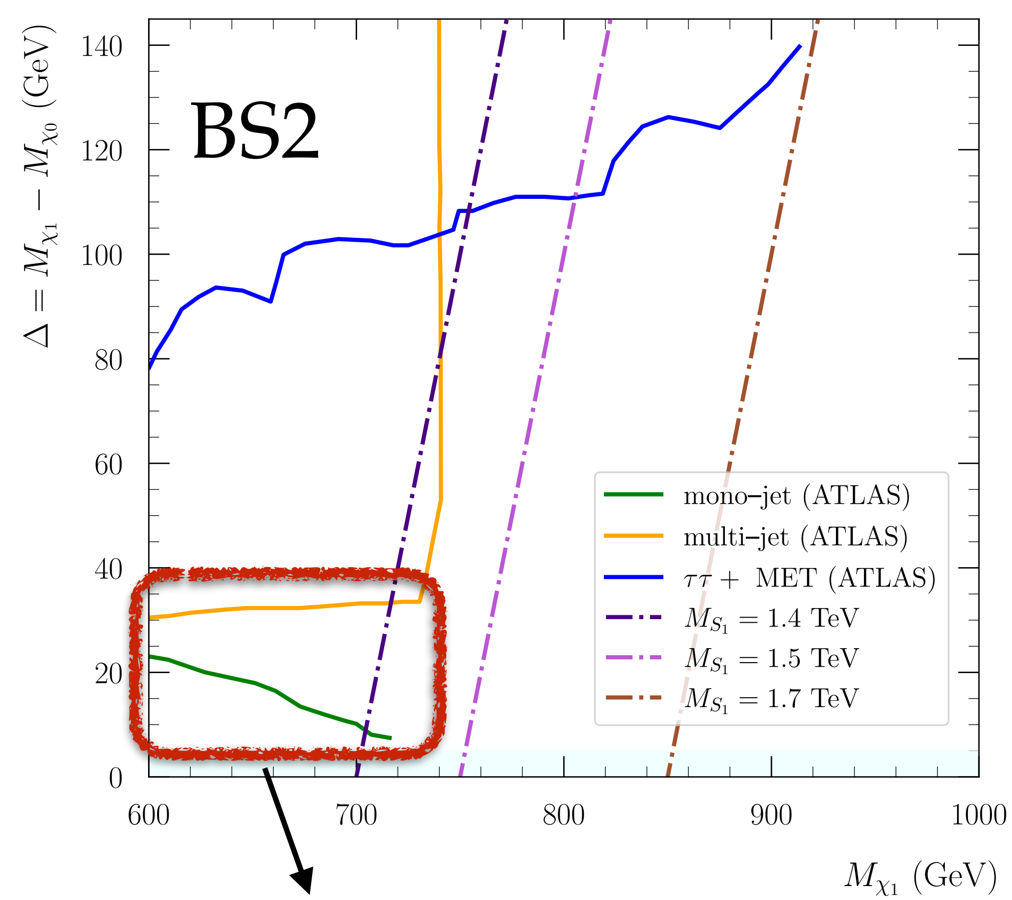
2-MET searches



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	✓



Nice probe of the compressed region!



BS2 less constrained!

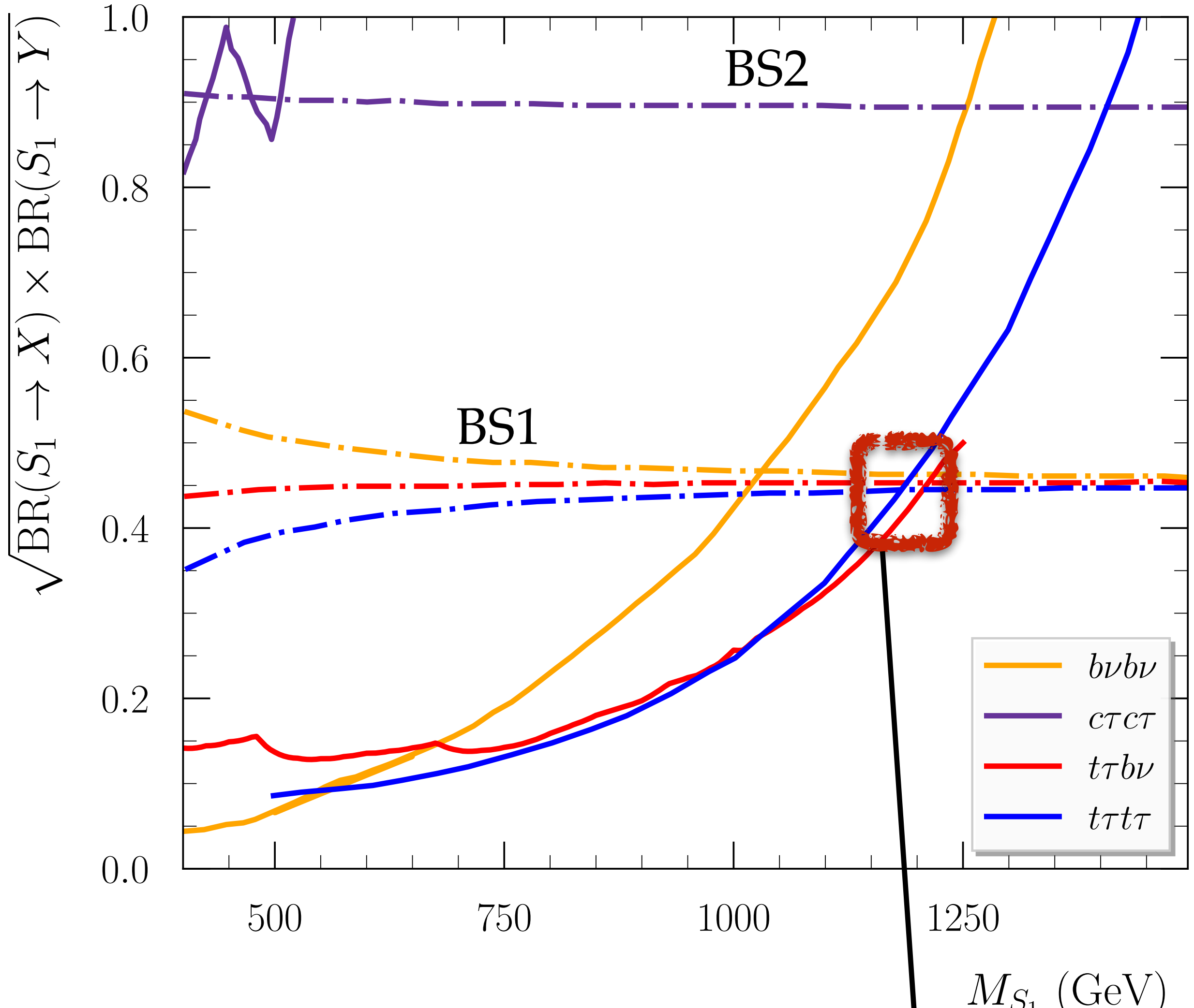
$\Delta \geq 5$ GeV

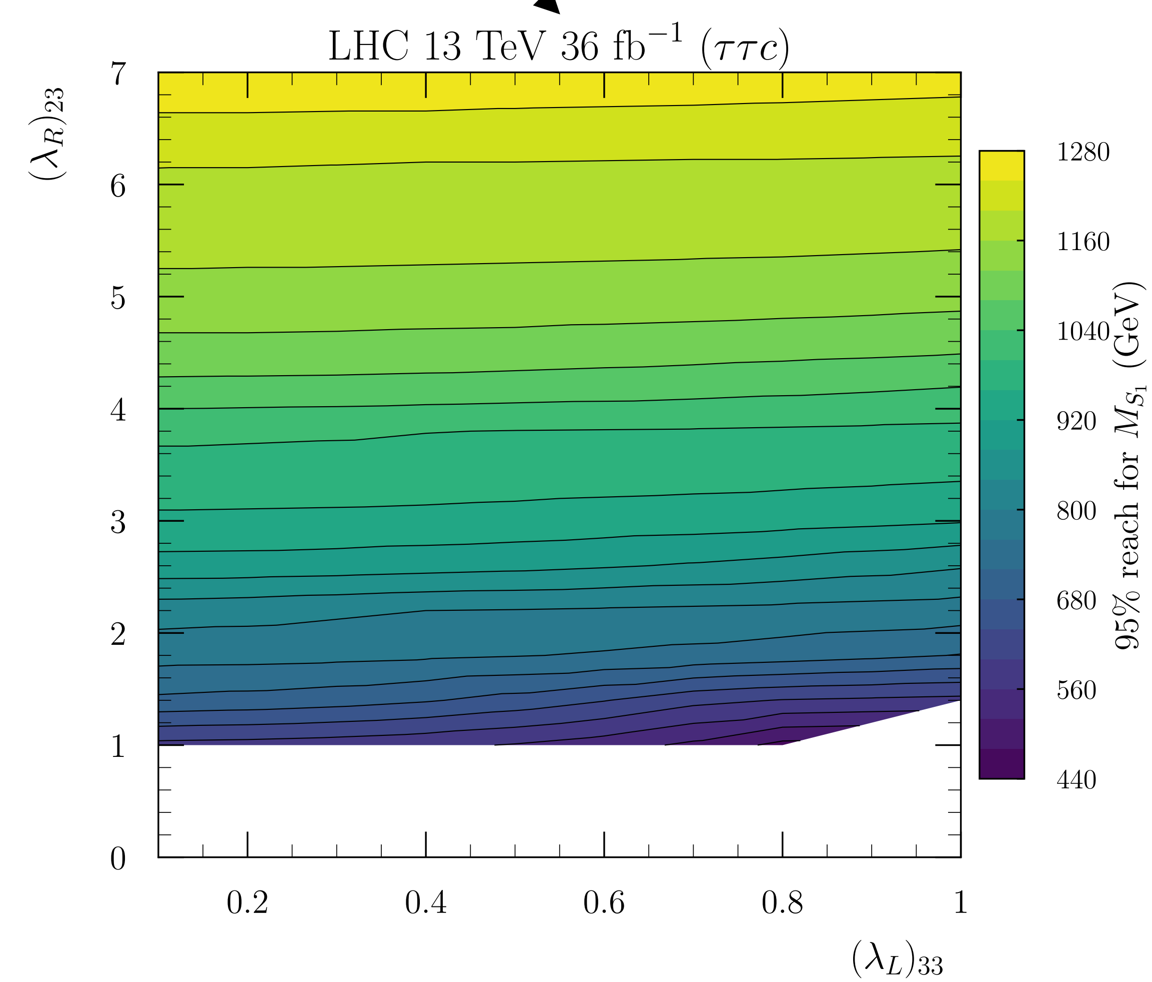
(χ_1 prompt)

1-LQ searches

Decays	$t\tau$	$b\nu$	$c\tau$
$t\tau$	ATLAS-CONF-2020-029 [20]	ATLAS-CONF-2021-008 [22]	No public search yet
$b\nu$	–	2101.12527 [46]	
$c\tau$	–	–	Rescaling of 1803.08103 [58]

Rescaling bτbτ: no dedicated search yet!





Mixed search wins!!!

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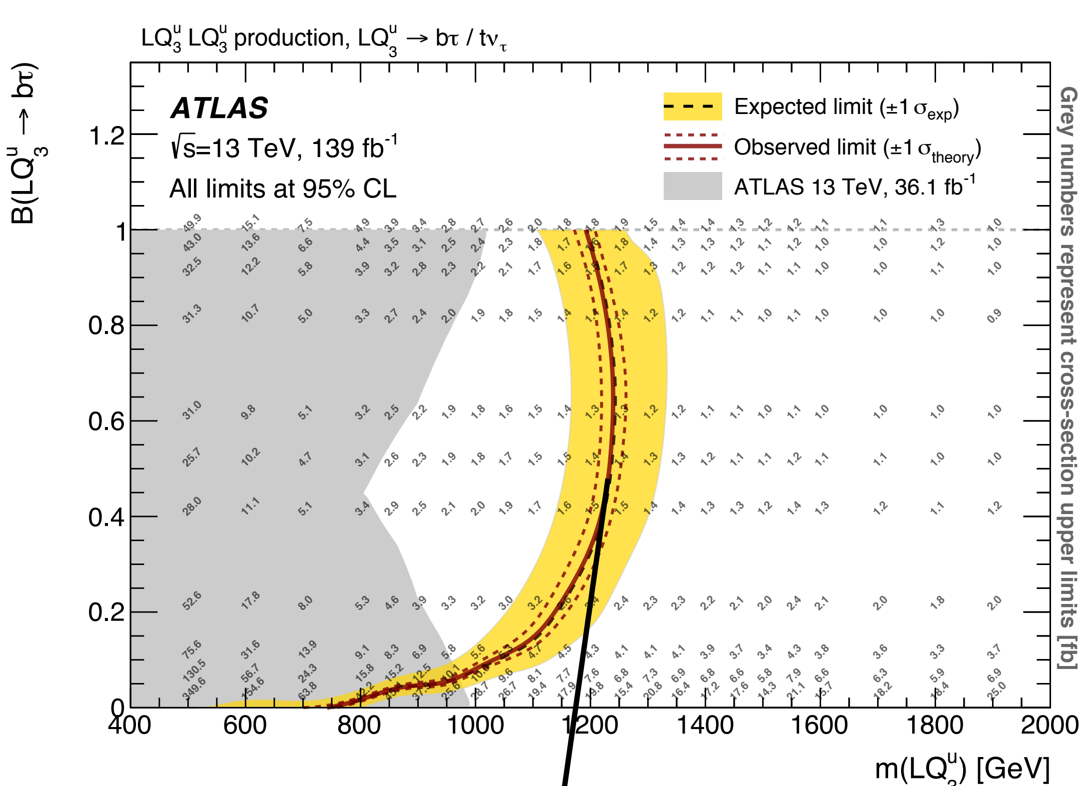
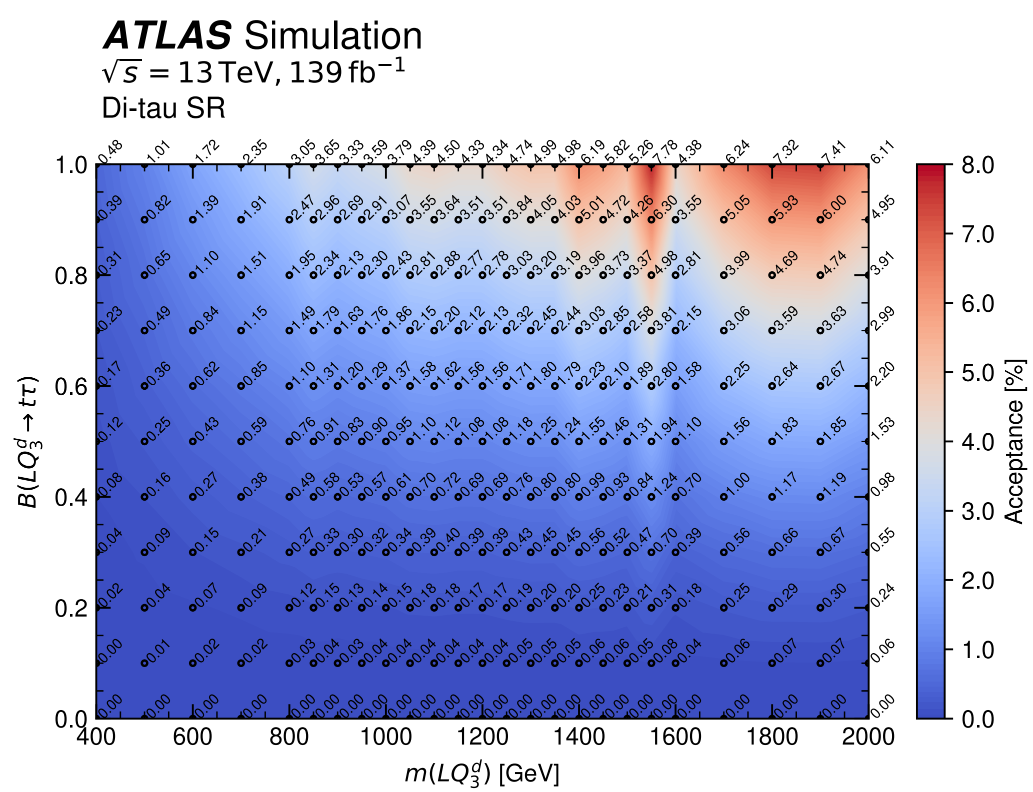
Reinterpreting the bντ search

ATLAS analysis assumes BR(S_1 ->tτ) + BR(S_1 ->bν) = 1. But we have BR(S_1 ->cτ), that we assumed does not pollute the signal region, and also BR(S_1 ->tτ) ≈ BR(S_1 ->bν).

Acceptance and efficiency maps provided as function of mass and BR(S_1 ->tτ), but the relevant quantity would be x′=BR(S_1 ->tτ) / (BR(S_1 ->tτ)+ BR(S_1 ->bν)) [relative proportion]

N ∝ σ (p p -> S_1 S_1) BR(S_1 ->tτ) BR(S_1 ->bν) A(x′,m_{S1}) ε(x′,m_{S1})





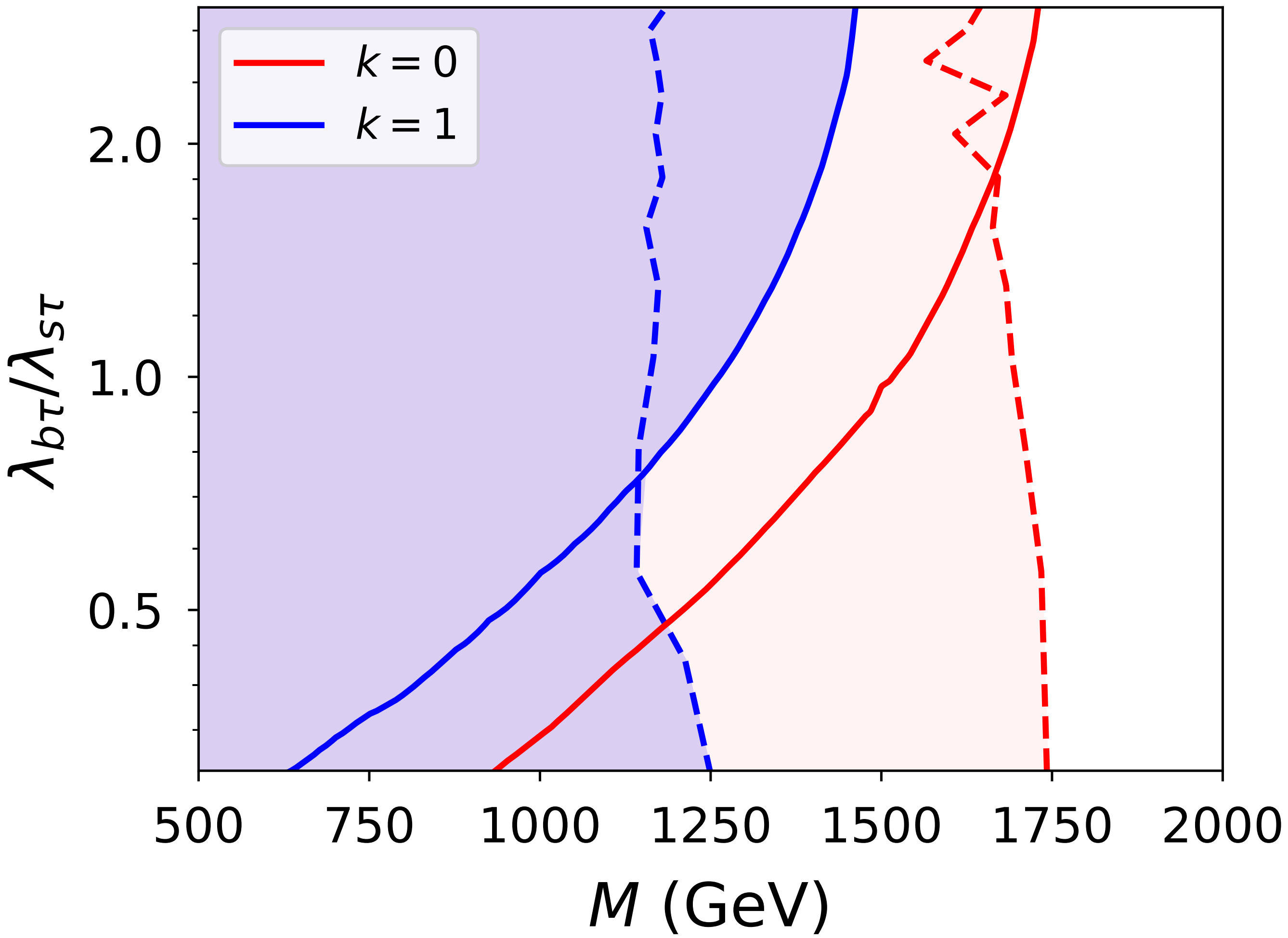
ATLAS excludes m_{95}=1250 GeV for x′=0.5

$$\mathrm{BR}(S_1 \to t\tau)^{95}(m) = 0.5 \left(\frac{\sigma(m_{95}) A(m_{95}, 0.5) E(m_{95}, 0.5)}{\sigma(m) A(m, 0.5) E(m, 0.5)} \right)^{1/2}$$

for BR(S_1 ->tτ) ≈ BR(S_1 ->bν).

Mixed search for vector LQ model

See M. Blanke's talk (this session, the previous talk)



Vector leptoquark U_1
(up quark quantum numbers)

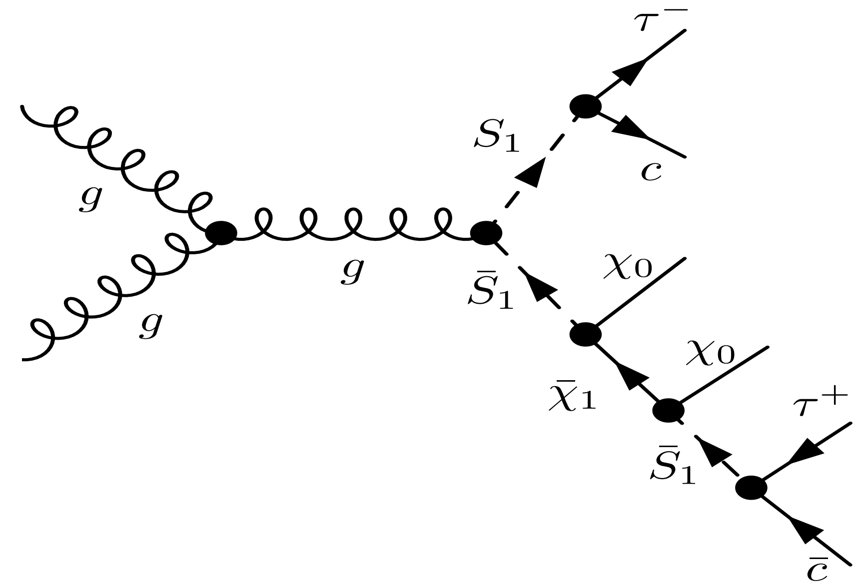
solid: LQ mixed search
dashed: CheckMATE
(exclusion driven by ATLAS
multi-jet 1712.02332)

J. Bernigaud, M. Blanke, J. Talbert, I. de Medeiros Varzielas, JZ, arXiv 2112.12129, accepted by JHEP

This model also has left-handed 3-3 couplings: BR(U_1 ->tν) ≈ BR(U_1 ->bτ), (x' = 0.5) and U_1 can have sizeable decays into cν and sτ as well.

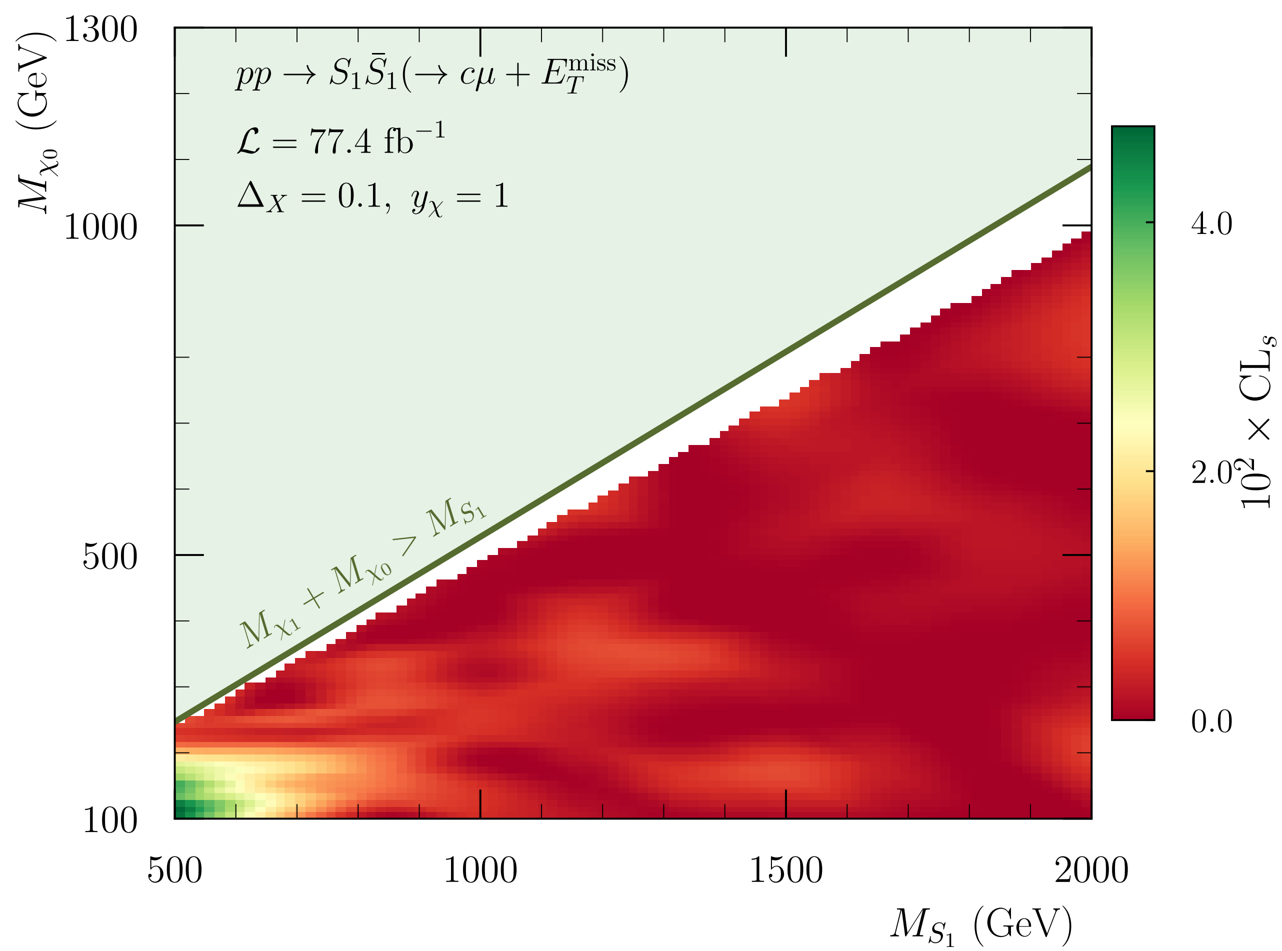
3-LQ + MET

CMS search targets (cμ) + MET.
Final state proposed in *Coannihilation Codex*, Baker et al, 1510.03434.
Reinterpretation and validation in MadAnalysis5, B.Fuks, A. Jueid, 2021



For the reinterpretation μ must come from τ decays. Two big disadvantages:
i) branching ratio
ii) muons are rather soft
The search has low sensitivity.

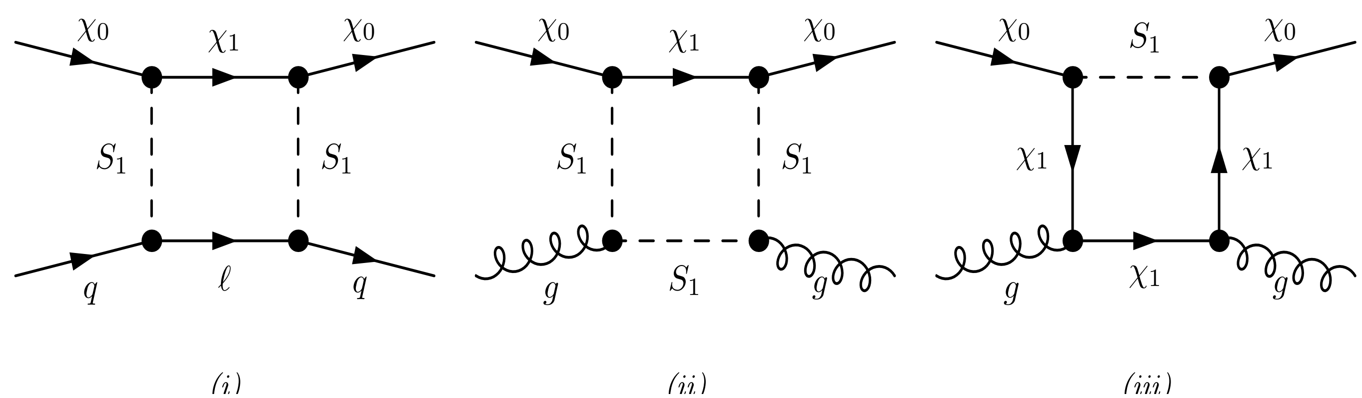
A dedicated cτ+MET search is certainly an arduous task, but would be quite interesting to have!



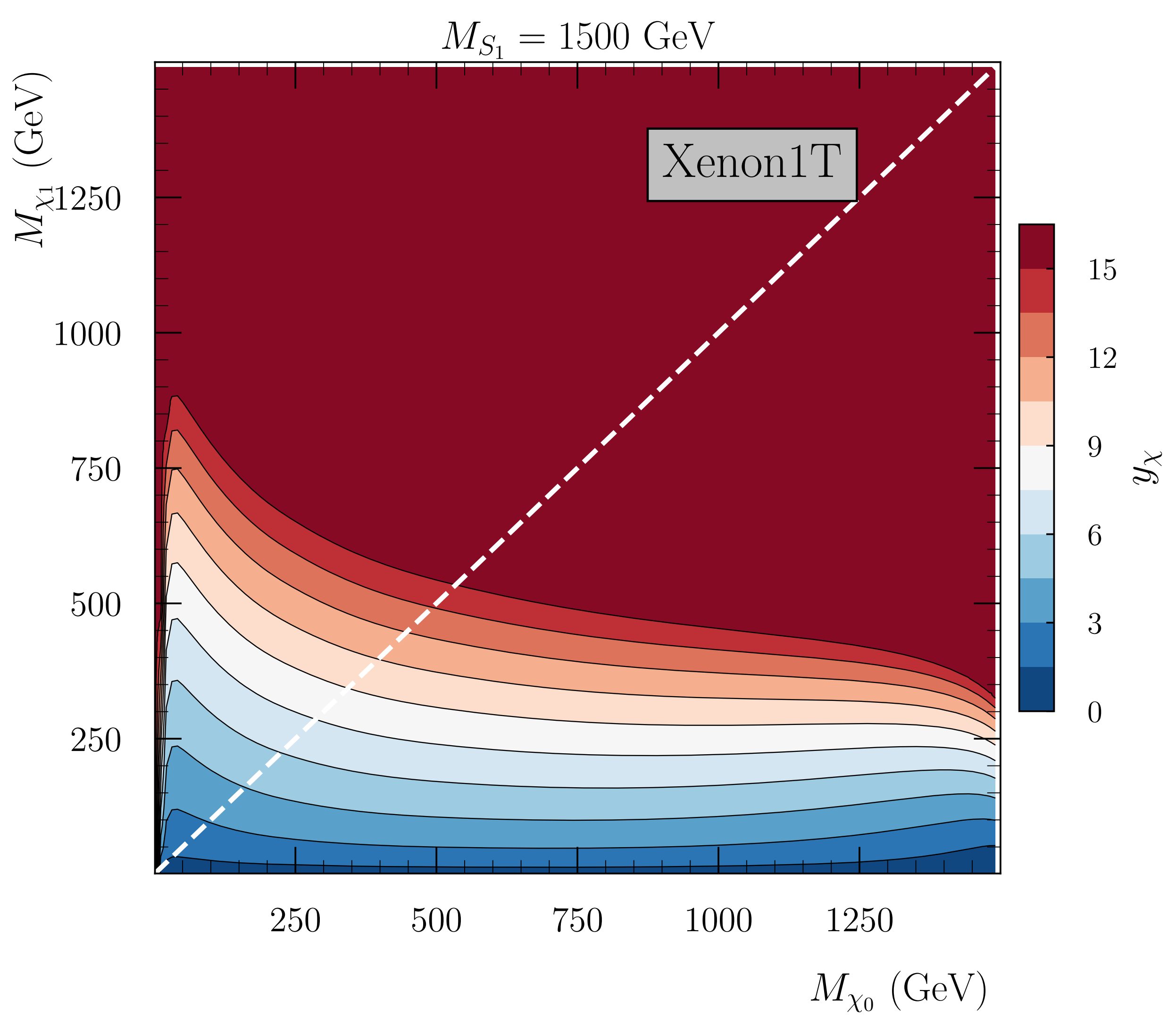
Dark Matter phenomenology (relic density and direct detection)

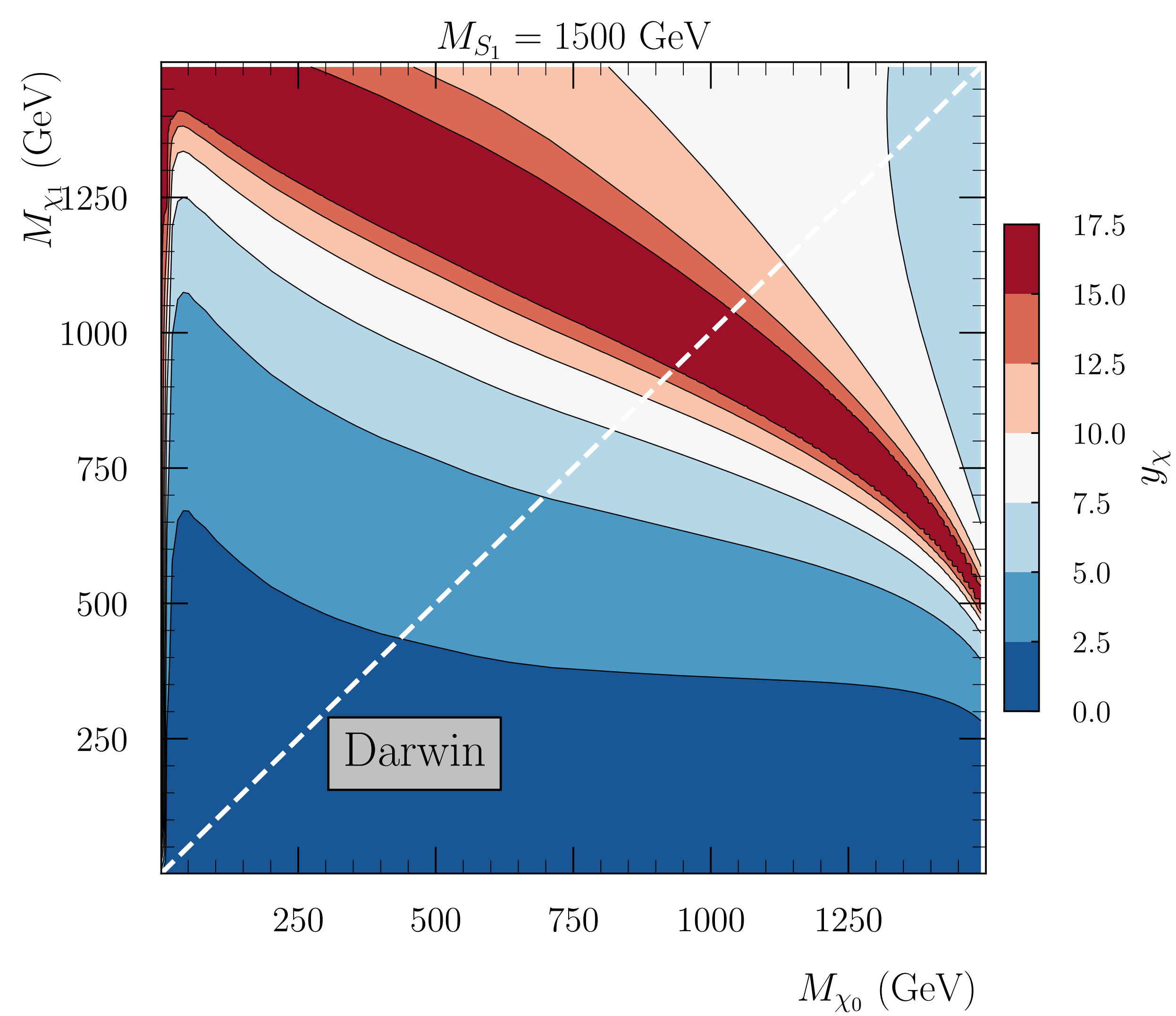
Direct detection

Direct detection enters at 1-loop, but since DD is also quite precise



Gluon form factor dominates:
only y_χ, mχ1, mχ0 (no dep on BS!)





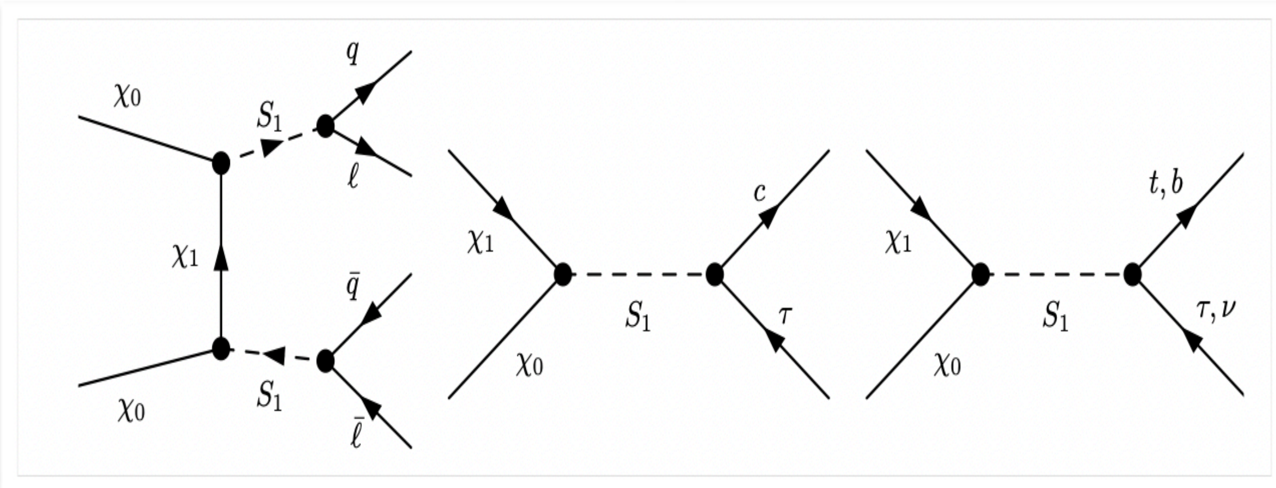
Relic density

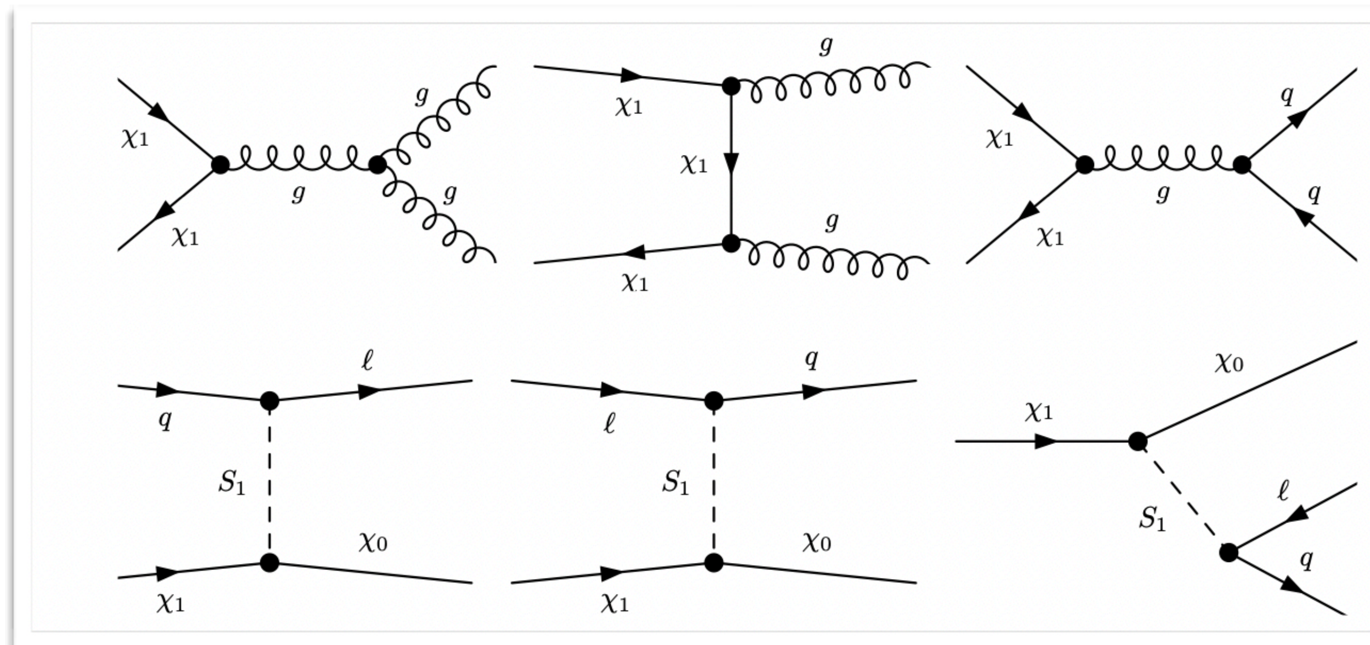
χ_0 can be produced in the early universe via:

1) Vanilla "freeze-out" with (co-)annihilation (small Δ)

2) Conversion-driven freeze-out:

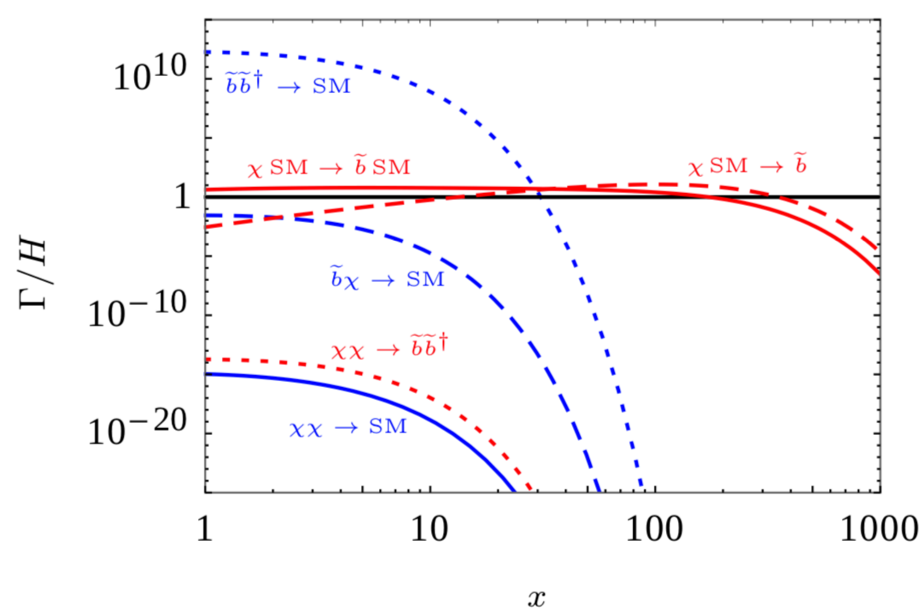
CDFO: Garny, Heisig, Lüfl, Vogl, 1705.09292
co-scattering: D'Agnolo, Pappadopulo, Ruderman, 1705.08450

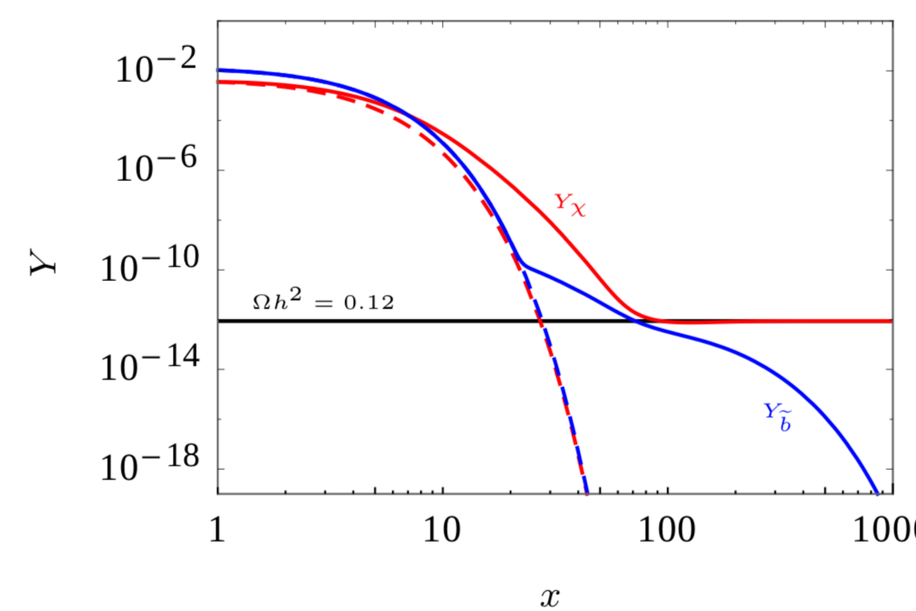




freeze-out takes place outside of chemical equilibrium

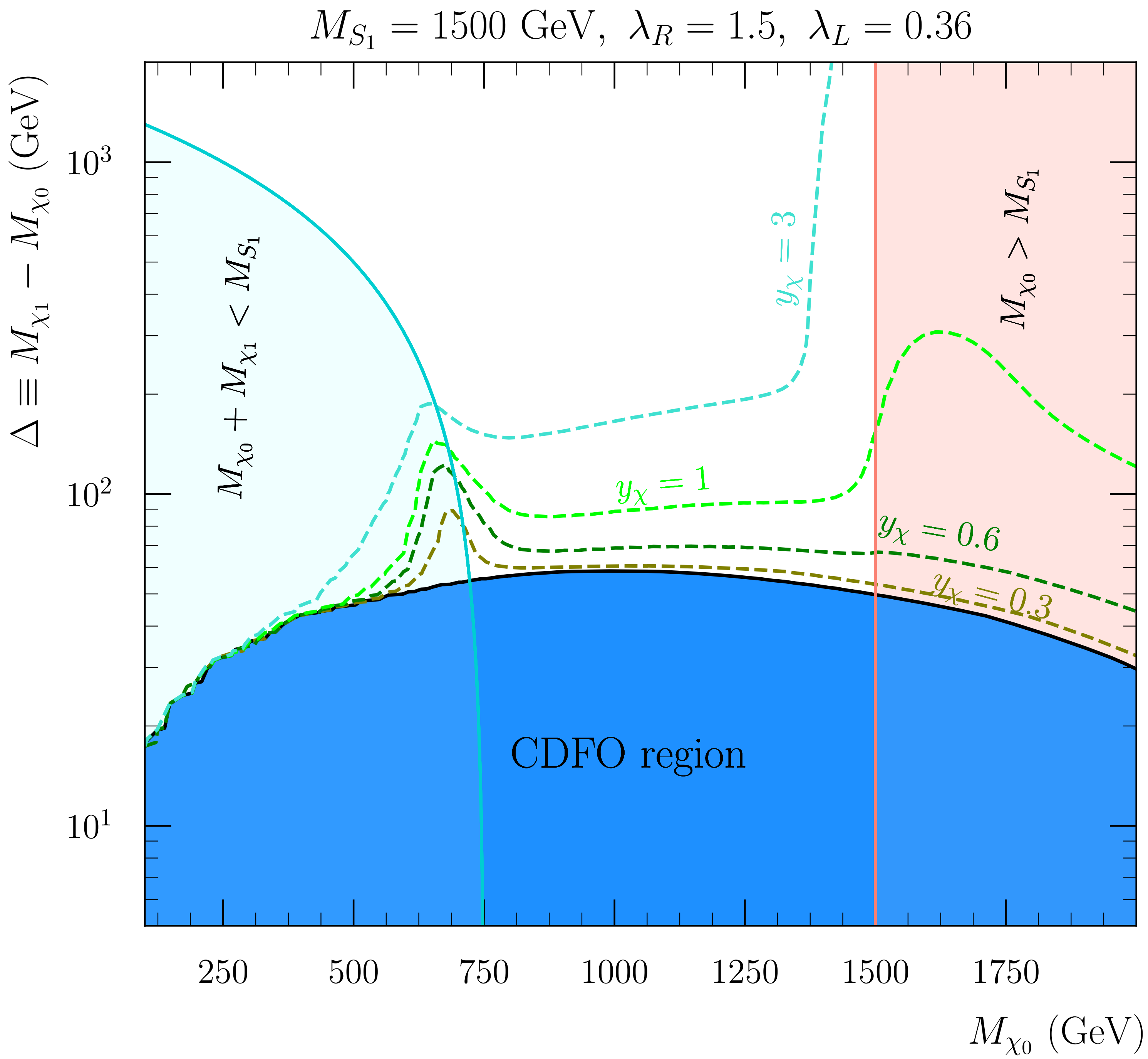
relic density set by conversion processes (inefficient annihilation)





Opens-up the region of small y_χ and / or small Δ

Relic density



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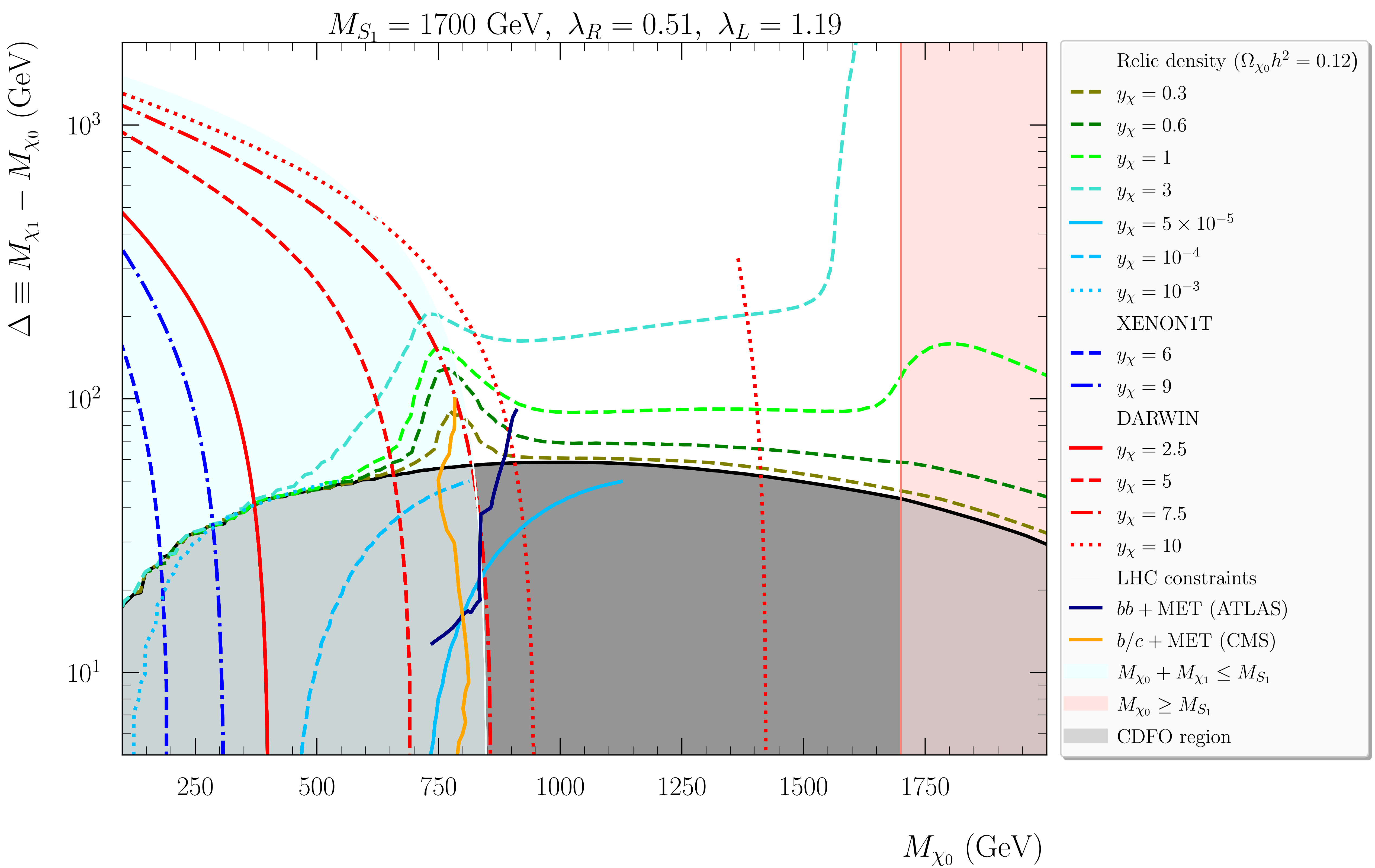
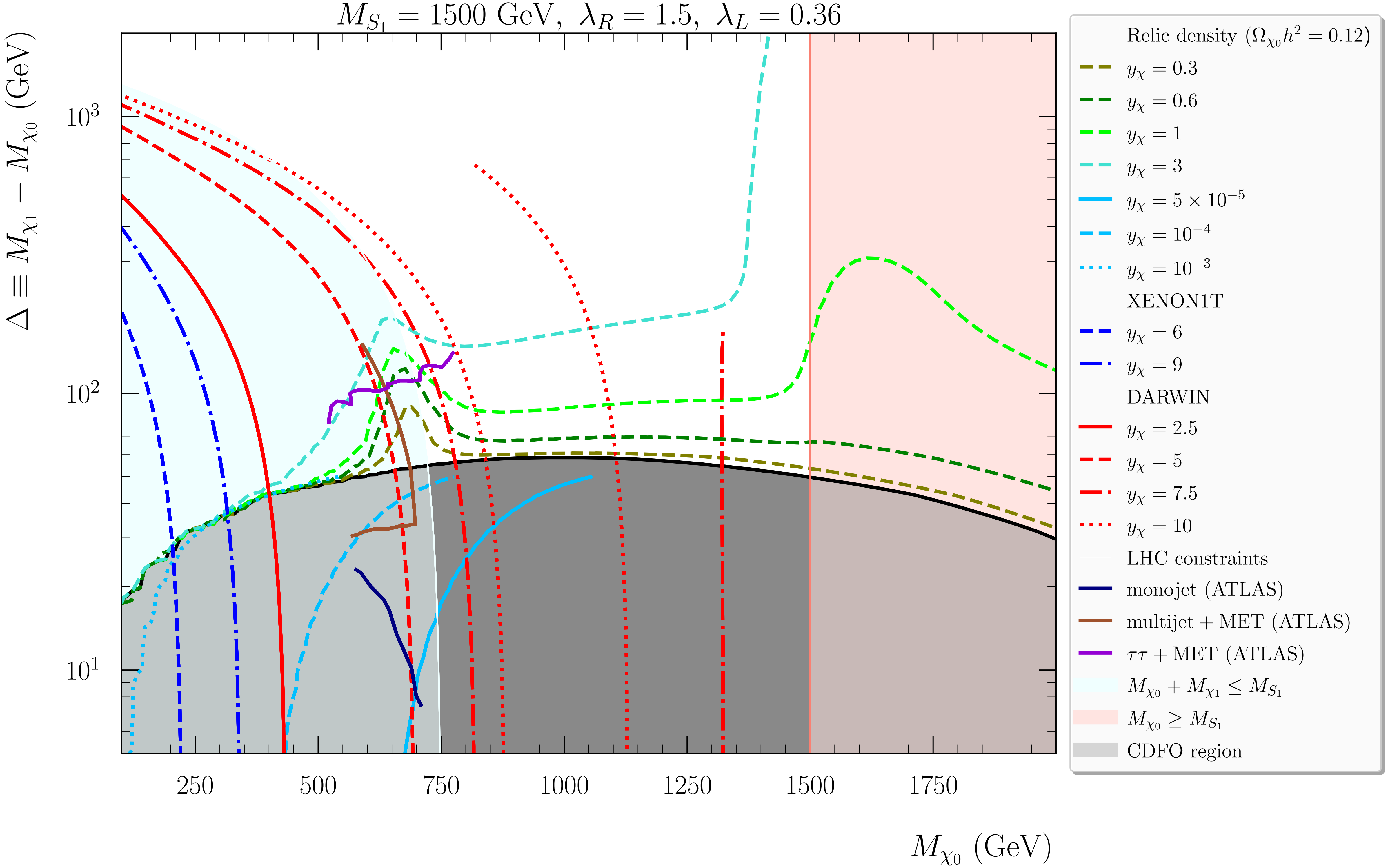
All together (BS1)



All together (BS2)

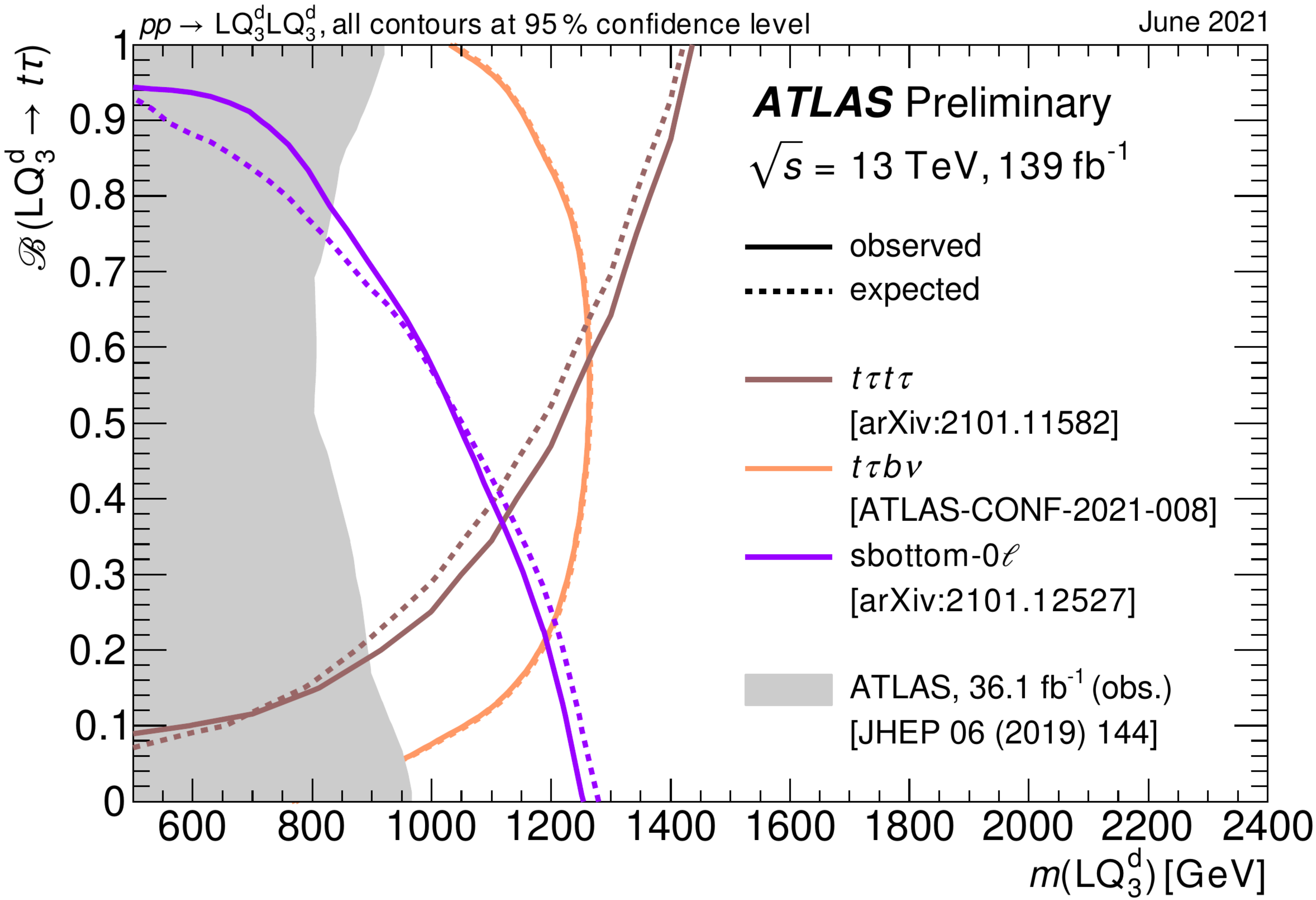


Outlook

- I discussed a minimal setup addressing the RD anomalies and dark matter. The model introduces a leptoquark S1 (d_R gauge charges) and two dark fermions χ_1,χ_0. This simple setup is under siege (collider-wise) from MET, LQ and LQ+MET.
- We studied two benchmarks with S1 decaying dominantly into $c\tau$ / $b\nu$+$t\tau$.
- MET searches prefer x1 ~ x0 (with D <~= 10 GeV), but then mLQ >= 1.4 - 1.7 TeV (important to target the compressed region!). Offers no information about couplings.
- LQ searches would constrain mLQ >= 1.2-1.3 TeV (less than MET), but they are highly relevant to characterise the signal.
- High impact of the *mixed* search S1 S1 -> b nu t tau (and first reinterpretation!)
- Important to explore c-quarks decays and also new mixed channels!
- LQ+MET is key to connect two seemingly uncorrelated excesses (and to measure the S1-> invisible branching ratio).
- Rich interplay with dark matter phenomenology (relic and direct detection).

Backup slides

ATLAS LQ exclusions



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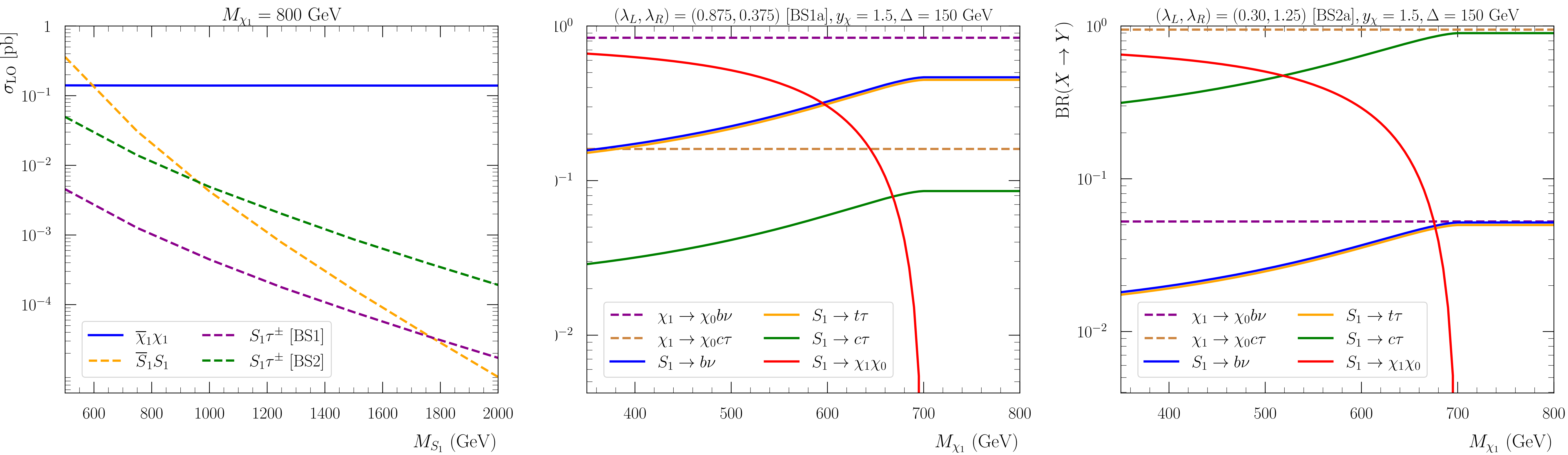
LHC side

- Production:
  - p p -> S_1 S_1 and p p -> χ_1 χ_1 depend only (respectively) on S_1 and χ_1 masses.
  - p p -> S_1 *l* : single LQ involves λ_L, λ_R as well.
- Decays:
  - S1 goes to bν, tτ with equal rate, also decays to cτ and χ_1 χ_0
  - χ_1 -> c τ χ_0 and χ_1 -> b ν χ_0 (we assume $\Delta < m_t$)



Conversion-driven Freeze-Out

Boltzmann Equation with annihilation (and coannihilations with Chemical Equlibirium)

$$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\left[\langle\sigma_{\chi\chi}v\rangle\left(Y_\chi^2 - Y_\chi^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde{b}}v\rangle\left(Y_\chi Y_{\tilde{b}} - Y_\chi^{\mathrm{eq}}Y_{\tilde{b}}^{\mathrm{eq}}\right)\right]$$

Complete Boltzmann Equation (including conversion and out of CE)

$$\begin{aligned}\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\Bigg[&\langle\sigma_{\chi\chi}v\rangle\left(Y_\chi^2 - Y_\chi^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde{b}}v\rangle\left(Y_\chi Y_{\tilde{b}} - Y_\chi^{\mathrm{eq}}Y_{\tilde{b}}^{\mathrm{eq}}\right)\\ &+ \frac{\Gamma_{\chi\to\tilde{b}}}{s}\left(Y_\chi - Y_{\tilde{b}}\frac{Y_\chi^{\mathrm{eq}}}{Y_{\tilde{b}}^{\mathrm{eq}}}\right) - \frac{\Gamma_{\tilde{b}}}{s}\left(Y_{\tilde{b}} - Y_\chi\frac{Y_{\tilde{b}}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right) + \langle\sigma_{\chi\chi\to\tilde{b}\tilde{b}^\dagger}v\rangle\left(Y_\chi^2 - Y_{\tilde{b}}^2\frac{Y_\chi^{\mathrm{eq}\,2}}{Y_{\tilde{b}}^{\mathrm{eq}\,2}}\right)\Bigg]\\ \frac{\mathrm{d}Y_{\tilde{b}}}{\mathrm{d}x} = \frac{1}{3H}\frac{\mathrm{d}s}{\mathrm{d}x}\Bigg[&\frac{1}{2}\langle\sigma_{\tilde{b}\tilde{b}^\dagger}v\rangle\left(Y_{\tilde{b}}^2 - Y_{\tilde{b}}^{\mathrm{eq}\,2}\right) + \langle\sigma_{\chi\tilde{b}}v\rangle\left(Y_\chi Y_{\tilde{b}} - Y_\chi^{\mathrm{eq}}Y_{\tilde{b}}^{\mathrm{eq}}\right)\\ &- \frac{\Gamma_{\chi\to\tilde{b}}}{s}\left(Y_\chi - Y_{\tilde{b}}\frac{Y_\chi^{\mathrm{eq}}}{Y_{\tilde{b}}^{\mathrm{eq}}}\right) + \frac{\Gamma_{\tilde{b}}}{s}\left(Y_{\tilde{b}} - Y_\chi\frac{Y_{\tilde{b}}^{\mathrm{eq}}}{Y_\chi^{\mathrm{eq}}}\right) - \langle\sigma_{\chi\chi\to\tilde{b}\tilde{b}^\dagger}v\rangle\left(Y_\chi^2 - Y_{\tilde{b}}^2\frac{Y_\chi^{\mathrm{eq}\,2}}{Y_{\tilde{b}}^{\mathrm{eq}\,2}}\right)\Bigg],\end{aligned}$$

Garny, Heisig, Lüfl, Vogl, 1705.09292