SEARCHING FOR PSEUDO NAMBU-GOLDSTONE BOSON DARK MATTER PRODUCTION IN ASSOCIATION WITH TOP QUARKS

Based on collaborative work with U. Haisch and G. Polesello.
To be found on the arXiv **tomorrow**!

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MAX-PLANCK-INSTITUT FÜR PHYSIK

Dark Matter as pseudo Nambu-Goldstone boson

- If the SM Higgs boson emerges as a *pseudo Nambu-Goldstone boson* (pNGB) from some extended symmetry structure: Higgs naturally light, hierarchy problem solved!

- Such models can also predict other massive pNGBs → possible DM candidates!

- pNGB DM can both solve the Hierarchy Problem and explain DM!

pNGB DM interactions

In general, pNGB DM gives rise to the following operators:[1]

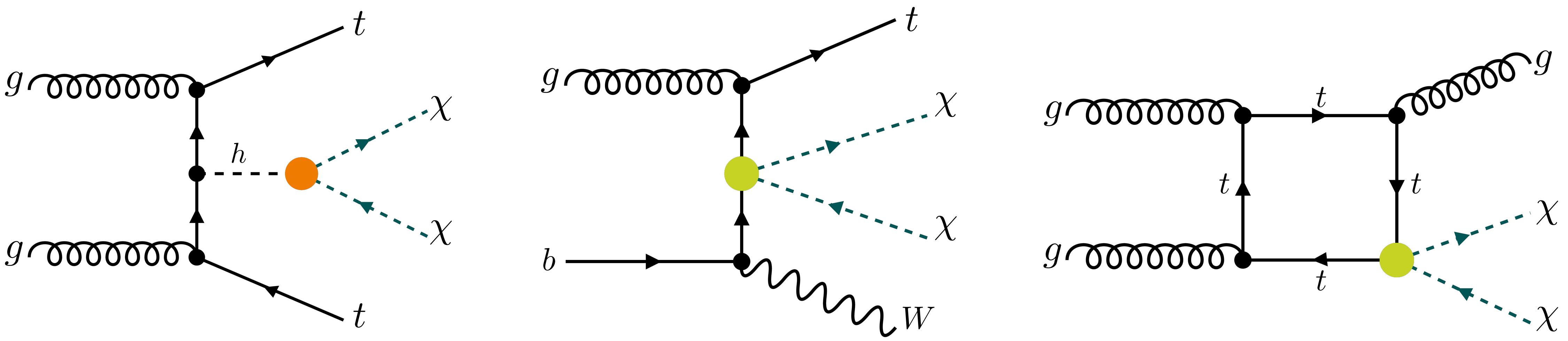
$$\mathcal{L}_{\chi H} = \frac{c_d}{f^2}\,\partial_\mu|\chi|^2\,\partial^\mu|H|^2 - \lambda\,|\chi|^2|H|^2\,,$$

$$\mathcal{L}_{\chi\psi} = \frac{|\chi|^2}{f^2}\left(c_t\,y_t\,\bar{q}_L\tilde{H}t_R + \text{h.c.}\right) + \frac{i}{f^2}\,\chi^*\overleftrightarrow{\partial_\mu}\,\chi \sum_{\psi=q_L,t_R,b_R} d_\psi\,\bar{\psi}\gamma^\mu\psi\,.$$

- Distinguish the *derivative* and *marginal* Higgs portals & *Yukawa-type* and *current-current-type* interactions with fermions
- All operators suppressed by common pNGB decay constant f (except for the marginal Higgs portal)
- Coupling to SM fermions ~Yukawa couplings or momentum suppressed (→ lower sensitivity of DM direct detection?)
- Predominant interactions with heavy particles (e.g. top quarks)

[1] Ruhdorfer et al., SciPost Phys. 8, 027 (2020), arXiv:1910.04170 [hep-ph]

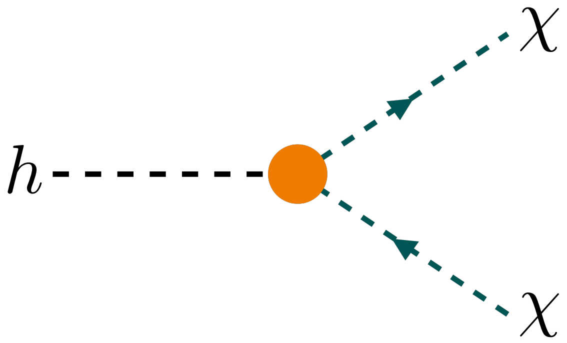
Top quark associated DM production: $tX{+}E_T^{\text{miss}}$ channels

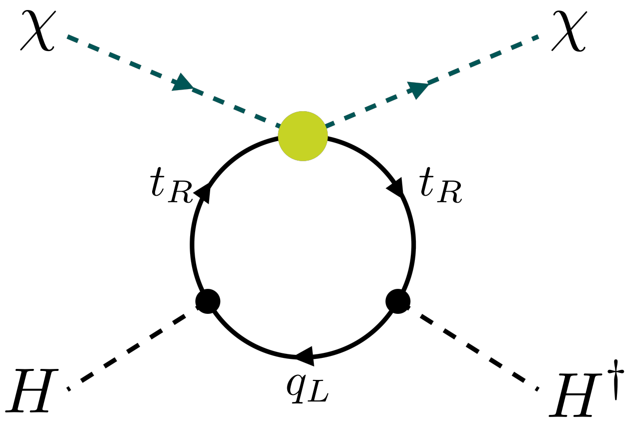


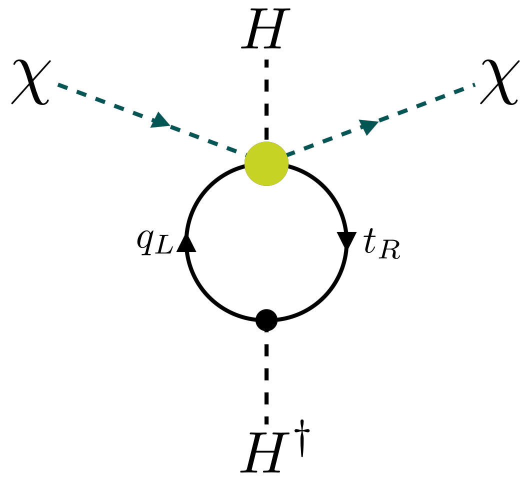
- 3 orthogonal signal regions for $tX{+}E_T^{\text{miss}}$: semileptonic SR1, fully leptonic SR2 & SR3
- Kinematical cuts inspired by previous studies[2] ; cross-checked by implementation into CheckMATE
- Systematic uncertainties: 15% on the backgrounds, 5% on the signal
- Mono-jet search only sensitive to Yukawa-type interaction: weaker constraints than $tX{+}E_T^{\text{miss}}$

[2]The ATLAS Collaboration. Eur. Phys. J. C 78, 18 (2018); Eur. Phys. J. C 80 (2020) 737; JHEP 04 (2021) 165; JHEP 04 (2021) 174

Invisible Higgs Decays



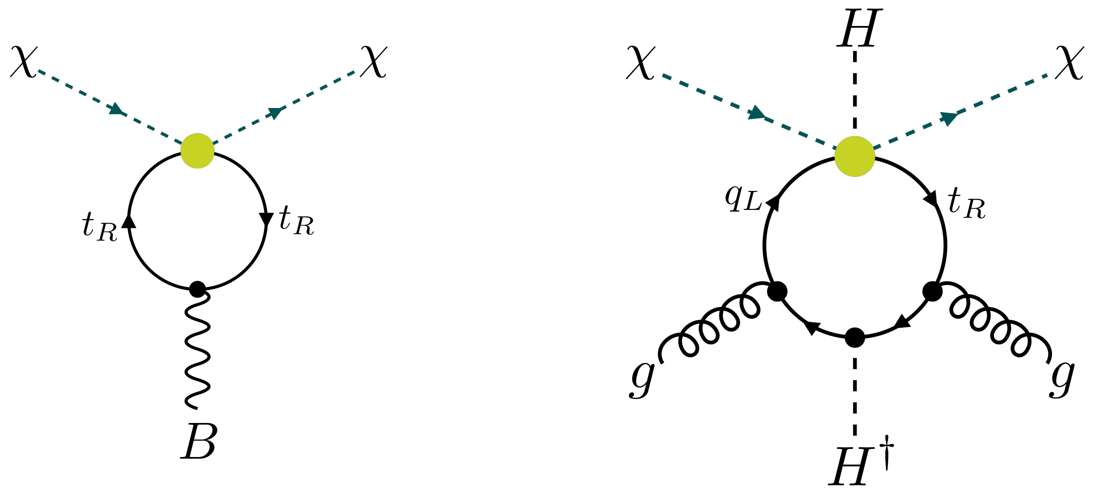




- Tree-level Higgs decays from the marginal and derivative Higgs portals
- DM-fermion operators can be probed via loop-induced processes
- Current bound[3] of $\mathrm{BR}(h \longrightarrow \mathrm{inv}) < 0.11$ yields stringent constraints on couplings for $m_\chi < m_h/2$
- Projected sensitivity HL-LHC[4]: $\mathrm{BR}\,(h \longrightarrow \mathrm{inv}) < 2.5 \cdot 10^{-2}$

[3] The ATLAS Collaboration, Tech. Rep. ATLAS-CONF-2020-052
[4] Cepeda et al., arXiv:1902.00134 [hep-ph]

Direct Detection I



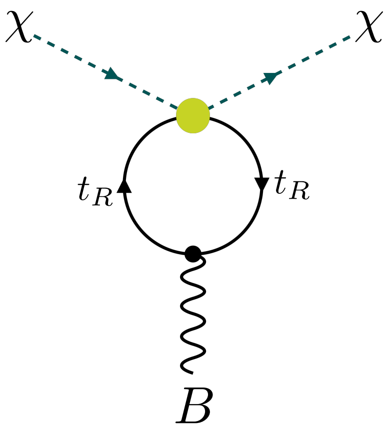
At low energies, pNGB DM Lagrangian can be mapped onto operators with gauge bosons:

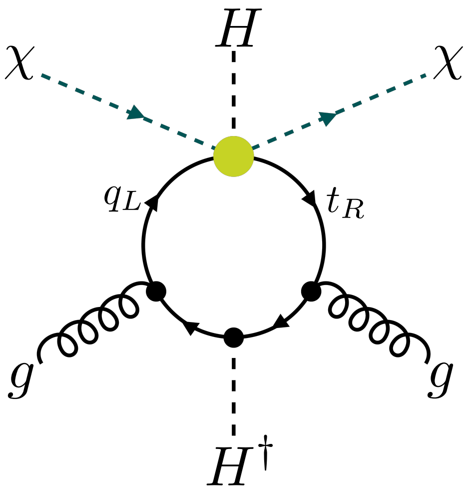
$$\mathcal{L}_{\chi V} = \frac{iec_A}{16\pi^2 f^2}\,\chi^* \overleftrightarrow{\partial}_\mu \chi \partial_\nu F^{\mu\nu} + \frac{g_s^2 d_G}{16\pi^2 f^2}\,|\chi|^2 G^a_{\mu\nu} G^{a,\mu\nu}\,.$$

➢ Matching with low energy Lagrangian gives:

$$c_A = \frac{4}{3}\left(d_{q_L} + 2d_{t_R} - d_{b_R}\right)\ln\frac{\mu_f}{\mu_h}\,, \qquad d_G = -\frac{c_t}{3}\,.$$

Direct Detection II





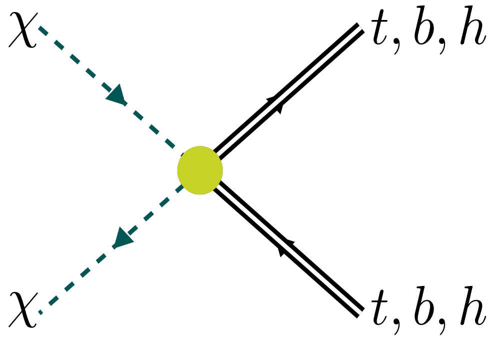
Resulting Spin-Independent DM-Nucleon cross section:

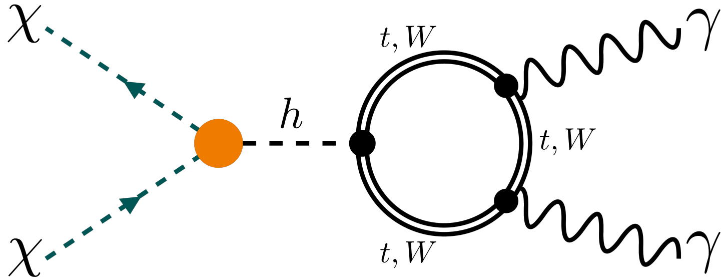
$$\sigma_{\rm SI} = \frac{1}{\pi}\left(\frac{m_\chi m_N}{m_\chi + m_N}\right)^2 \frac{1}{A^2}\left\{\frac{A m_N}{2 m_\chi}\left[\left(1 - \frac{7 f_{T_G}^N}{9}\right)\frac{\lambda}{m_h^2} - \frac{2 f_{T_G}^N d_G}{9 f^2}\right] + \frac{Z e^2 c_A}{16\pi^2 f^2}\right\}^2 .$$

- Can be compared to the limit $\sigma_{\rm SI} < 9.12 \cdot 10^{-47}\,\mathrm{cm}^2$ published by Xenon1T[4]
- No sensitivity to derivative Higgs portal, strong constraints for the other couplings

[4]E. Aprile et al. (XENON), Phys. Rev. Lett. 121, 111302 (2018)

Relic Density and Indirect Detection

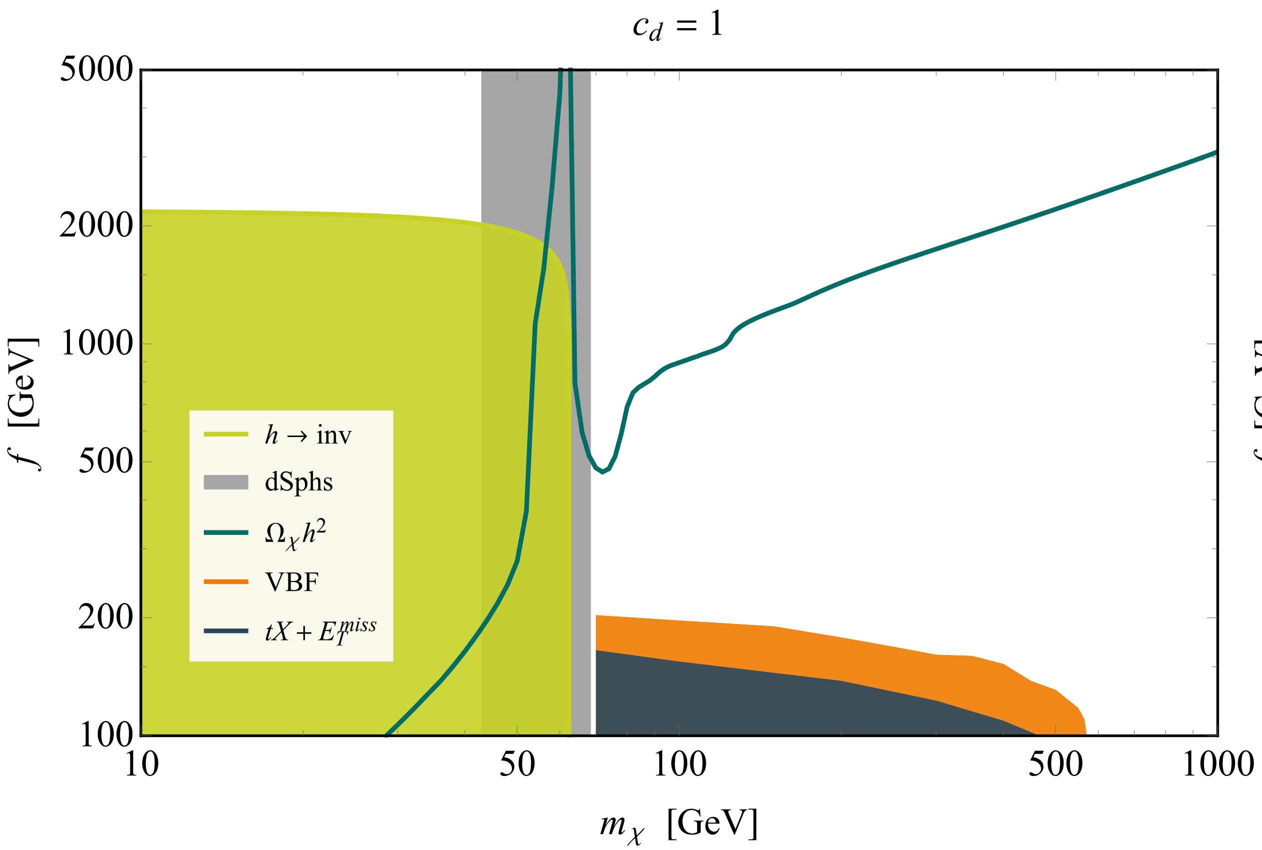




- Compute all relevant DM annihilation cross sections
- Dominating annihilation channels for relic density determined by the DM mass:
  - For $m_b < m_\chi \lesssim m_W$: p-wave annihilation into b-quarks via current-current type interaction
  - For $m_\chi \gtrsim m_W$: s-wave annihilations $\chi^*\chi \longrightarrow W^+W^-,\ ZZ,\ hh,\ t\bar{t}$ set by derivative Higgs portal
- Strongest indirect detection constraints via on-shell Higgs exchange
- Constraints computed with MicrOMEGAs code (provided by Ruhdorfer et al.[1])

[1]Ruhdorfer et al., SciPost Phys. 8, 027 (2020) arXiv:1910.04170 [hep-ph]

Results I


$c_d = 1$
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f [GeV]
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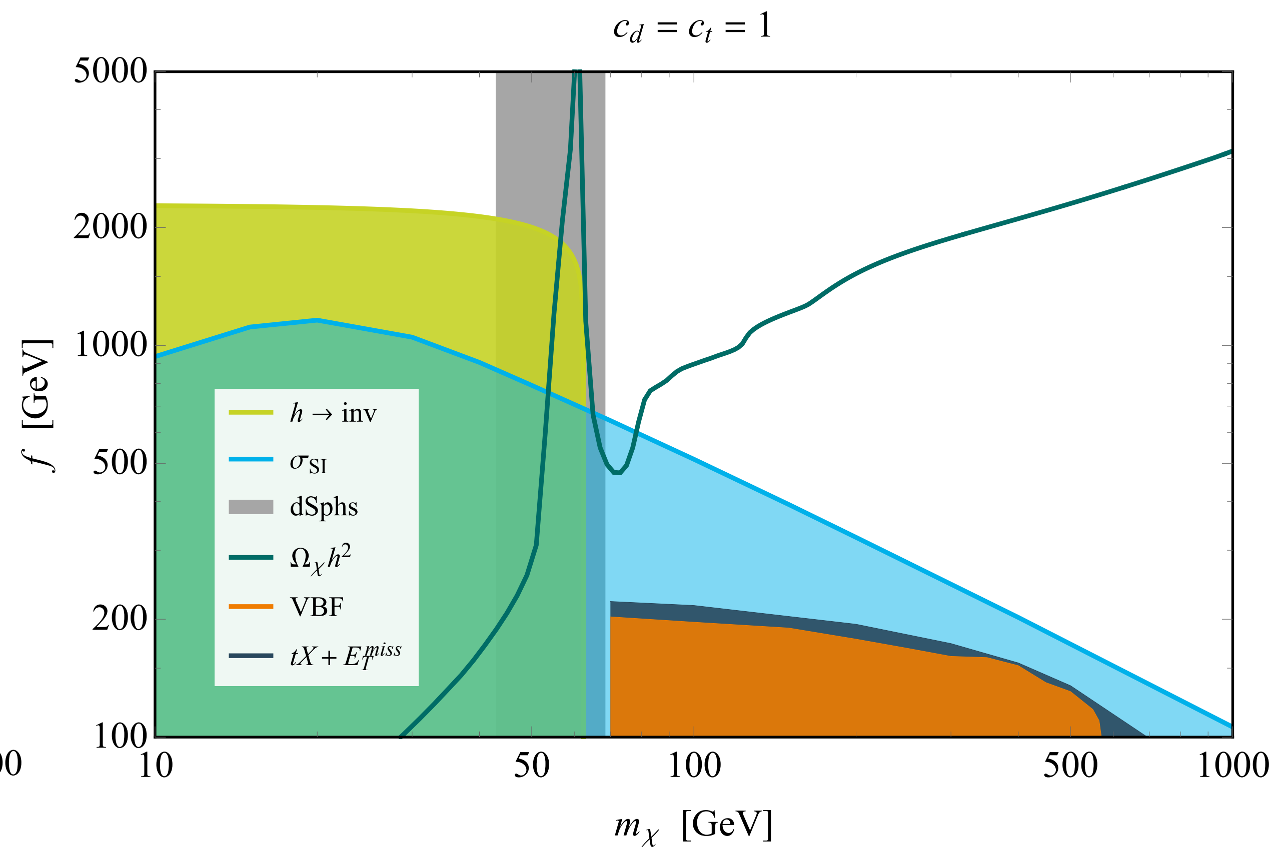
$\Omega_\chi h^2$
VBF
$tX + E_T^{miss}$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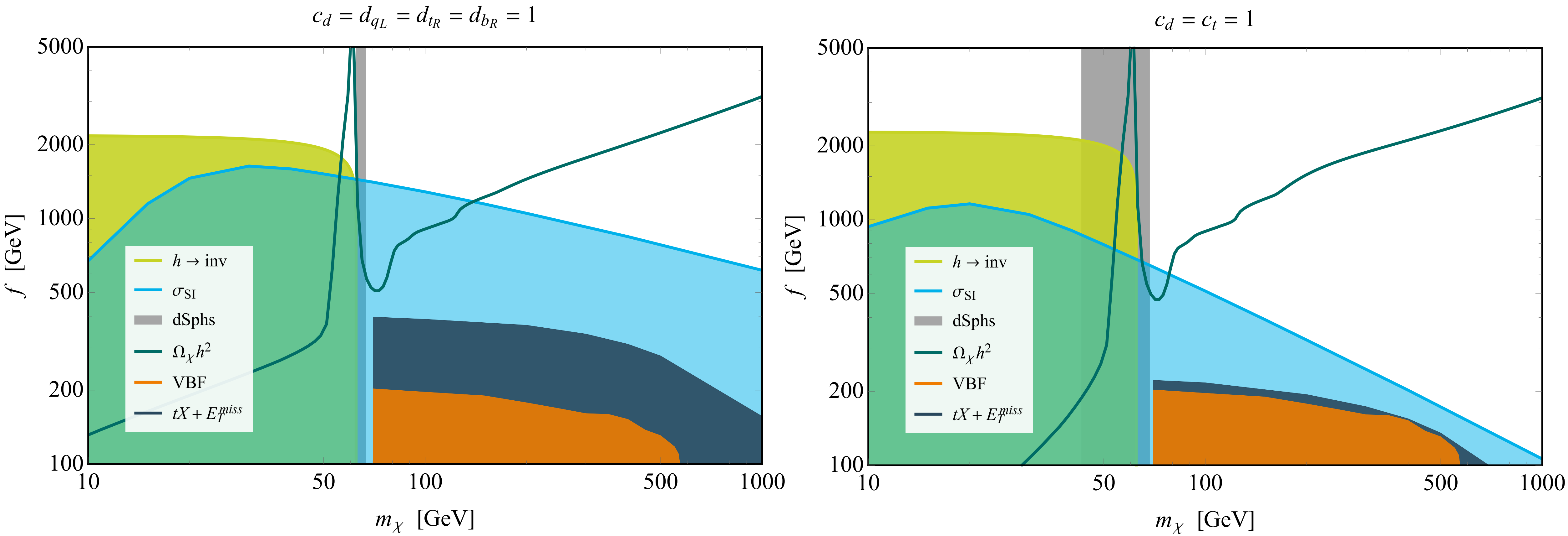
Results II



$c_d = d_{q_L} = d_{t_R} = d_{b_R} = 1$
$c_d = c_t = 1$
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f [GeV]
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$h \to$ inv
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Conclusion

- Collider searches can probe otherwise inaccessible regions of the parameter space
- Loop-induced interactions lead to sensitivity of direct detection experiments
- Direct detection constraints can dominate collider constraints depending on specific coupling configuration
- pNGB DM remains a viable DM candidate that can both explain the relic abundance and solve the hierarchy problem

Thank you for your attention!