Strong dynamics & dark matter
Investigating the minimal setup

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LFC19: Strong dynamics for physics within and beyond the SM at LHC and future colliders

ECT*, Trento (Italy), 12 September 2019

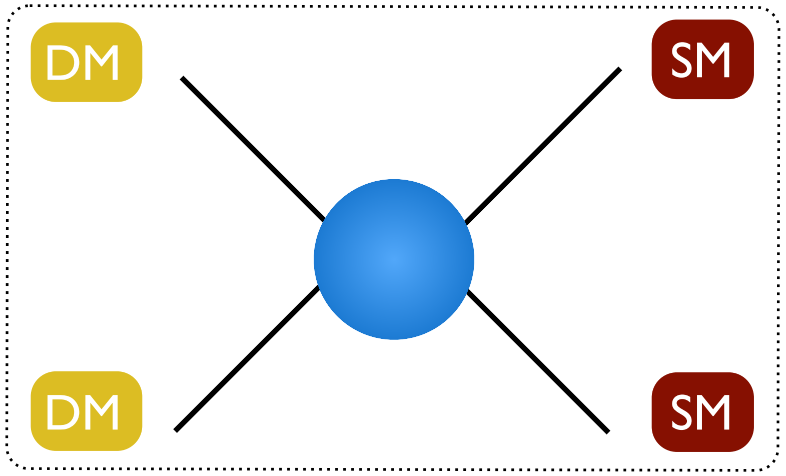
Outline

1. Introduction
2. Cosmological constraints
3. Complementarity with colliders
4. Summary - conclusions

Dark matter in cosmology and at colliders

- ✦ Dark matter is searched for directly, indirectly and at colliders
  - ✤ Huge experimental effort → strategy to constrain models

- ✦ Complementary between colliders and cosmology
  - ✤ Relic abundance
  - ✤ Direct/indirect detection
  - ✤ Production at colliders



A toy model inspired by strong dynamics models

✦ Dark matter naturally appears in non-minimal composite models

- ✤ Example: *SU(6)/SO(6)* includes several stable neutral scalars
- ✤ Partial compositeness → special role of the top quark

[Cacciapaglia, Cai, Deandrea & Kushwaha (2019)]

✦ A simplified model for composite dark matter

- ✤ Features shared by several UV-complete models
- ✤ Scalar dark matter and a vector-like fermionic mediator

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \Big[\tilde{y}_t\, S\, \bar{T} P_R t + {\rm h.c.}\Big]$$

- ★ SU(2) singlet vector-like mediator *T*
- ★ EW singlet scalar dark matter *S*

- ✤ Simplest dark matter parameter space
  - ★ 2 masses: m_S, m_T/m_S-1; 1 Yukawa coupling $\tilde{y}_t$

Is this viable?

Relic abundance: generalities

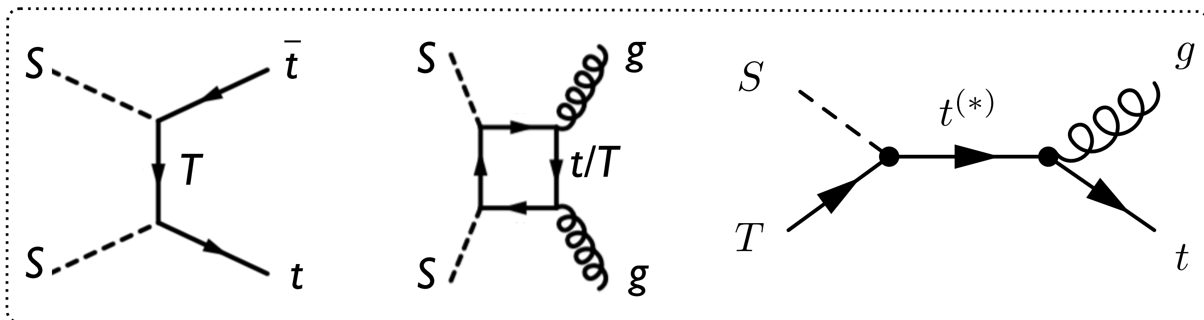
[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

✦ Several competing annihilation channels

★ Into (potentially virtual) tops

★ Into gluons (loop-induced)

★ $S\,T \to t^{(*)}$ co-annihilations (potentially resonant)



✤ Coloured point ≡ viable scenario

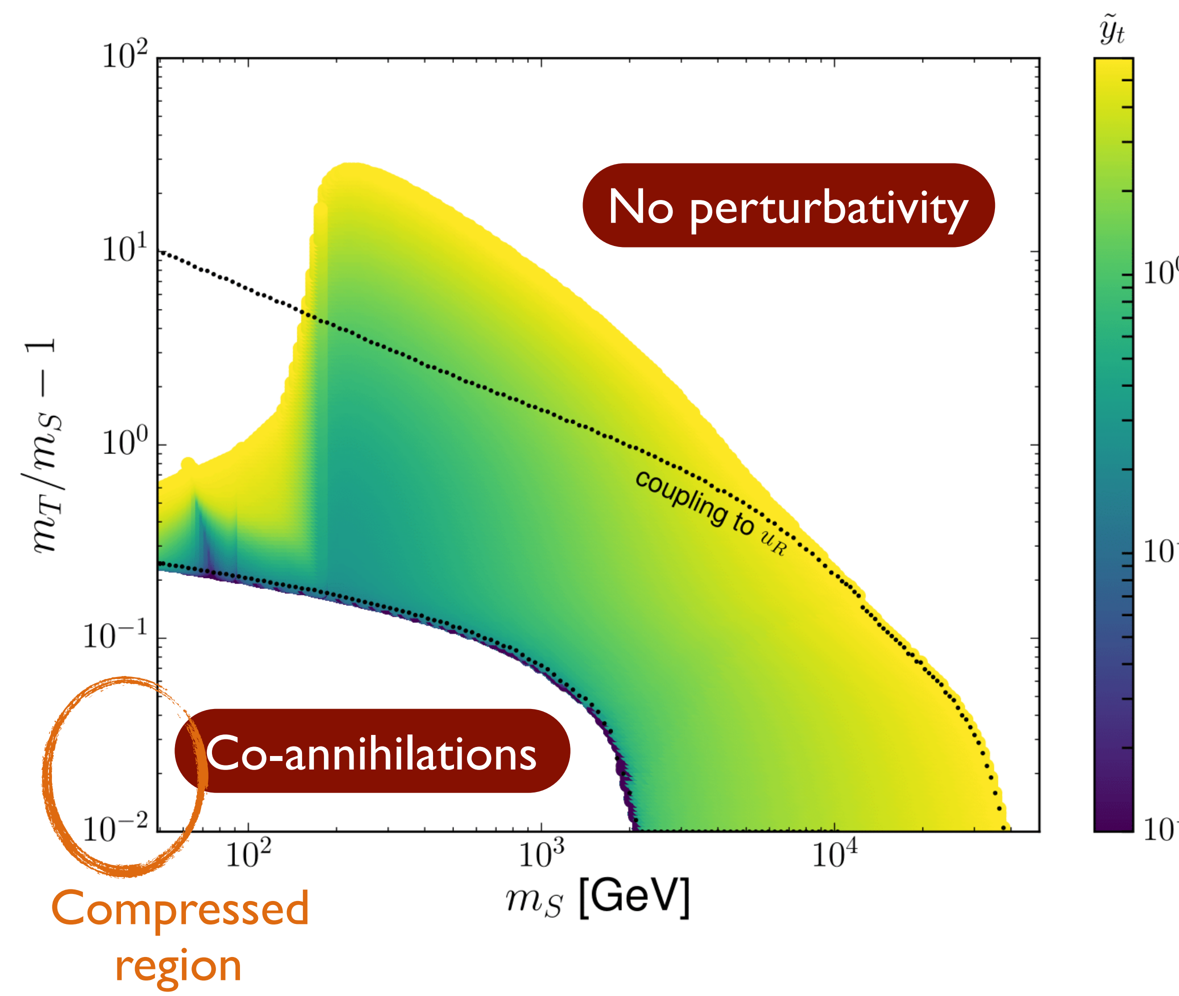
$$\Omega_{\rm DM} h^2 = 0.12$$ [Planck Collaboration (AA`14)]

★ NLO QCD corrections included

✤ Right relic abundance → $\tilde{y}_t$

★ Min: 0.001 (co-annihilations)

★ Max: 6 (perturbativity)

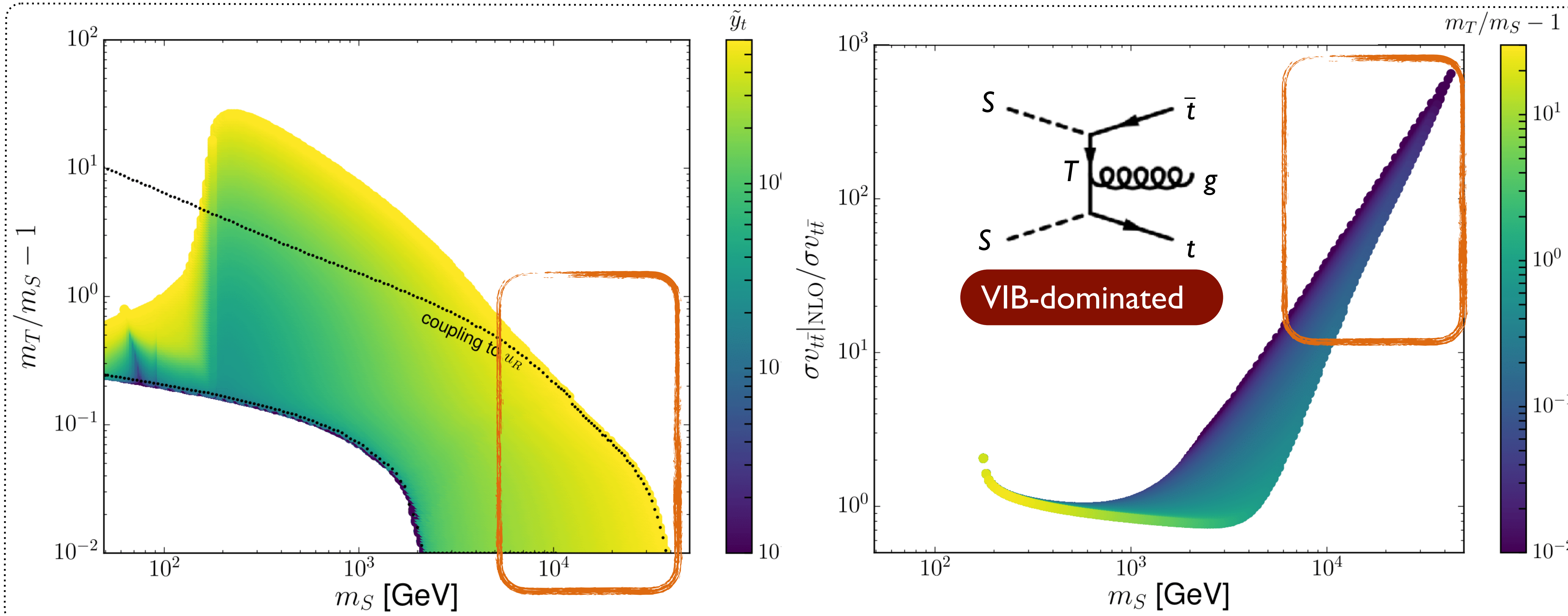


Large viable parameter space region from the relic standpoint

Relic abundance: multi-TeV dark matter

[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

✦ Regime with a heavy scalar (m_S > 5 TeV)



✤ Annihilations into tops dominate

$$(\sigma v)_{\rm NLO} \approx (\sigma v)_{\rm LO}\left[1 + \frac{\alpha_s C_F}{\pi}\left(\frac{9}{4} - \frac{3}{2}\log\frac{M_S^2}{m_t^2}\right)\right]$$

★ Top-mass effects negligible

★ Velocity-independent (~1)

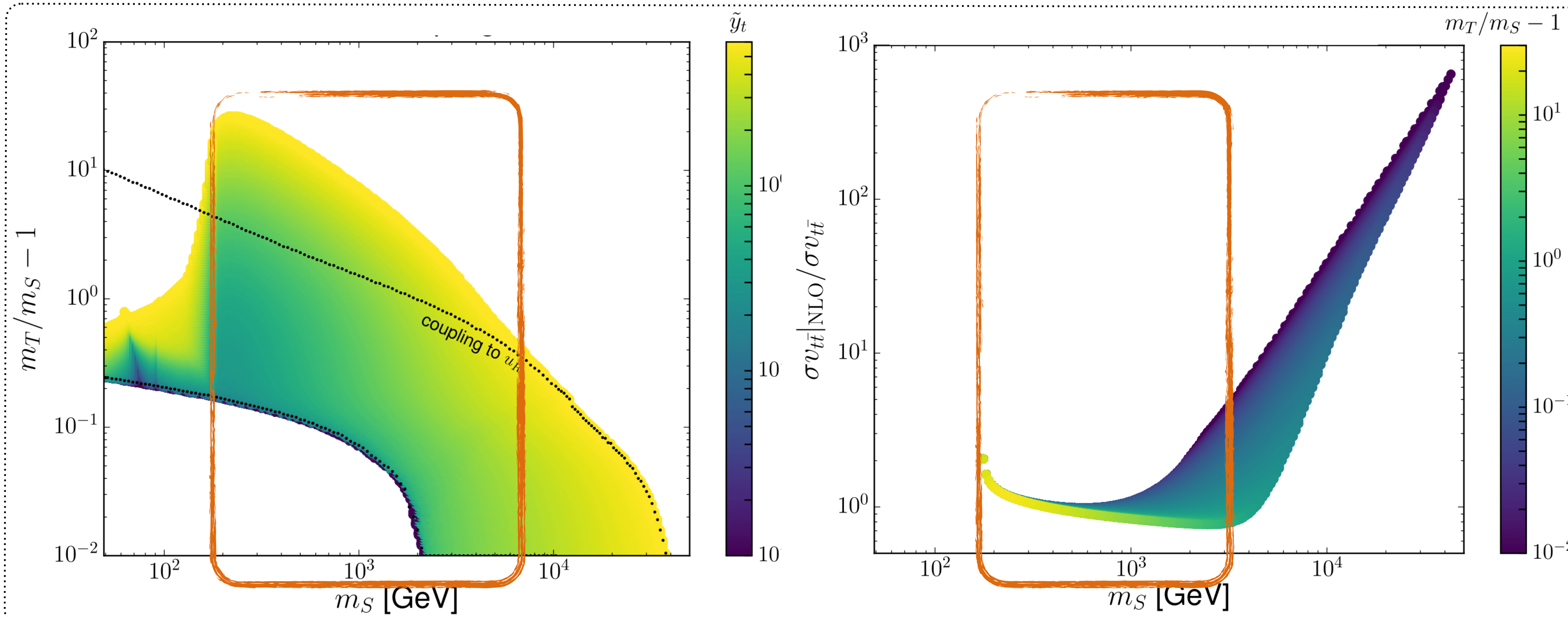
✤ Huge QCD *K*-factors

★ Virtual internal bremsstrahlung (VIB) (∝ $(m_T/m_S)^{-4}$)

Relic abundance: moderately heavy dark matter

[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

✦ Regime with ($m_t < m_S <$ 5 TeV)



✤ Annihilations into tops dominate

- ★ Important top-mass effects
- ★ Opens up a new region (≠ light quarks)
  - ➢ annihilations into quarks negligible
- ★ Mild *K*-factors

✤ Close to threshold

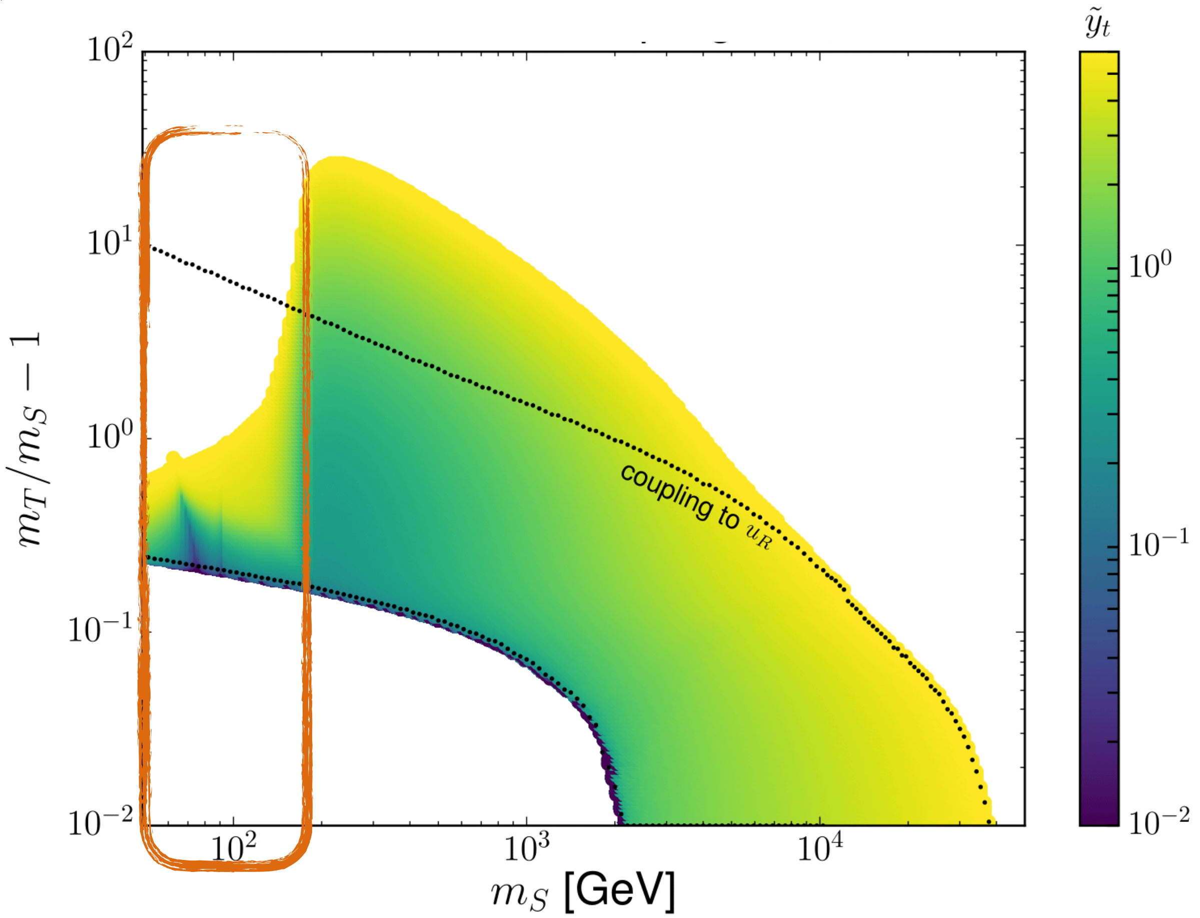
$$(\sigma v)_{\rm NLO} \approx (\sigma v)_{\rm LO}\left[1+\frac{\alpha_s C_F}{\pi}\left(\frac{\pi^2}{2\beta_0}-1\right)\right]$$

- ★ Velocity small
- ★ Spurious results at threshold (→ *p*-wave)

Relic abundance: light dark matter

[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

✦ Regime with ($m_S < m_t$)



✤ Annihilations into tops is closed

★ 3-body annihilations (into tWb)

$$m_S \in \left[\frac{m_t + m_W}{2}, m_t\right]$$

★ SS→gg important for $m_S < (m_t+m_W)/2$

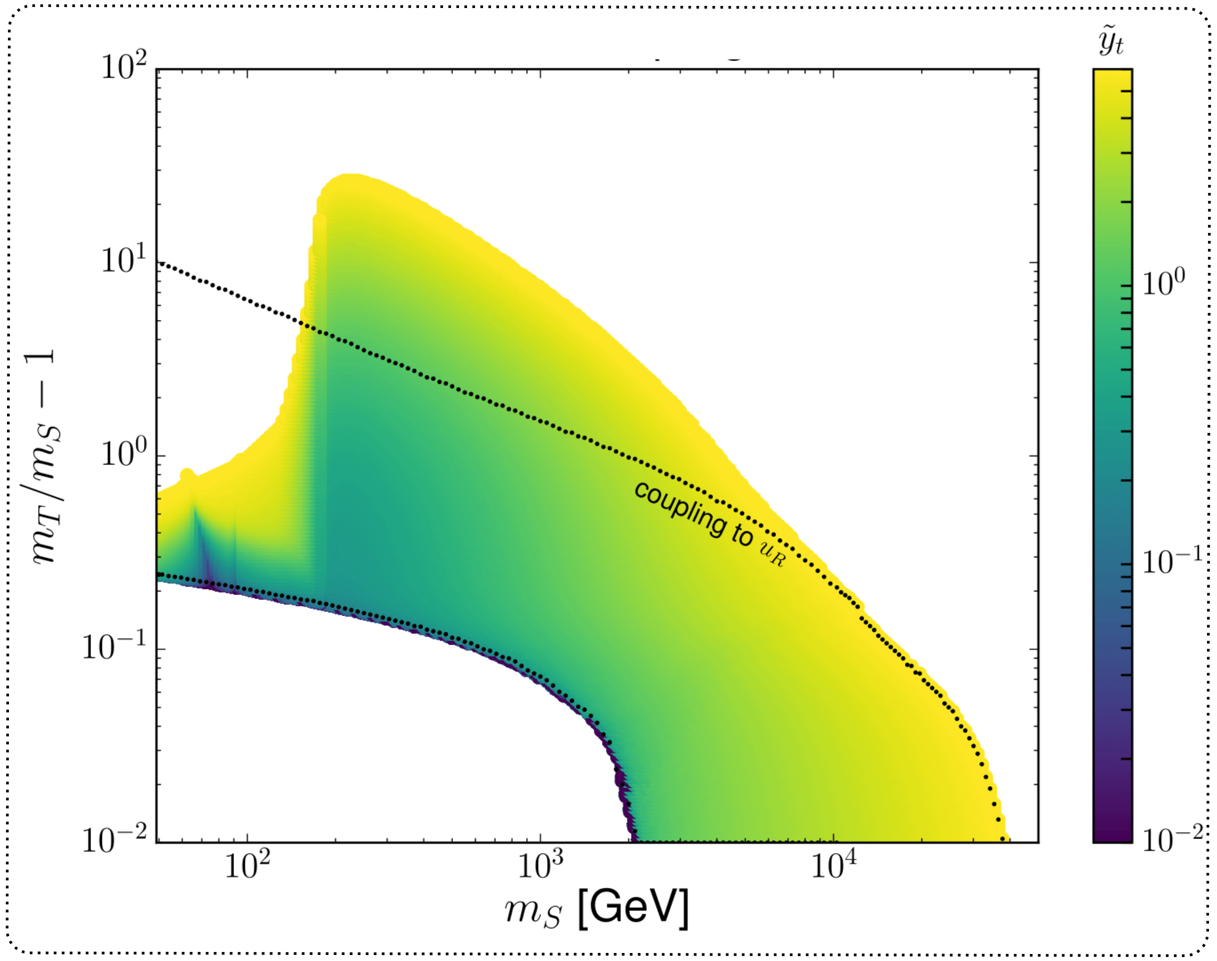
➢ loop-induced

★ Co-annihilations crucial near $m_T + m_S \sim m_t$

➢ resonant enhancement ($m_S \sim 75$ GeV)

Relic abundance: summary

[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]



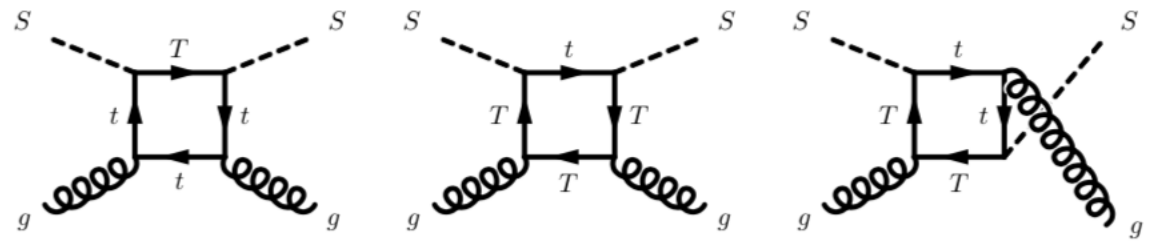
✤ The Yukawa is fixed to match Planck data
- ★ We focus on the coloured points only

✤ Large variety of acceptable scenarios
- ★ Dark matter masses from 50 to 40000 GeV

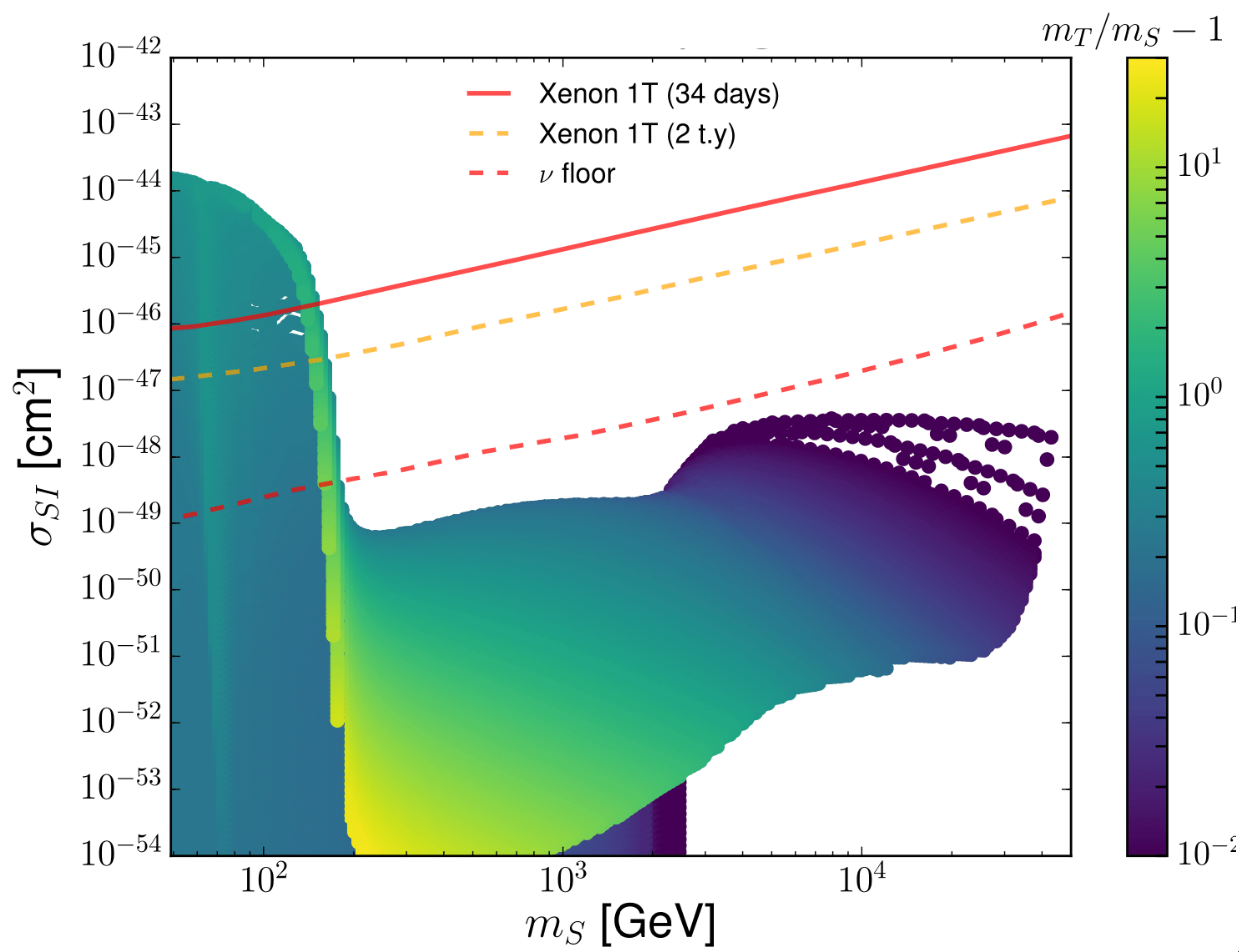
Direct detection: light dark matter

[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

✦ Loop-suppressed DM interactions with gluons ⇔ weak direct detection constraints



Loop suppression: reduction of σ_{SI}



✤ Light dark matter:

- ★ Relic density driven by $SS \to gg$ (for $m_S < (m_t+m_W)/2$)
- ★ Large σ_{SI} expected in this regime
- ★ Yellow band at ~ 75 GeV
  - ➢ $ST \to t$ resonant co-annihilation regim

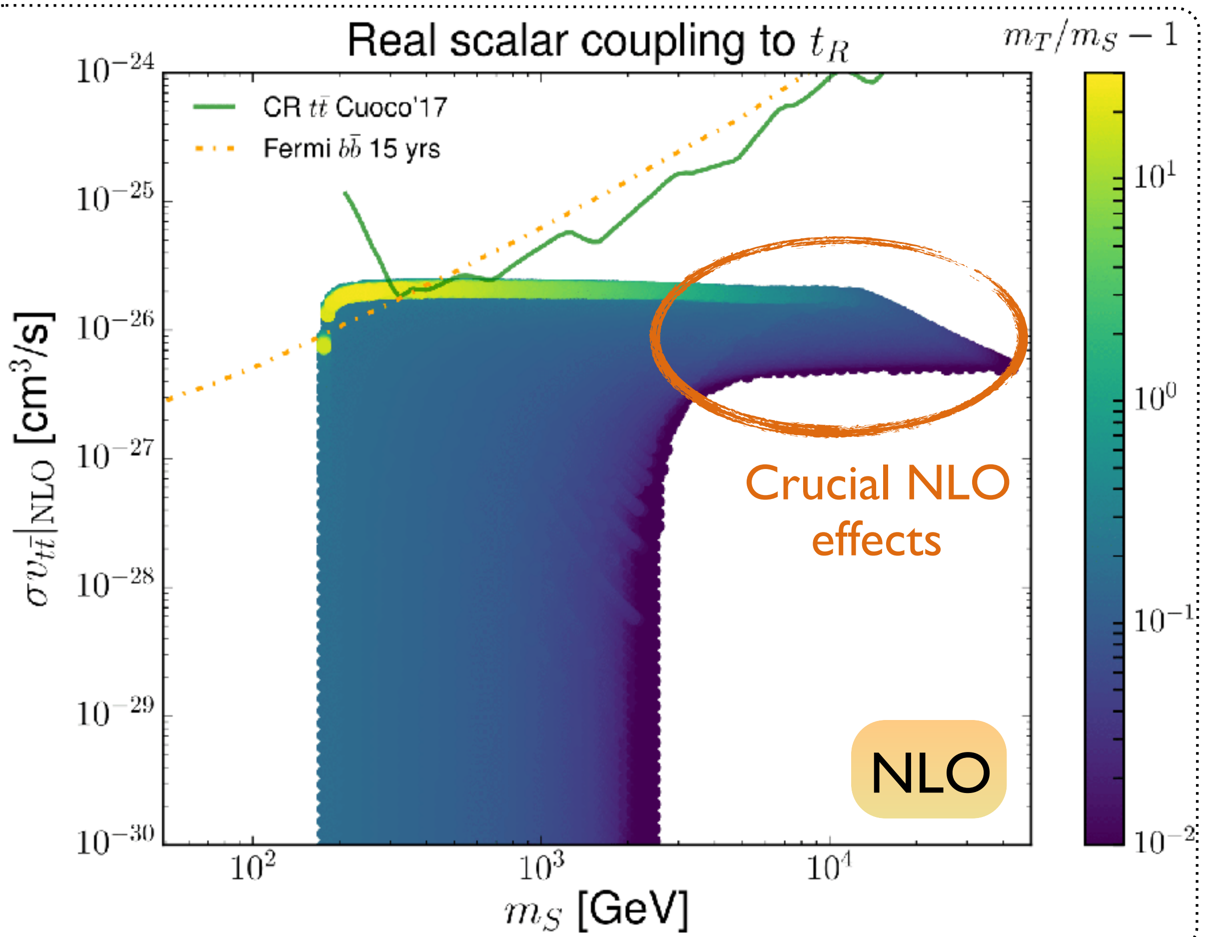
✤ Heavy dark matter:

- ★ Negligible $SS \to gg$
- ★ Smaller Yukawa value needed to match the relic
  - ➢ Most parameter space below the ν floor

Indirect detection: annihilations in tops/gluons

[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

✦ Secondary photon flux originating from DM annihilations



✤ Gamma ray continuum (from $b\bar{b}$ limits)

$$\sigma v_{gg,t\bar{t}} = \sigma v_{b\bar{b}} \frac{N_\gamma^{b\bar{b}}}{N_\gamma^{gg,t\bar{t}}}$$

★ N^X is the number of γ from an X state

[Bringmann, Huang, Ibarra, Vogl & Weniger (JCAP`12)]

✤ Mild constraints from Fermi projections

★ Dwarf spheroidal analysis → bottom quarks

✤ Mild constraints from AMS antiprotons

★ Annihilations into SM particles → $\bar{p}$ flux

Indirect detection: annihilations in photons

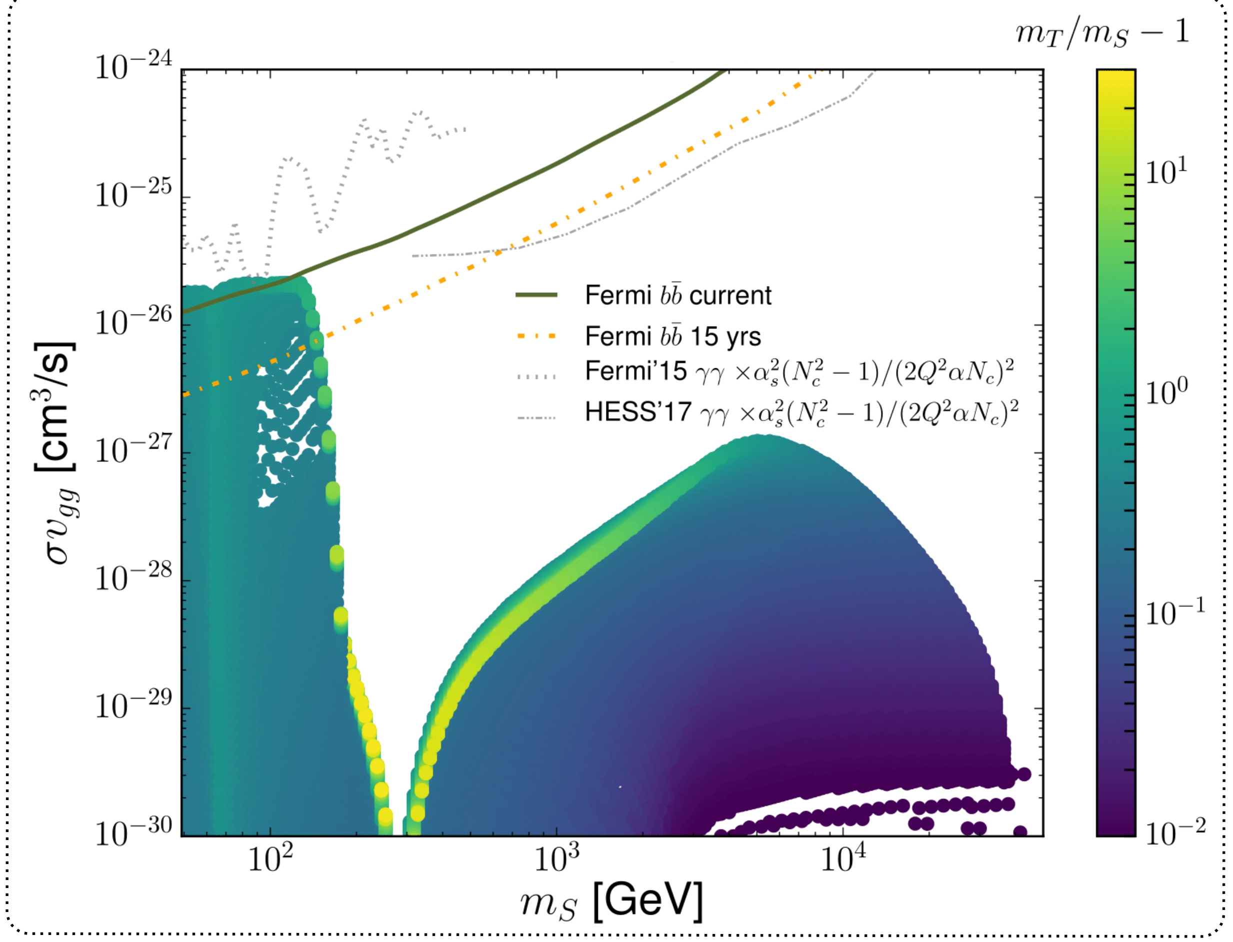
[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

- Light dark matter ($m_S < m_t$)
  - Annihilation into gluons dominates
  - Annihilations into photons is large

$$\frac{\sigma v_{\gamma\gamma}}{\sigma v_{gg}} = \frac{4Q^4\alpha^2 N_c^2}{\alpha_S^2\,(N_c^2-1)} \approx 4.3\cdot 10^{-3}$$

- Heavy dark matter ($m_S > 2$ TeV)
  - Annihilation into tops dominates
  - Photon emission is important (VIB)

$$\frac{\sigma v_{t\bar{t}\gamma}}{\sigma v_{t\bar{t}g}} = \frac{2N_c Q^2\alpha}{(N_c^2-1)\alpha_s} \approx 2.3\cdot 10^{-2}$$

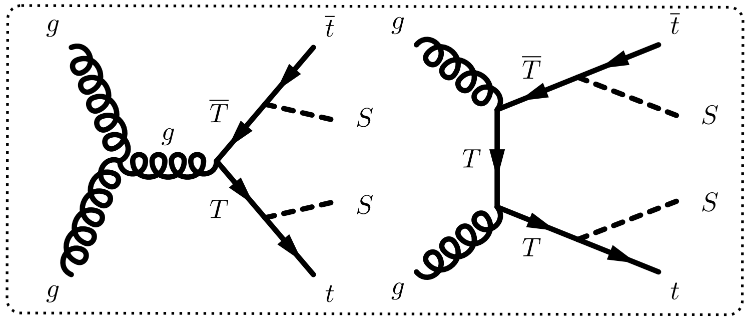


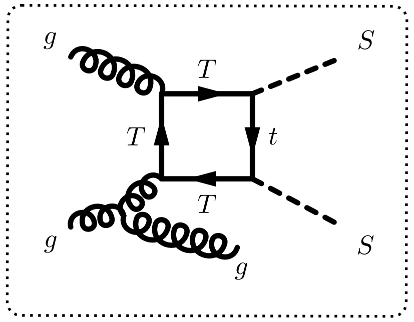
- Mild constraints from H.E.S.S. and Fermi

Dark matter searches at colliders

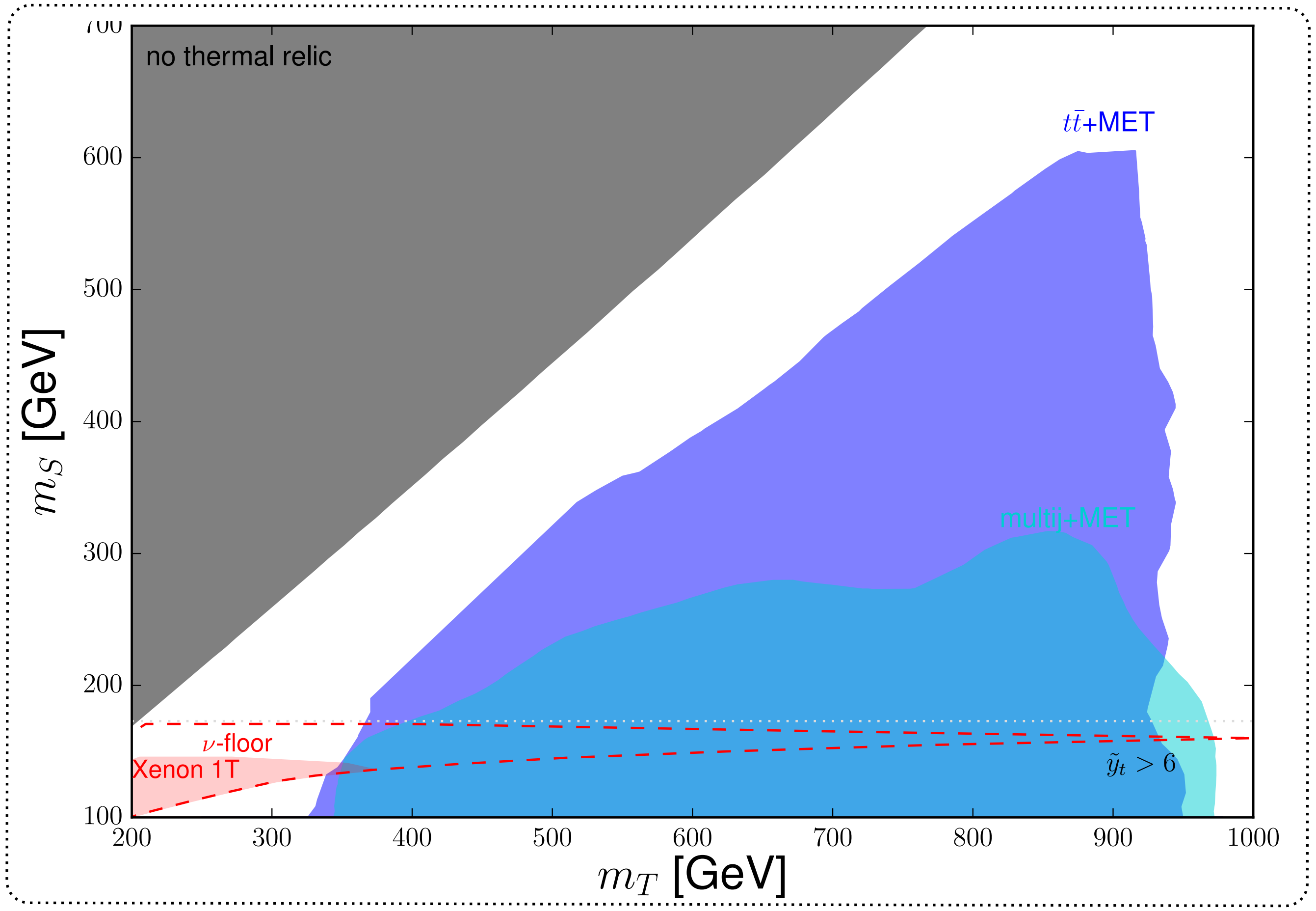
[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

✦ Two main modes @ LHC: monojets, multijets+MET, and $t\bar{t}$ + MET





$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \Big[\tilde{y}_t\, S\, \bar{T} P_R t + {\rm h.c.}\Big]$$



✤ General features

★ Γ_T must be larger than $\Lambda_{\rm QCD}$ (no LLP)

★ Bounds independent of the Yukawa

➢ monojet production negligible

✤ Multijet probes

★ Monojet-inspired (at least one very hard jet)

★ Loss of sensitivity ⇔ decay phase space

✤ Top-antitop plus MET

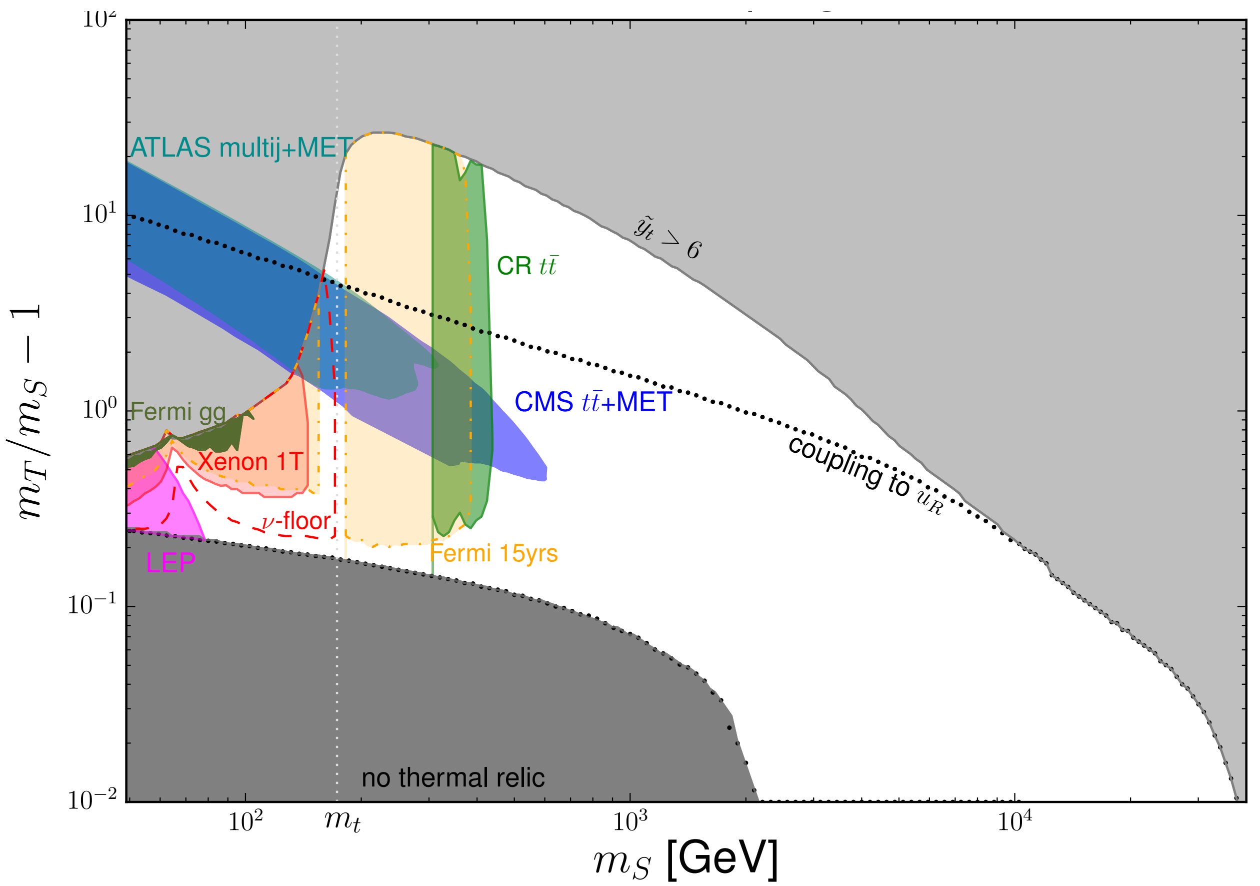
★ Well adapted to our topology

★ Best constraints (and chance of discovery)

Composite scalar dark matter - summary

[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

✦ Collider-cosmology complementarily at work



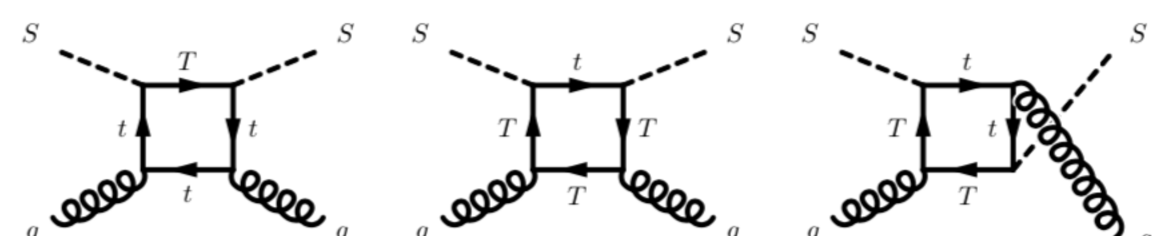
✤ Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \left[\tilde{y}_t\, S\, \bar{T} P_R t + {\rm h.c.}\right]$$

★ Vector-like mediator T
★ Scalar dark matter S

✤ Relic-density favored regions exist
★ Fixes the Yukawa $\tilde{y}_t$
★ Dark grey: no thermal relic
★ Light grey: loss of perturbativity
★ Annihilation into gg below the m_t threshold

✤ DM direct detection constraints
★ Poor sensitivity (loop-induced interactions)
★ Most parameter space below the ν floor



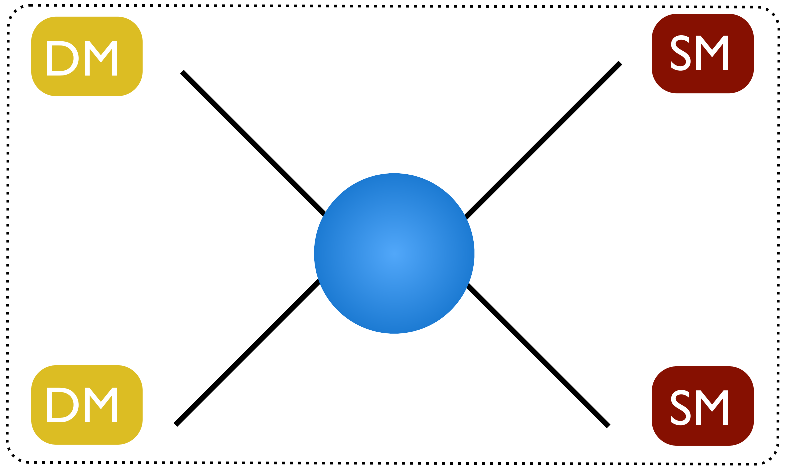
✤ DM indirect detection constraints
★ Exclude (will rule out) limited light DM regions

✤ Colliders (present and future)
★ Sole probes to tackle the unconstrained regions

Summary

✦ Dark matter is a very appealing option to explain cosmological data

- ✤ Can be probed complementarily
  - ★ Relic density
  - ★ Direct/indirect detection
  - ★ Collider searches



- ✤ We explored a simplified setup inspired by strong dynamics

✦ Past developments of high-energy physics tools have been crucial

- ✤ Any model of dark matter (complete or simplified) can be studied
- ✤ Higher-order corrections can be included as easily
- ✤ Robust predictions ⇔ crucial for a discovery