Closing in on *t*-channel simplified dark matter models

Benjamin Fuks
(LPTHE / Sorbonne Université)

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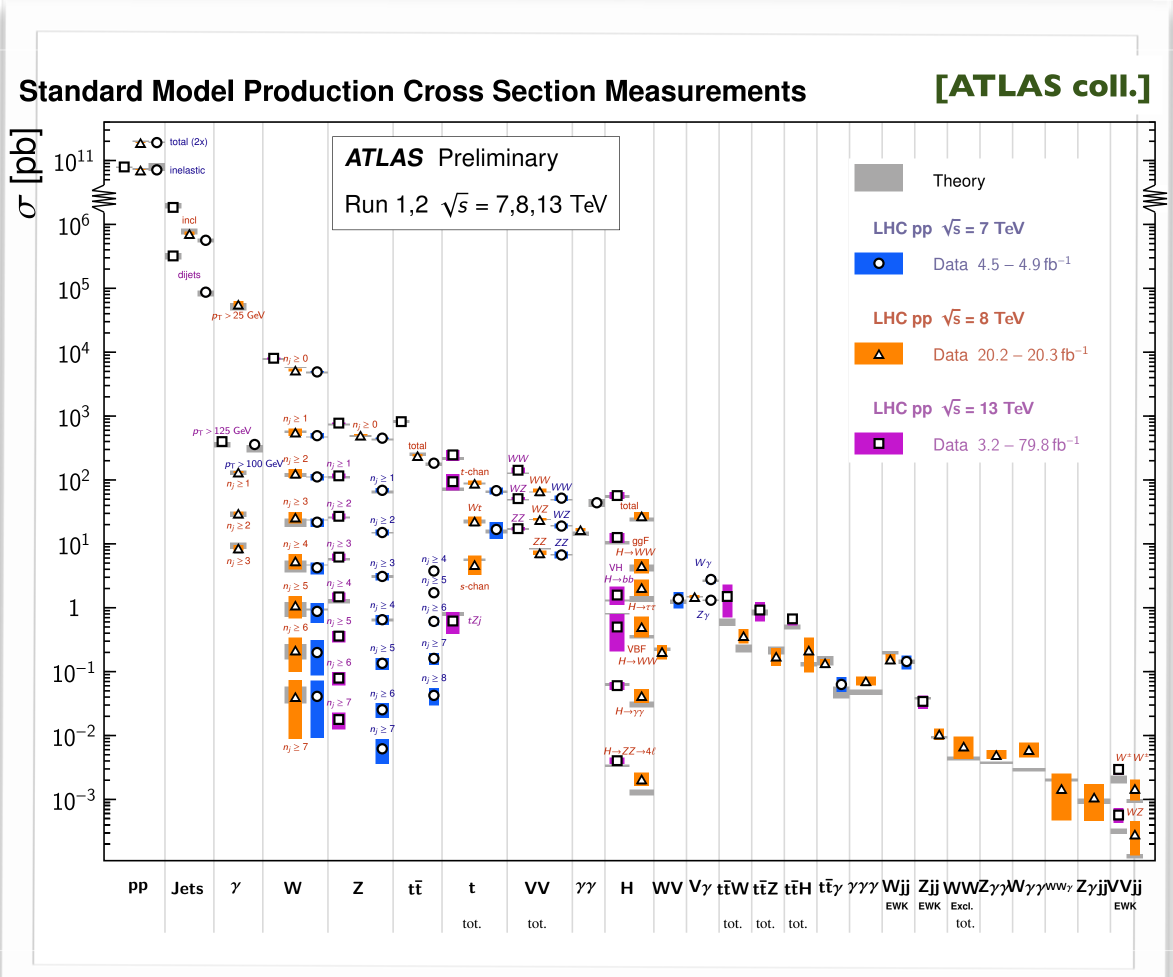
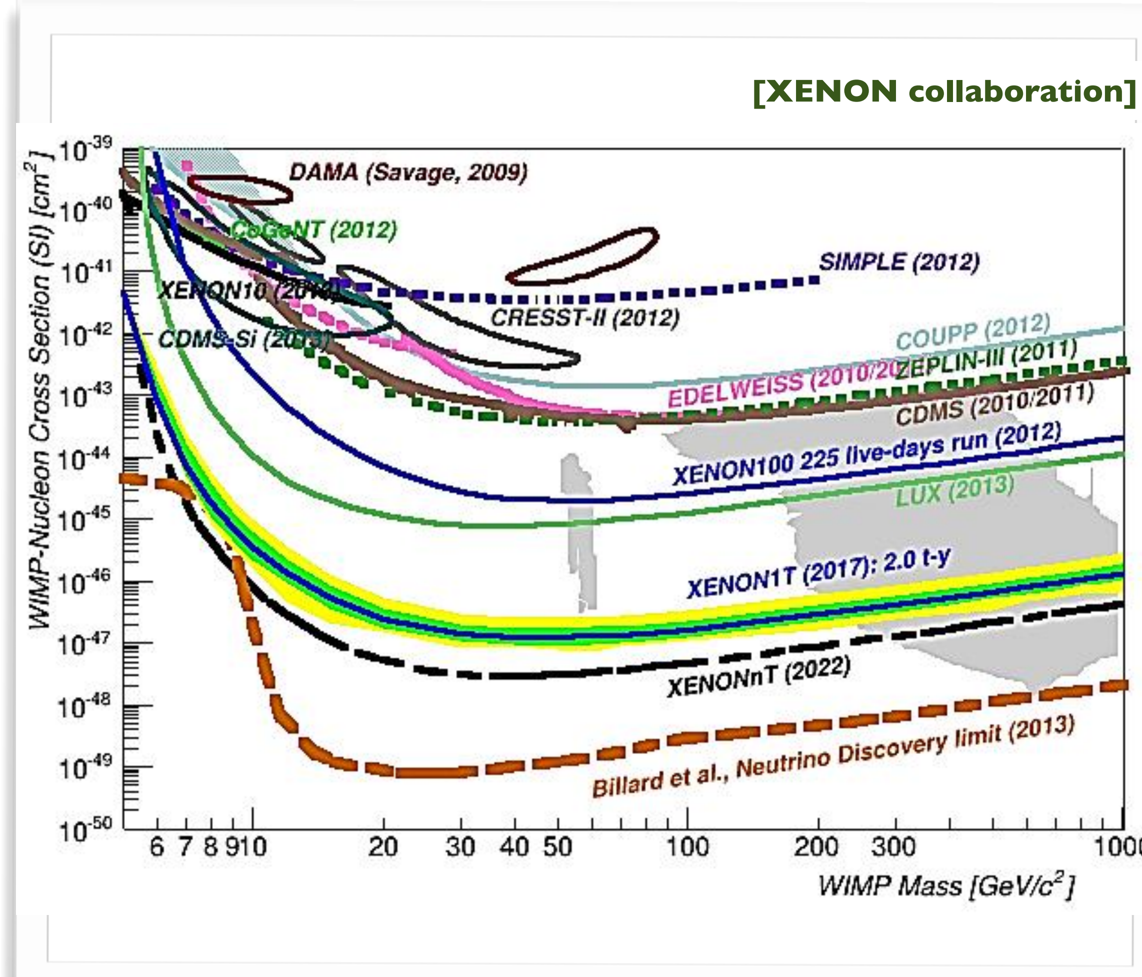
Outline

1. Introduction
2. A simplified model for *t*-channel dark matter
3. Dark matter at colliders: generalities, signals and re-interpretations
4. Cosmological constraints and their complementarity
5. Summary - conclusions

New physics searches in 2020

- ✦ Theoretically, we are in the dark
  - ✤ No sign of new physics, measurements compatible with the SM
    - → intriguing features need confirmation
  - ✤ No leading new physics candidate theory
    - → crucial: no loophole in new physics explorations



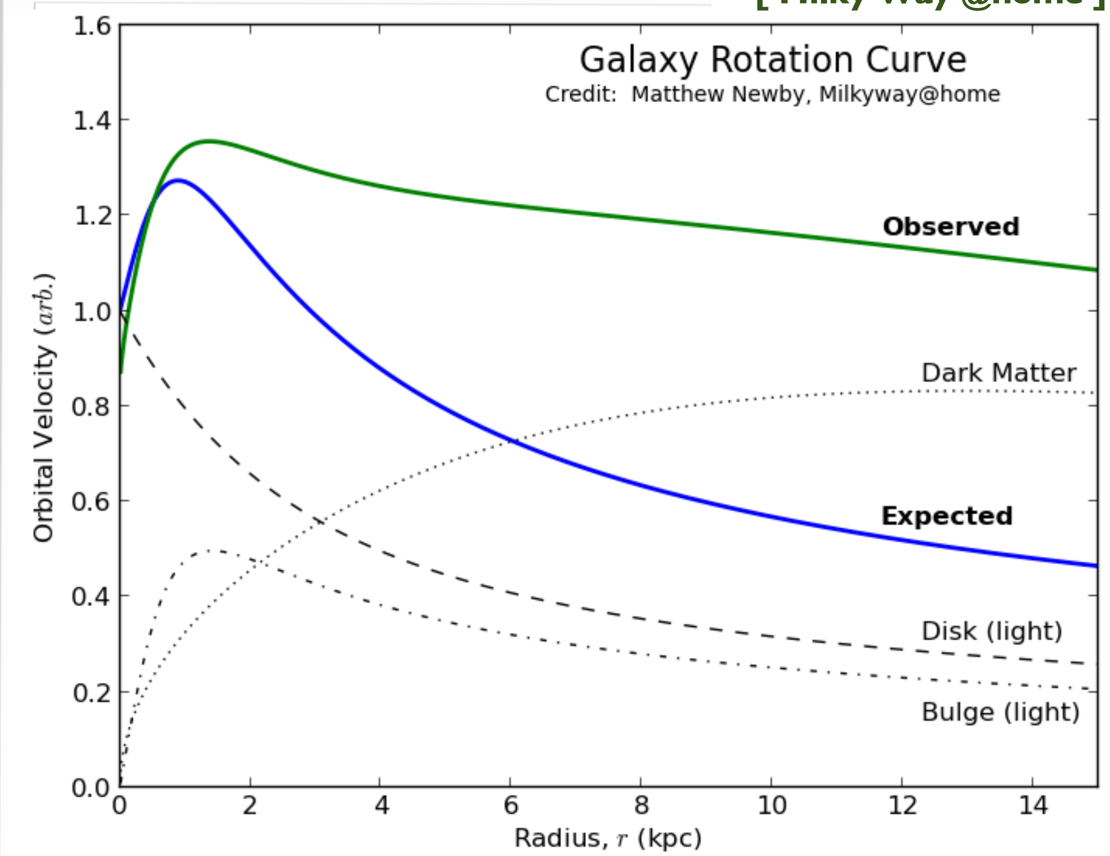


New physics and dark matter

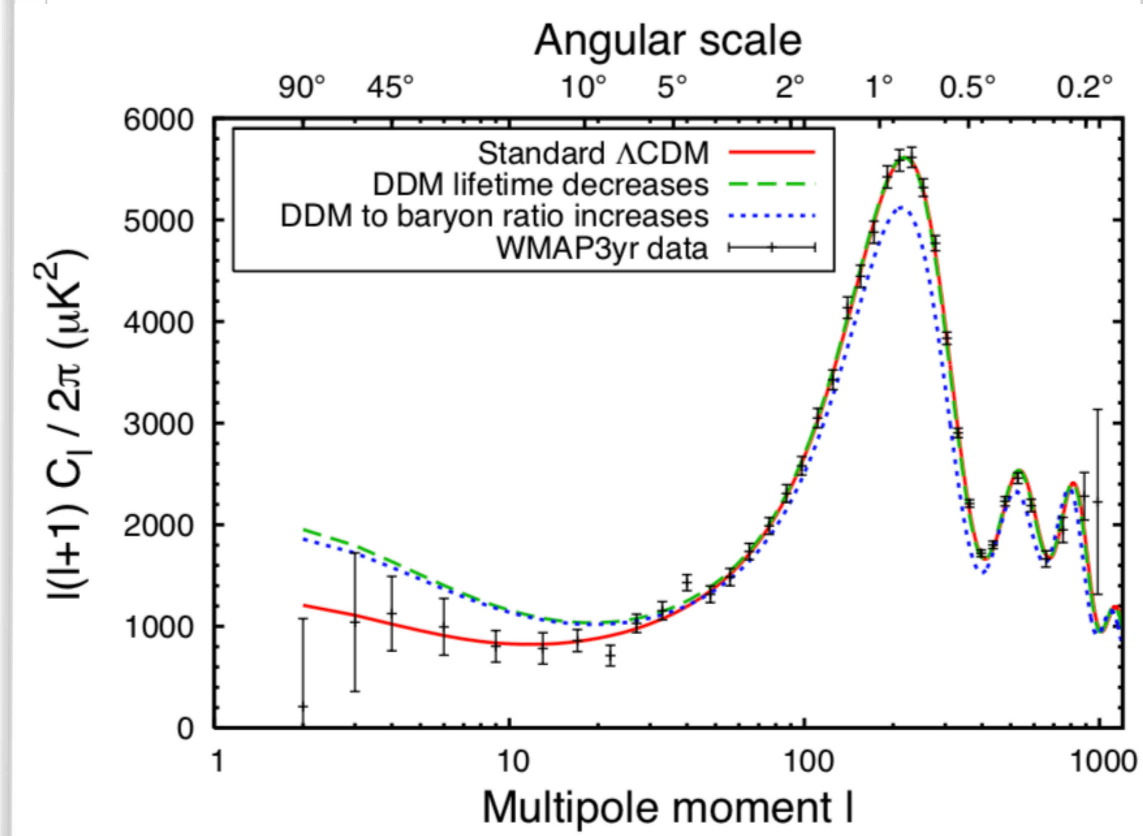
✦ Dark matter is an important motivation for new physics
- ✤ Flattening of the galaxy rotation curves
- ✤ Gravitational lensing
- ✤ Cosmic microwave background
- ✤ Structure formation

Enormous endeavour to detect dark matter

[Milky Way @home]



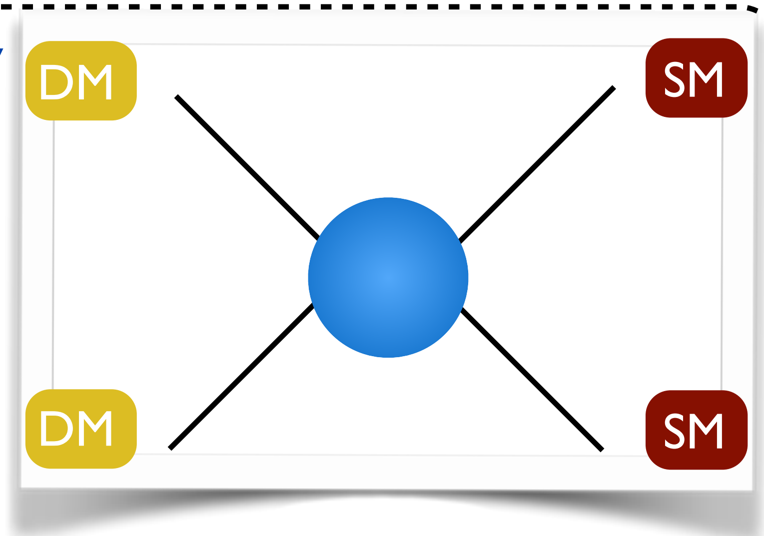
[Latanzi & Valle (PRL`07)]



Dark matter in cosmology and at colliders

✦ Dark matter is searched for directly, indirectly and at colliders
- ✤ This huge experimental effort offers a strategy to constrain models

✦ Complementary between colliders and cosmology
- ✤ Dark matter relic abundance must be reproduced
- ✤ Dark matter direct/indirect detection constraints
- ✤ Direct production at colliders



✦ One important issue: precision
- ✤ Do QCD corrections matter?
- ✤ Can QCD corrections change conclusions?
- ✤ Especially relevant if DM interacts with quarks and gluons

Dark matter simplified models

[Arina, BF & Mantani (EPJC'20)]

Simplified dark matter models @ LHC

✦ Generic simplified models for dark matter @ LHC

✤ Minimality: SM + 1 DM candidate + 1 mediator (coupling to quarks and gluons)

★ Representative of different theoretically-motivated new physics scenarios

★ Lack non-minimal features (multiple mediators, multi-component DM, *etc.*)

★ Can change the picture presented in this talk

✦ Properties

✤ DM (X) is stable

→ Odd under some $\mathbb{Z}_2$ discrete symmetry

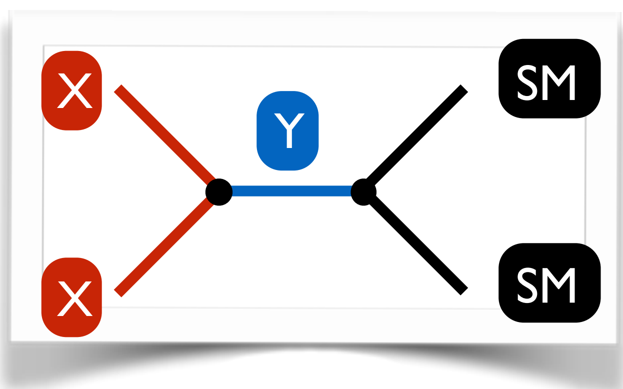
→ SM states even

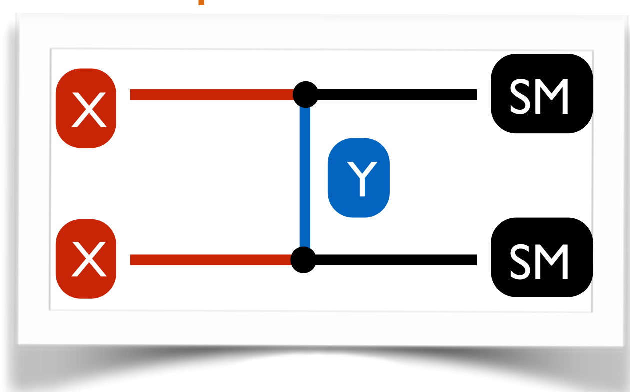
✤ The mediator (Y) connects DM and quarks/gluons

★ $\mathbb{Z}_2$-even: *s*-channel models → colour singlet and electrically neutral

★ $\mathbb{Z}_2$-odd: *t*-channel models → colour triplet and electrically charged

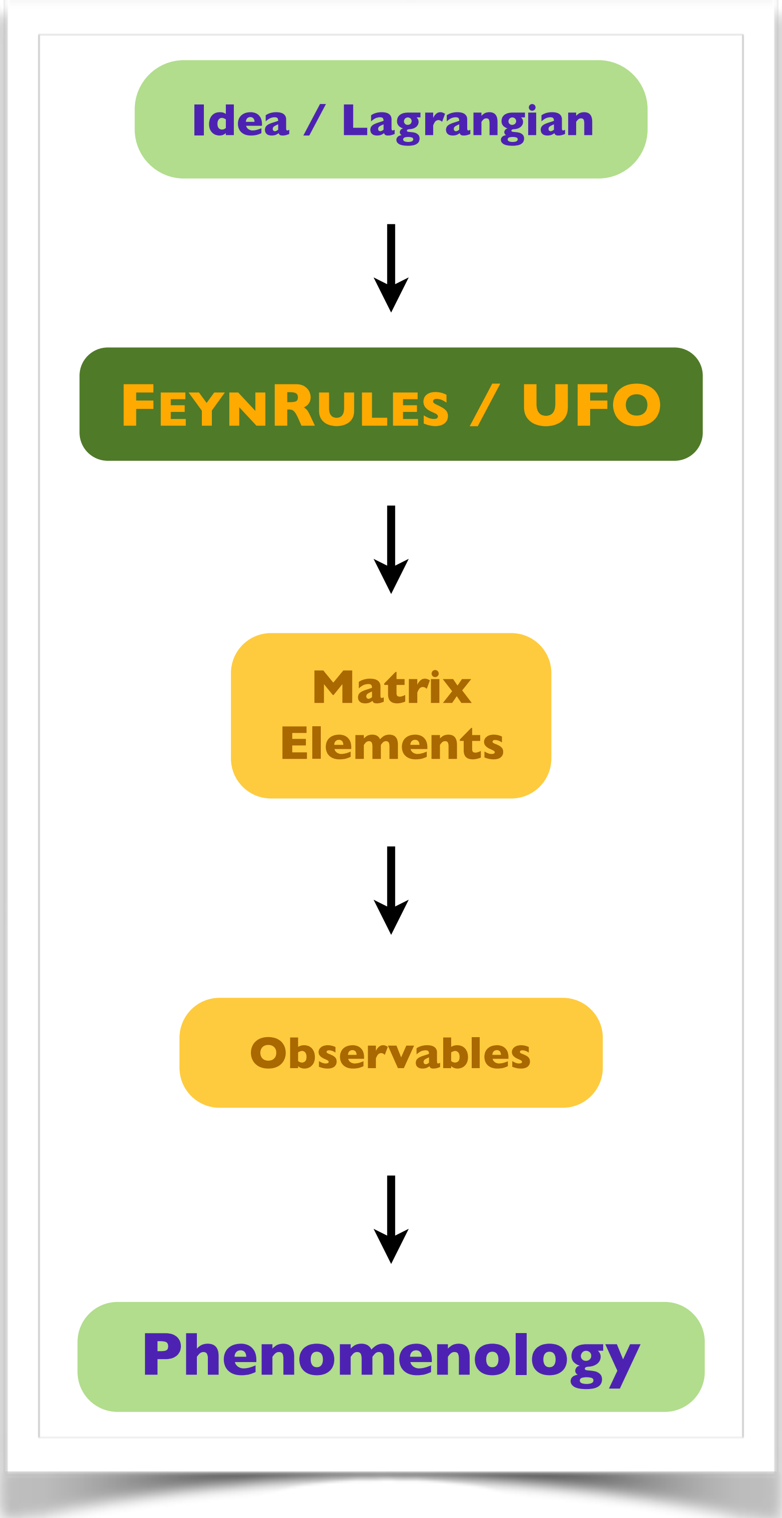
Topic of this talk





A comprehensive approach to new physics simulations

[Christensen, de Aquino, Degrande, Duhr, BF, Herquet, Maltoni & Schumann (EPJC`11)]



✦ Model building: from Lagrangian to tools

- ✤ FEYNRULES ⊕ MOGRE ⊕ NLOCT → UFO @ NLO
- ✤ General on-shell renormalisation scheme

[Alloul, Christensen, Degrande, Duhr & BF (CPC'14) ; Degrande (CPC'15)]
[Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (JHEP`19)]

✦ Hard scattering

- ✤ LO/NLO Feynman diagram, matrix elements
- ✤ MG5aMC/MadDM → cosmology/colliders at LO/NLO

[Alwall et al. (JHEP'14)]
[Ambrogi et al. (PDU'19)]

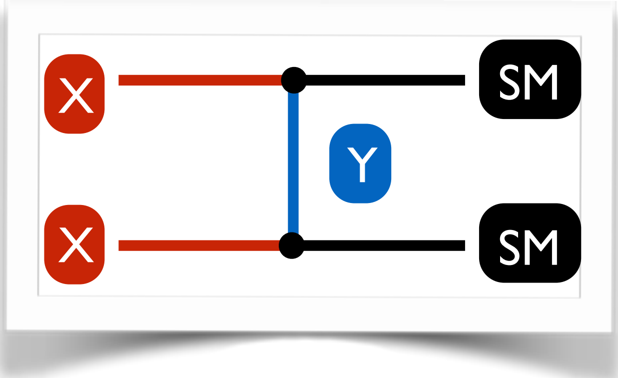
✦ BSM phenomenology @ colliders with MG5_aMC

- ✤ Matching matrix elements with parton showers
- ✤ Simplified treatment of the resonances (MADSTR)

[Alwall et al. (JHEP'14)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (JHEP`19)]

A generic *t*-channel DM

✦ A generic *t*-channel DM model



Many parameters / spin combination
→ simplifications/restrictions

- 2 spins: J_X, J_Y
- 13 masses:
  - ★ 1 DM mass: m_X
  - ★ 12 mediator masses (SM = u_L, d_L, u_R, d_R)
- 9 couplings (with $SU(2)_L \times U(1)_Y$ invariance)
  - ★ 3 vectors in flavour space
  - ★ SM = Q_L, u_R, d_R

✦ Spin options

X (DM)	Spin	Self-conj.	Y (med.)	Spin
$\tilde{S}$	0	yes	ψ_Q, ψ_u, ψ_d	1/2
S	0	no		
$\tilde{\chi}$	1/2	yes	$\varphi_Q, \varphi_u, \varphi_d$	0
χ	1/2	no		
$\tilde{V}_\mu$	1	yes	ψ_Q, ψ_u, ψ_d	1/2
V_μ	1	no		

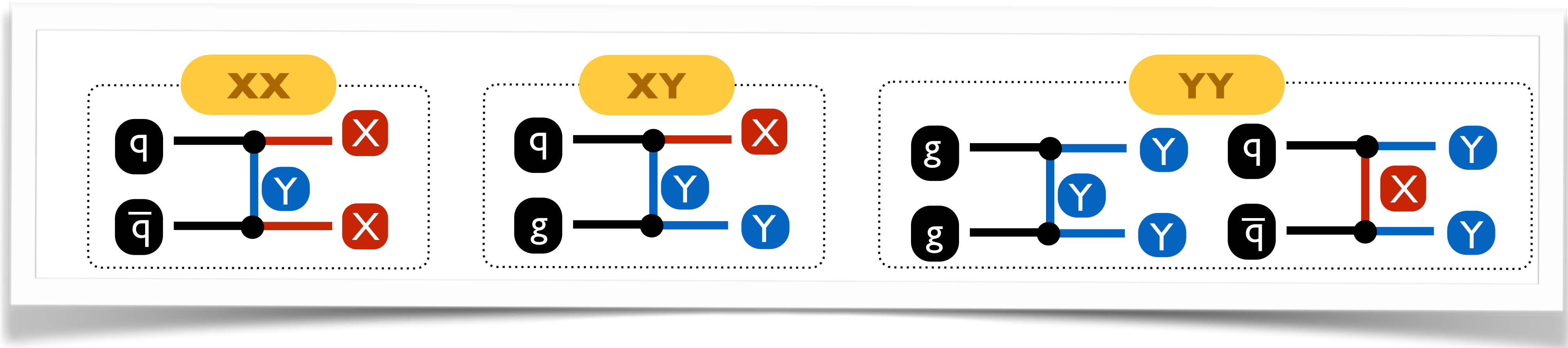
- Dark matter
  - ★ Spin 0, 1/2 and 1
  - ★ Majorana or not
- 12 mediators
  - ★ Spin 0 or 1/2 (no spin 1)
  - ★ Independent couplings to all gauge eigenstates

Dark matter at colliders

Generalities (no top)

DM @ colliders: light generation mediators

✦ Three classes of processes → jets generated from radiation or mediator decays



✤ Signal less naive than considering XX production only

★ DM pair production

★ DM/mediator associated production (with mediator decays into DM+jet)

★ Mediator pair production (with mediator decays into DM+jet)

✤ Mediator pair-production: *t*-channel and QCD contributions

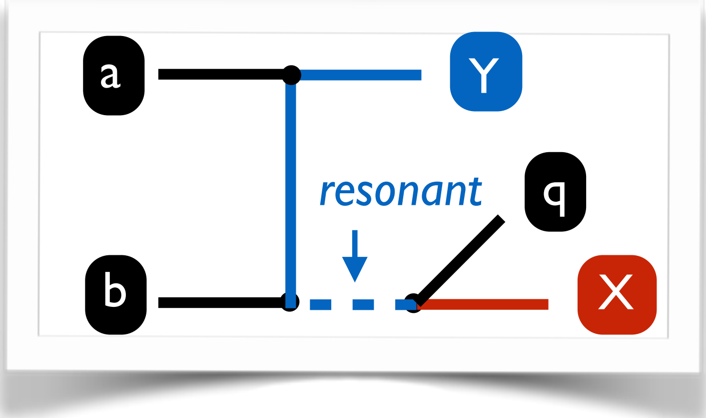
★ Model-dependent relative dominance → couplings, masses

★ Mixed order situation → to be simulated separately with MG5_aMC

★ Interference issue → re-weighted LO simulations

Resonance subtraction: generalities

✦ NLO computations are not trivial



✤ Overlap

★ YY @ LO ⊗ Y → Xq decay

★ YX @ NLO (real emission)

✤ Possible (huge) enhancement w.r.t. LO (if YY dominates over XY)

★ Spoiling the perturbative expansion for the original process

✤ All three subprocesses need to be considered separately to avoid double counting

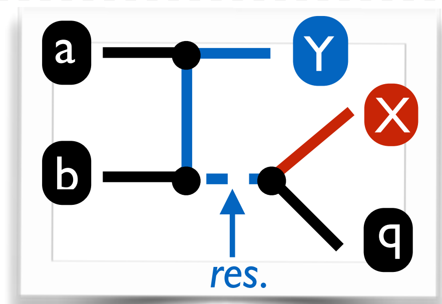
★ Resonances must be subtracted

Resonance treatment in practice

[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (JHEP`19)]

✦ Matrix element: resonant and non-resonant pieces

$$\Big|\mathcal{A}\Big|^2 = \Big|\mathcal{A}^{(\mathrm{non-res.})}\Big|^2 + 2\Re\Big(\mathcal{A}^{(\mathrm{non-res.})}\mathcal{A}^{(\mathrm{res.})\dagger}\Big) + \Big|\mathcal{A}^{(\mathrm{res.})}\Big|^2$$



✦ Diagram removal

$$\Big|\mathcal{A}\Big|^2 = \Big|\mathcal{A}^{(\mathrm{non-res.})}\Big|^2 \cancel{+ 2\Re\Big(\mathcal{A}^{(\mathrm{non-res.})}\mathcal{A}^{(\mathrm{res.})\dagger}\Big)} \cancel{+ \Big|\mathcal{A}^{(\mathrm{res.})}\Big|^2}$$

- ✤ DR: removal of the resonant diagrams
- ✤ DR+I: interferences are kept [our choice]

✦ Projection of the kinematics on the resonance

$$\Big|\mathcal{A}^{(\mathrm{res.})}\Big|^2 \mathrm{d}\Phi \quad \Rightarrow \quad \Big|\mathcal{A}^{(\mathrm{res.})}\Big|^2 \mathrm{d}\Phi - f(m^2)\ \mathbb{P}\bigg(\Big|\mathcal{A}^{(\mathrm{res.})}\Big|^2 \mathrm{d}\Phi\bigg)$$

★ *t*-channel example: $m = m_{Xq} \sim m_Y$

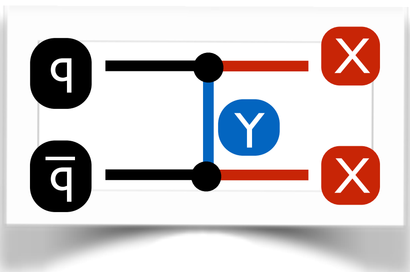
- ✤ The projector operator $\mathbb{P}$
  - ★ From an *n*-body kinematics to an $(n\text{-}1) \otimes (1 \to 2)$ kinematics

$$\Big|\mathcal{A}^{(\mathrm{res.})}(ab \to XYq)\Big|^2 = \Big|\mathcal{A}(ab \to YY)\Big|^2 \otimes \Big|\mathcal{A}(Y \to Xq)\Big|^2$$

- ✤ The pre-factor *f* is arbitrary (tends to 1 in the resonant limit)
- ✤ DS: Initial-state or final-state reshuffling

A fivefold signal event generation procedure

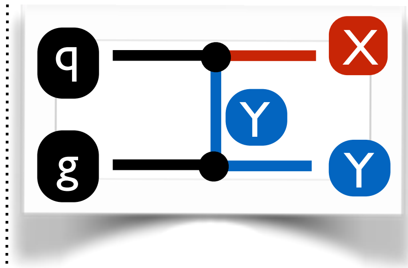
XX @ NLO



★ Jet activity → QCD radiation

★ Resonance: XY prod. + decay

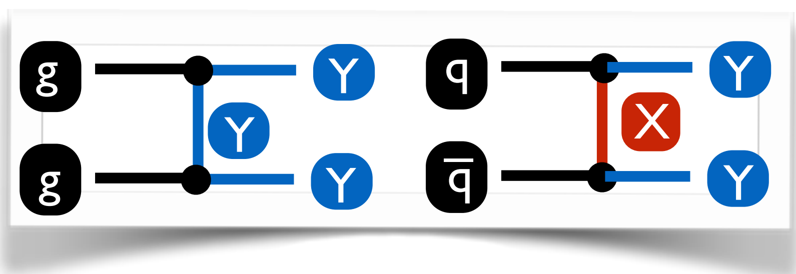
XY @ NLO



★ Jet activity → QCD radiation
→ mediator decay

★ Resonances: YY/XX prod. + decay (benchmark dependent)

YY @ NLO



★ Jet activity → QCD radiation and mediator decay

★ Resonance: YX production + (off-shell) decay

★ 2 interfering channels (from qqbar initial states)

Dark matter at colliders
NLO *vs* LO simulations

[Arina, BF & Mantani (EPJC'20)]

1st gen. mediator & Dirac DM

✦ Dirac DM coupling to the right-handed up quark

X (DM)	Spin	Self-conj.	Y (med.)	Spin
χ	1/2	no	φ_{u_1}	0

$$\mathcal{L}_{\texttt{X\_uR}}(X) = \Big[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \text{h.c.}\Big]$$

- ✤ Benchmark BM1: m_X = 150 GeV, m_Y = 500 GeV, λ=1
- ✤ Benchmark BM2: m_X = 150 GeV, m_Y = 1000 GeV, λ=1
- ✤ Largish DM-mediator coupling

✦ Total rates

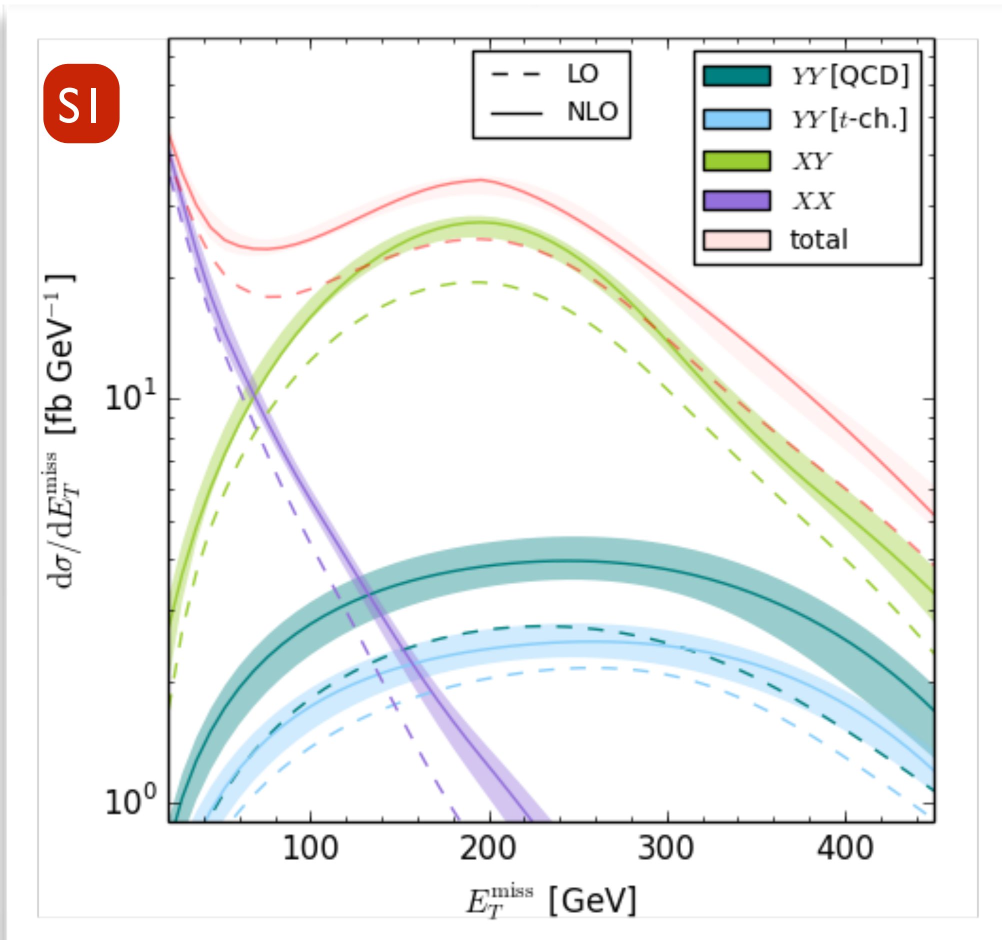
	Scen.	XX [fb]	XY [fb]	YY (total) [fb]	YY (QCD) [fb]	YY (t-channel) [fb]
LO	S1	$775.3^{+0.4\%}_{-0.8\%} \pm 1.9\%$	$1617^{+16.5\%}_{-13.4\%} \pm 1.0\%$	$473.5^{+23.6\%}_{-16.9\%} \pm 3.0\%$	$324.2^{+34.2\%}_{-23.8\%} \pm 3.4\%$	$261.5^{+7.1\%}_{-6.3\%} \pm 2.5\%$
LO	S2	$122.0^{+1.8\%}_{-2.0\%} \pm 1.9\%$	$74.1^{+20.3\%}_{-15.8\%} \pm 1.2\%$	$7.452^{+19.8\%}_{-14.5\%} \pm 5.6\%$	$3.545^{+37.3\%}_{-25.4\%} \pm 7.2\%$	$6.939^{+11.1\%}_{-9.4\%} \pm 5.0\%$
NLO	S1	$929.8^{+1.9\%}_{-1.3\%} \pm 1.9\%$	$2212^{+5.9\%}_{-6.3\%} \pm 1.0\%$	$648.4^{+8.0\%}_{-9.2\%} \pm 3.1\%$	$484.7^{+10.7\%}_{-12.4\%} \pm 3.4\%$	$314.1^{+2.6\%}_{-2.6\%} \pm 2.5\%$
NLO	S2	$139.1^{+1.3\%}_{-1.1\%} \pm 2.0\%$	$101.8^{+6.0\%}_{-7.1\%} \pm 1.2\%$	$9.888^{+6.5\%}_{-7.6\%} \pm 5.8\%$	$5.303^{+11.2\%}_{-13.3\%} \pm 7.4\%$	$8.749^{+3.6\%}_{-3.9\%} \pm 4.9\%$

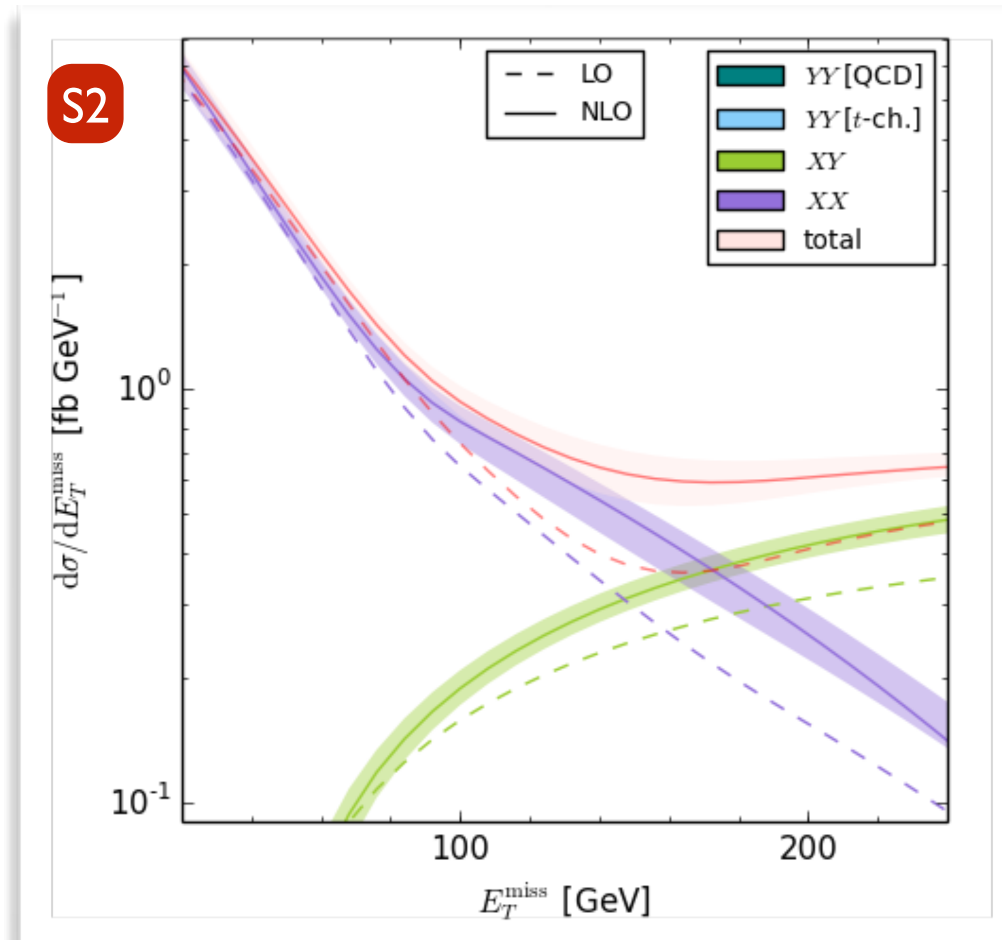
- ✤ Large XX and XY contributions
  → could be a significant component of the signal
- ✤ YY is smaller
  - ★ QCD and *t*-channel diagrams both important
  - ★ Large destructive interferences

- ✤ Large K-factors
  → NLO rates matter
- ✤ Reduction of the TH errors
  → to a few percents
- ✤ Smaller λ
  → YY-QCD always remains

Differential distributions: missing energy

✦ Properties of the signal at the LHC





- ✤XX: large cross section and only contributes for small MET
  → irrelevant for the signal (preselection requires large MET)
- ✤XY dominates in the intermediate MET regime
- ✤YY kicks in at intermediate MET (sub-dominant)
  - ★ QCD and *t*-channel diagrams both important (different shapes)

Recasting ATLAS SUSY 2016-27 (monojet; 36/fb)

✦ CLs exclusion from the best region

S2

Process	CL_s [LO]	E_T^{miss} constraint	CL_s [NLO]	E_T^{miss} constrtaint
Total	$75.6^{+10.1}_{-10.5}$ %	$\in [700, 800]$ GeV	$97.8^{+0.9}_{-1.4}$ %	≥ 700 GeV
XX	$0.7^{+0.6}_{-0.6}$ %	$\in [250, 300]$ GeV	$3.6^{+0.3}_{-0.6}$ %	≥ 900 GeV
XY	$62.7^{+12.3}_{-10.4}$ %	$\in [500, 600]$ GeV	$83.9^{+2.9}_{-4.3}$ %	$\in [700, 800]$ GeV
YY [total]	$24.0^{+3.1}_{-3.1}$ %	≥ 900 GeV	$58.1^{+2.2}_{-3.1}$ %	≥ 900 GeV
YY [QCD]	$10.7^{+4.4}_{-2.6}$ %	≥ 900 GeV	$17.0^{+2.1}_{-2.1}$ %	≥ 900 GeV
YY [t-channel]	$29.6^{+3.3}_{-2.6}$ %	≥ 900 GeV	$38.9^{+1.2}_{-1.8}$ %	≥ 900 GeV

[MadAnalysis 5]

- ✤ NLO simulations are crucial
  - ★ Modification of the rates (larger yields) and shapes (different best region)
  - ★ Better control of the theory errors
- ✤ Considering all signal components is crucial
  - ★ One component alone is not sufficient to exclude the scenario

✦ S1 (lighter mediator) is excluded (from YX, YY and the total)

Benchmarking

Fixing λ or Γ_Y

[Arina, BF, Mantani, Mies, Panizzi & Salko (2020)]

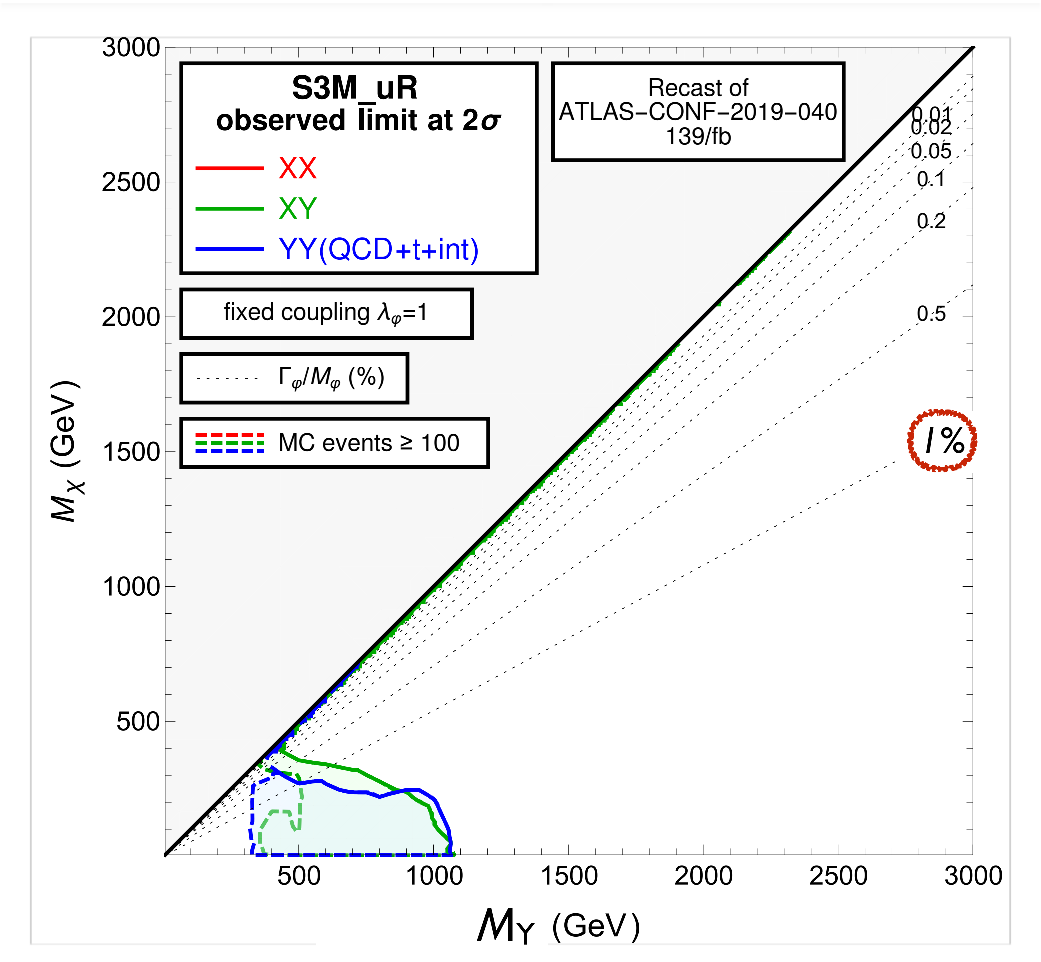
1st gen. mediator & Majorana DM

✦ Majorana DM coupling to the right-handed up quark

X (DM)	Spin	Self-conj.	Y (med.)	Spin
$\tilde{\chi}$	1/2	yes	φ_{u_1}	0

$$\mathcal{L}_{\texttt{X\_uR}}(X) = \Big[\lambda_\varphi \bar{X} u_1 \varphi^\dagger_{u_1} + \text{h.c.}\Big]$$

- Masses free
- Still a fixed λ = 1 coupling (typical of *s*-channel DM literature)



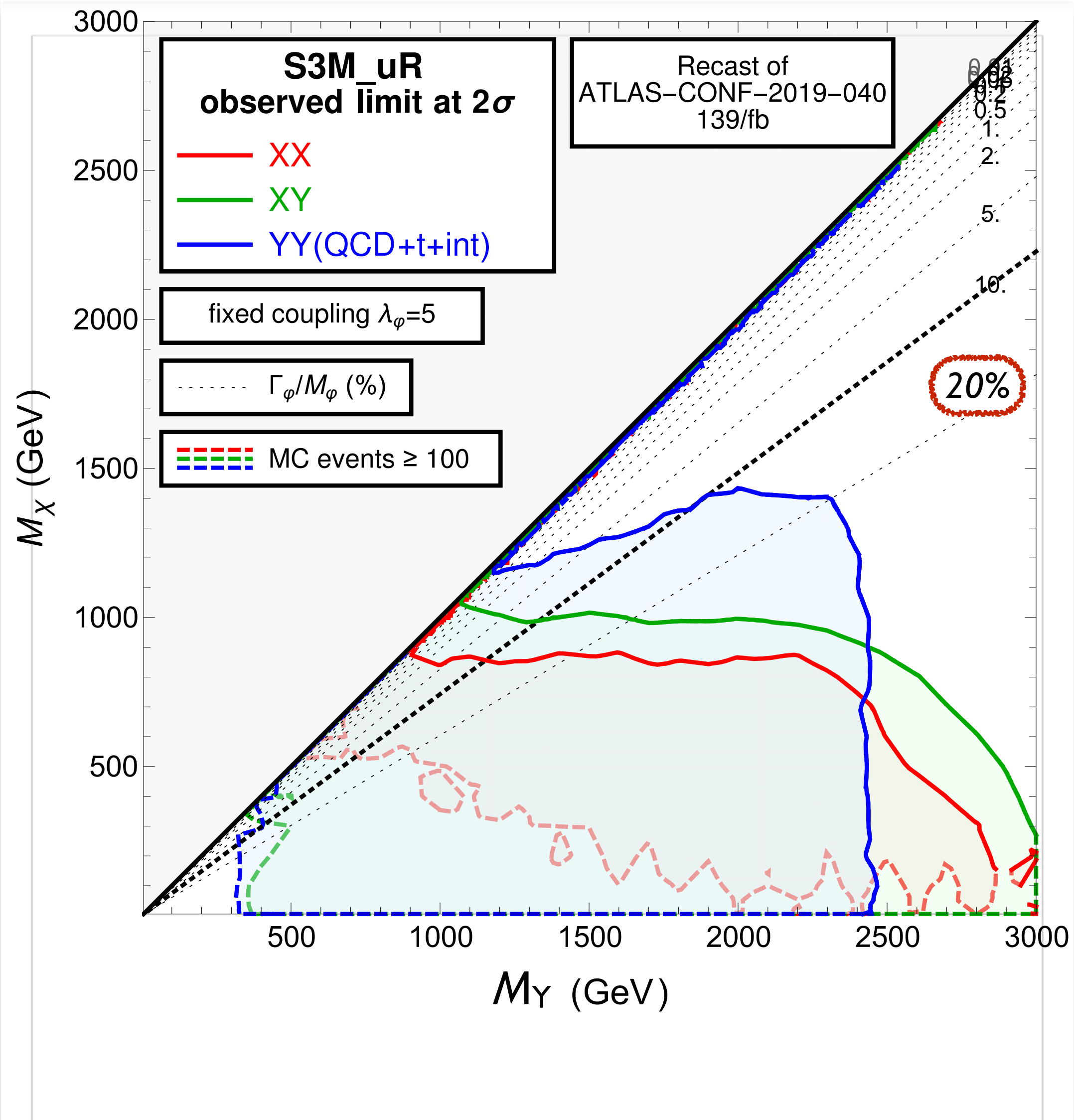
✦ Recast: ATLAS multijet + MET search

- 139/fb
- Monojet-like and multijet + MET regions

✦ Signal component complementarity

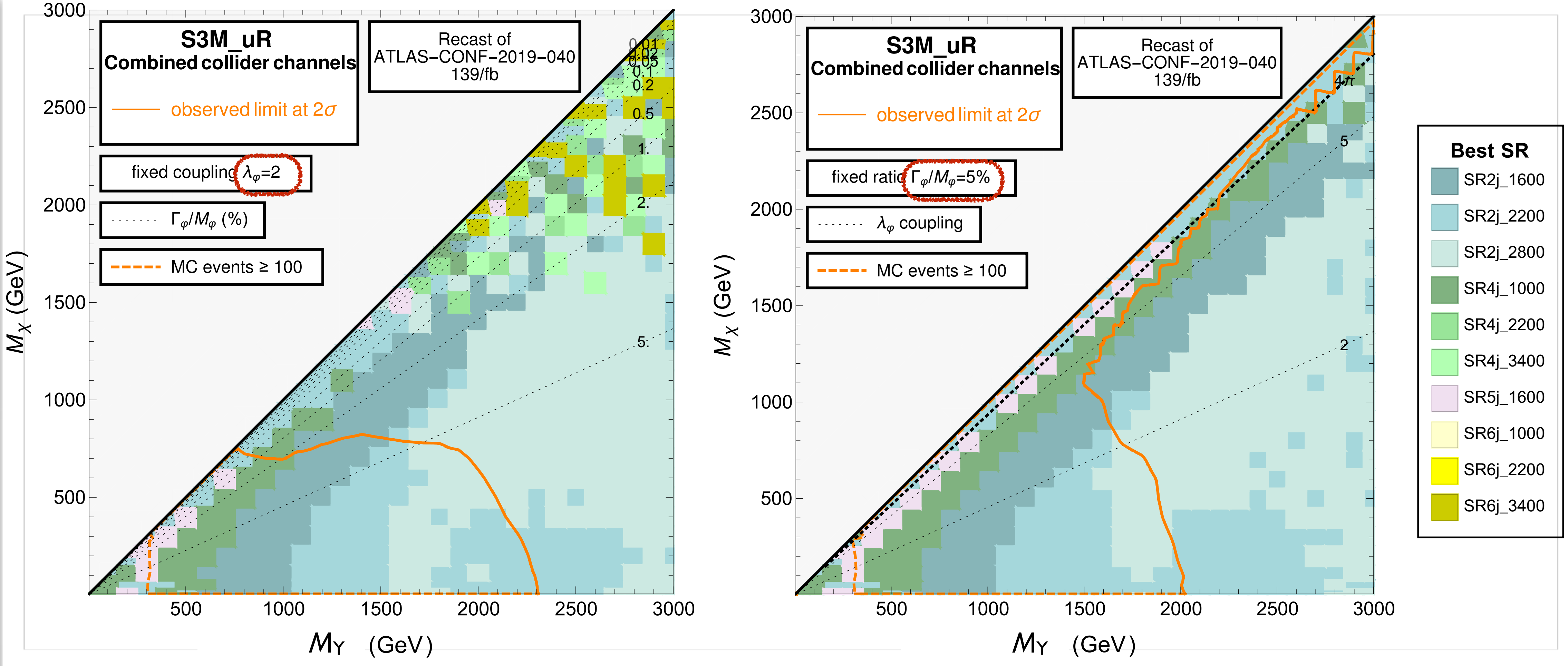
- DM production is irrelevant
- YY and XY production: comparable reach
  - → M_Y below 1 TeV
  - → M_X below few hundred GeV
  - → Mild coverage of the parameter space
- The width of the mediator can play a role
  - → especially for larger λ values

More strongly coupled dark matter



- $\lambda = 5$
  - All channels contribute (larger rates)
    - $XX \sim \lambda^4$
    - $XY \sim \lambda^2$
    - $YY \sim \lambda^4 + \lambda^2 + \lambda^0$
  - Simulations unreliable
    - The NWA breaks down
    - Γ_Y/M_Y >10% or compressed spectrum
    - Most 'excluded' points inconclusive
  - Γ_Y plays a role for large λ values
- Sensitivity to all channels
  - Different jetty properties
    - → XX: small N_j, mostly soft jets
    - → XY: medium N_j, hard and softer jets
    - → YY: large N_j, hard jets
  - Dedicated regions for all cases

Fixed coupling *vs* fixed width



- $\lambda = 2$ *vs* $\Gamma_Y/M_Y = 5\%$
  - Signal ≡ XX + XY + YY
  - Regions with 2 very hard jets (SR2j) → YY production and decay
  - Regions with more not so hard jets (SR4j, SR5j, SR6j) → compressed regime
  - Reliability of the simulations
    - ★ Fixed Γ_Y/M_Y: compressed spectrum ≡ non-perturbative regime
    - ★ Fixed λ: split spectrum ≡ broad mediator

Cosmological constraints

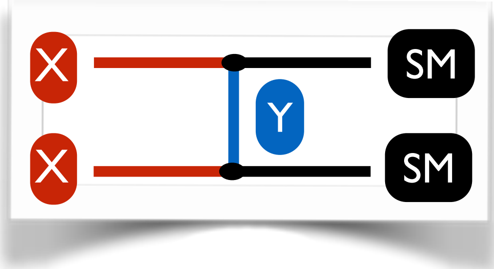
LO *vs* NLO

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

t-channel DM annihilations @ NLO

✦ Many competing channels opening up at NLO

✤ Tree-level annihilations



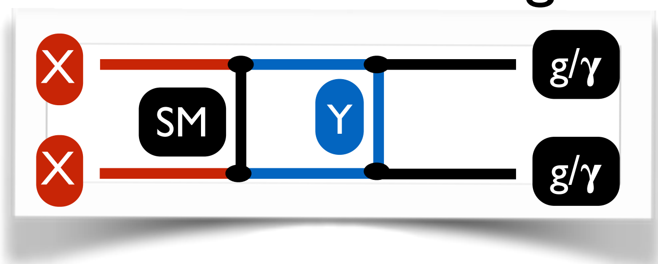
★ Scalar DM: *d*-wave suppressed

★ Majorana DM: *p*-wave suppressed

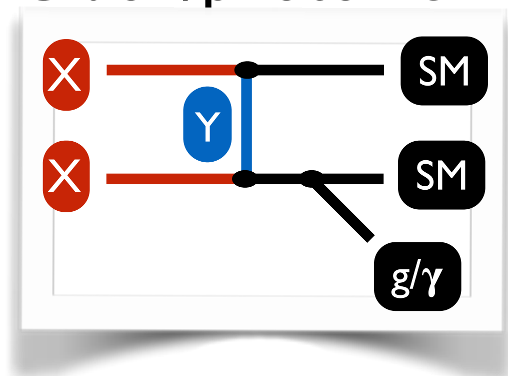
→ NLO corrections can be crucial

✤ At $O(\alpha_s)$

★ Annihilations into gluons/photons



★ Gluon/photon emission



→ Role of VIB

✤ Co-annihilations may matter (XY and YY)

✦ Scalar DM coupling to the right-handed top quark

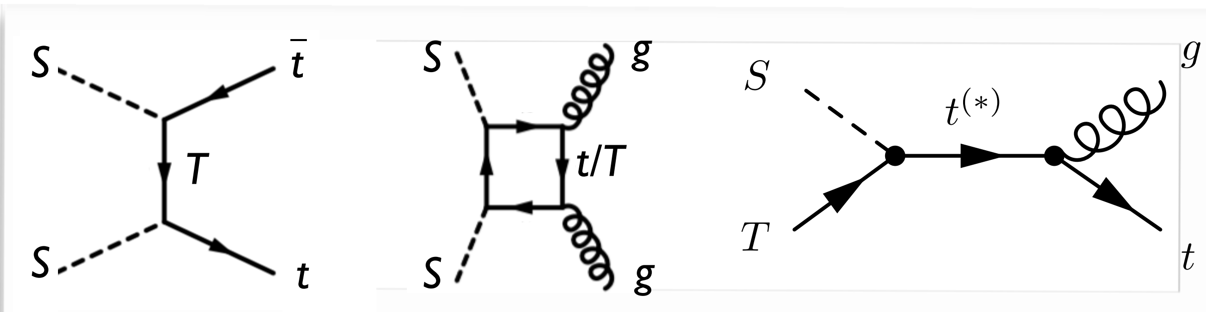
X (DM)	Spin	Self-conj.	Y (med.)	Spin
S	0	yes	T	1/2

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

✤ Masses and coupling free

Relic abundance: generalities

- Several competing annihilation channels
  - ★ Into (potentially virtual) tops
  - ★ Into gluons (loop-induced)
  - ★ $S\,T \to t^{(*)}$ co-annihilations (potentially resonant)

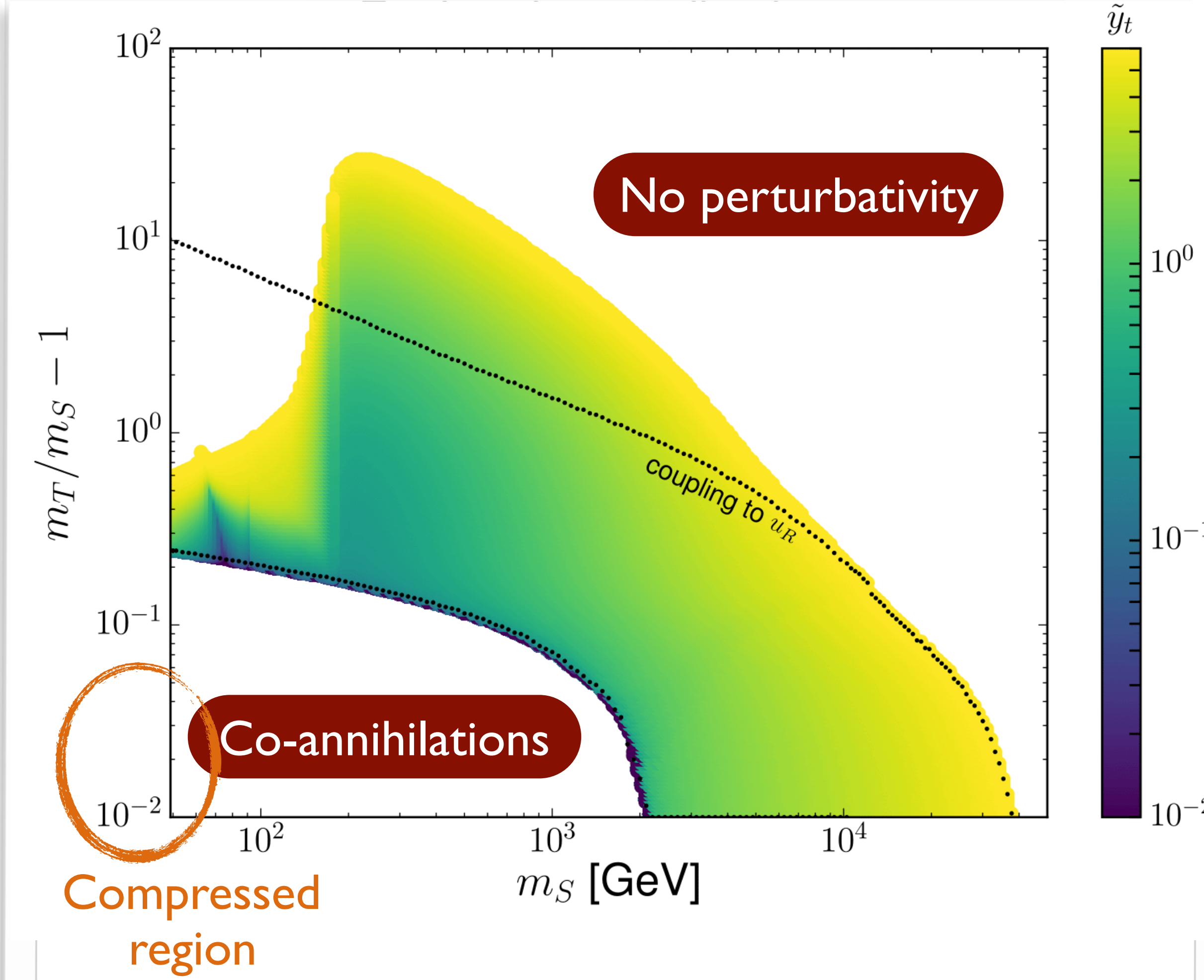


- Coloured point ≡ viable scenario

$$\Omega_{\rm DM} h^2 = 0.12$$ [Planck Collaboration (AA`20)]

  - ★ NLO QCD corrections included

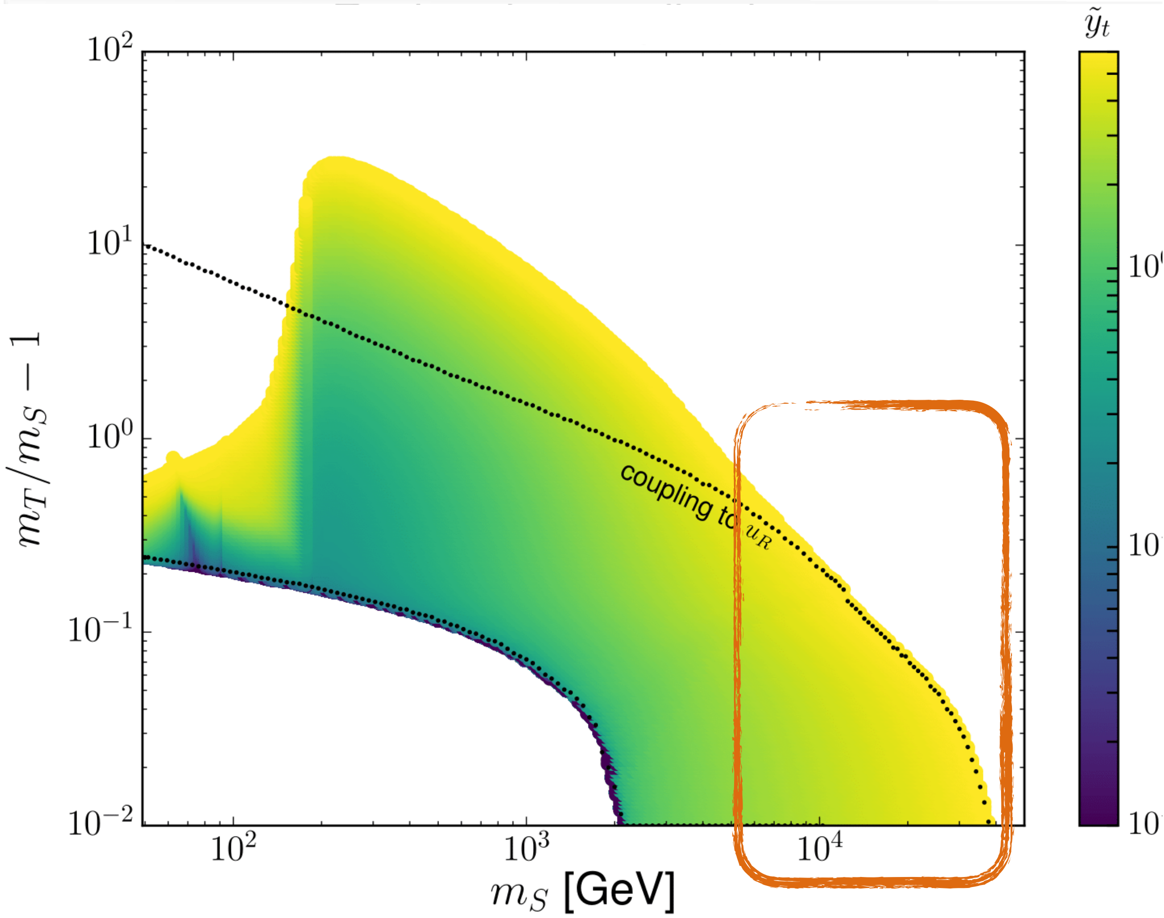
- Right relic abundance → $\tilde{y}_t$
  - ★ Min: 0.001 (co-annihilations)
  - ★ Max: 6 (perturbativity)

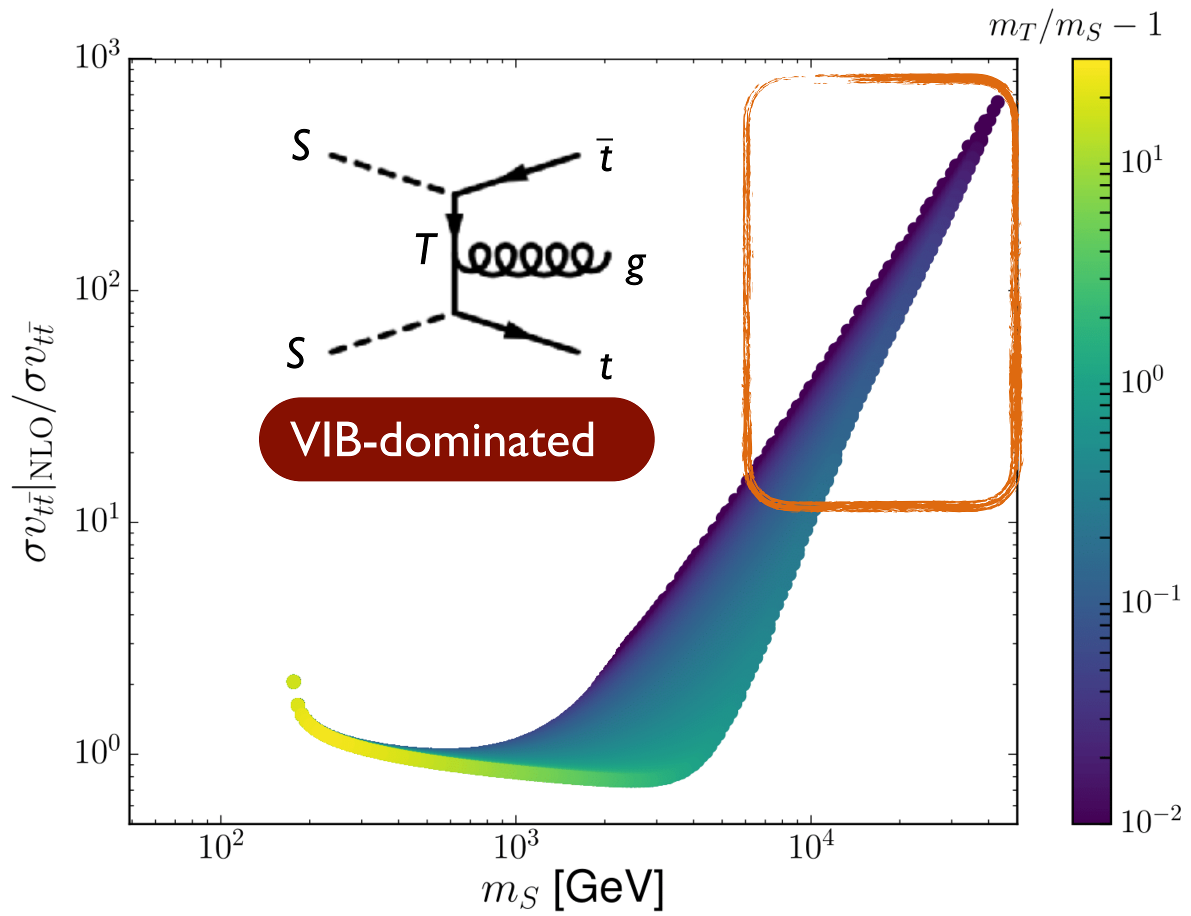


Large viable parameter space region from the relic standpoint

Multi-TeV dark matter

✦ 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

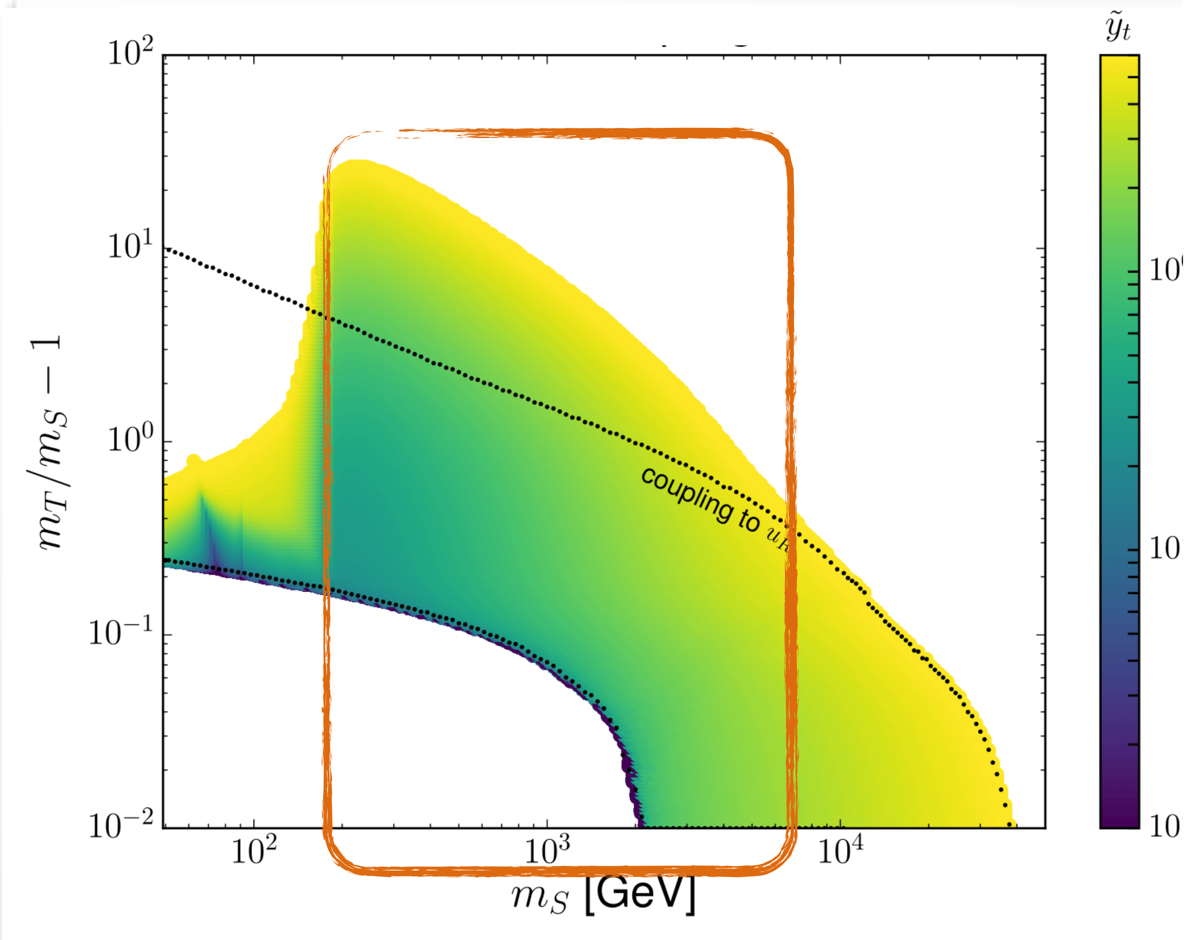
★ Velocity-independent (~1)

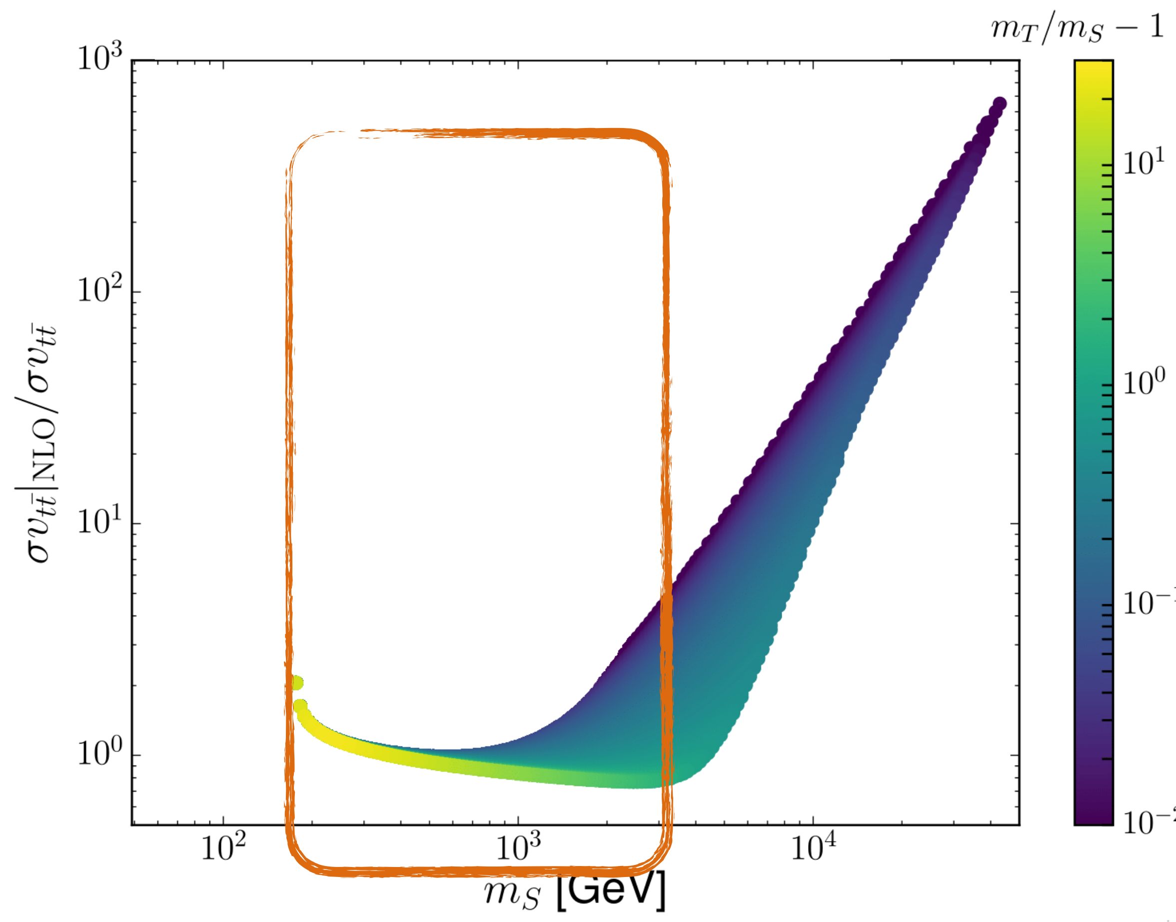
✤ Huge QCD *K*-factors

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

Moderately heavy dark matter

✦ 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

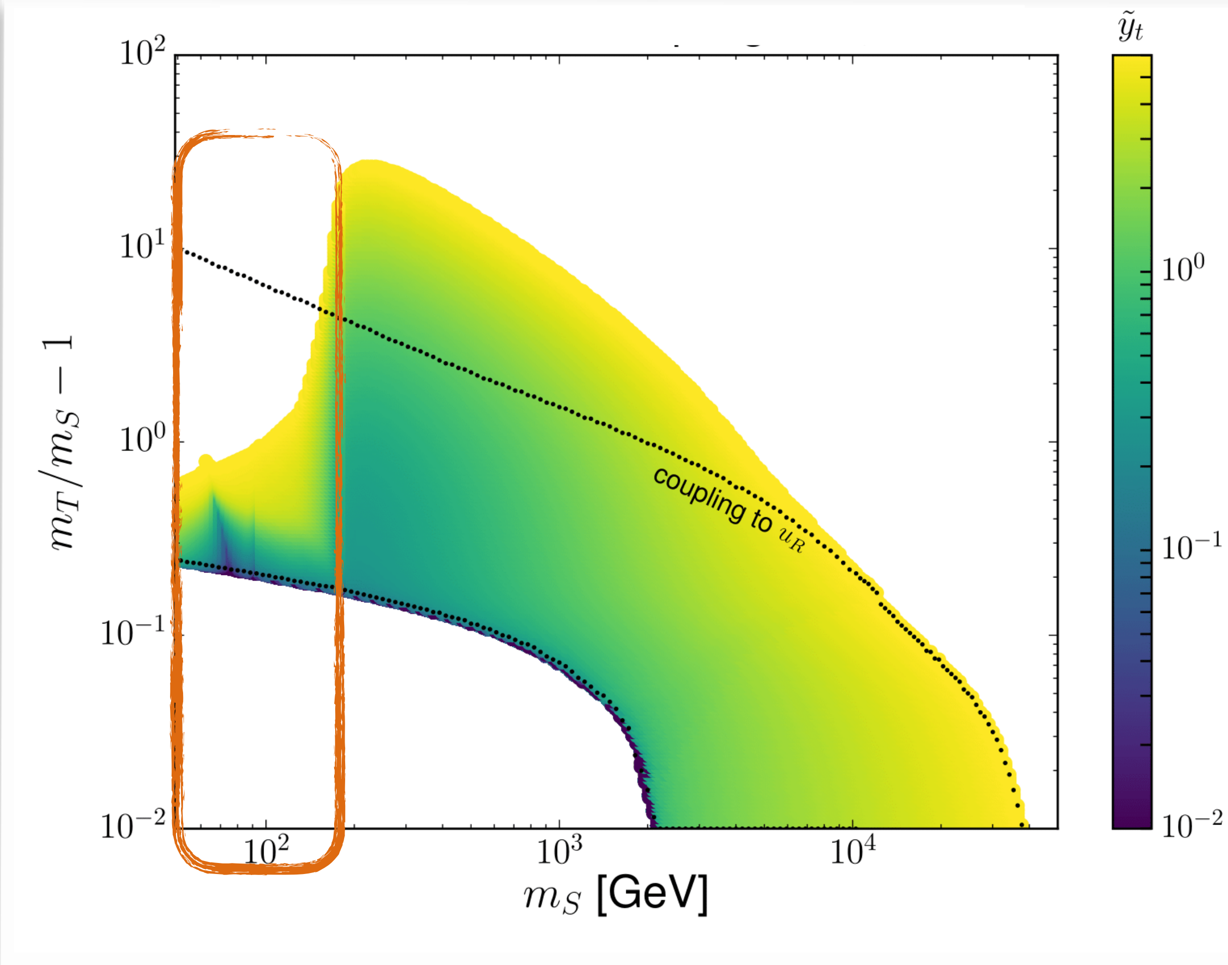
✤ Close to threshold

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

- ★ Velocity small
- ★ Spurious results at threshold

Light dark matter

✦ Regime with ($m_S < m_t$)



✤ Annihilations into tops is closed

★ 3-body annihilations (into tWb)

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

★ $SS \to gg$ 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)

Direct and indirect detection

[Arina, BF, Mantani, Mies, Panizzi & Salko (2020)]

Direct and indirect detection

✦ Higher-order contributions impact indirect/direct detection

- ✤ g/γ radiation ⇝ features in gamma and cosmic ray spectra
- ✤ Loop-induced g-DM scattering → DM/nucleon scattering
- ✤ More accurate estimations of the scattering cross sections

✦ Constraints

- ✤ PICO: spin-dependent direct detection [PICO Collaboration (PRL`17)]
- ✤ XENON1T: spin-independent direct detection [XENON Collaboration (PRL`18)]
- ✤ FERMI-LAT & HESS: gamma ray spectra [FERMI-LAT Collaboration (PRD`15); HESS Collaboration (PRL`18)]
- ✤ Dwarf spheroidal galaxies: annihilations into gg [DES, FERMI-LAT Collaboration (AJ`17)]

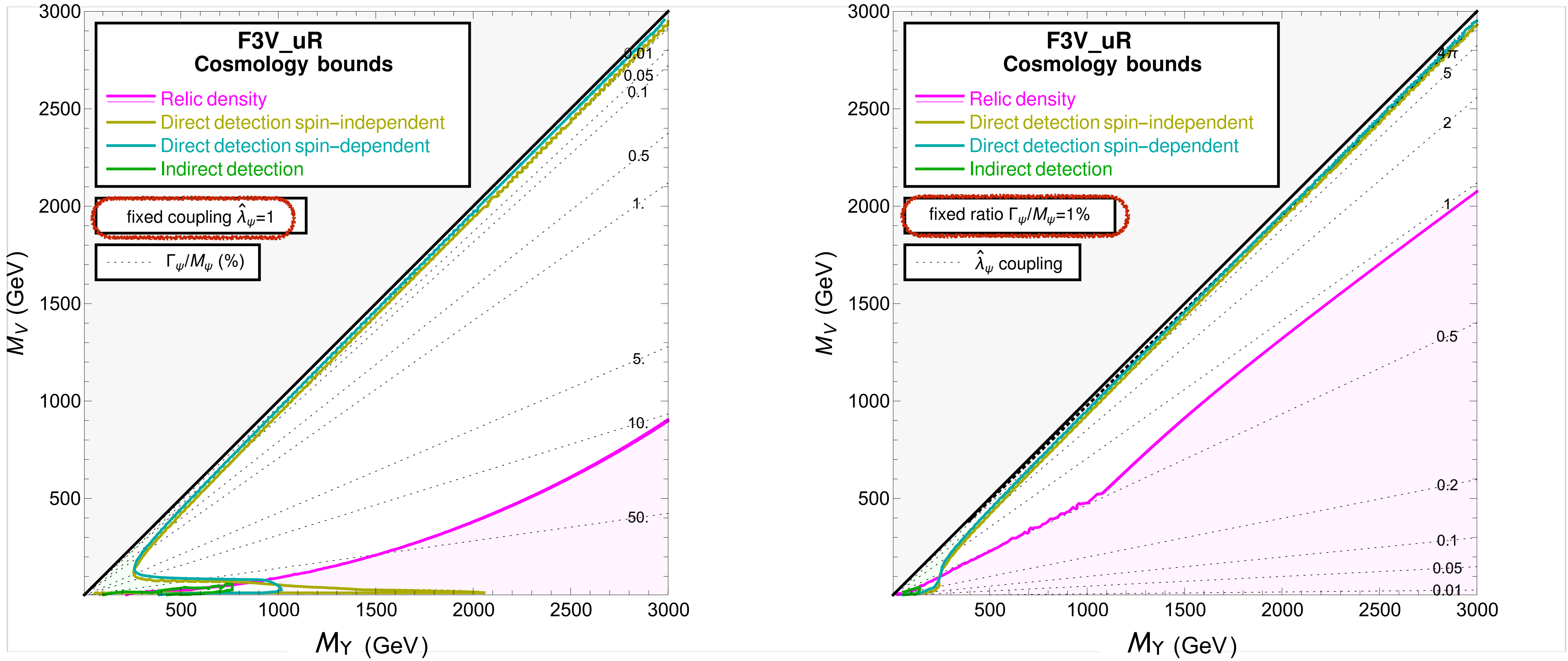
✦ Vector DM coupling to the right-handed up quark

X (DM)	Spin	Self-conj.	Y (med.)	Spin
V	1	yes	ψ	1/2

$$\mathcal{L}_{\texttt{F3V\_uR}} = \left[\hat{\lambda}_{\mathbf{u}}\ \bar{\psi}\not{V} u_R + \text{h.c.}\right]$$

- ✤ Masses and coupling free

Fixed coupling / fixed width



✦ Constraints on the model parameter spaces

✤ Relic density: over-abundant DM forbidden (magenta areas)

★ Fixed λ=1: broad mediators excluded (not a problem as non resonant)

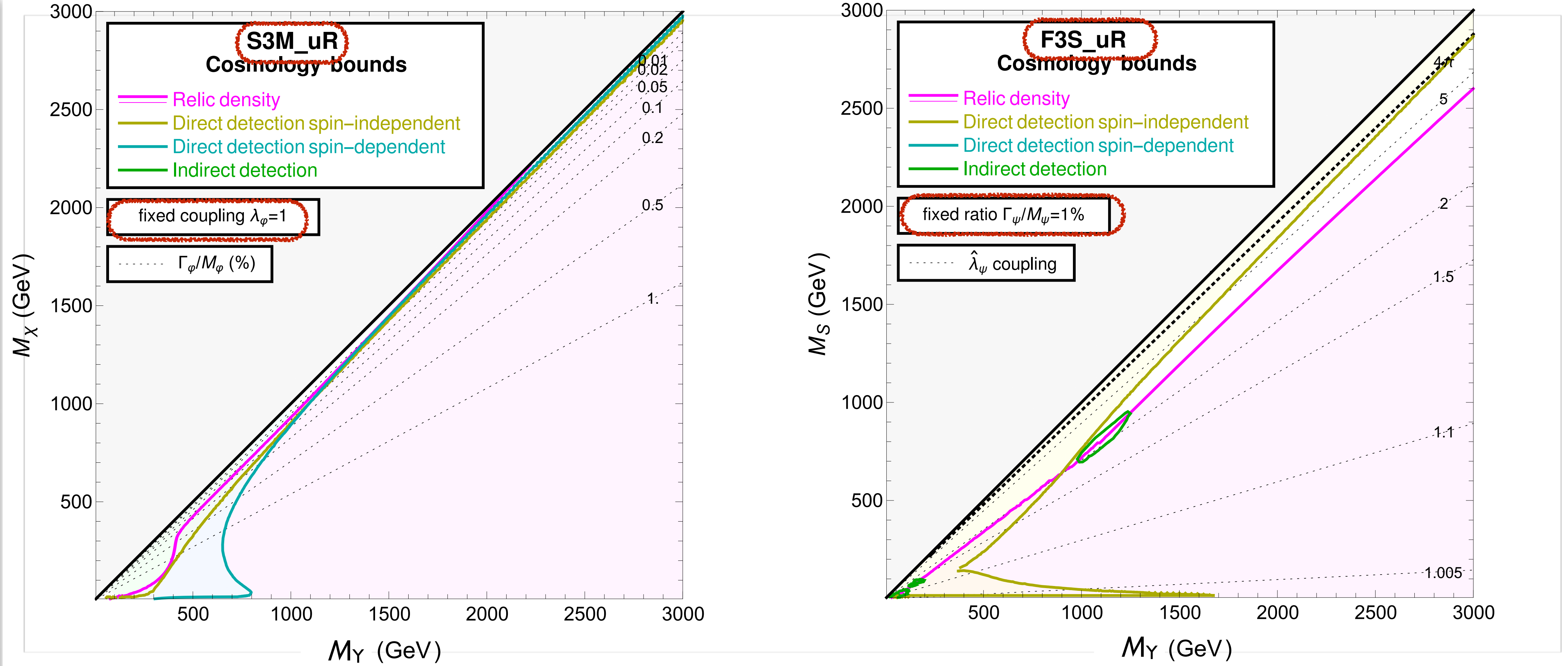
★ Fixed Γ_Y/M_Y = 1%: large coupling is needed

✤ SI/SD DD + ID: targets the compressed regime, as well as light DM

✤ A significant part of the parameter space is still allowed by cosmology

→ Quite model dependent!

More extreme cases



- ✦ Barely viable configurations (for u_R-mediators)
  - ✤ Many quite (dis)favoured configurations
    - ★ Majorana DM with λ=1: relic + ID ⇒ excludes all mass configurations
    - ★ Scalar DM with Γ_Y/M_Y = 1%: relic + DD ⇒ strongly-coupled DM
- ✦ Cosmology severely constrains *t*-channel simplified models
  - ✤ Regardless of λ and Γ_Y/M_Y

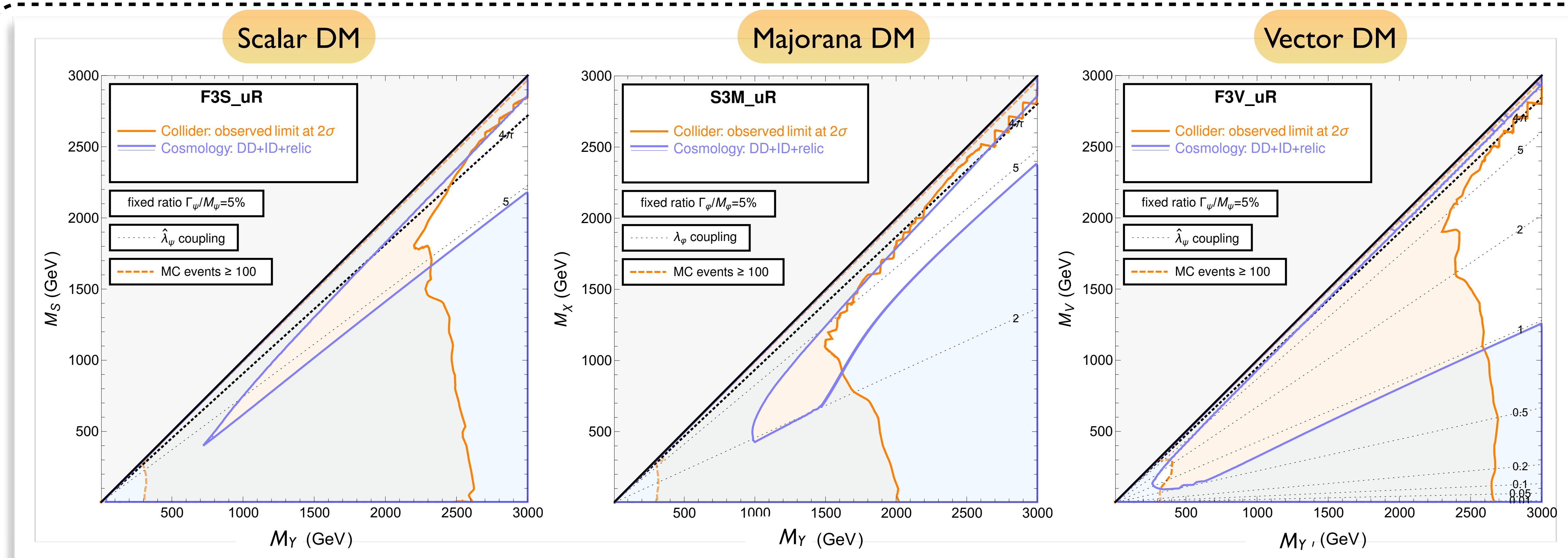
Cosmology-collider complementarity

Closing in it on!

[Arina, BF, Mantani, Mies, Panizzi & Salko (2020)]

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

Example 1: u_R mediator $\oplus$ $\Gamma_Y/M_Y = 5\%$



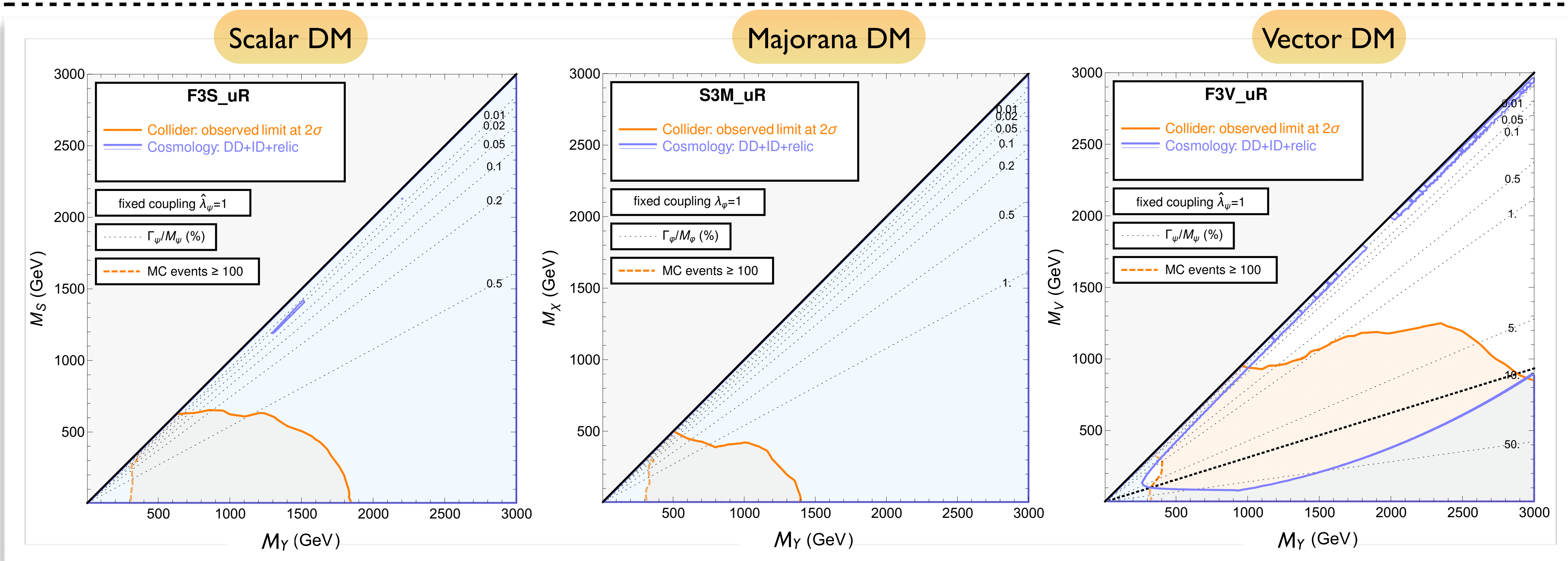
✦ Colliders and cosmology are complementary

- ✤ The mediator must be heavy → production at colliders
- ✤ Cosmology further restricts DM → not too light
- ✤ The spectrum cannot be too compressed → colliders/cosmo

✦ Implications for viable scenarios

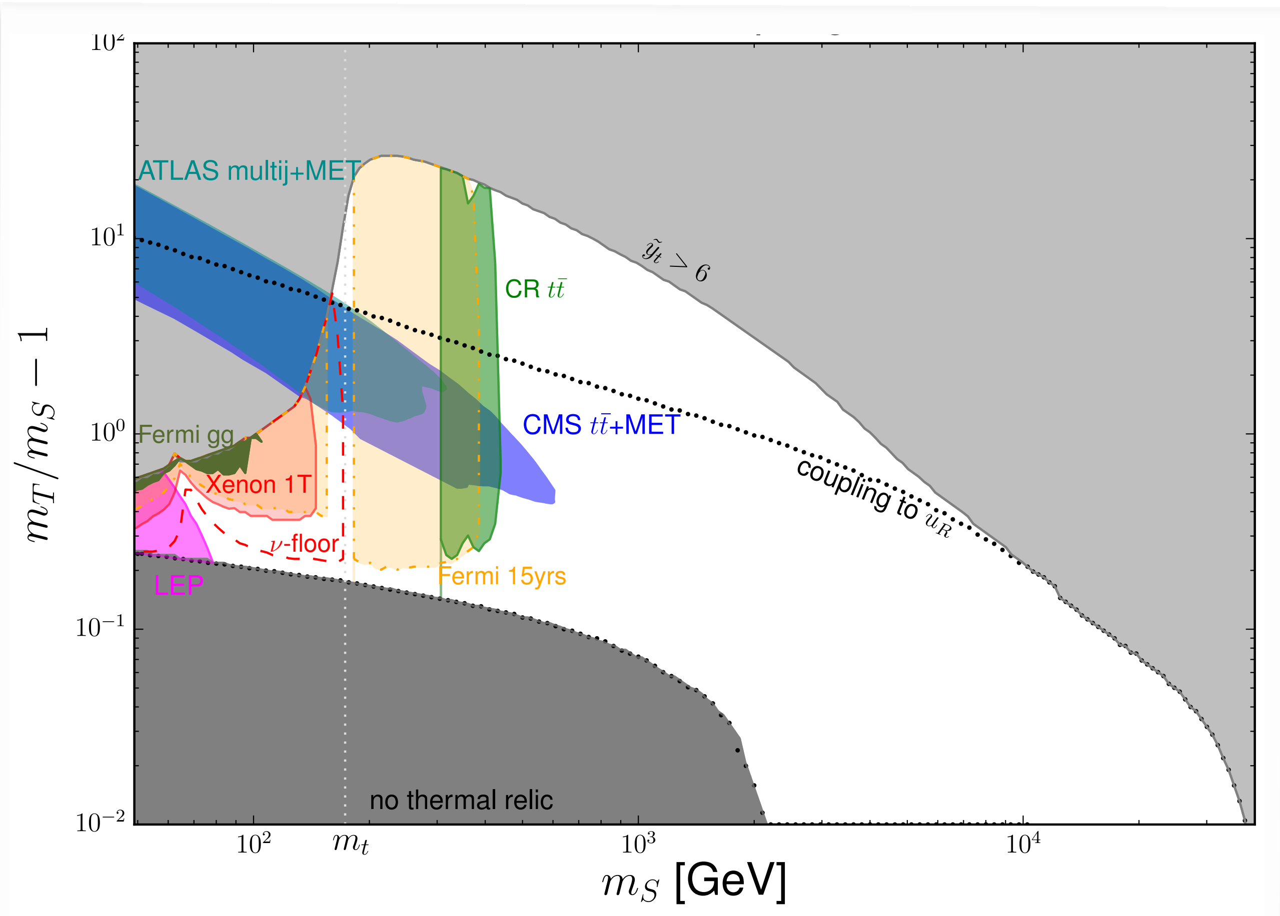
- ✤ Heavy DM and heavy mediator
- ✤ A not too compressed/split spectrum
- ✤ Strongly coupled regime

Example 2: u_R mediator ⊕ λ = 1

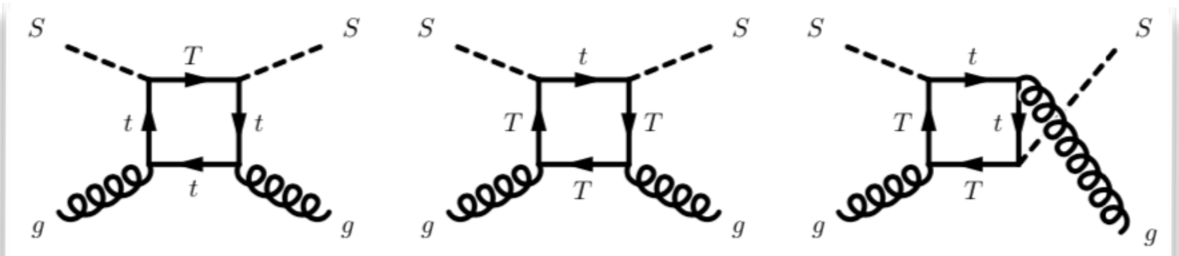


- ✦ Majorana and scalar DM disfavoured by cosmology alone
- ✦ Vector DM remains mostly viable (if m_X > 1 TeV)

✦ Collider-cosmology complementarily at work



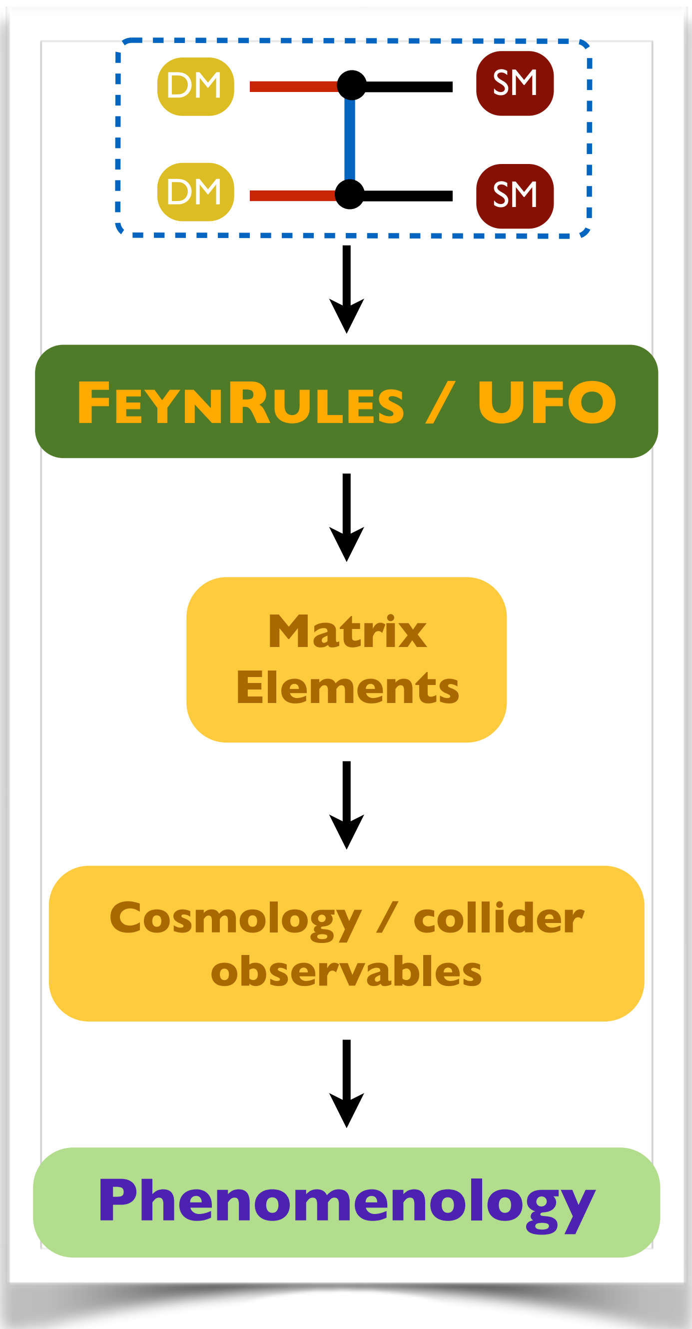
- ✤ Relic-density favoured region
  - ★ Fixes the coupling
  - ★ Dark grey: no thermal relic
  - ★ Light grey: loss of perturbativity
  - ★ Annihilation into gg below the m_t threshold
- ✤ DM direct detection constraints
  - ★ Poor sensitivity (loop-induced interactions)
  - ★ Most parameter space below the ν floor



- ✤ DM indirect detection constraints
  - ★ Exclude limited light DM regions
- ✤ Colliders: future probe of viable setups

Conclusions

Summary



- A generic *t*-channel DM framework is available
  - Higher order corrections included
  - Robust predictions ⇔ crucial for a discovery
- Features
  - Minimal
  - Representative of different new physics scenarios
  - Strongly constrained by current bounds
    - → Conclusive statements in the next decades
- Fineprints
  - No non-minimal features (multi-component DM, *etc.*)
  - Can change the picture
- Automated NLO calculations
  - Important impact on the predictions and the bounds
  - More information:
    - ★ See the papers: 2001.05024, 2010.07559
    - ★ Web: http://feynrules.irmp.ucl.ac.be/wiki/DMsimpt