Cornering dark matter with colliders and cosmology
The role of precision calculations

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High Energy Physics seminar @ CTPU

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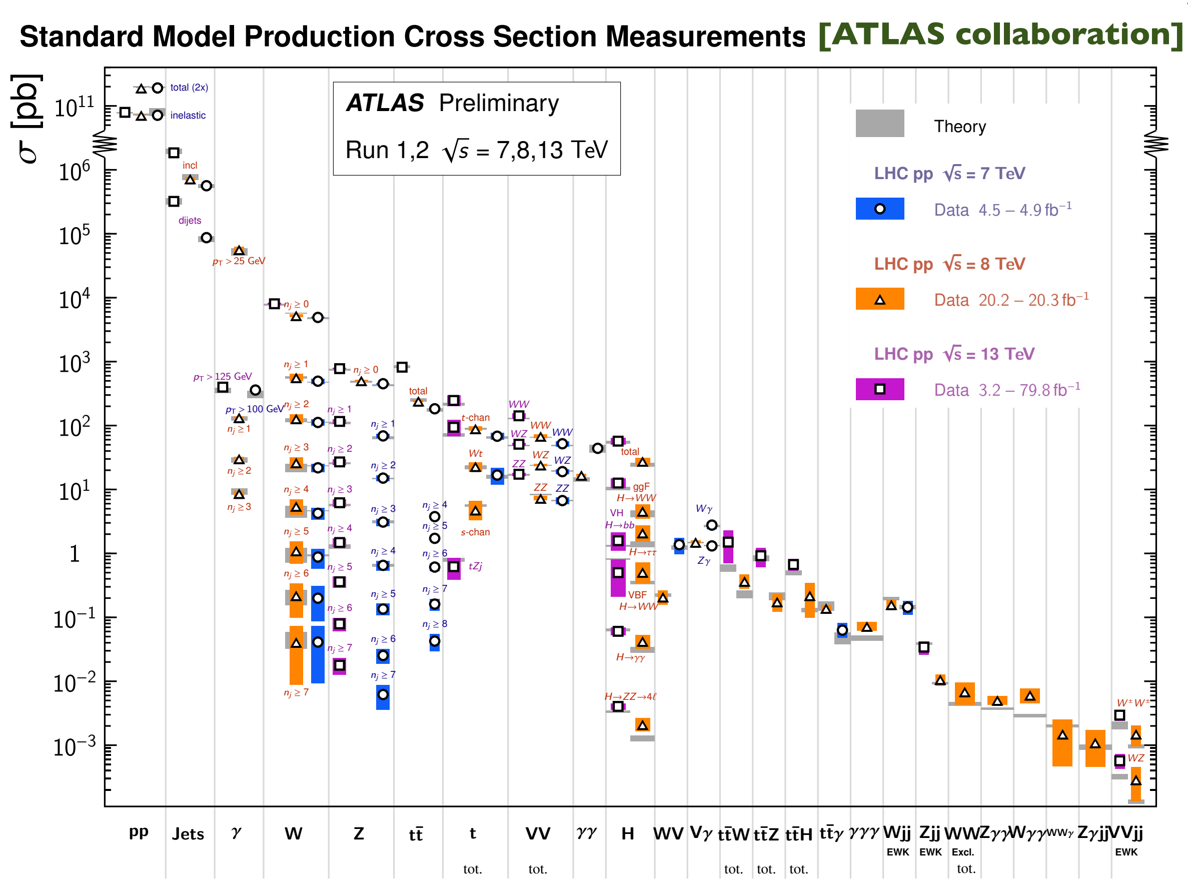
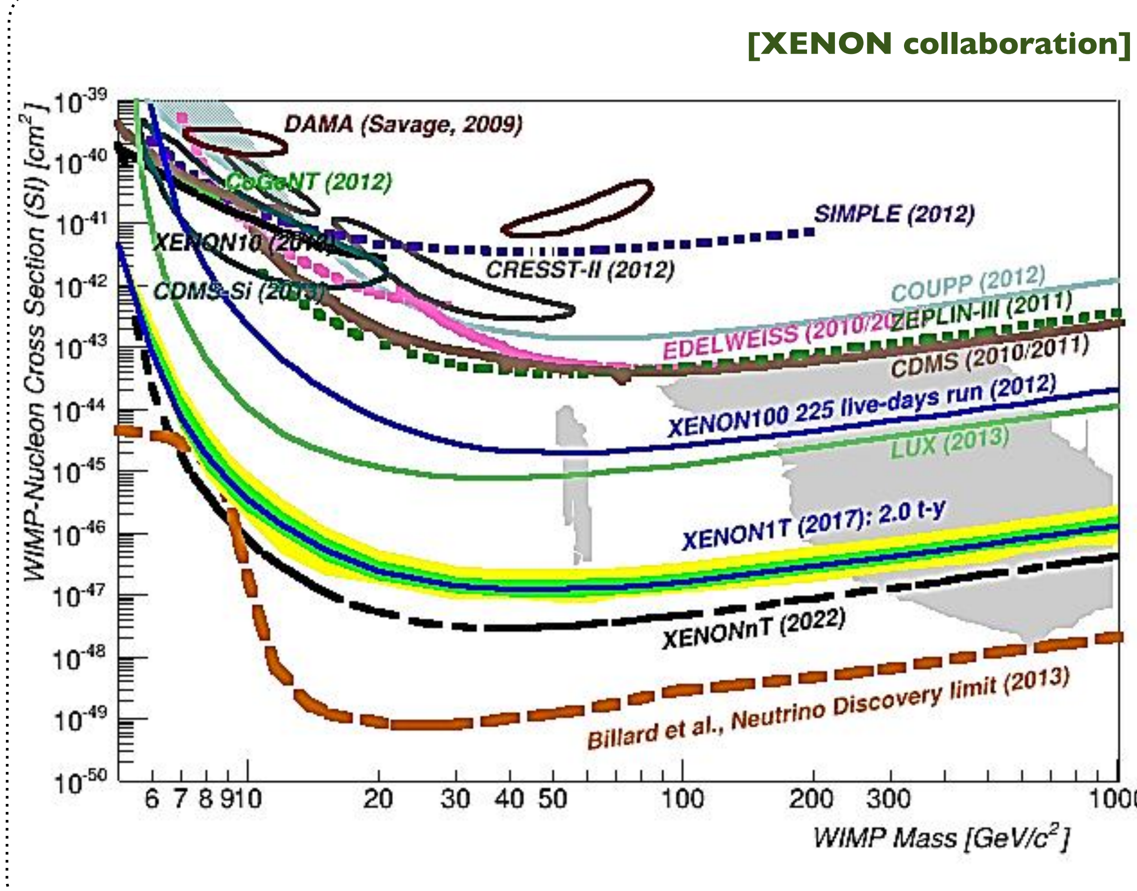
Outline

New physics searches in 2019

- ✦ The status of new physics in January 2019
  - ✤ Theoretically, we are in the dark
    - ★ No sign of new physics, measurements are compatible with the Standard Model
    - ★ Several intriguing features however require confirmation
    - ★ There are good reasons to believe the Standard Model is the beginning…
  - ✤ No leading new physics candidate theory
    - ★ Need to make sure there is no loophole in new physics explorations



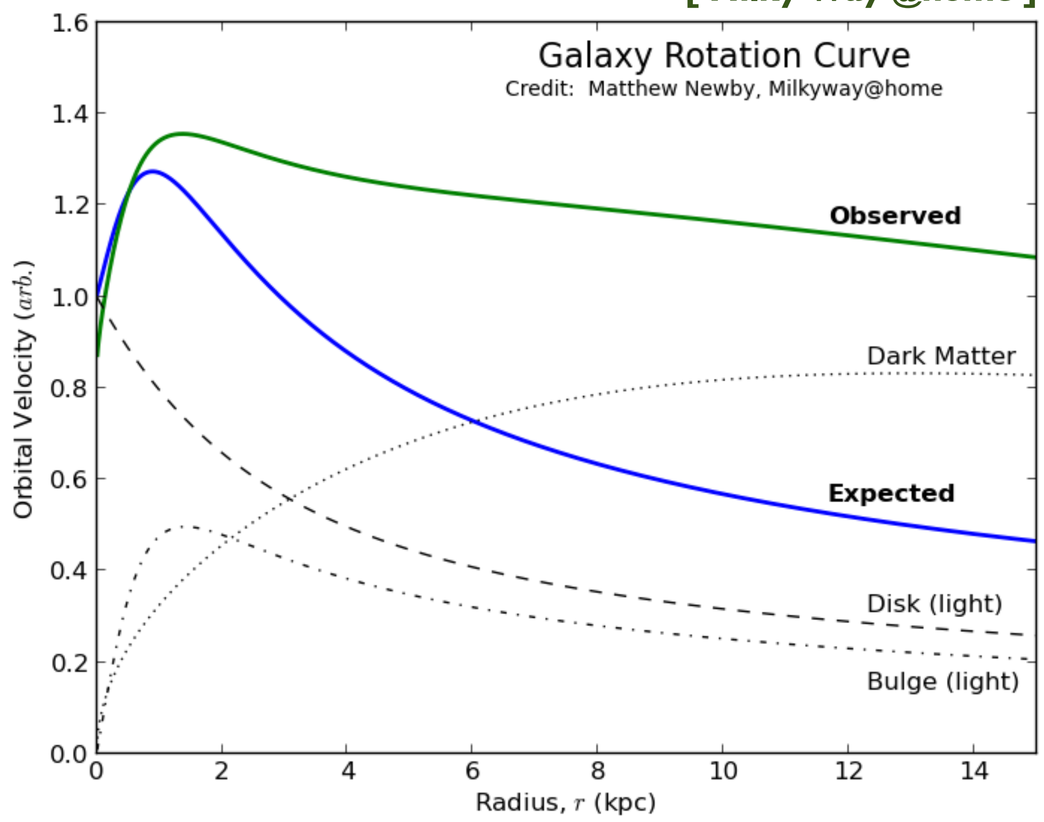


New physics and dark matter

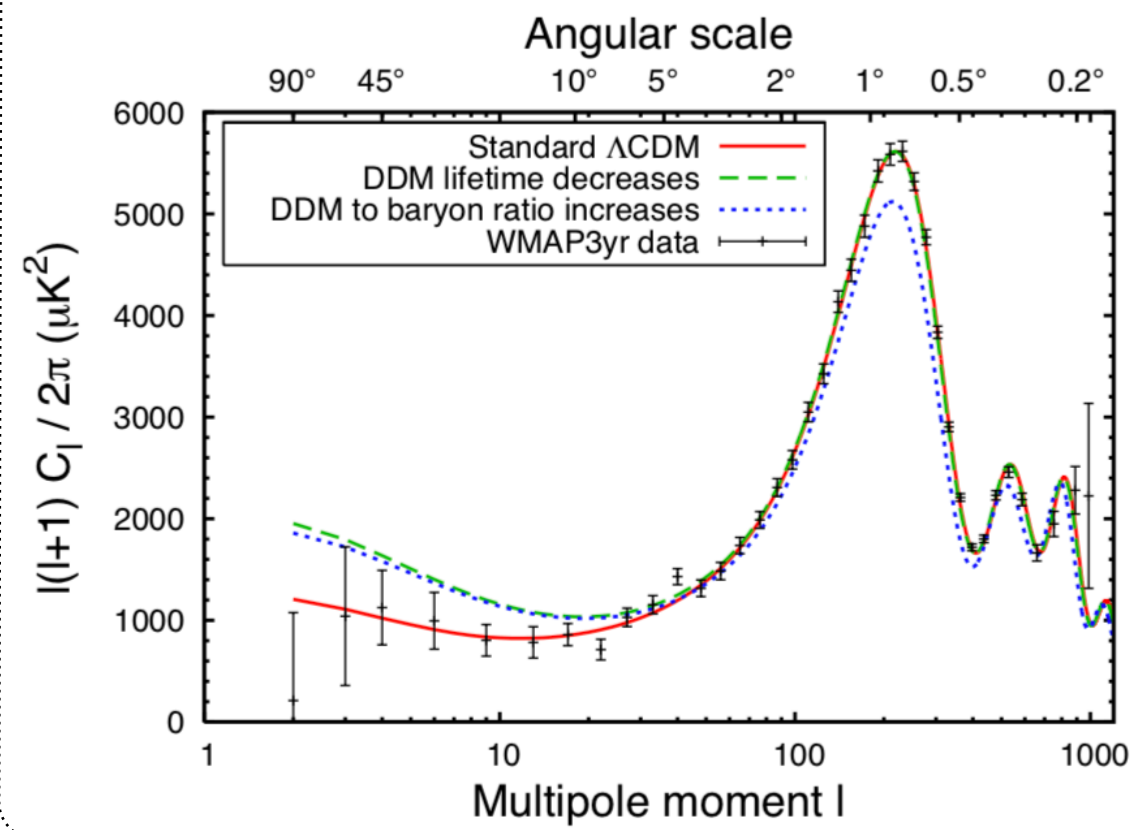
- ✦ Dark matter is an important motivation for new physics
  - ✤ Convincing evidence
    - ★ Flattening of the galaxy rotation curves
    - ★ Gravitational lensing
    - ★ Cosmic microwave background
    - ★ Structure formation
    - ★ *etc.*

Enormous endeavour to detect dark matter

[Milky Way @home]



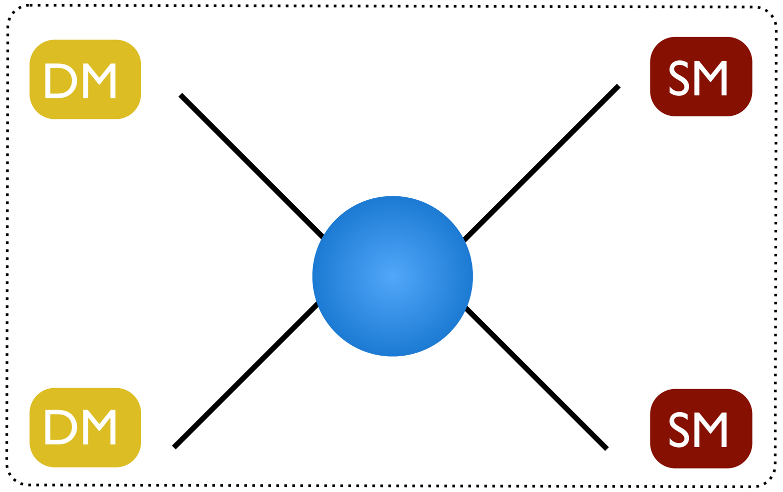
[Latanzi & Valle (PRL`07)]



Dark matter in cosmology and at colliders

- ✦ Dark matter is searched for directly, indirectly and at colliders
  - ✤ Dark matter is elusive ➢ only gravitationally-interacting?
  - ✤ This huge experimental effort however 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 invisible



- ✦ One important issue: precision
  - ✤ Do QCD corrections matter?
  - ✤ Can QCD corrections change conclusions?

Questions addressed in this talk

A toy model: scalar top-philic dark matter

✦ A simplified model for dark matter phenomenology

- To be considered as a toy model
- Useful tool to characterize given phenomena
  - ★ Reinterpretation made easy thanks to very few new parameters
- Reproduction of features shared by several UV-complet models

✦ The top quark is believed to play a special role

- Large mass ⇔ strong connection to electroweak symmetry breaking
  - ★ Setups featuring dark matter interactions with the top quark only

✦ Toy model inspired by compositeness

- Scalar dark matter (*S*) and a VL mediator to the Standard Model (*T*)

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

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

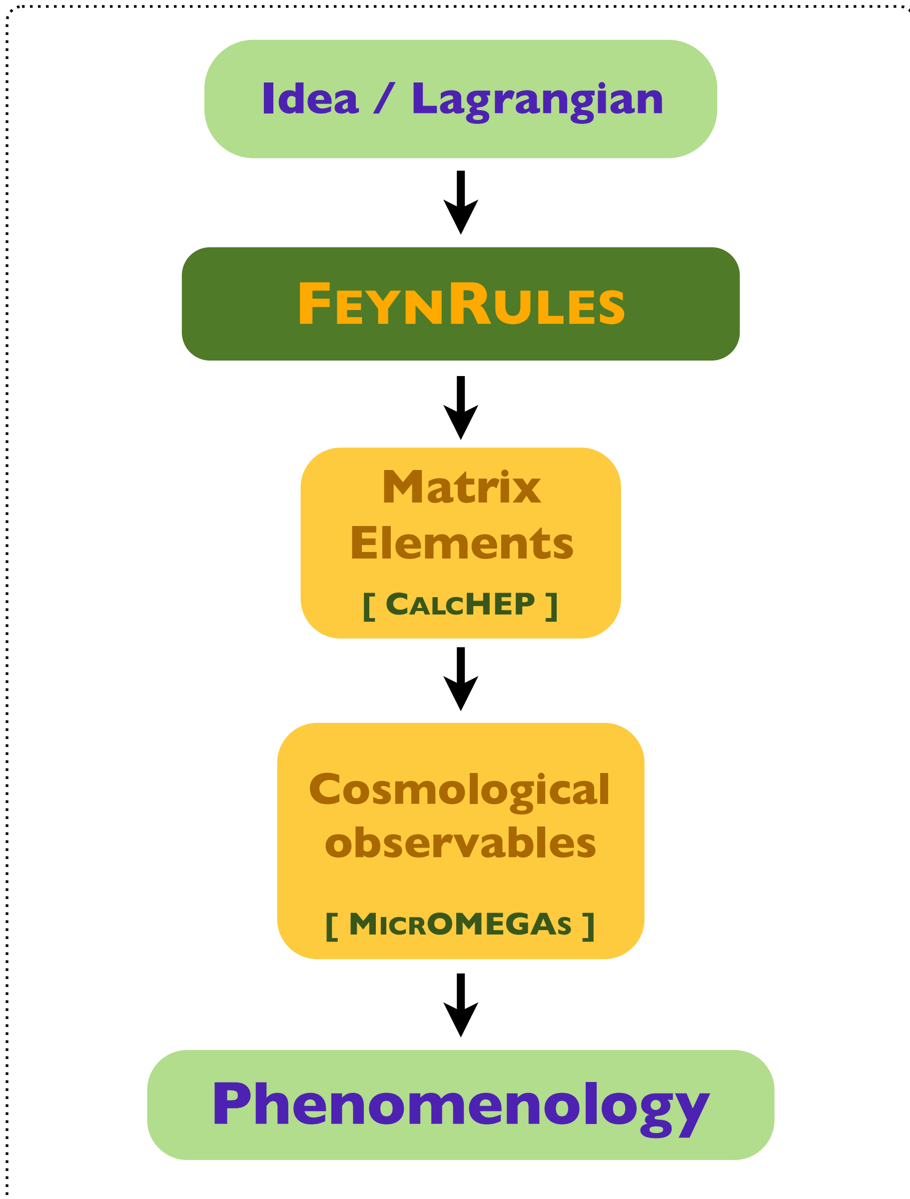
- Simplified parameter space
  - ★ 2 masses: m_S, m_T/m_S-1; 1 Yukawa coupling $\tilde{y}_t$

Outline

A comprehensive approach to new physics calculations

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

✦ Connecting an idea to simulation tools



✤ Model building

- ★ Connecting a Lagrangian to code
- ★ FeynRules

[Alloul, Christensen, Degrande, Duhr, BF (CPC'14)]

✤ Hard scattering

- ★ Feynman diagram and amplitude generation
- ★ Squaring of the matrix elements
- ★ LO accuracy
- ★ CalcHEP [Belyaev, Christensen & Pukhov (CPC'13)]

✤ Cosmology

- ★ Annihilation cross section evaluation
- ★ Relic density, scattering off nuclei rates, *etc.*
- ★ MicrOMEGAs

[Bélanger, Boudjema, Goudelis, Pukhov & Zaldivar (CPC'18)]

QCD corrections computed and added by hand

Relic abundance

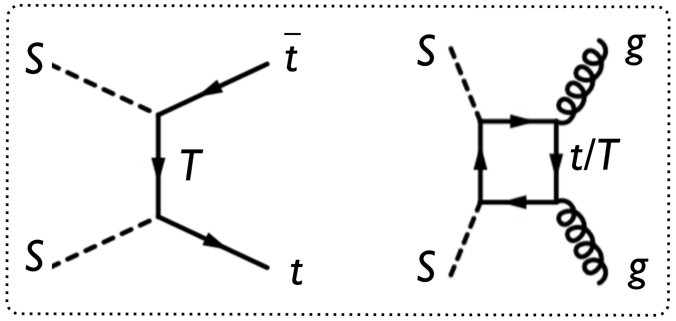
[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

Relic abundance: generalities

✦ Several competing annihilation channels

✤ Annihilation channels

- ★ Annihilations into (potentially virtual) tops
- ★ Loop-induced annihilations into gluons



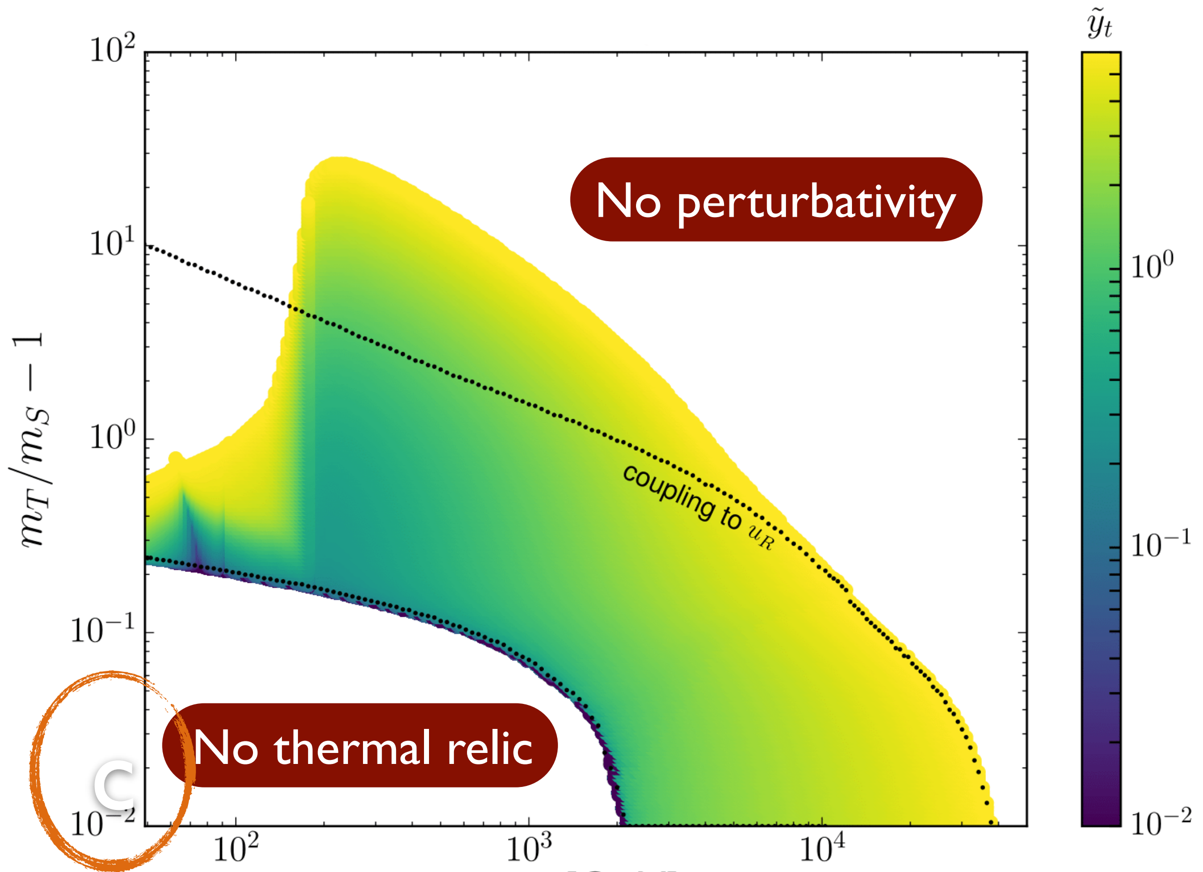
- ★ Potentially resonant co-annihilations: $S\,T \to t^{(*)}$

✤ Colored point = viable scenario

- ★ The predicted relic density agrees with data

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

- ★ NLO QCD corrections are included

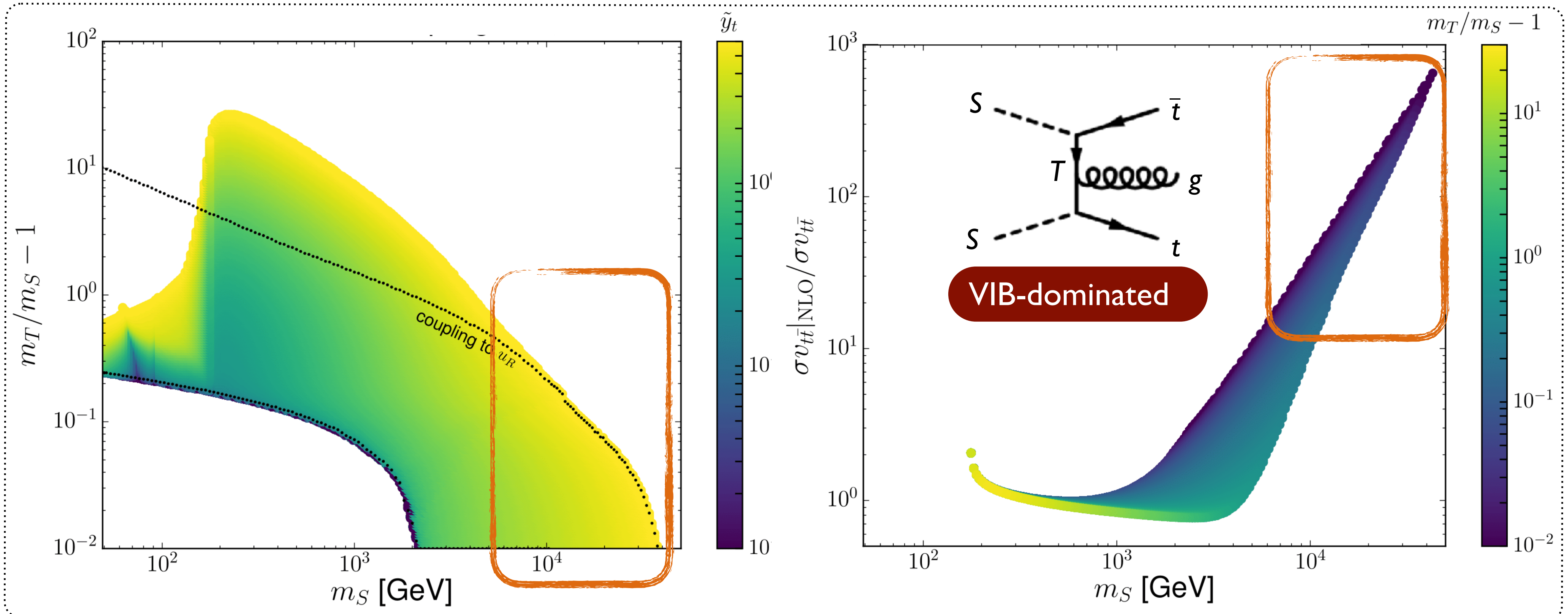


✤ Imposing the right relic abundance fixes $\tilde{y}_t$

- ★ Minimum value = 0.001 for technical reasons
- ★ Maximum value = 6 (perturbativity)

Relic abundance: 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 (s-wave @ LO) negligible

★ Velocity close to 1

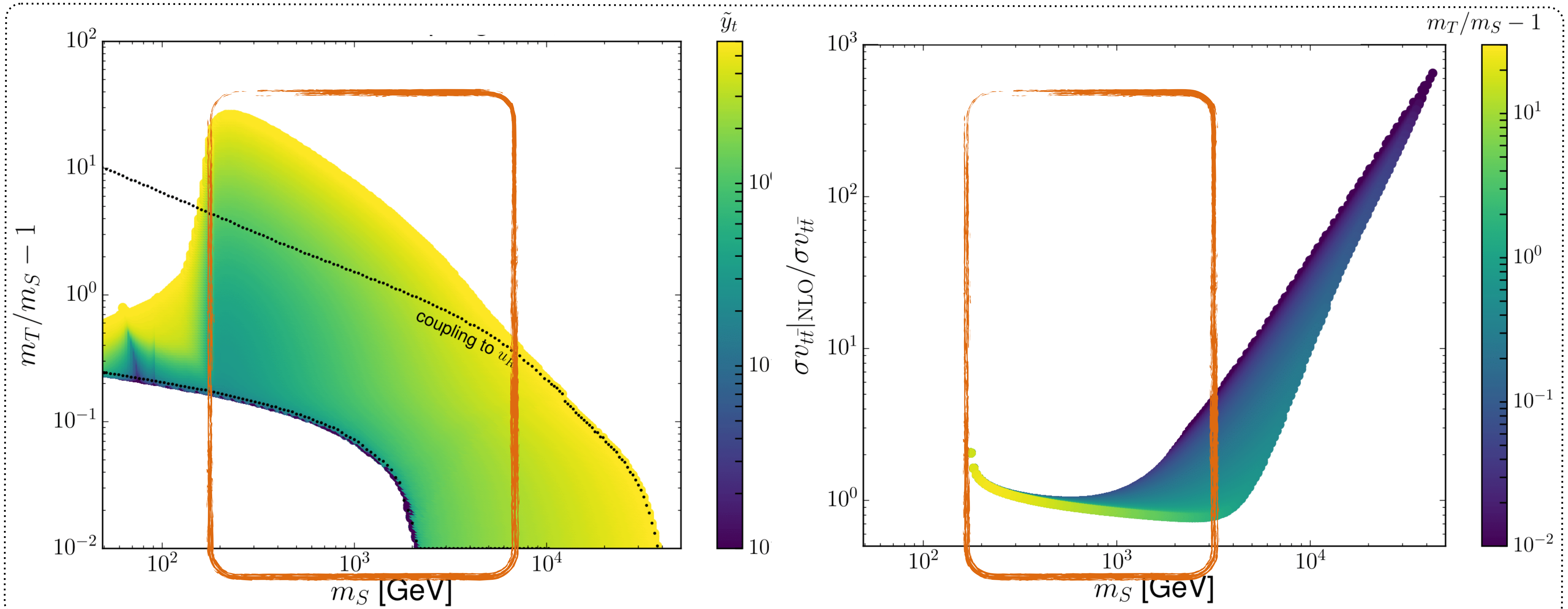
✤ Huge *K*-factors: QCD corrections crucial

★ Leading term: virtual internal bremsstrahlung (VIB)

★ Results leading-order accurate!

Relic abundance: moderately heavy dark matter

✦ Regime with (m_t < m_S < 5 TeV)



✤ Annihilations into tops dominate

★ Top-mass effects (*s*-wave @ LO) important

★ Opens up a region not viable for light quarks

★ Mild *K*-factors

✤ Close to threshold

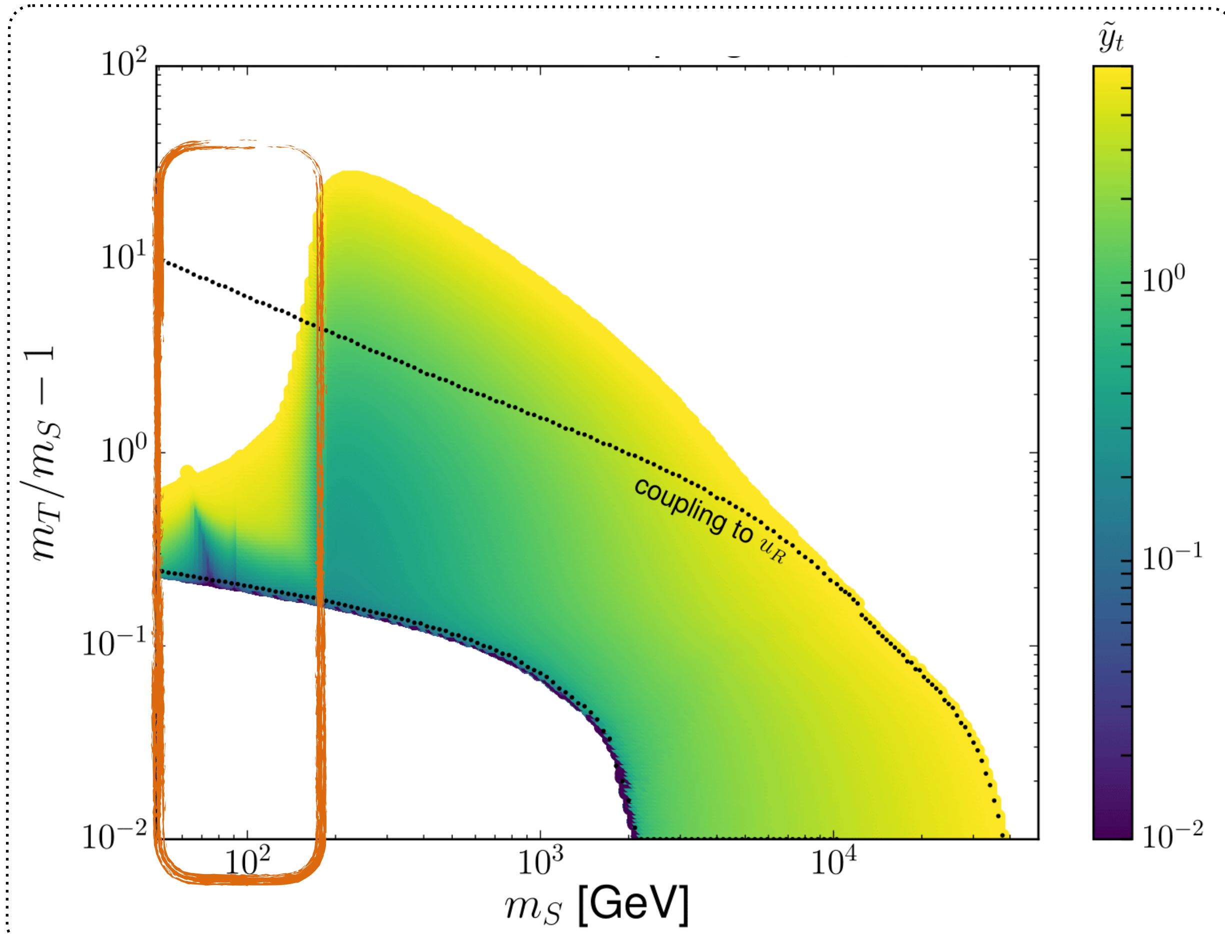
$$(\sigma v)_{\rm NLO} \approx (\sigma v)_{\rm LO}\left[1 + \frac{\alpha_s C_F}{\pi}\left(\frac{\pi^2}{2\beta_0} - 1\right)\right]$$

★ Velocity close to 0

★ Spurious results (no *p*-wave behavior)

Relic abundance: light dark matter

✦ Regime with ($m_S < m_t$)



✤ Annihilations into tops is closed

★ 3-body annihilations (into tWb systems)
➢ relevant for

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

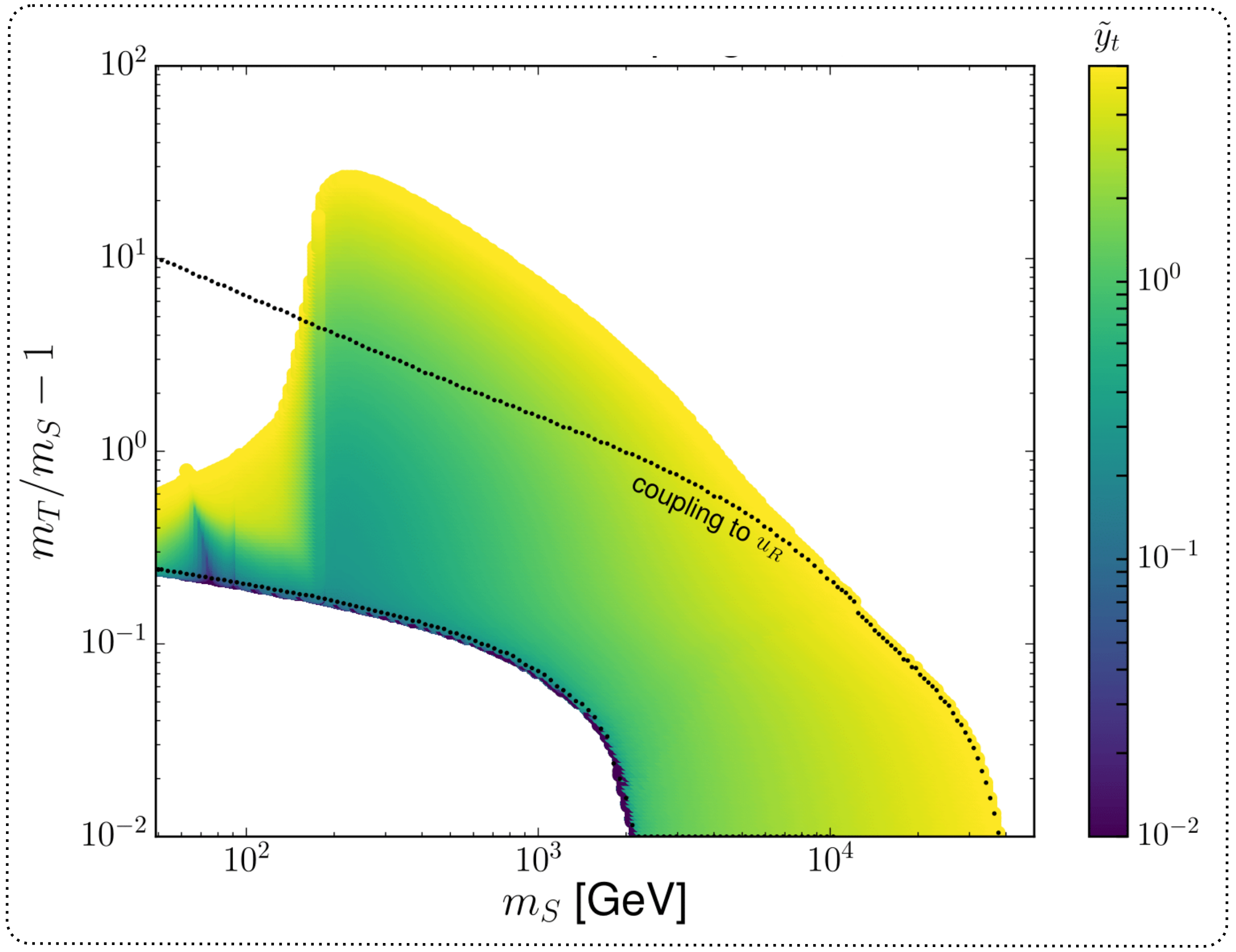
★ At $m_S \sim m_t$, the Yukawa drastically changes
➢ new regime

★ $SS \to gg$ 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)

Relic abundance: summary

✦ Simplification of the parameter space



✤ The Yukawa is fixed to match Planck data

★ We focus on the colored points only

★ Next results: expressed as a function of m_S

★ Color code: spectrum compressibility

✤ Large variety of acceptable scenarios

★ Dark matter masses from 50 to 40000 GeV

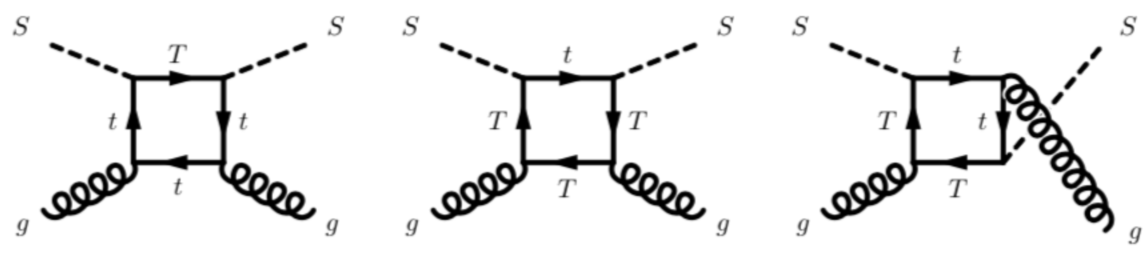
Direct and indirect detection constraints?

Direct and indirect detection

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

Direct detection: generalities

✦ Loop-suppressed dark matter interactions with light quarks and gluons



✤ This loop suppression reduces the dark matter scattering cross section off nuclei

✤ Only interactions with gluons are relevant (light quark connection at two-loop)

✦ Effective interactions

✤ Dimension-five coupling to gluons

$$\mathcal{L}_g = C_S^g \frac{\alpha_s}{\pi} S^2 G^{\mu\nu} G_{\mu\nu} \quad \text{with} \quad C_S^g = \frac{\tilde{y}_t^2}{48\big[M_T^2 - M_S^2\big]}$$

✦ Spin-independent cross section for dark matter scattering off a nucleus Z/A

$$\sigma_A = \frac{m_A^2}{\pi(m_S + m_A)^2}\Big[Z f_p + (A - Z) f_n\Big]^2$$

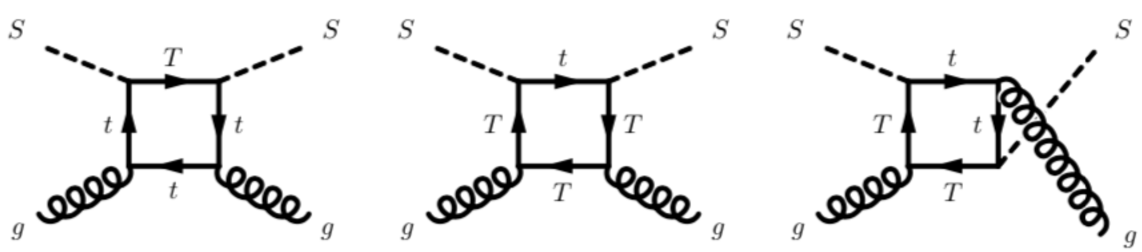
The coupling to nucleons $f_{p/n}$ are deduced:

$$f_N/m_N = -\frac{8}{9} C_S^g(\mu^2) f_{T_G}^{(N)}$$

Direct detection constraints: light dark matter

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

✤ Direct detection relies on loop diagrams



★ Relic density driven by $SS \to gg$
(for $m_S < (m_t + m_W)/2$)

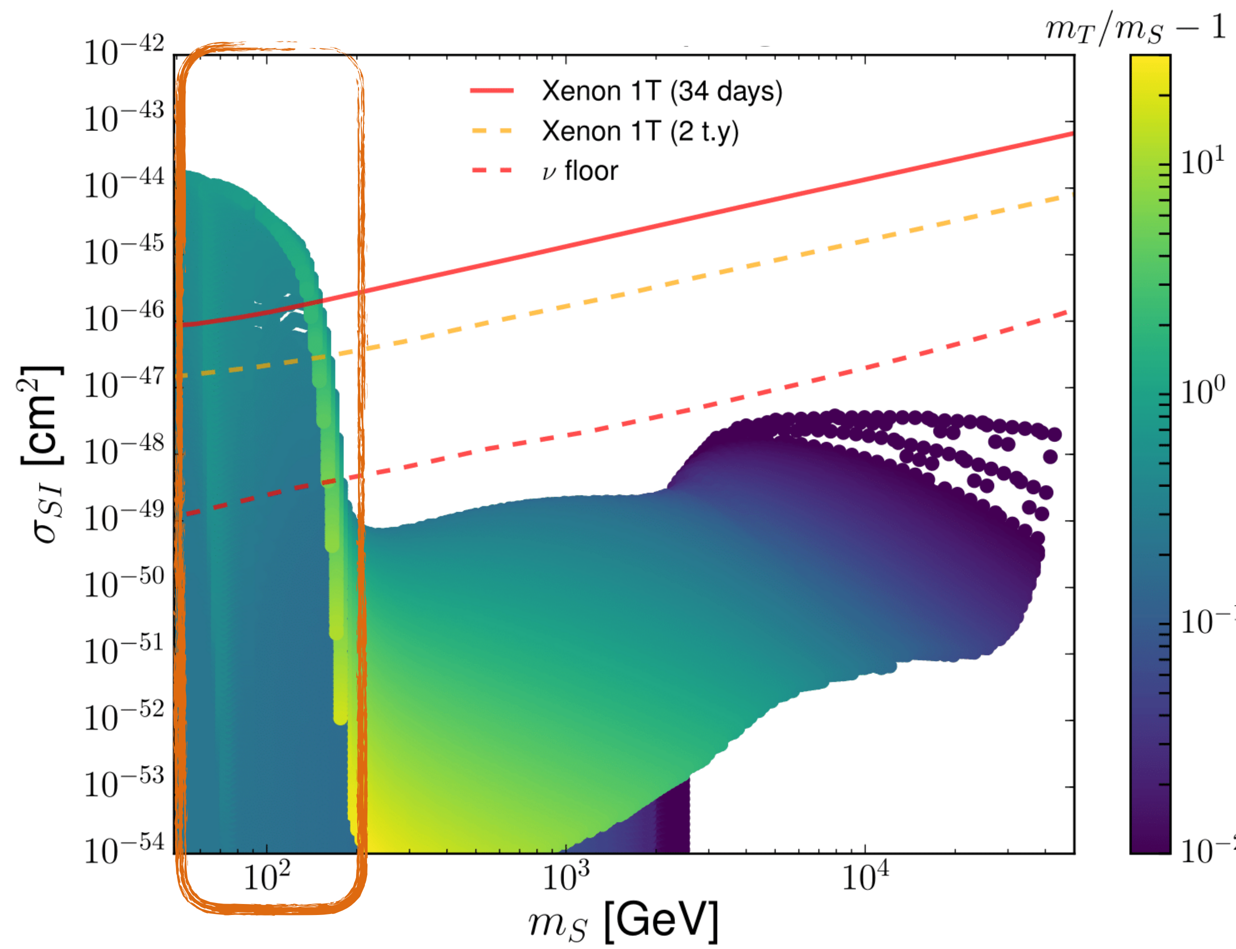
★ Contribution small but significant otherwise

★ Large σ_A expected in this regime

★ Yellow band at ~ 75 GeV

➢ $ST \to t$ resonant co-annihilation regime

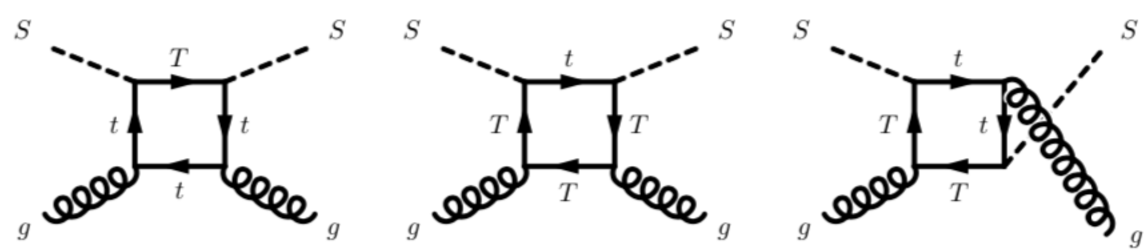
➢ Different phenomenology



Direct detection constraints: heavy dark matter

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

✤ Direct detection relies on loop diagrams



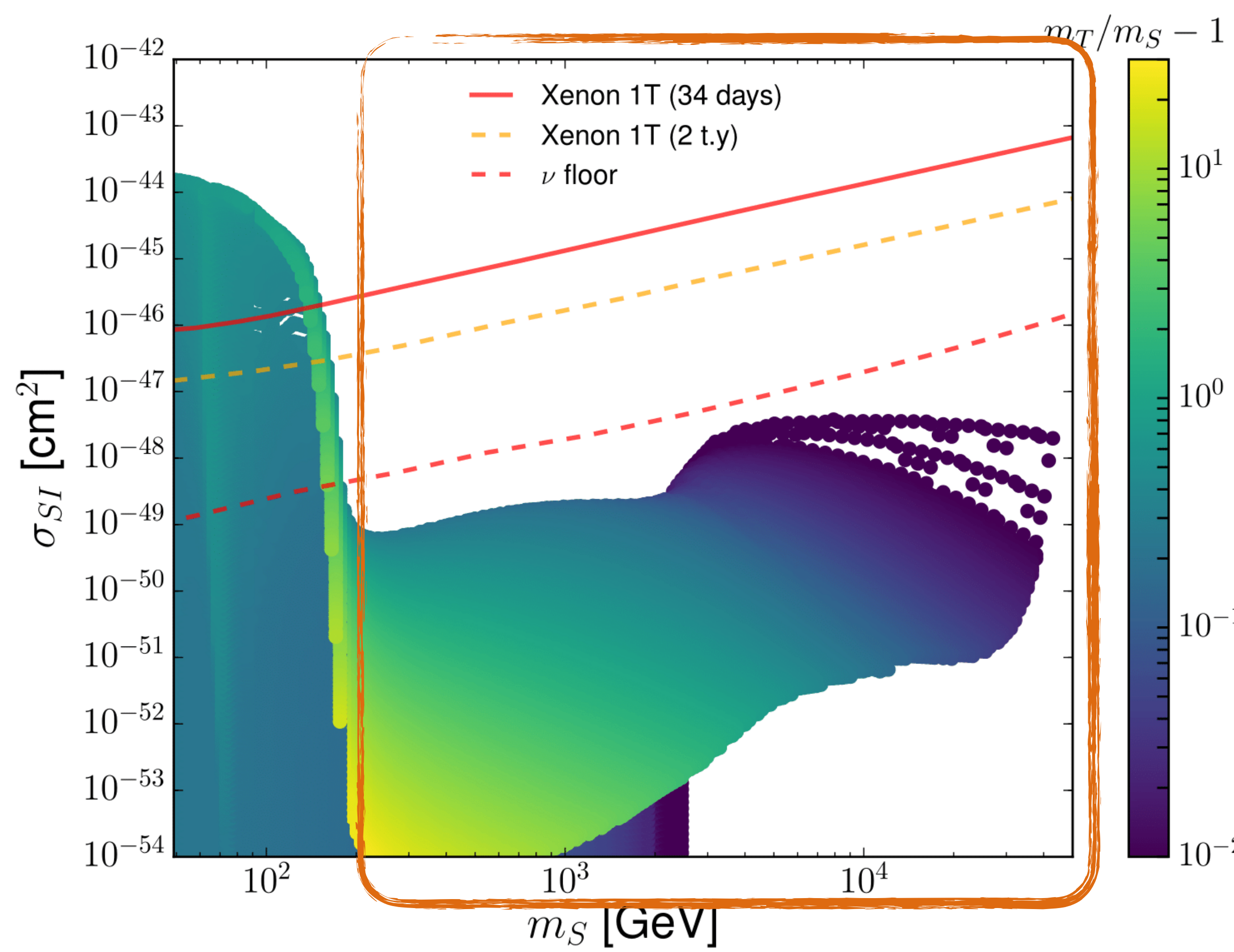
★ Negligible $SS \to gg$ channel

★ Smaller Yukawa value needed to match the relic

➢ Most parameter space below the ν floor

★ Bump in σ_A for $m_S \sim 2.5$ TeV

➢ $m_t + m_S \sim m_T$ yielding an increase in C_S^g



Indirect detection with top final states

✦ Bounds on the 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)]

★ Gamma ray spectra from t/b similar

✤ Mild constraints from AMS antiprotons

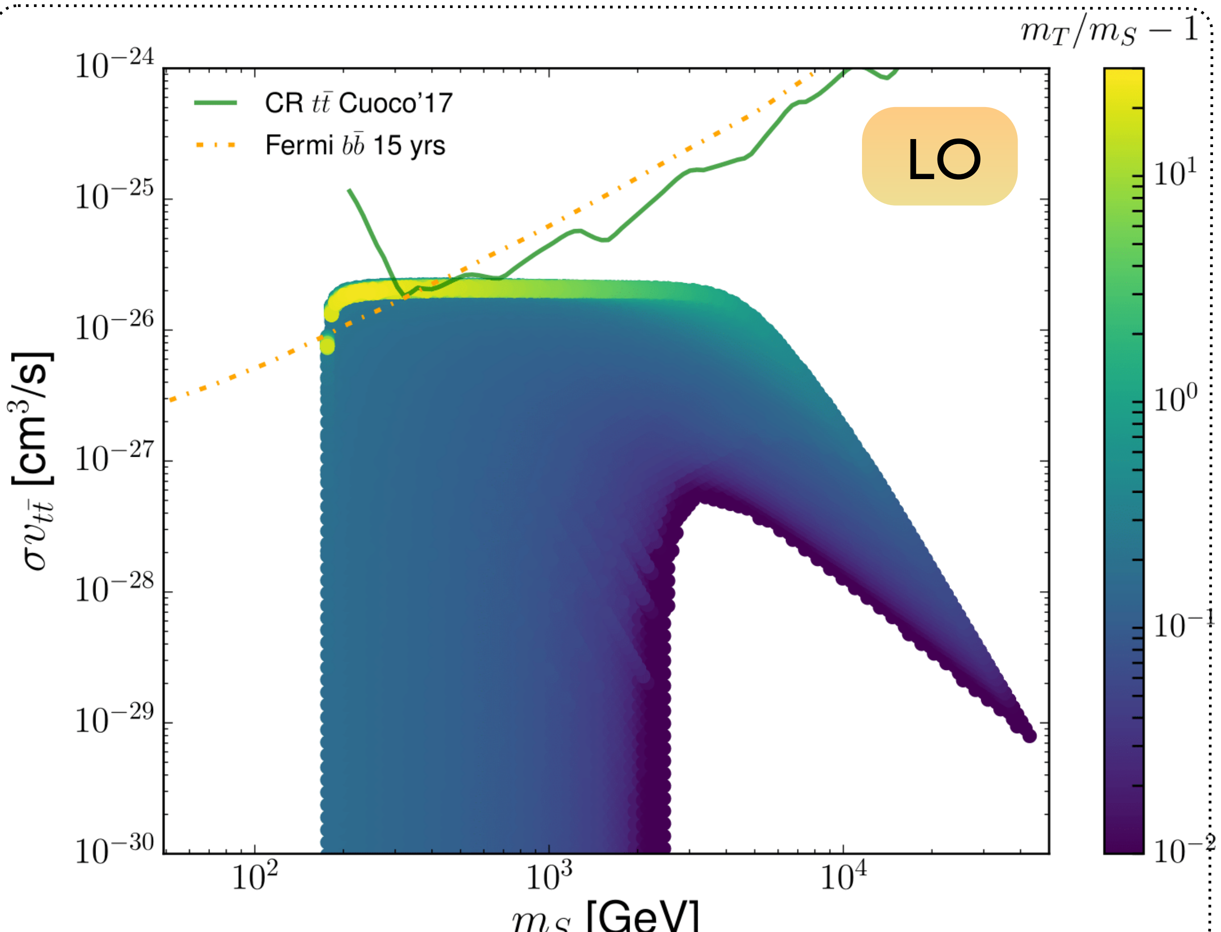
★ Annihilations into SM particles

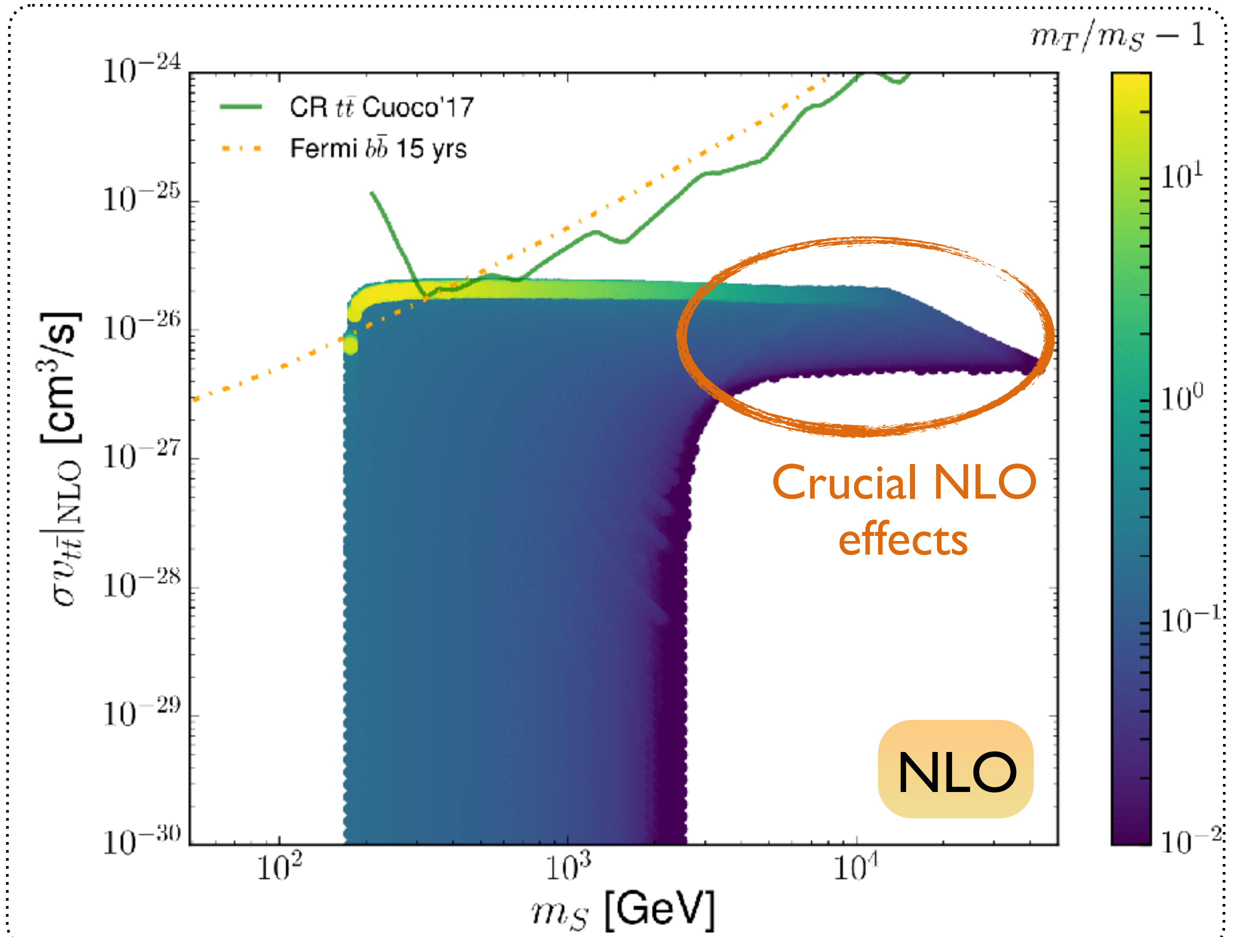
★ Derivation of the associated antiproton flux

✤ Mild constraints from Fermi projections

★ Reinterpretation of the dwarf spheroidal analysis

★ Direct constraints on annihilations into bottoms





Indirect detection with photon final states

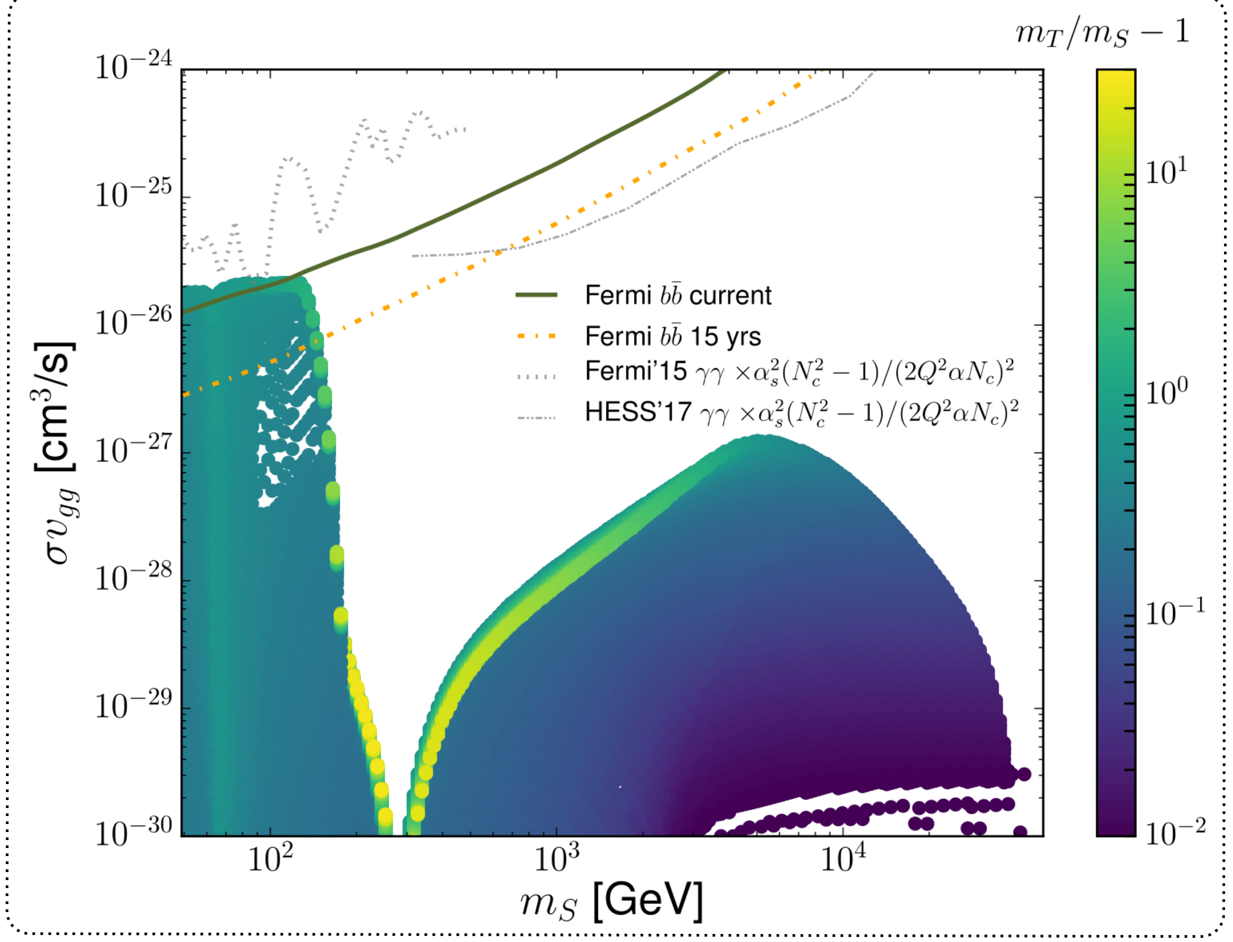
- Light dark matter ($m_S < m_t$)
  - Annihilations into gluons dominate
  - Direct annihilation into photons is large

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

- Heavy dark matter ($m_S > 2$ TeV)
  - Annihilations into top-antitop dominate
  - 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

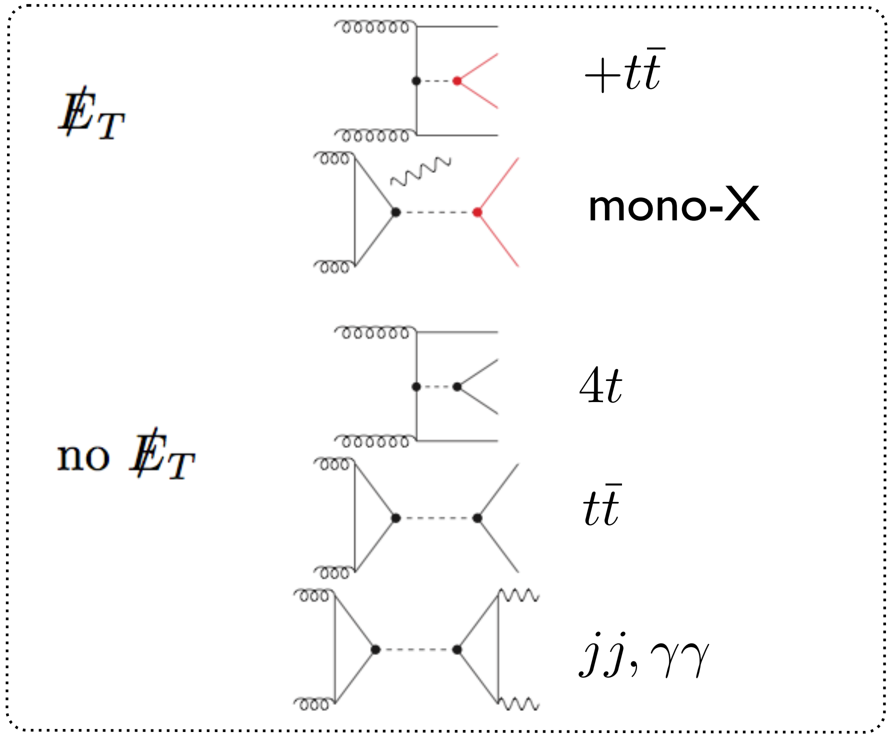


Indirect constraints do not yield much on the model

Outline

Top-philic dark matter @ LHC

✦ Top-philic dark matter scenarios can be probed in many ways at the LHC



★ With or without missing energy

➢ The mediator can be produced too

★ Via tree or loop-induced processes

★ Via top-enriched final states or not

Precision simulations & recasting

✦ 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

Talk of Oct 2018

Automating QCD corrections

NLO calculations in a nutshell

✦ Contributions to an NLO result in QCD

✤ Three ingredients: the Born, virtual loop and real emission contributions

$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n \mathcal{B} \quad + \quad \int \mathrm{d}^4\Phi_n \int_{\mathrm{loop}} \mathrm{d}^d\ell \ \mathcal{V} \quad + \quad \int \mathrm{d}^4\Phi_{n+1} \ \mathcal{R}$$

Born

Virtuals: one extra power of α_s and divergent

Reals: one extra power of α_s and divergent

✤ Challenge: automatically computing predictions for any process in any model

Virtual contributions

✦ Loop diagram calculations

✤ Calculations to be done in *d*=*4-2ε* dimensions

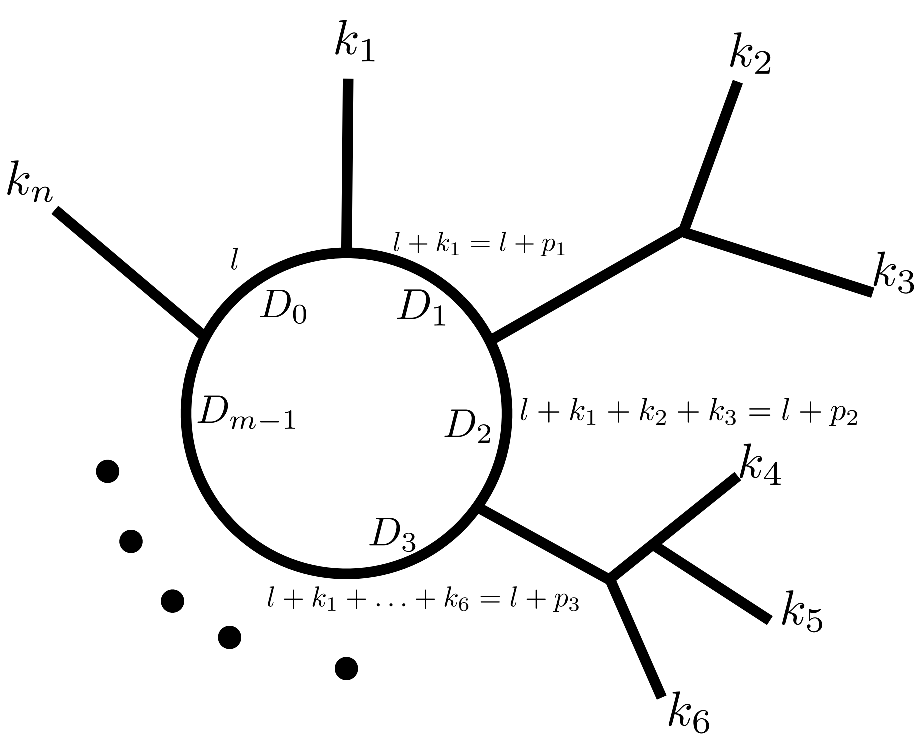
- ★ Divergences made explicit (1/*ε*², 1/*ε*)
- ★ Numerical challenge

✤ Reduction of the loop integrals

$$\int \mathrm{d}^d\ell \frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} = \sum a_i \int \mathrm{d}^d\ell \frac{1}{D_{i_0} D_{i_1} \cdots}$$

- ★ Scalar integrals with up to four denominators
- ★ The decomposition basis is finite
- ★ Many reduction methods are available

m-point diagram with *n* external momenta



The rational terms

[del Aguila & Pittau (JHEP'04); Ossala, Papadopoulos & Pittau (NPB'07; JHEP'08)]

✦ The loop momentum lives in a *d*-dimensional space

- ✤ The reduction should be done in *d* dimensions and not in 4 dimensions

$$\int \mathrm{d}^d\ell \frac{N(\ell,\tilde{\ell})}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}} \quad \text{with } \bar{\ell} = \ell + \tilde{\ell}$$

$\bar{\ell}$: D-dim; ℓ: 4-dim; $\tilde{\ell}$: (-2ε)-dim

- ✤ Numerical methods work in 4 dimensions: need to be compensated!

✦ The R_1 terms originate from the denominators

$$\frac{1}{\bar{D}} = \frac{1}{D}\left(1 - \frac{\tilde{\ell}^2}{\bar{D}}\right)$$

- ✤ These extra pieces can be calculated generically (3 integrals in total)

✦ The R_2 terms originate from the numerator

- ✤ Process-dependent contributions proportional to $\tilde{\ell}^2$
- ✤ In a renormalizable theory, there is a finite number of such R_2 pieces
  - ★ They can be calculated once and for all for a specific model

Matching fixed order with parton showers

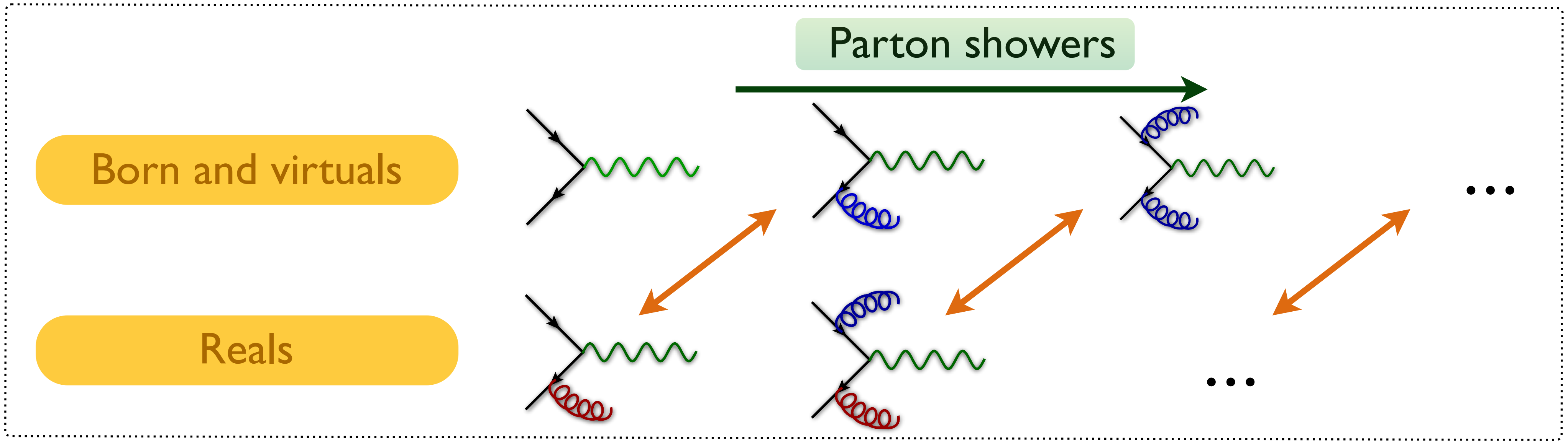
✦ Subtracting the poles

✤ The structure of the poles appearing at NLO is known ➢ subtraction methods

- ★ $\mathcal{C}$ subtracted from the reals ➢ makes them finite
- ★ $\mathcal{C}$ integrated and added back to the virtuals ➢ makes them finite
- ★ Integrals can be made numerically (in four dimensions)

$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n\, \mathcal{B} + \int \mathrm{d}^4\Phi_{n+1} \Big[\mathcal{R} - \mathcal{C}\Big] + \int \mathrm{d}^4\Phi_n \Big[\int_{\text{loop}} \mathrm{d}^d\ell\, \mathcal{V} + \int \mathrm{d}^d\Phi_1 \mathcal{C}\Big]$$

✦ Double counting when matching with parton showers

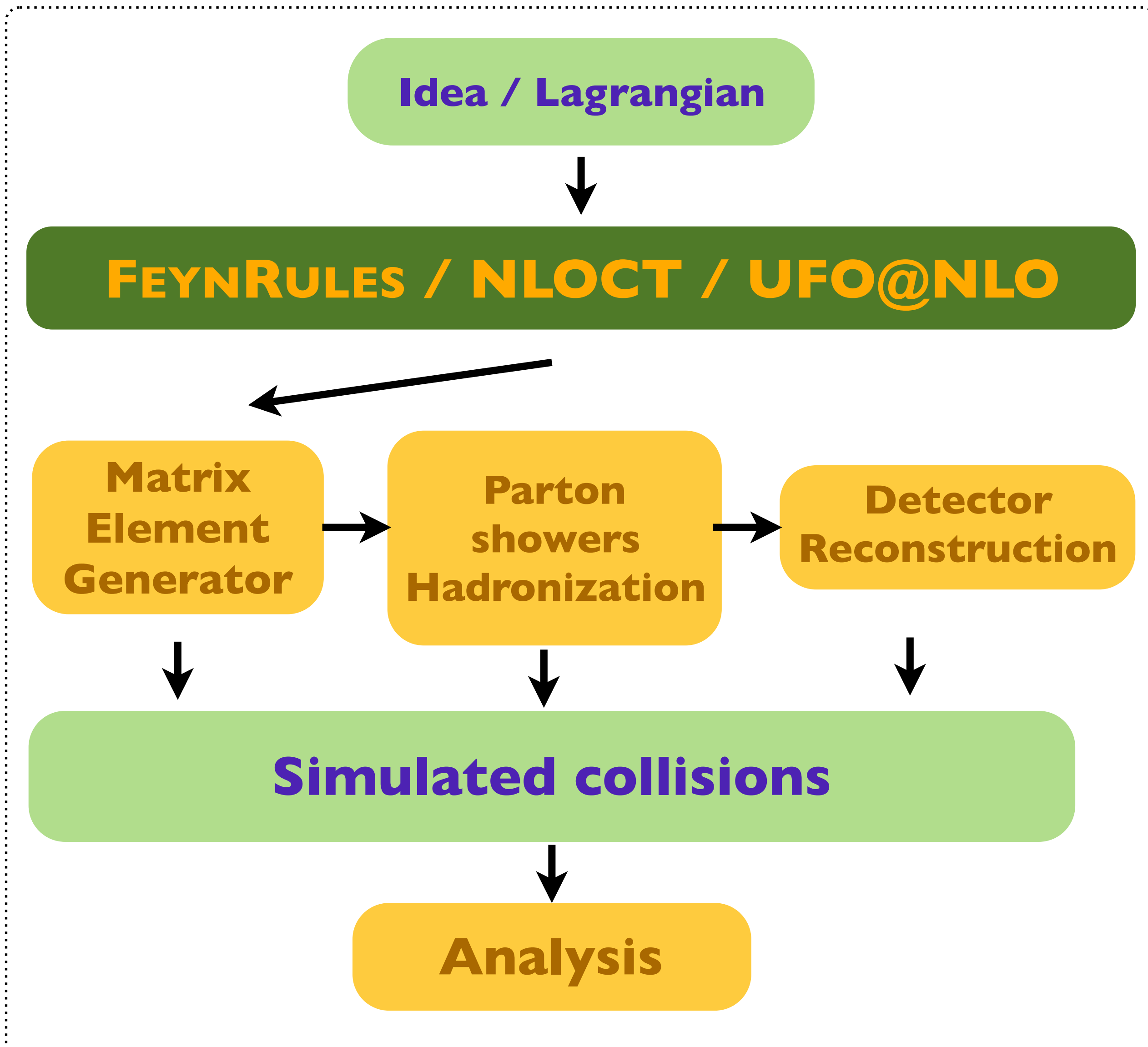


✤ Two sources of double counting that compensate each other (shower unitarity)

- ★ Radiation: both at the level of the reals and of the shower
- ★ No radiation: both in the virtuals and in the no-emission probability

Automated NLO simulations with MG5_aMC

✦ From Lagrangians to analyzed NLO simulated collisions



- FeynRules is linked to NLOCT
  - ★ Calculation of UV and R_2 counterterms
  - ★ Export of the information to the UFO

  [Alloul, Christensen, Degrande, Duhr & BF (CPC'14)]
  [Degrande (CPC'15)]
  [Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]
  [Degrande, Duhr, BF, Hirschi, Mattelaer, Shao *et al.* (*in prep.*)]

- Parton shower matching: MC@NLO
  - ★ Automatic (MG5_aMC)
  - ★ Restrictions on the renormalization scheme

  [Alwall *et al.* (JHEP'14)]

- LHC recasting done with MadAnalysis 5
  - ★ Automatic

  [Conte, BF, Serret (CPC '13)]
  [Conte, Dumont, BF, Wymant (EPJC '14)]
  [Dumont, BF, Kraml *et al.* (EPJC '15)]
  [Conte & BF (IJMPA`18)]

LHC recasting with MadAnalysis 5

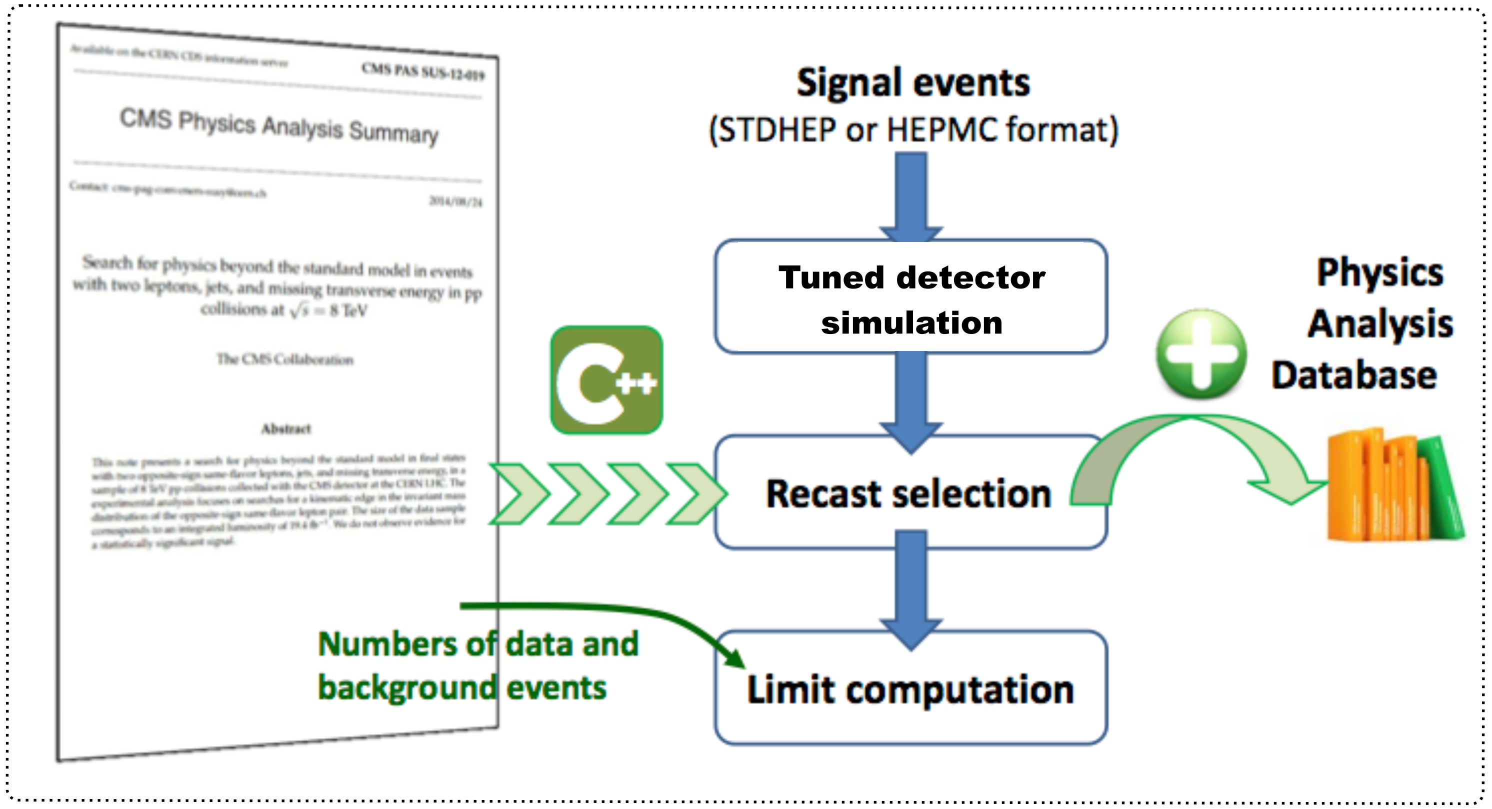
[Conte, BF, Serret (CPC '13); Conte, Dumont, BF, Wymant (EPJC '14); Dumont, BF, Kraml *et al.* (EPJC '15); Conte & BF (IJMPA`18)]

Recasting with MadAnalysis 5

✦ The MadAnalysis 5 strategy for the reinterpretation of an LHC analysis

- Relies on a (public) detector simulation mimicking ATLAS-CMS simulations
- Relies on a (public) framework where LHC analyses can be easily implemented

✦ Scheme



- 2 options for detector effects
  - ★ Delphes/Pgs-like (resolutions, efficiencies, *etc.*)
  - ★ Rivet-like (transfer functions)

Picked approach in MadAnalysis 5

Implementing a new analysis in MadAnalysis 5

- ✦ Picking up an experimental publication
  - ✤ Reading
  - ✤ Understanding

✅ Relatively easy

- ✦ Writing the analysis code in the tool internal language

✅ Relatively easy

- ✦ Getting the information missing from the publication for a proper validation
  - ✤ Efficiencies (trigger, electrons, muons, b-tagging, JES, *etc.*)
    - ★ Including p_T and/or η dependence
    - ★ Accurate information
  - ✤ Detailed cutflows for some well-defined benchmark scenarios
    - ★ Exact definition of the benchmarks (SLHA spectra)
    - ★ Event generation information (cards, tunes, LHE files if possible)
  - ✤ Expected number of events in each region and cross sections
  - ✤ Digitized histograms (e.g., on HepData)

⚠️ Essential
❌ Often difficult!

Discussions with experimentalists

- ✦ Comparing theory tools and real life
  (and beware of the genuine differences between both approaches)

Recasting of CMS-SUS-17-001

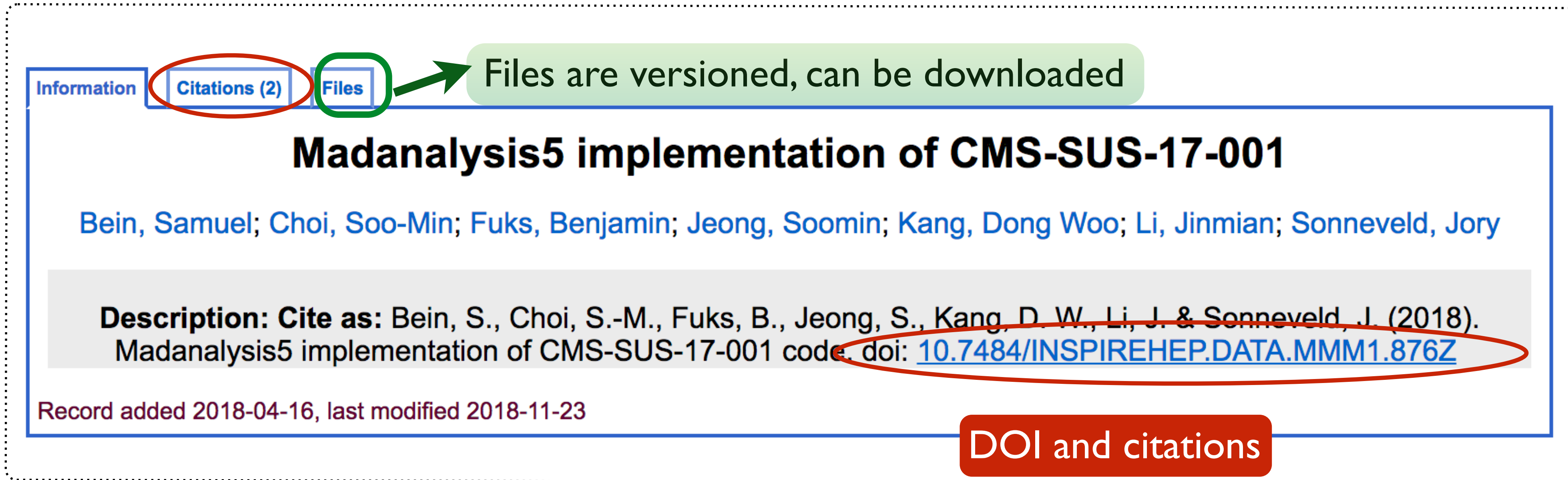
[Bein, Choi, BF, Jeong, Kang, Li & Sonneveld ('18)]

- CMS search for dark matter in the top-antitop plus missing energy channel
  - Dileptonic final state
  - Cutflows and Monte Carlo information for given benchmarks
- Validation at a very good level, cut by cut

Cut	$(m_{\tilde{t}}, m_{\tilde{\chi}}) = (750, 1)$ GeV		$(m_{\tilde{t}}, m_{\tilde{\chi}}) = (600, 300)$ GeV	
	CMS	MA5	CMS	MA5
n(OS μ or e)= 2	-	-	-	-
$m_{\ell\ell} > 20$ GeV	0.99	0.99	0.99	0.97
$\lvert m_Z - m_{\ell\ell}\rvert > 15$ GeV	0.95	0.94)	0.89	0.89
$N_j \geq 2$	0.87	0.93)	0.85	0.89
$N_b \geq 1$	0.73	0.84)	0.83	0.83
$E_T^{\rm miss} > 80$ GeV	0.94	0.95	0.89	0.88
$S > 5$ GeV$^{1/2}$	0.98	0.92	0.96	0.91
$c_1 < 0.80$	0.9	0.97	0.92	0.97
$c_2 < 0.96$	1.0	0.96	1.0	0.94
$M_{T2}(\ell_1\ell_2) > 140$ GeV	0.49	0.42	0.17	0.16
All cuts	0.24	0.25	0.083	0.075

MadAnalysis 5 analyses on Inspire

- Implementation of LHC analyses can be uploaded on Inspire
  - DOI are assigned: can be cited, searched for, *etc.*



The Public Analysis Database of MADANALYSIS

- A database with MADANALYSIS 5 implementations of LHC analyses exists
  - http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase

CMS analyses, 13 TeV

Analysis	Short Description	Implemented by	Code	Validation note	Version
CMS-SUS-16-033	Supersymmetry in the multijet plus missing energy channel (35.9 fb-1)	F. Ambrogi and J. Sonneveld	Inspire	PDF	v1.7/Delphes3
CMS-SUS-16-039	Electroweakinos in the SS2L, 3L and 4L channels (35.9 fb-1)	B. Fuks and S. Mondal	Inspire	PDF	v1.7/Delphes3
CMS-SUS-16-052	SUSY in the 1l + jets channel (36 fb-1)	D. Sengupta	Inspire	PDF	v1.6/Delphes3
CMS-SUS-17-001	Stops in the OS dilepton mode (35.9 fb-1)	S.-M. Choi, S. Jeong, D.-W. Kang, J. Li *et al.*	Inspire	PDF	v1.6/Delphes3
CMS-EXO-16-010	Mono-Z-boson (2.3 fb-1)	B. Fuks	Inspire	PDF	v1.6/Delphes3
CMS-EXO-16-012	Mono-Higgs (2.3 fb-1)	S. Ahn, J. Park, W. Zhang	Inspire	PDF	v1.6/Delphes3
CMS-EXO-16-022	Long-lived leptons (2.6 fb-1)	J. Chang	Inspire	PDF	v1.6_tracks/Delphes3
CMS-TOP-17-009	SM four-top analysis (35.9 fb-1)	L. Darmé and B. Fuks	Inspire	PDF	v1.7/Delphes3

- Delphes card for CMS-EXO-16-010 and CMS-SUS-17-001
- Delphes card for CMS-EXO-16-012
- Delphes card for CMS-SUS-16-039
- Delphes card for CMS-SUS-16-041
- Delphes card for CMS-SUS-16-052
- Delphes card for CMS-TOP-17-009

Dedicated DELPHES cards

Code from INSPIRE

Validation information (cutflows, distributions, *etc.*)

- Can be automatically installed within MADANALYSIS 5

Example

[Conte, BF, Serret (CPC '13); Conte, Dumont, BF, Wymant (EPJC '14); Dumont, BF, Kraml *et al.* (EPJC '15); Conte & BF (IJMPA`18)]

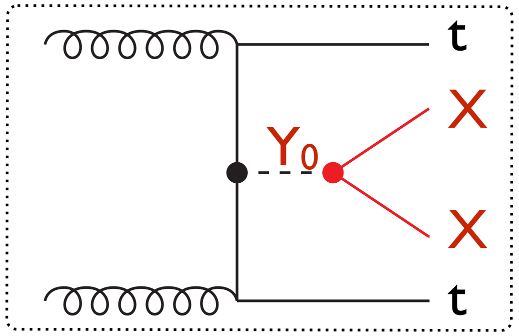
$t\bar{t}$+MET constraints on top-philic dark matter

[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

A simplified model for top-philic dark matter

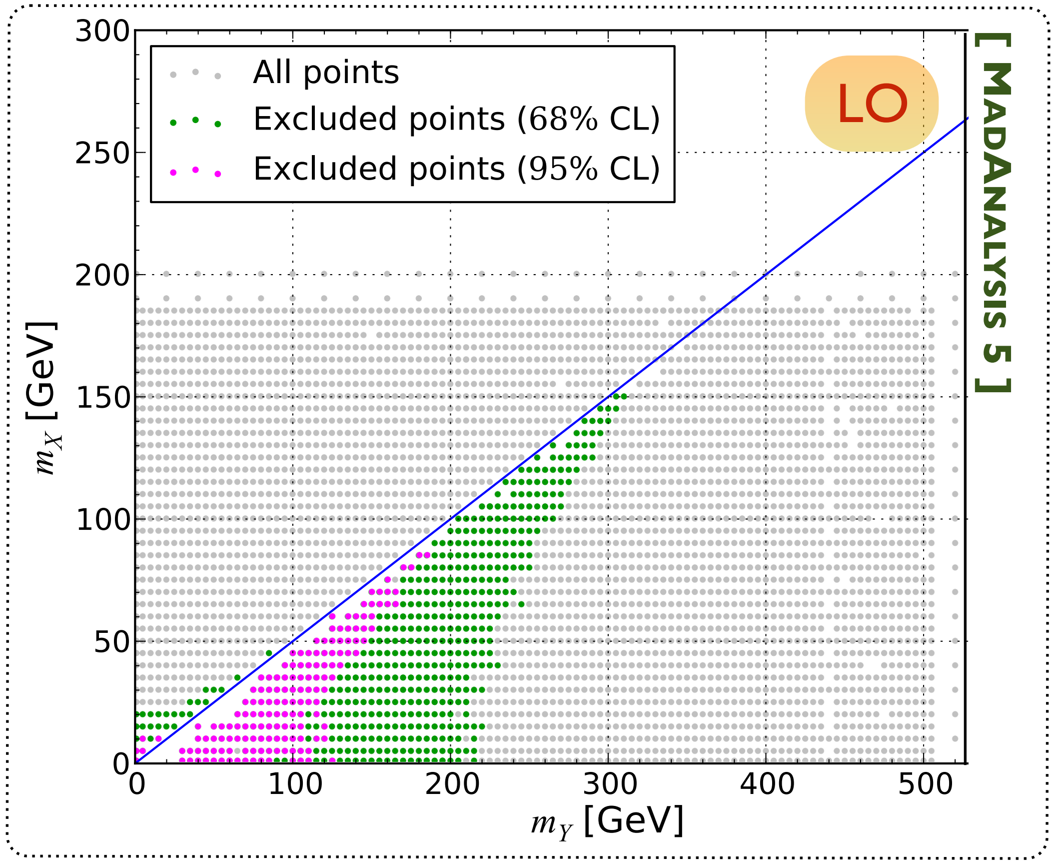
- A dark sector with a fermionic dark matter candidate X
- A (scalar) mediator Y_0 linking the dark sector and the top

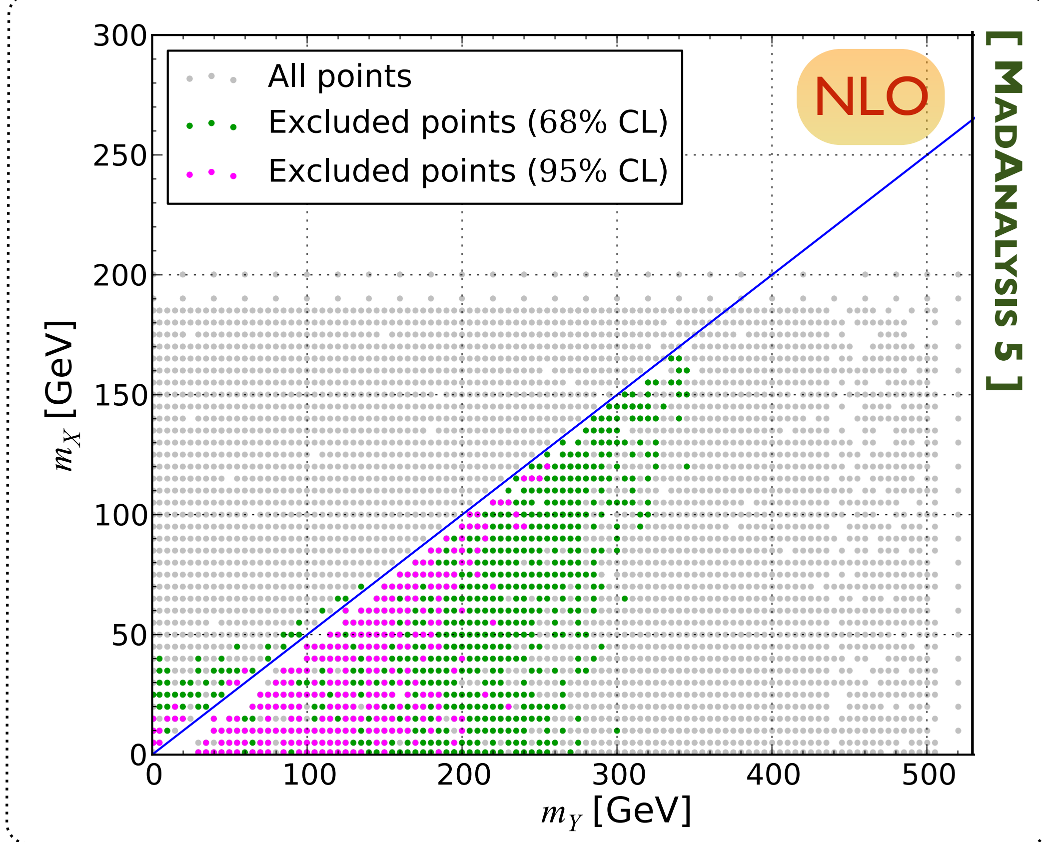
$$\mathcal{L}_{t,X}^{Y_0} = -\Big(g_t \frac{y_t}{\sqrt{2}} \bar{t}t + g_X \bar{X}X\Big) Y_0$$



- Could be probed with $t\bar{t}$+MET events (CMS-B2G-14-004)

For central scales: mild (but visible) NLO effects on the exclusions



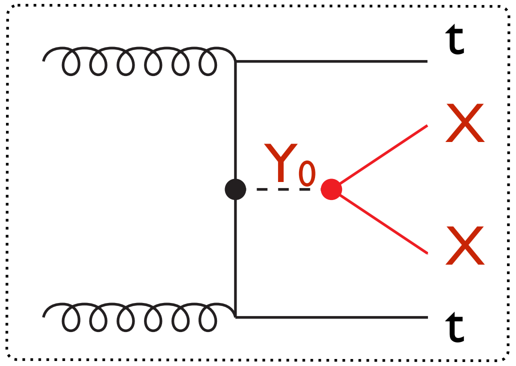


- How is the picture changing when including scale variations?

NLO effects on a CLs

[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

✦ There are theoretical uncertainties on a CLs number



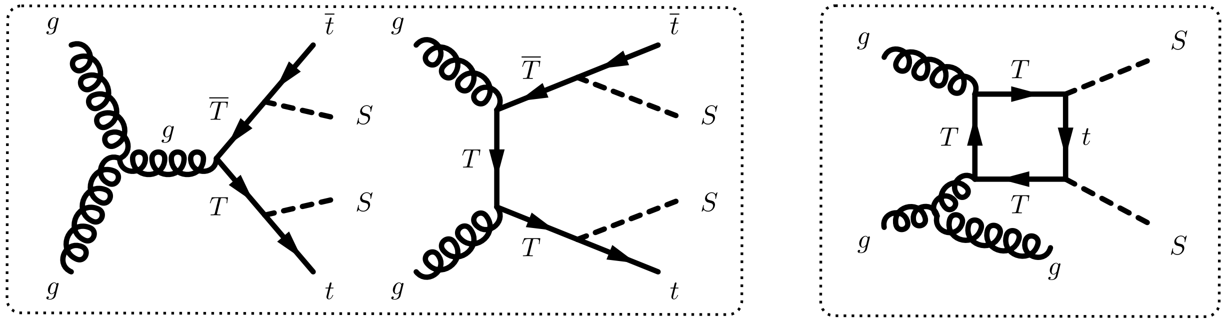
	(m_Y, m_X)	$\sigma_{\rm LO}$ [pb]	$\rm CL_{LO}$ [%]	$\sigma_{\rm NLO}$ [pb]	$\rm CL_{NLO}$ [%]
I	(150, 25) GeV	$0.658^{+34.9\%}_{-24.0\%}$	$98.7^{+0.8\%}_{-13.0\%}$	$0.773^{+6.1\%}_{-10.1\%}$	$95.0^{+2.7\%}_{-0.4\%}$
II	(40, 30) GeV	$0.776^{+34.2\%}_{-24.1\%}$	$74.7^{+19.7\%}_{-17.7\%}$	$0.926^{+5.7\%}_{-10.4\%}$	$84.2^{+0.4\%}_{-14.4\%}$
III	(240, 100) GeV	$0.187^{+37.1\%}_{-24.4\%}$	$91.6^{+6.4\%}_{-18.1\%}$	$0.216^{+6.7\%}_{-11.4\%}$	$86.5^{+8.6\%}_{-5.5\%}$

- ✤ An excluded point may not be excluded when accounting for uncertainties
- ✤ The CLs number can increase / decrease at NLO
- ✤ The error band is reduced

Dark matter searches at colliders

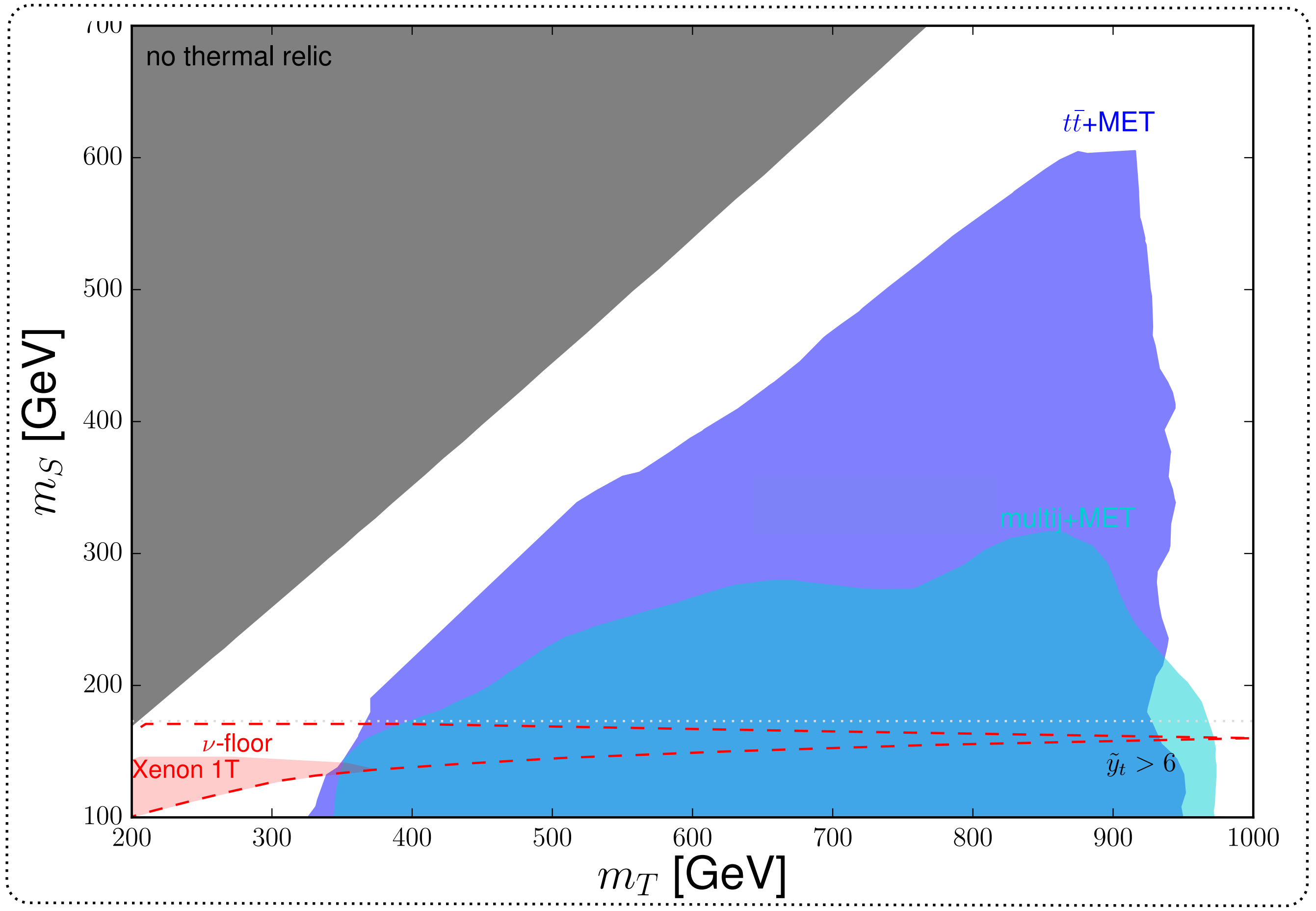
[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

✦ Two main constraining modes at the LHC: monojet and top-antitop plus MET



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

✤ The top-antitop mode is also constrained in the low scalar mass region by LEP



✤ 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

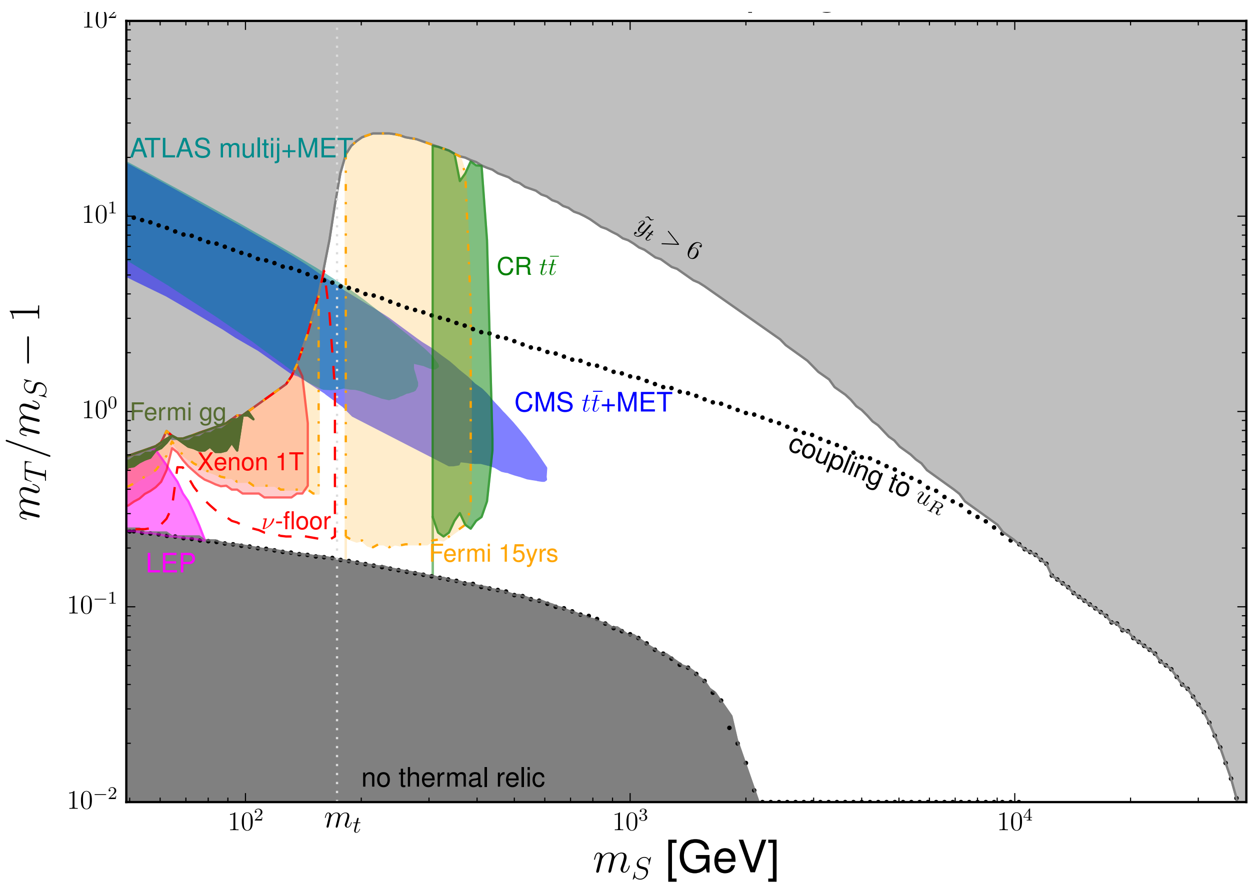
★ Best constraints (and chance of discovery)

Outline

Top-philic dark scalar matter with a VL mediator

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

✦ Collider-cosmology complementarily at work



✤ **DM indirect detection constraints**

★ Exclude (will rule out) limited light DM regions

✤ **Colliders** (present and future)

★ Sole probes to tackle the unconstrained regions

✤ **Lagrangian**

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

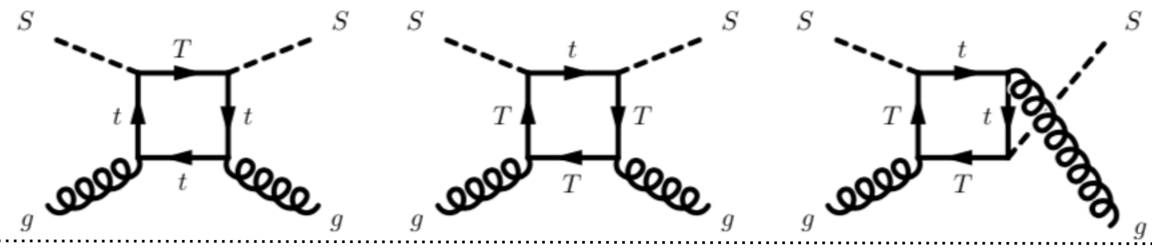
★ Vector like mediator *T*
★ Scalar dark matter *S*

✤ **Relic-density favored regions exist**

★ 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



Third-generation-philic dark matter

[Banerjee, Barducci, Bélanger, BF, Goudelis & Zaldivar (JHEP`17)]

✦ A simplified model for 3rd generation-philic dark matter

- A gauge singlet dark sector with a fermionic dark matter candidate χ
- A gauge singlet pseudoscalar mediator A linking the dark and SM sectors

$$\mathcal{L} = \mathcal{L}_{\rm kin} - i\frac{y_\chi}{2} A\bar{\chi}\gamma_5\chi - i\sum_{f_u} c_u \frac{m_{f_u}}{v} A\bar{f}_u\gamma_5 f_u - i\sum_{f_d} c_d \frac{m_{f_d}}{v} A\bar{f}_d\gamma_5 f_d$$

★ Loop-induced couplings to gluons (mediator production)

✦ Cosmologically attractive

- Evasion of direct detection bounds

✦ Benchmark

- 2HDM-inspired with enhanced Yukawas and tanβ = 1:

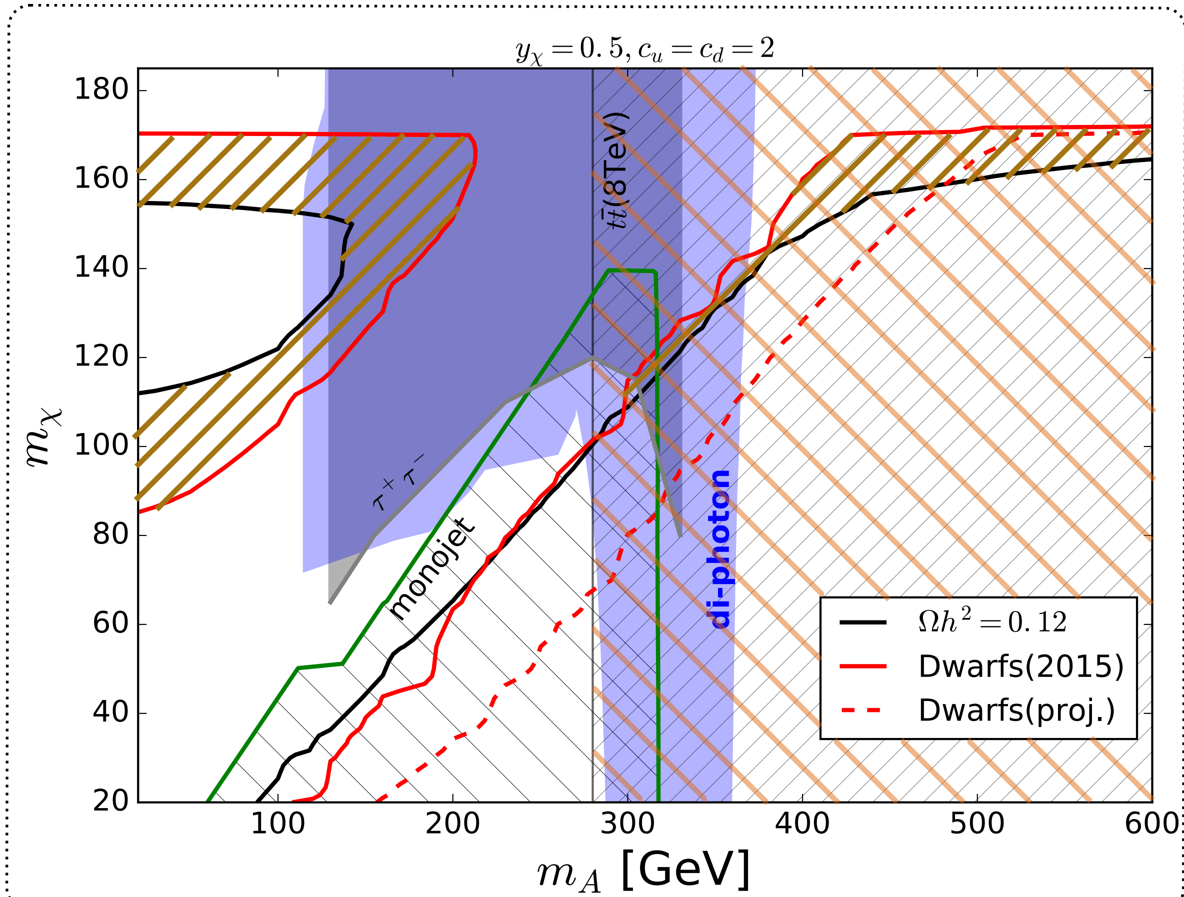
$$c_u = c_d = 2; y_\chi = 0.5$$

- Couplings that can reproduce cosmological data for weak scale masses

Top-philic dark matter with a pseudoscalar mediator

[Banerjee, Barducci, Bélanger, BF, Goudelis & Zaldivar (JHEP`17)]

✦ Current collider and cosmology data complementarily put the model into troubles



✤ Two regions favored by cosmology

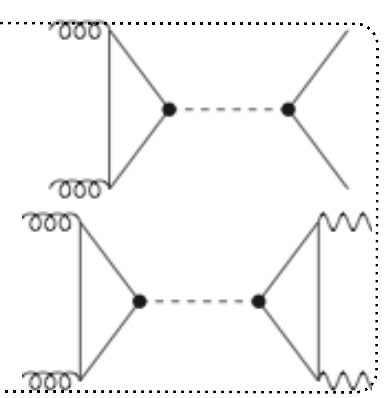
★ Light mediator (between red and black)
- Too light χ ➢ underabundant
- Too heavy χ ➢ underabundant ($t\bar{t}$ threshold)
- Same behavior for Fermi-LAT results, but shifted (present *vs* early universe time)

★ Heavier mediator (m_A > 200 GeV)
- Always some good combination of masses

✤ Diphoton and ditau

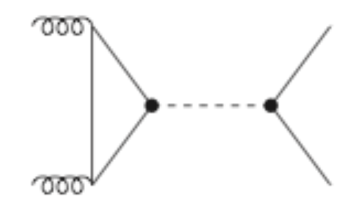
★ Driven by the BR behavior
- Invisible A decay
- $t\bar{t}$ effects (Γ_t and Γ_γ, Γ_g)

★ Sensitive to light mediators



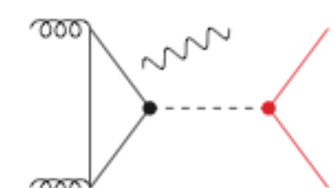
✤ Top-antitop exclusions (DM independent)

★ $t\bar{t}$ cross section (lighter A)
★ Resonance searches (heavy A)
★ 8 TeV still stronger than 13 TeV
★ $t\bar{t}$A (with A invisible, NLO) subleading



✤ Monojet and multijet + MET

★ Efficient if $m_A > 2\, m_\chi$
★ Efficient below the top threshold
★ The heavy mediator region is killed

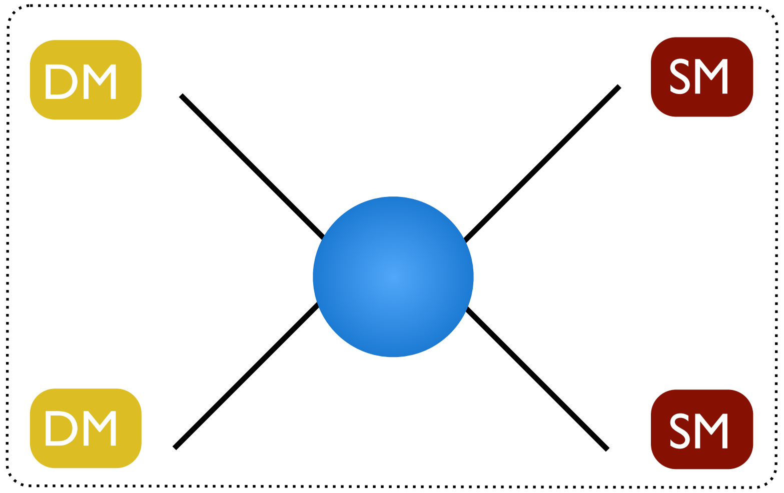


Outline

Summary

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

- Can be probed complementarily
  - ★ Relic density
  - ★ Direct detection
  - ★ Indirect detection
  - ★ Collider searches



✦ 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