A comprehensive approach to dark matter studies: exploration of simplified top-philic models

[C. Arina, M. Backović, E. Conte, B. Fuks, J. Guo, JH, B. Hespel, M. Krämer, F. Maltoni, A. Martini, K. Mawatari, M. Pellen, E. Vryonidou: **1605.09242**]

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HELMHOLTZ ASSOCIATION

DESY THEORY WORKSHOP
27 - 30 September 2016
DESY Hamburg, Germany

DESY

LHC goals: Find (WIMP) Dark Matter!

➔ Searches for missing energy

How to interprete Dark Matter searches?

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

August 8, 2016

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Ece Akilli *Université de Genève, DPNC, Switzerland*
Juan Alcaraz Maestre *Centro de Investigaciones Energéticas Medioambientales y*
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Ecole Normale Supérieure de Lyon, France and CERN Theory Division, Switzerla
Georges Azuelos *University of Montreal and TRIUMF, Canada*
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LHC Dark Matter Working Group:

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3] Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6] Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest,[8] Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1] Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*] Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17] Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*] Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21] Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22] Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*] Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]

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➔ Simplified Models of Dark Matter:
DM + *t*-channel or *s*-channel mediator

Simplified s-channel models for Dirac DM:

(assuming Minimal Flavor Violation [D'Ambrosio *et al.* 2002])

- Spin-1 mediator: [LHC DM WG: 1603.04156]

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q\,,$$

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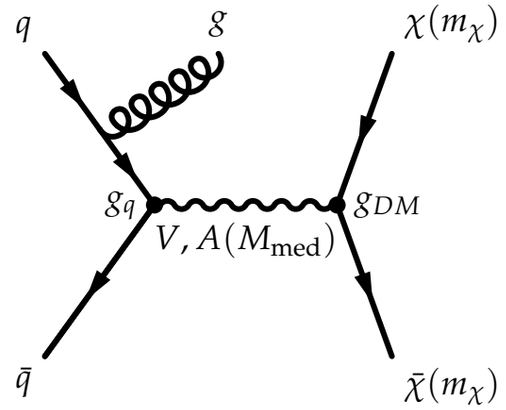

- Spin-0 mediator:

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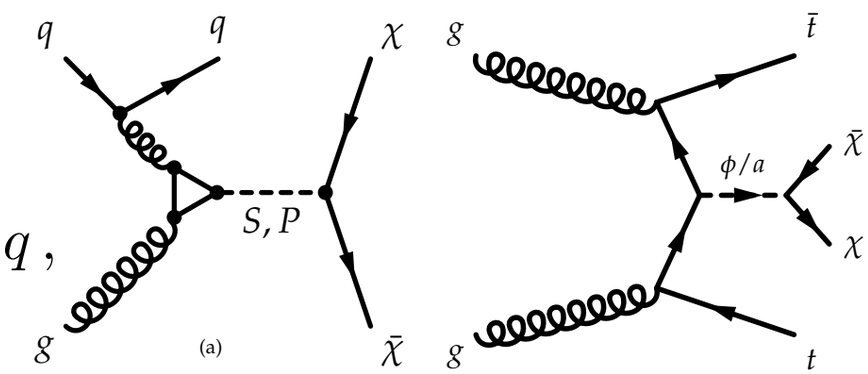

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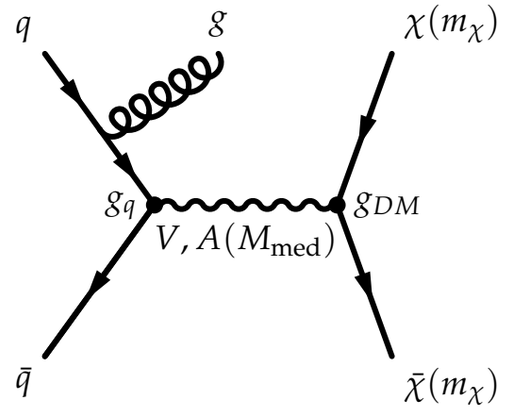

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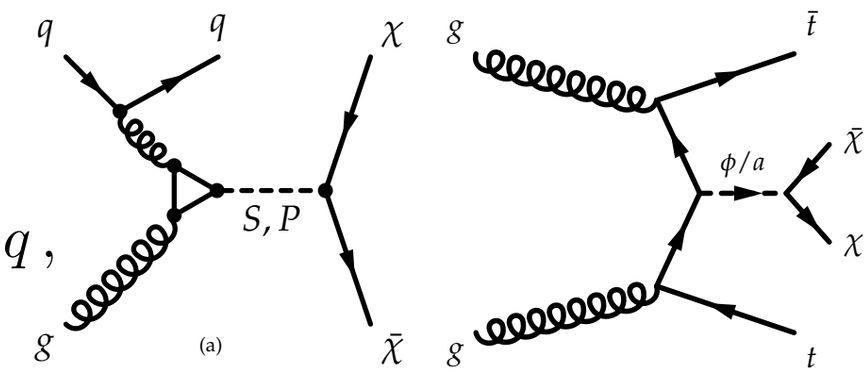

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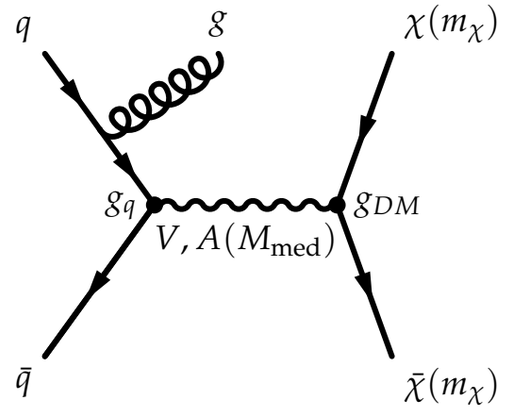

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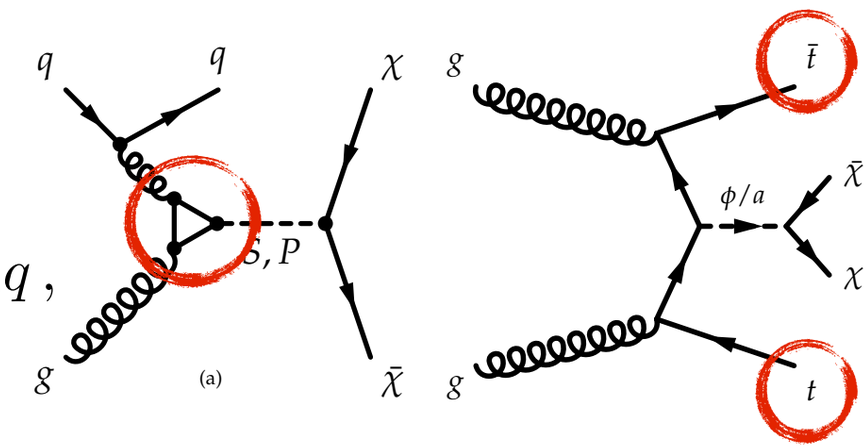

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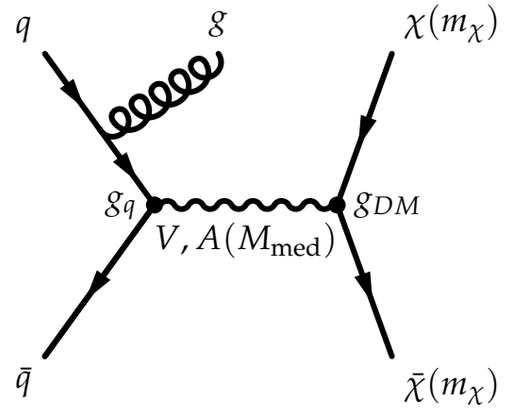

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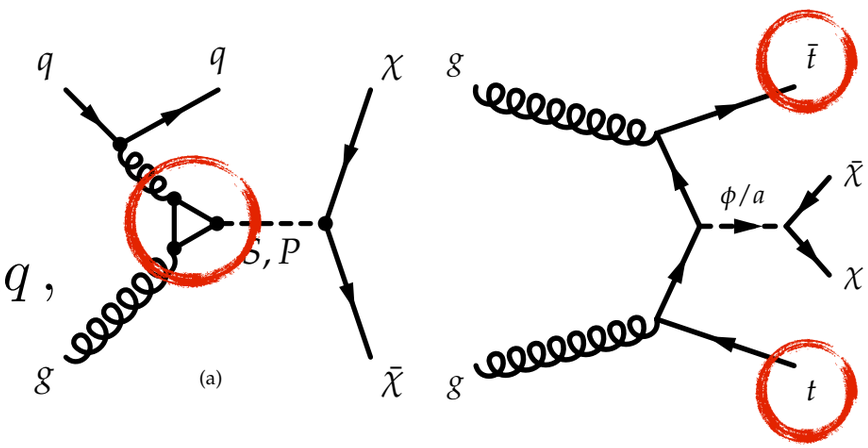

$m_t \gg m_q$ → Top-philic Dark Matter

[see also e.g. Buckley *et al.* '14; Haisch *et al.* '15; Harris *et al.* '14]

[DM Forum: 1507.00966]

Top-philic simplified DM model

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

Four free parameters: g_t, g_X, m_X, m_Y

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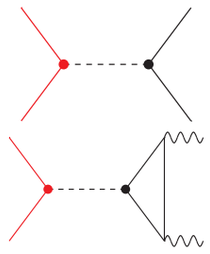
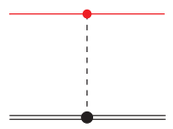
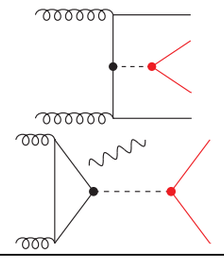
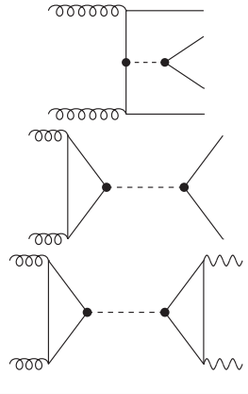
Four free parameters: $g_t,\ g_X,\ m_X,\ m_Y$

Arise from UV complete theories?

- Y_0 could be part of an SU(2) doublet
  → 2HDM with a large degree of alignment $\cos(\beta - \alpha) \sim 0$
  [see e.g. Craig *et al.* '13; Carena *et al.* '13]
- Y_0 SM singlet
  → Higgs-Portal model
  Additional phenomenological aspects
  [see e.g. Kim *et al.* '08; Baek *et al.* '11, '14; Lopez-Honorez *et al.* '12; Khoze *et al.* '15; Ko, *et al.* '16]

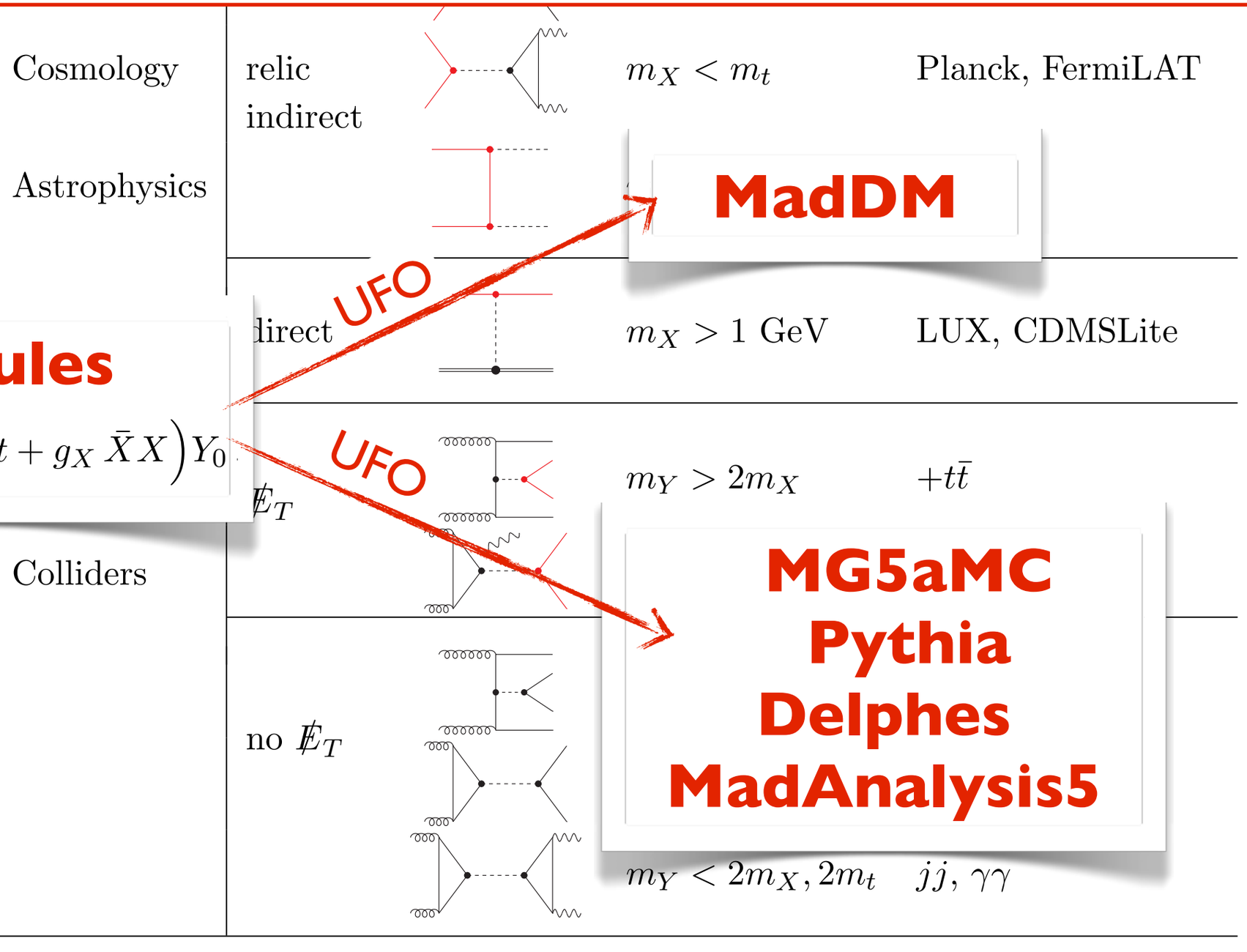
  ...

Plethora of signatures

Cosmology Astrophysics	relic indirect		$m_X > m_t$ $m_X < m_t$ $m_X > m_Y$	Planck, FermiLAT
	direct		$m_X > 1$ GeV	LUX, CDMSLite
Colliders	$\not{E}_T$		$m_Y > 2m_X$ $m_Y > 2m_X$	$+t\bar{t}$ $+j,\ +Z,\ +h$
	no $\not{E}_T$		$m_Y > 2m_t$ $m_Y > 2m_t$ $m_Y < 2m_X, 2m_t$	$4t$ $t\bar{t}$ $jj,\ \gamma\gamma$

Plethora of signatures ➔ one framework:

This work: comprehensive study



How to scan over the parameter space?

- Recommendation for LHC results:
  Show m_{med}-m_{DM} plane, slices in two couplings
  [LHC DM WG: 1603.04156]
- Other choices: consider width and product of couplings
  [see e.g. Harris *et al.* '15; Heisig *et al.* '16]

Here:

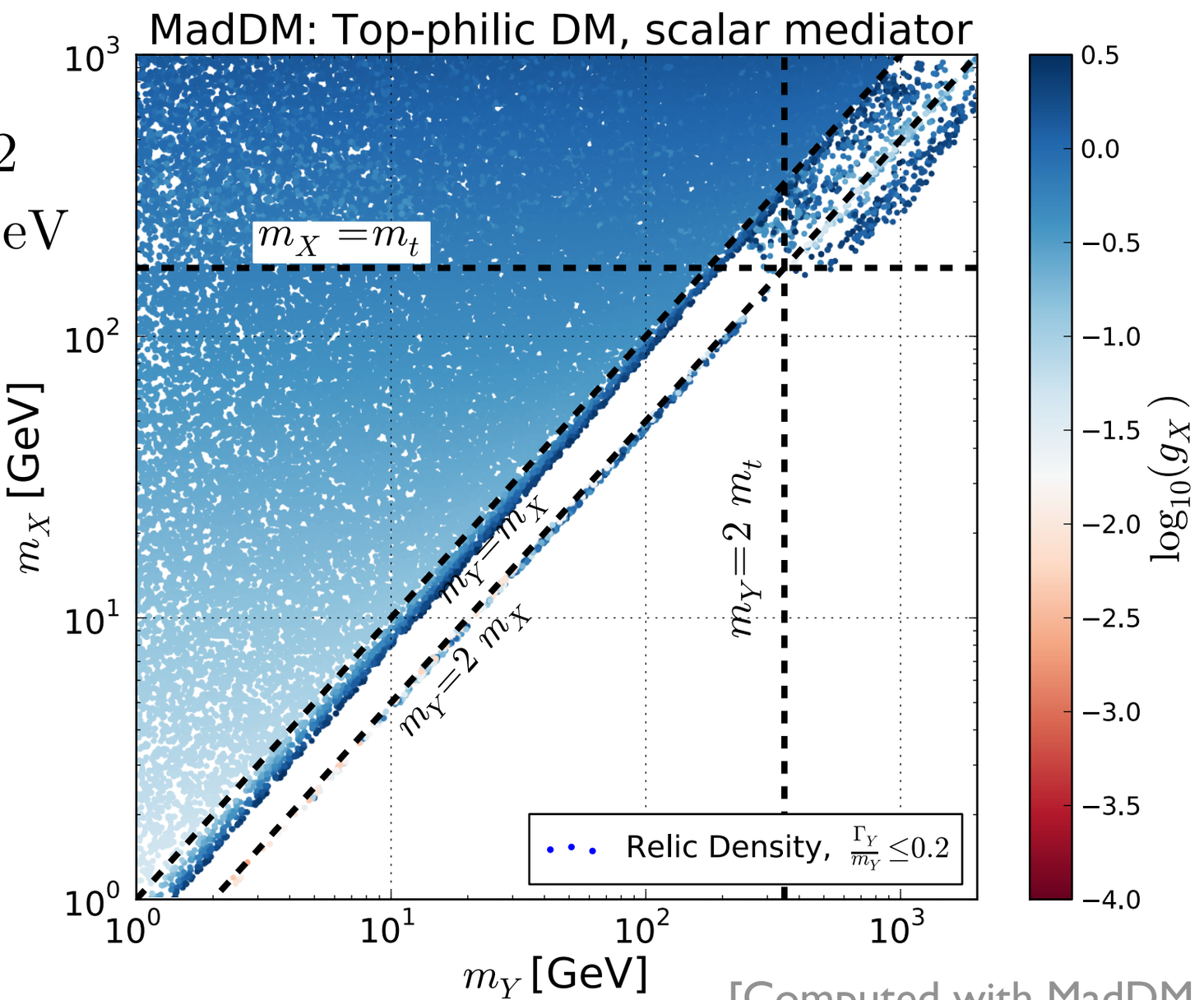
- Vary all four parameters scanned with MultiNest (nested sampling algorithm) [Feroz *et al.* '13]
- Fitting DM relic density constraints [Planck collaboration '15] (freeze-out within model and standard thermal history)
- Present various projections

MultiNest parameter	Prior
$\log(m_X/\ \mathrm{GeV})$	$0 \to 3$
$\log(m_Y/\ \mathrm{GeV})$	$0 \to 3.7$
$\log(g_X)$	$-4 \to \log(\pi)$
$\log(g_t)$	$-4 \to \log(\pi)$

Relic density constraints

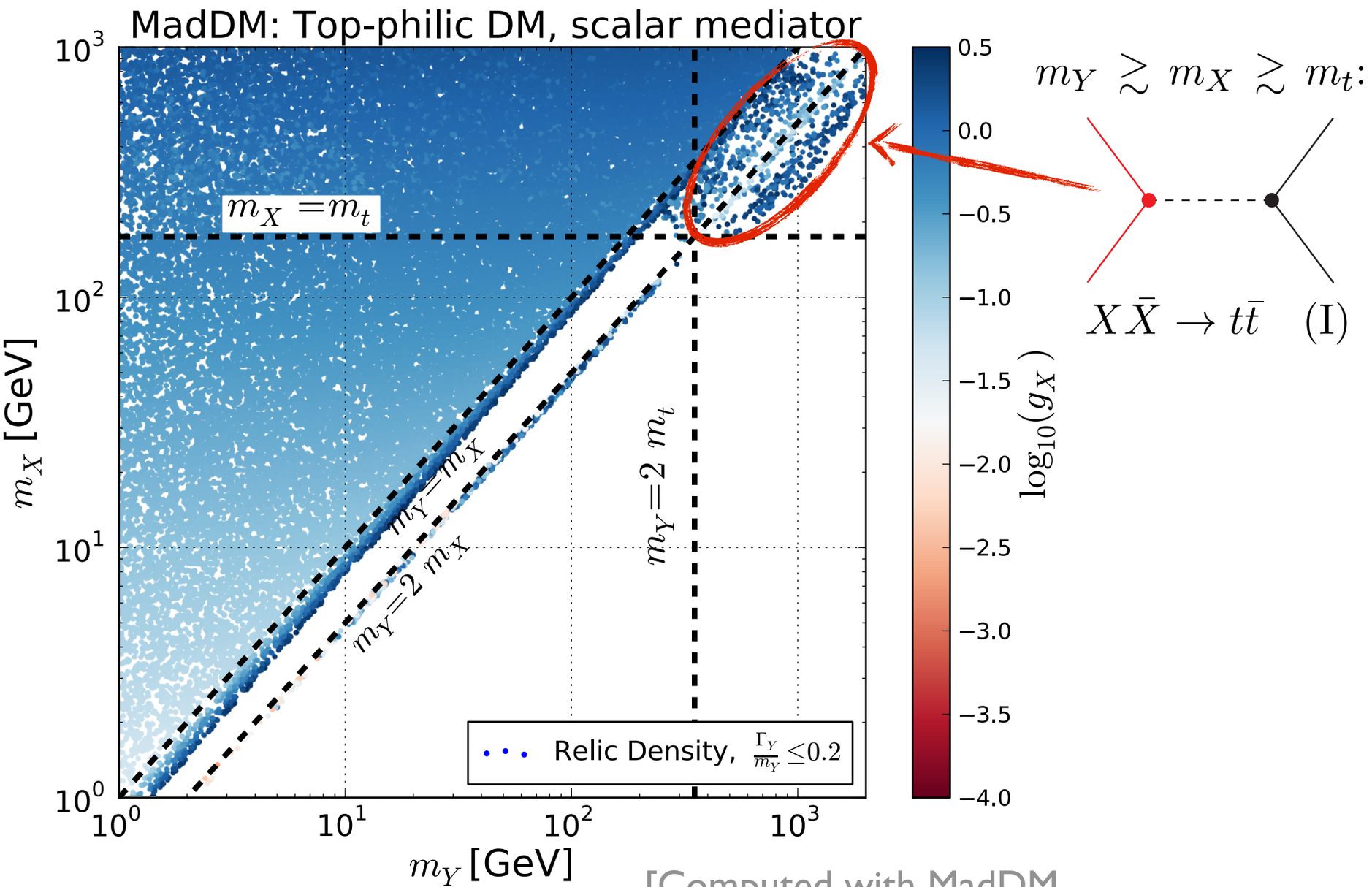
$\Gamma_Y / m_Y < 0.2$

$\Gamma_Y > 10^{-11}\,\mathrm{GeV}$



[Computed with MadDM, checked with mircOMEGAs]

Relic density constraints



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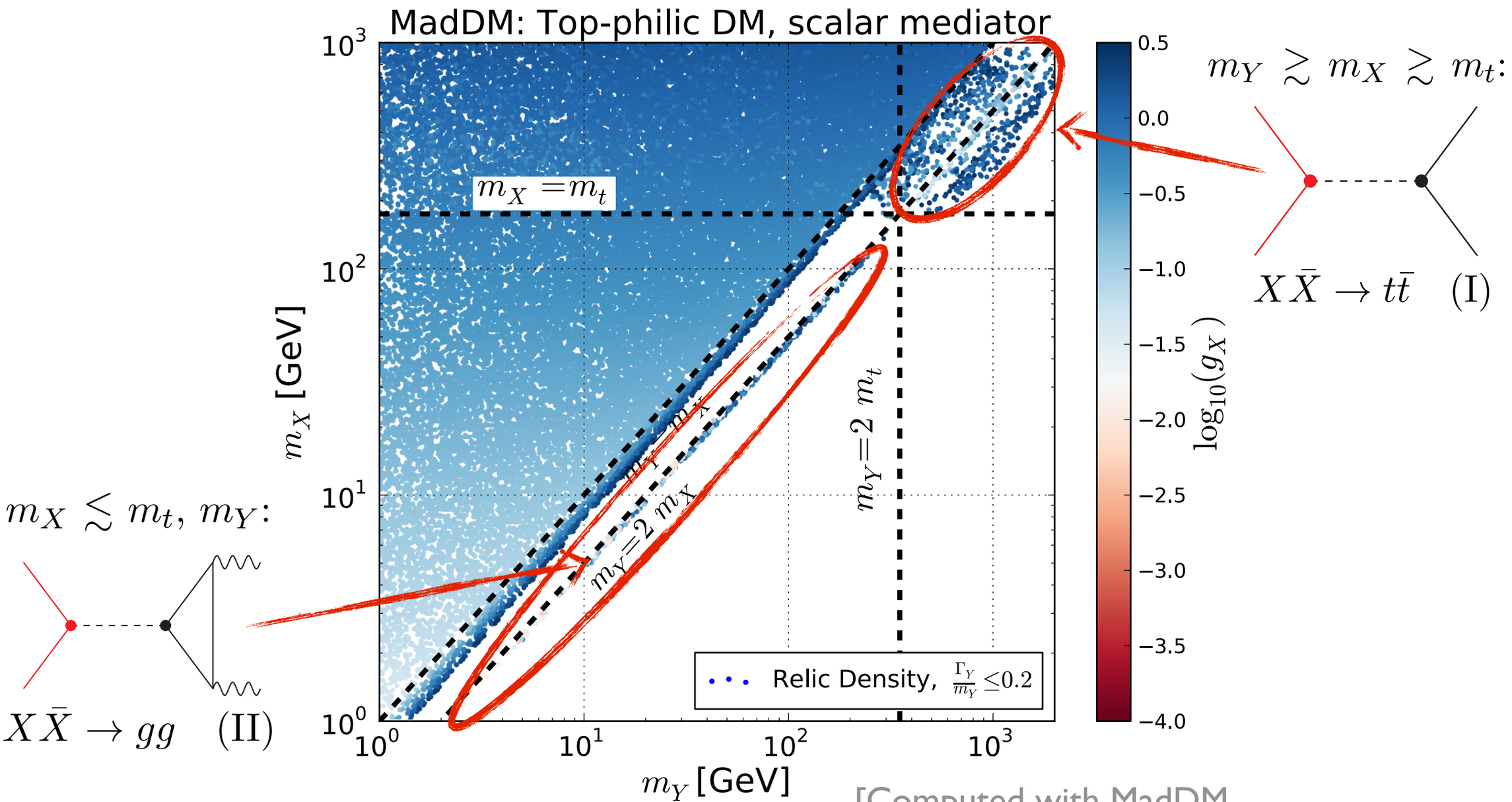

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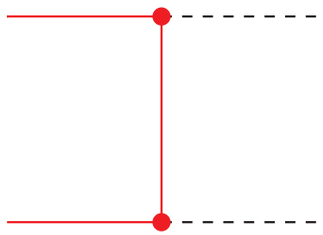
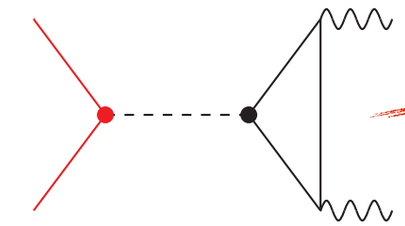
Relic density constraints

$m_X \gtrsim m_Y$:

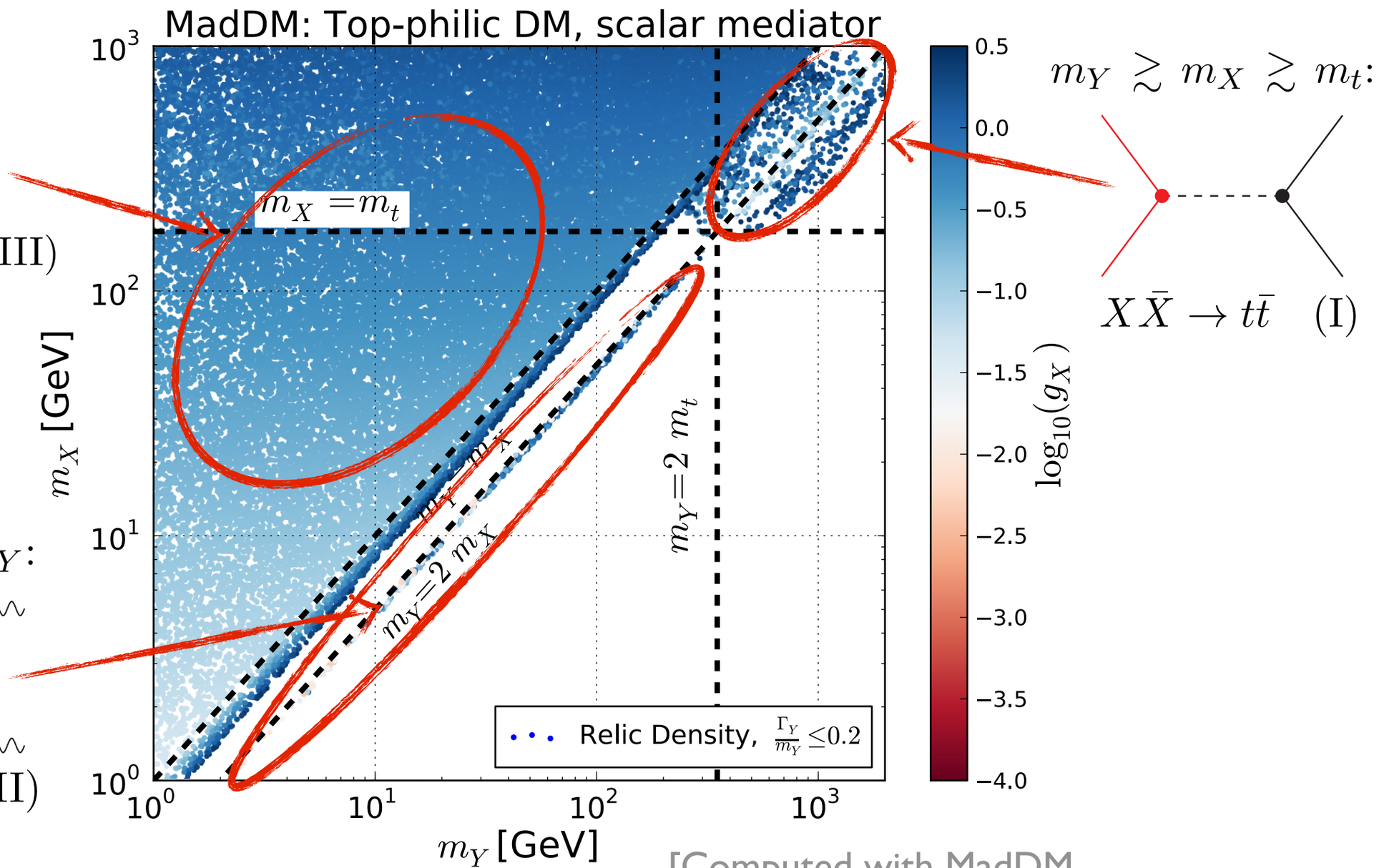


$X\bar{X} \to Y_0 Y_0$ (III)

$m_X \lesssim m_t$, m_Y:



$X\bar{X} \to gg$ (II)



$m_Y \gtrsim m_X \gtrsim m_t$:

$X\bar{X} \to t\bar{t}$ (I)

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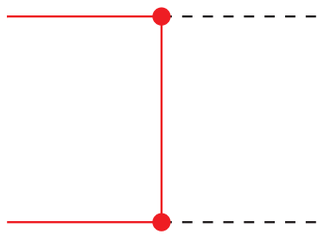

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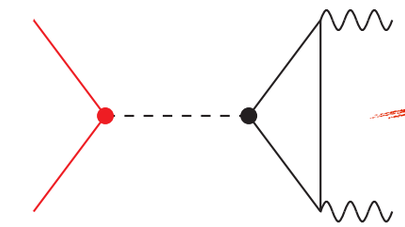

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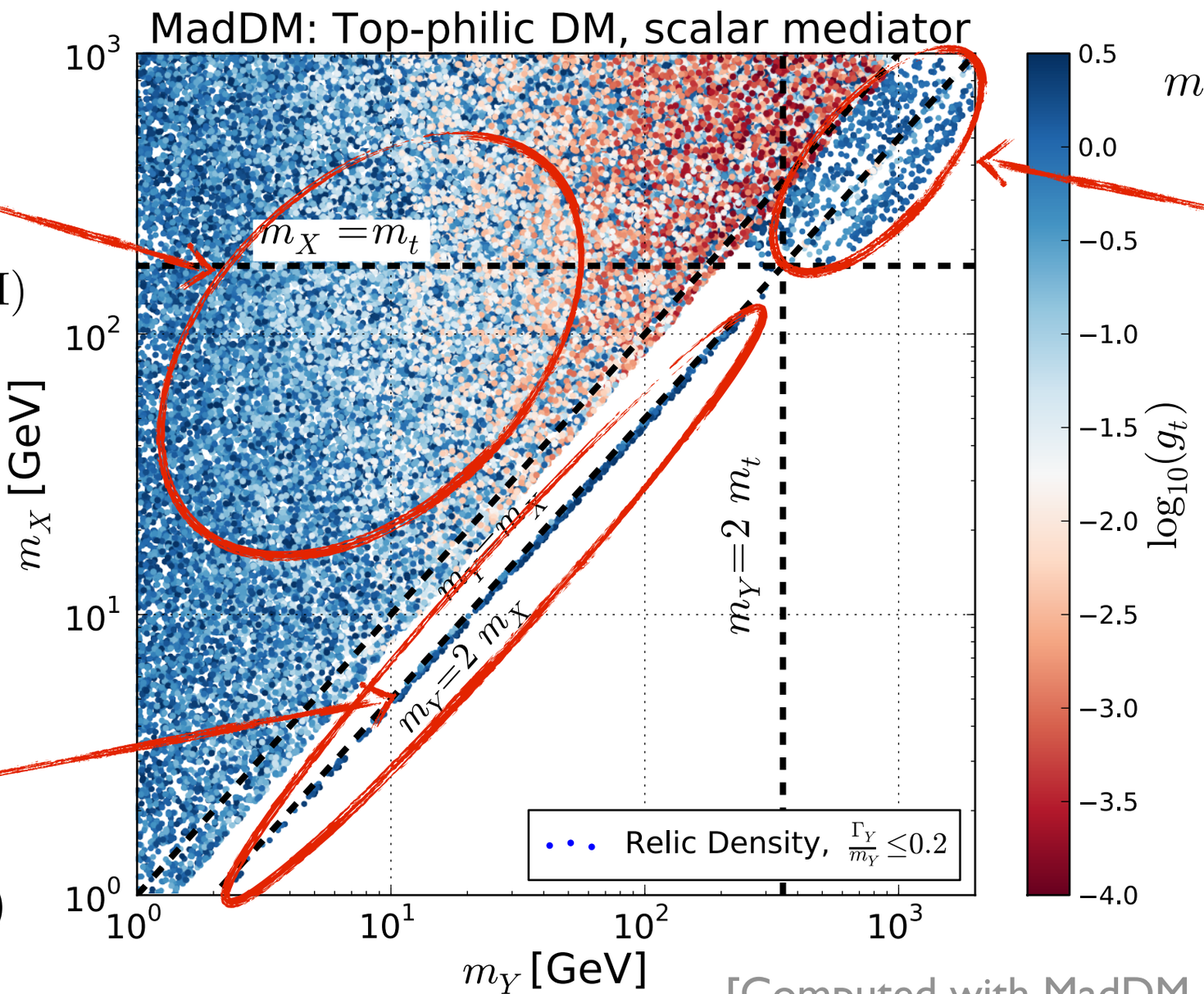

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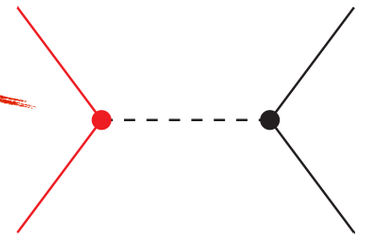

$X\bar{X} \to t\bar{t}$ (I)

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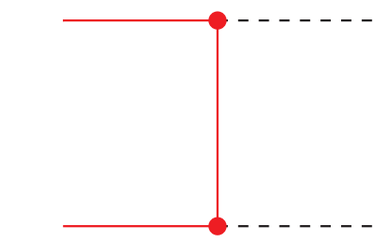

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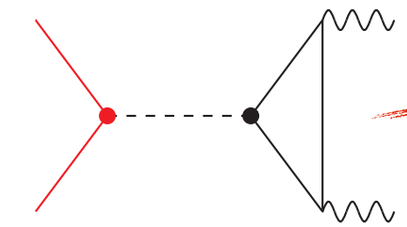

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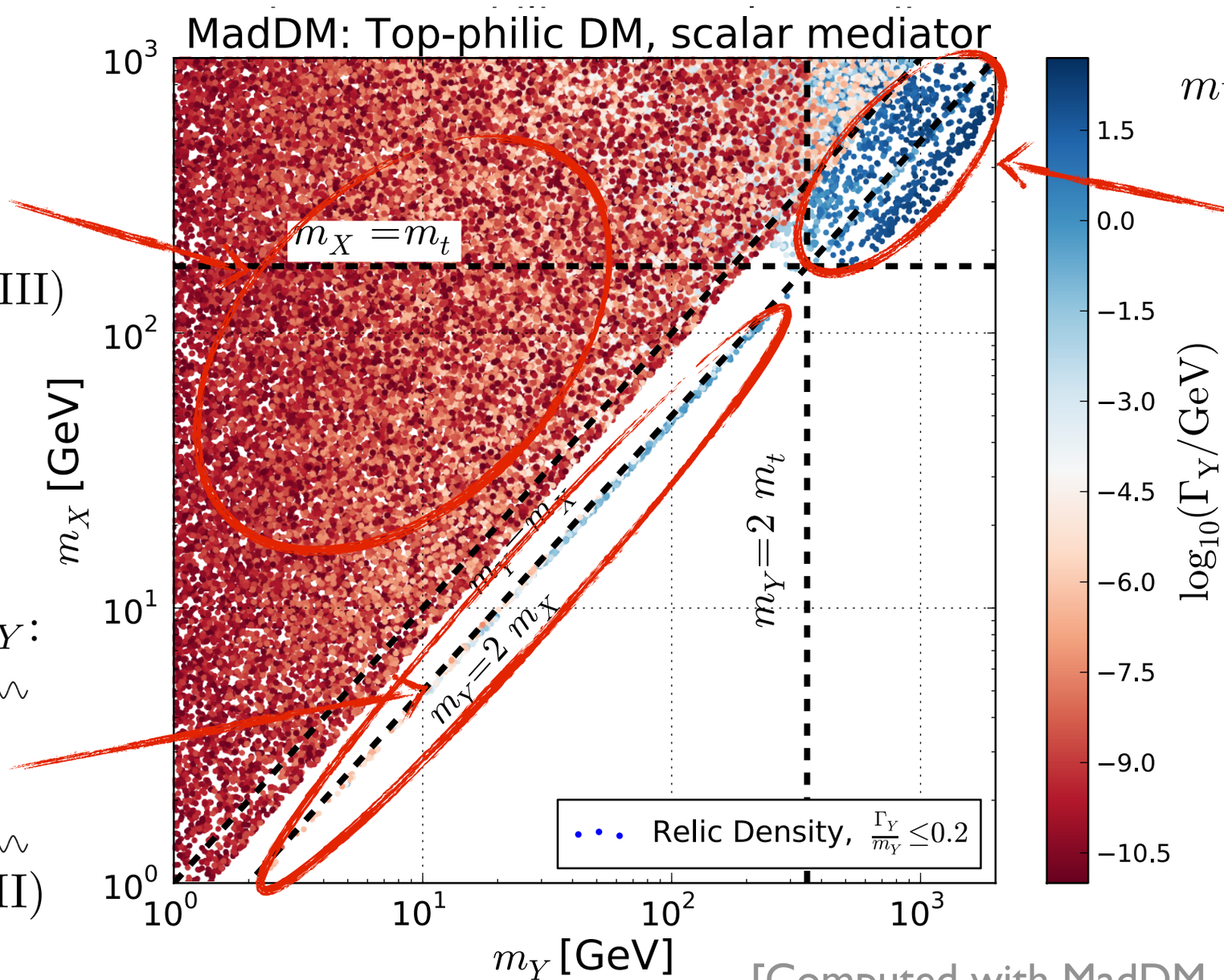

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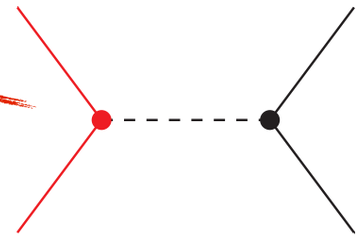

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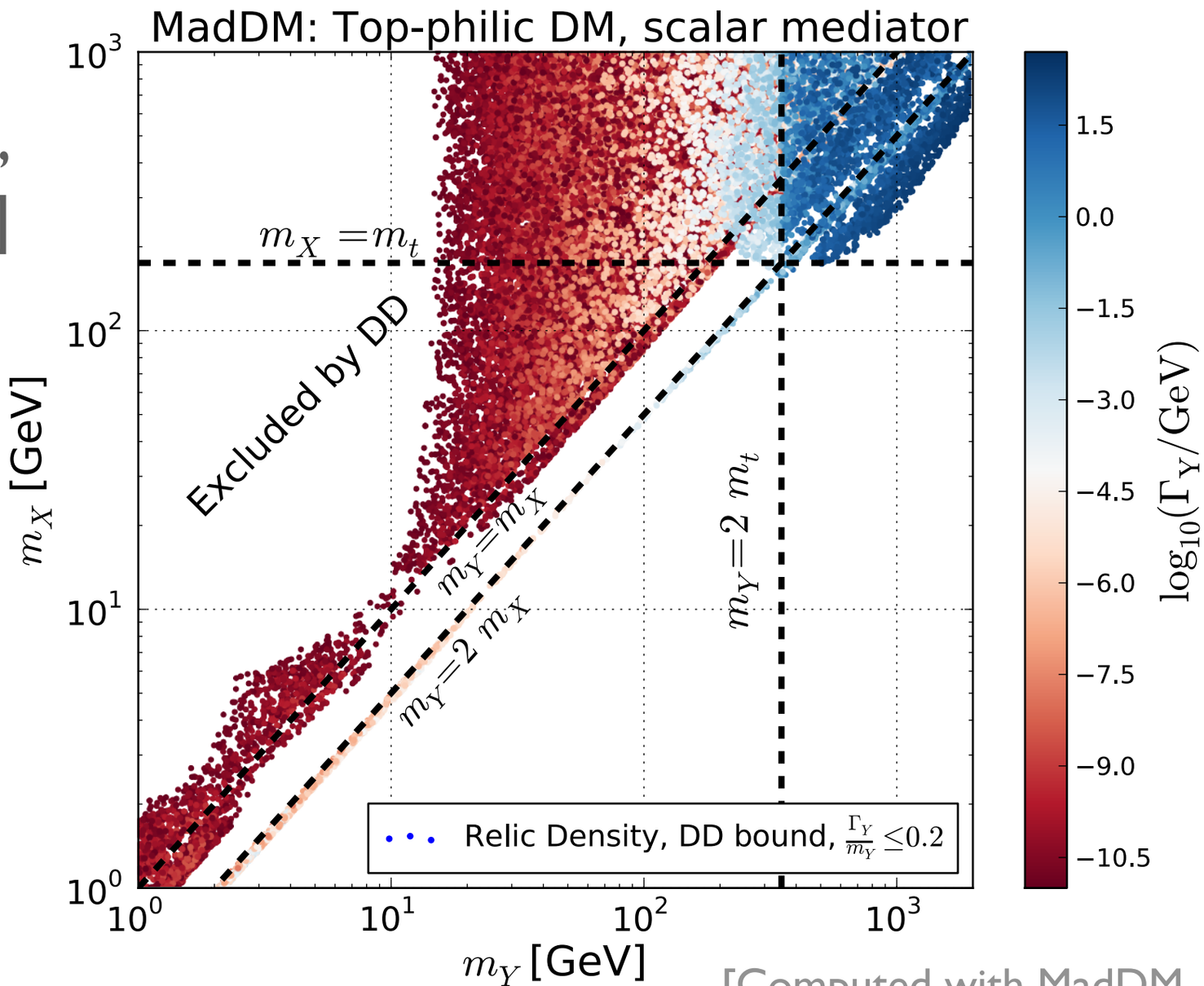
Direct detection bounds

[CDMSlite, LUX 2013]



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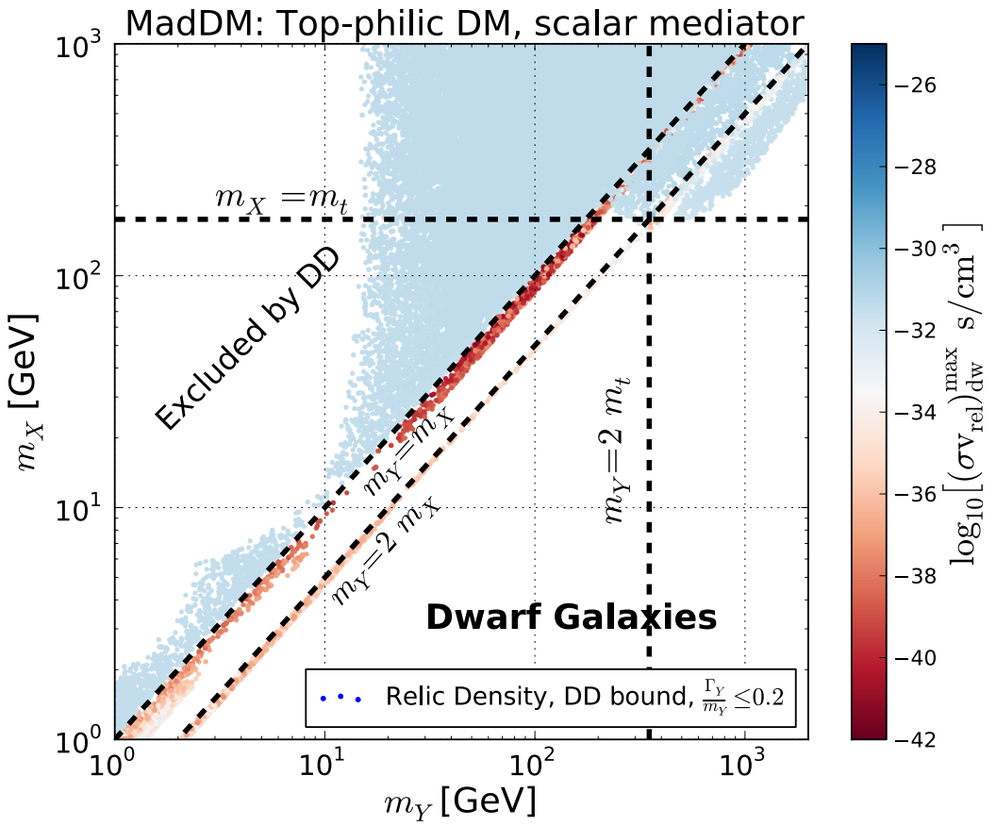
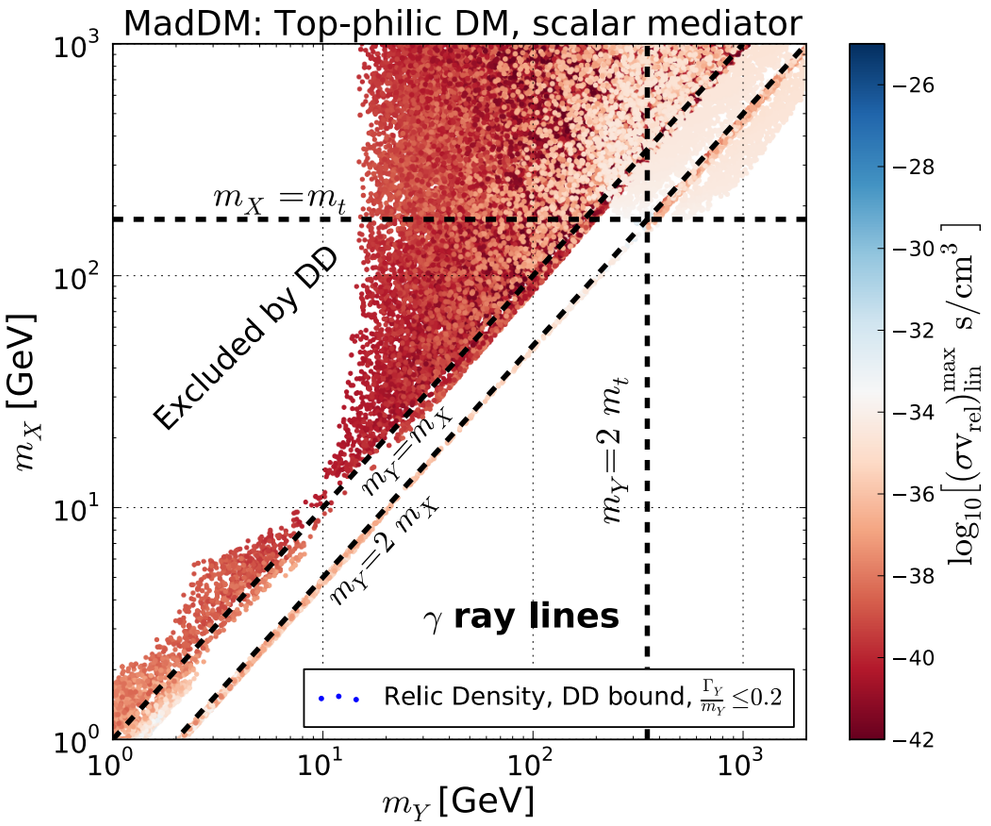
Indirect detection bounds

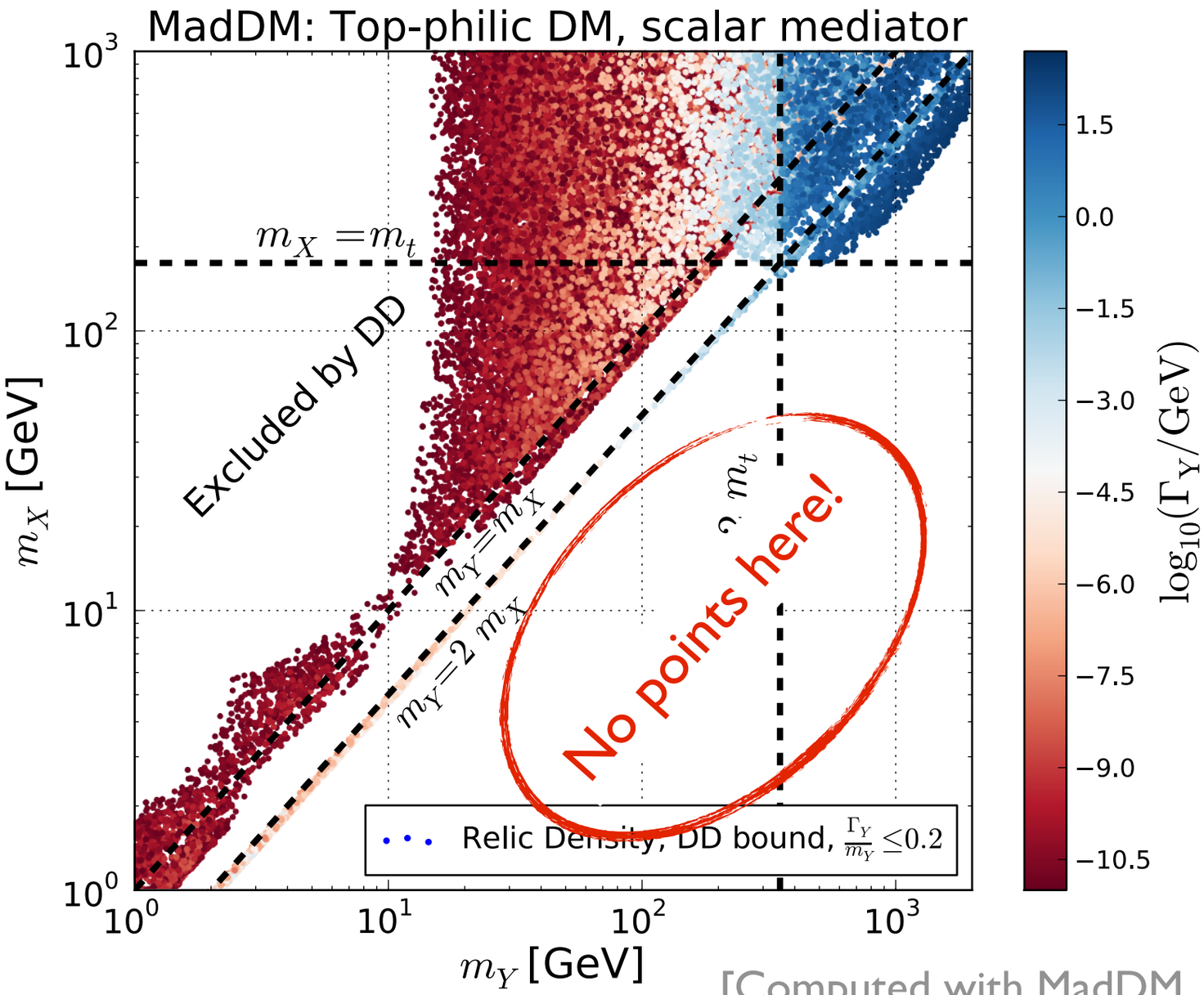
[*Fermi*-LAT 2015]





- *p*-wave suppression for all annihilation processes for scalar mediator
- For pseudo-scalar mediator only process (III) *p*-wave suppressed

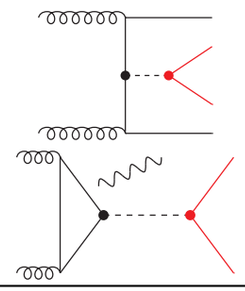
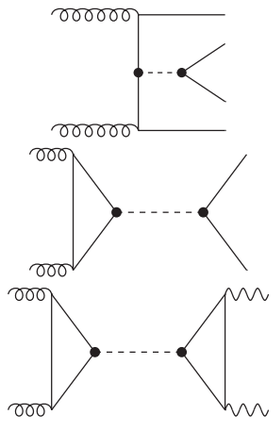
Cosmo & Astro constraints



[Computed with MadDM, checked with mircOMEGAs]

Collider searches

Collider searches

Colliders	$\not{E}_T$		$m_Y > 2m_X$	$+t\bar{t}$
			$m_Y > 2m_X$	$+j,\ +Z,\ +h$
	no $\not{E}_T$		$m_Y > 2m_t$	$4t$
			$m_Y > 2m_t$	$t\bar{t}$
			$m_Y < 2m_X, 2m_t$	$jj,\ \gamma\gamma$

Final state	Imposed constraint	Reference	Comments
$\not{E}_T + t\bar{t}$	MadAnalysis5 PAD (new)	CMS [1504.03198]	Semileptonic top-antitop decay
$\not{E}_T + j$	MadAnalysis5 PAD (new)	CMS [1408.3583]	
$\not{E}_T + Z$	$\sigma(\not{E}_T > 150\ \text{GeV}) < 0.85\,\text{fb}$	CMS [1511.09375]	Leptonic Z-boson decay
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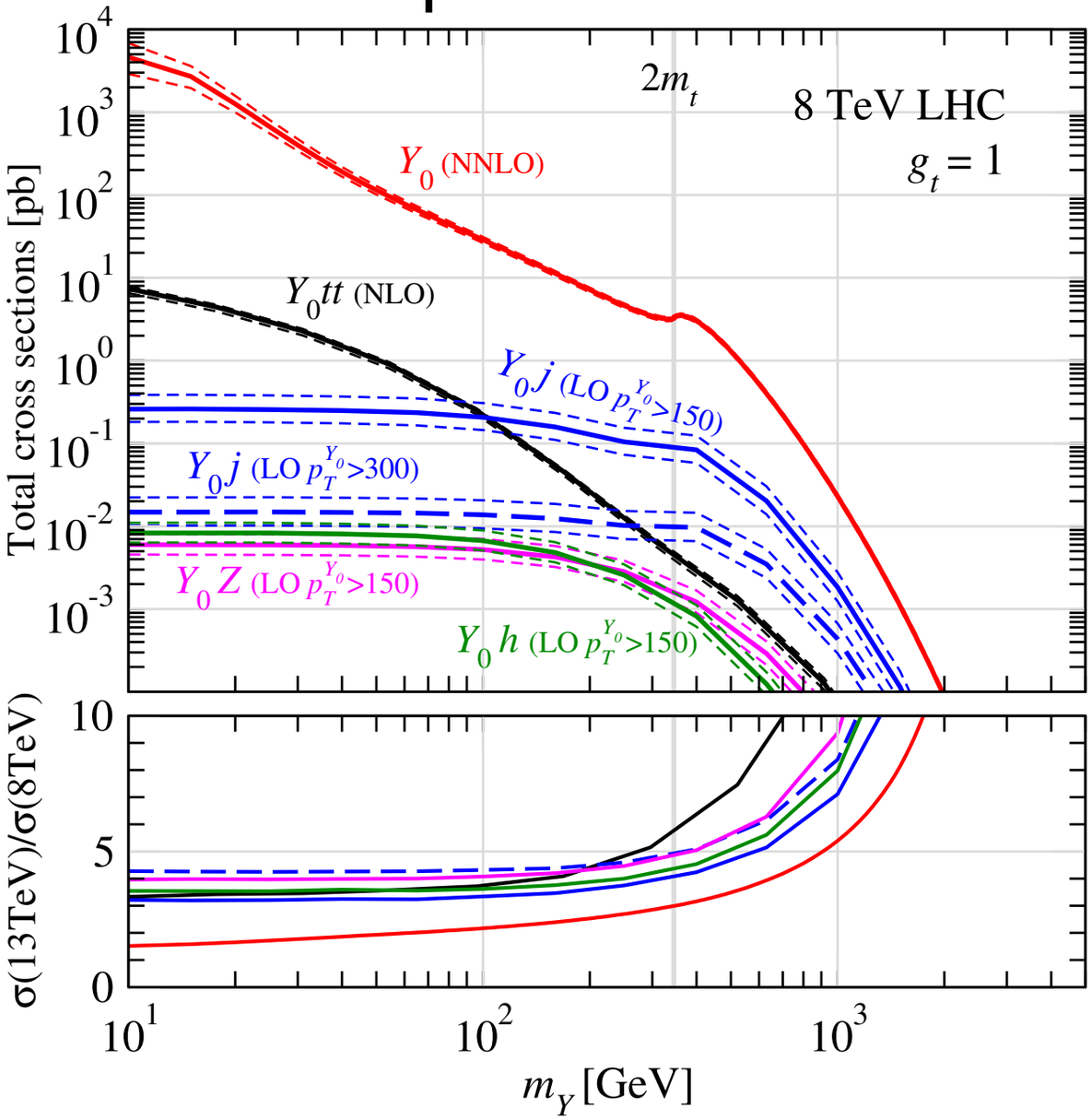
$\gamma\gamma$	$\sigma(m_Y = 150\ \text{GeV}) < 30\,\text{fb}$	CMS [1506.02301]	Only when $m_Y > 150\,\text{GeV}$
$t\bar{t}$	$\sigma(m_Y = 400\ \text{GeV}) < 3\,\text{pb}$	ATLAS [1505.07018]	Only when $m_Y > 400\,\text{GeV}$
$t\bar{t}t\bar{t}$	$\sigma < 32\,\text{fb}$	CMS [1409.7339]	Upper limit on the SM cross section

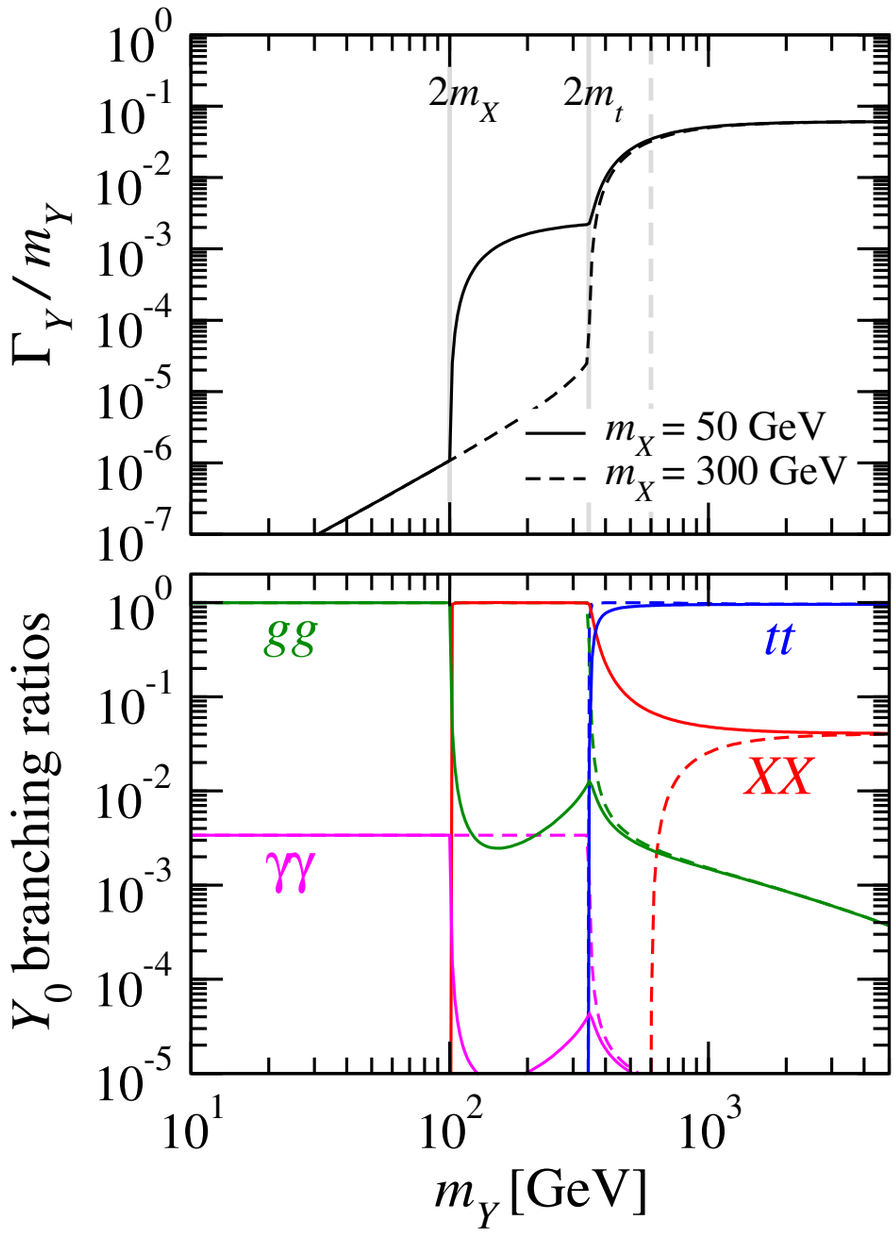
Collider searches

Mediator production



MG5aMC, NNPDF @NLO/LO

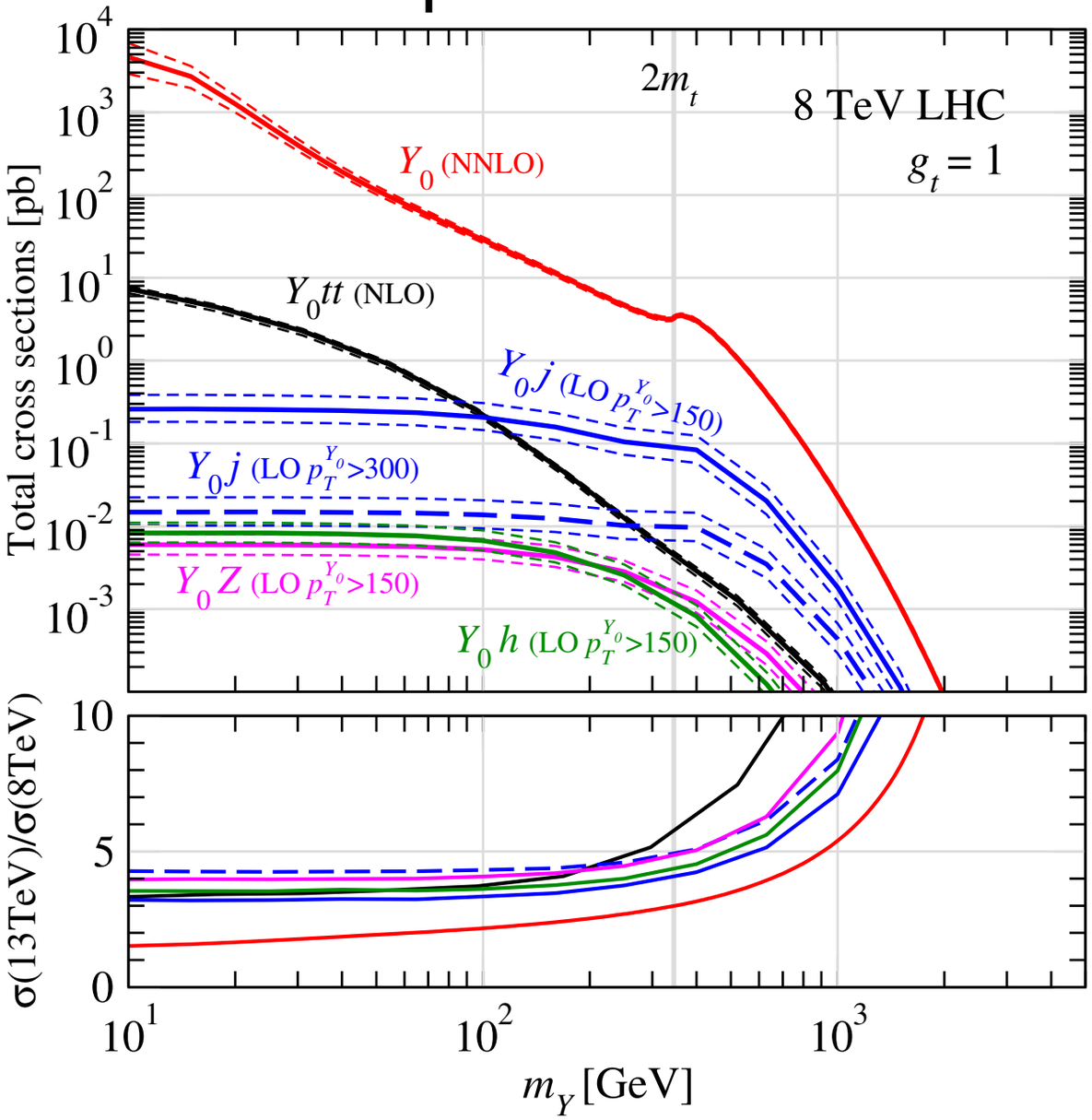
$(g_t, g_X) = (1, 0.25)$



$$\frac{\Gamma(Y_0 \to \gamma\gamma)}{\Gamma(Y_0 \to gg)} \sim \frac{8}{9}\frac{\alpha_e^2}{\alpha_s^2} \approx 10^{-3}$$

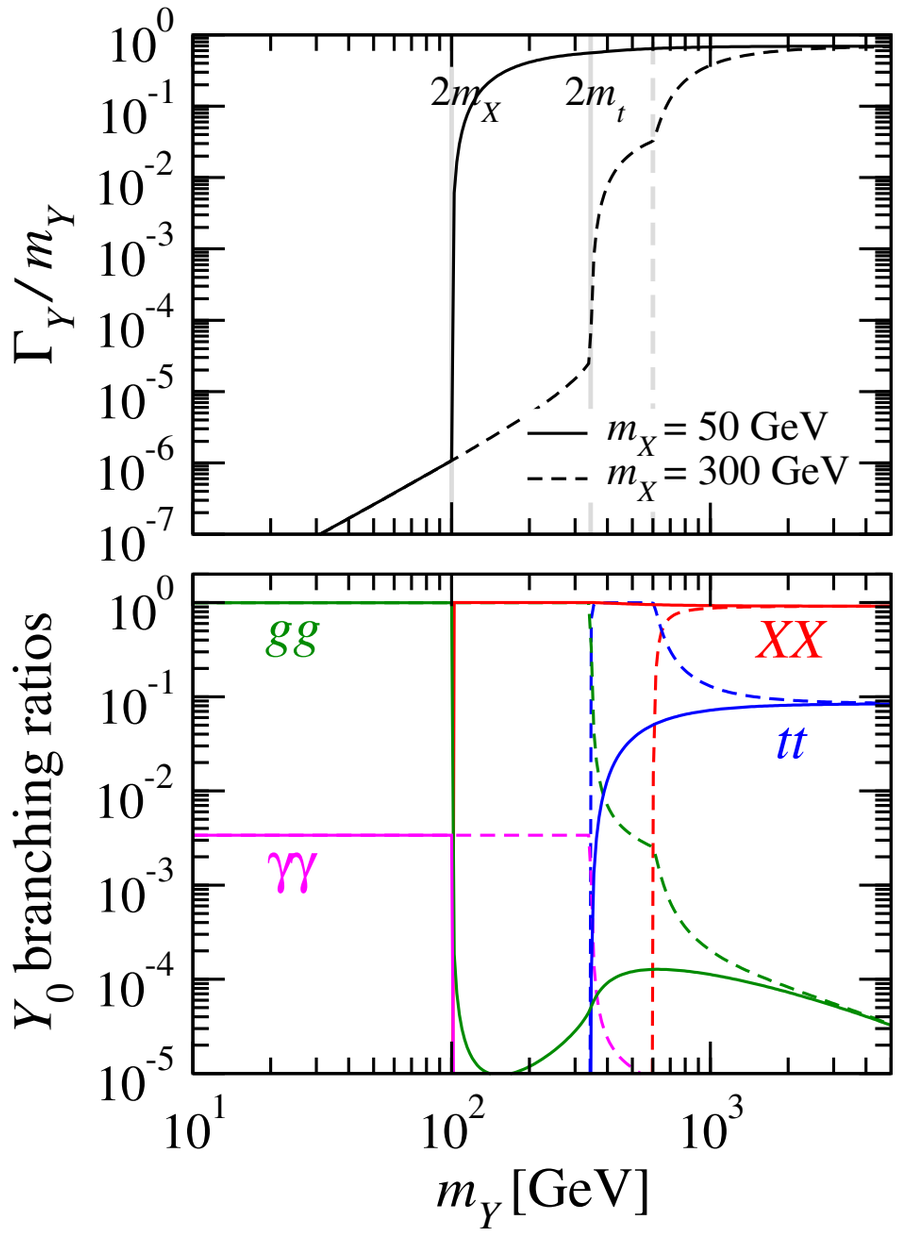
Collider searches

Mediator production



MG5aMC, NNPDF @NLO/LO

$(g_t, g_X) = (1, 4)$



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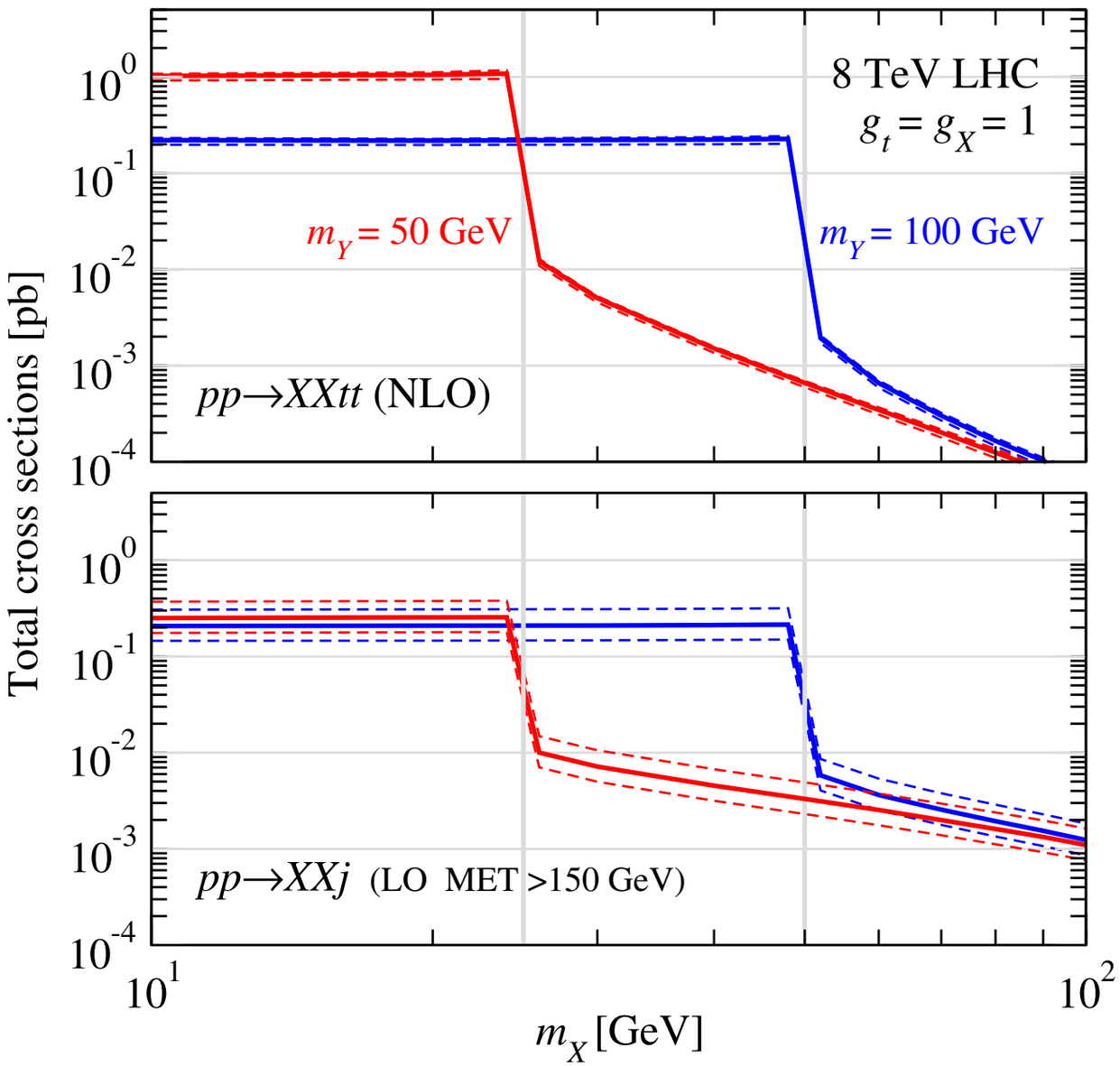
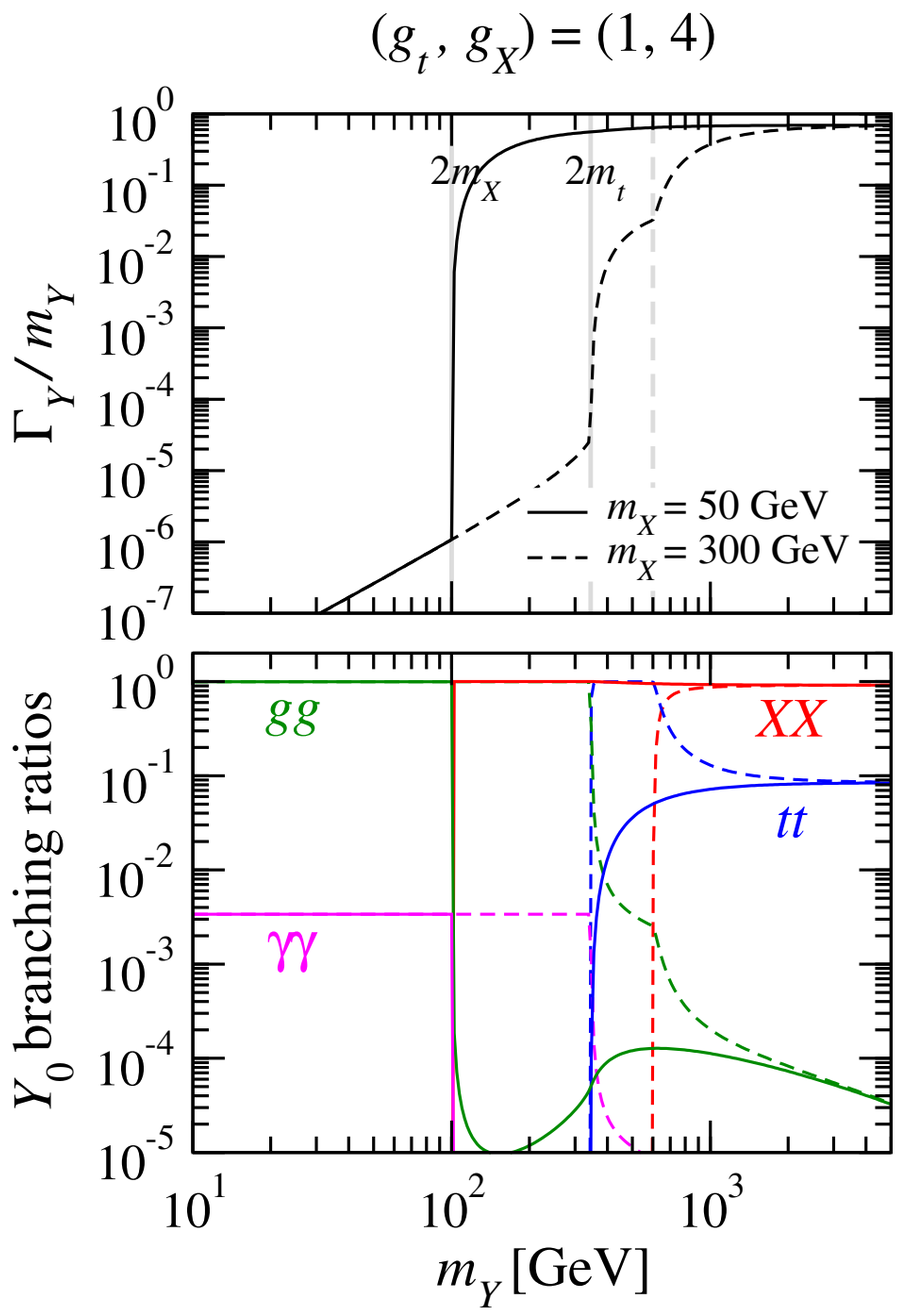
Collider searches

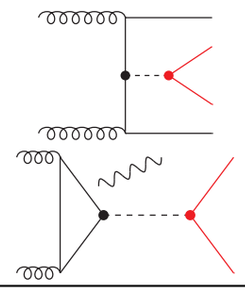
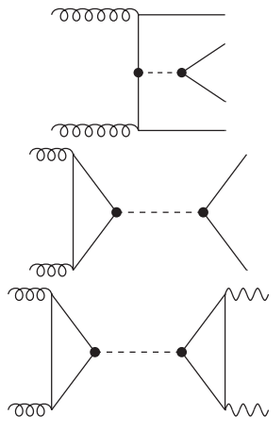
Dark Matter production





MG5aMC, NNPDF @NLO/LO

Collider searches

Colliders	$\not{E}_T$		$m_Y > 2m_X$	$+t\bar{t}$
			$m_Y > 2m_X$	$+j,\ +Z,\ +h$
	no $\not{E}_T$		$m_Y > 2m_t$	$4t$
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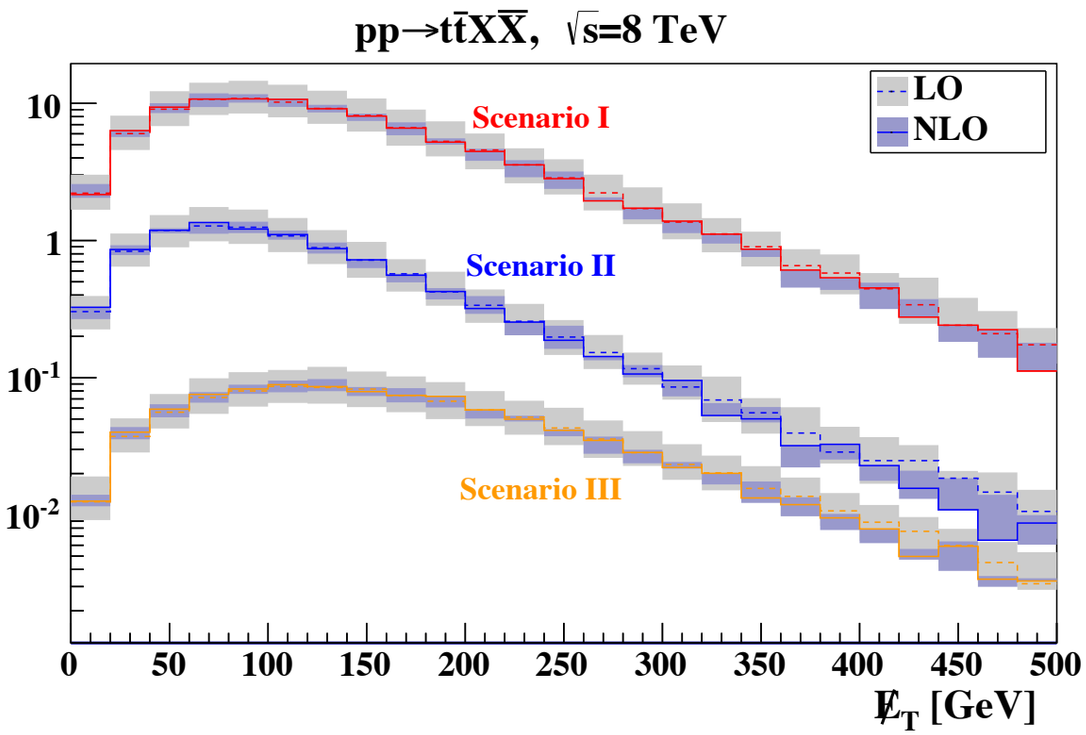
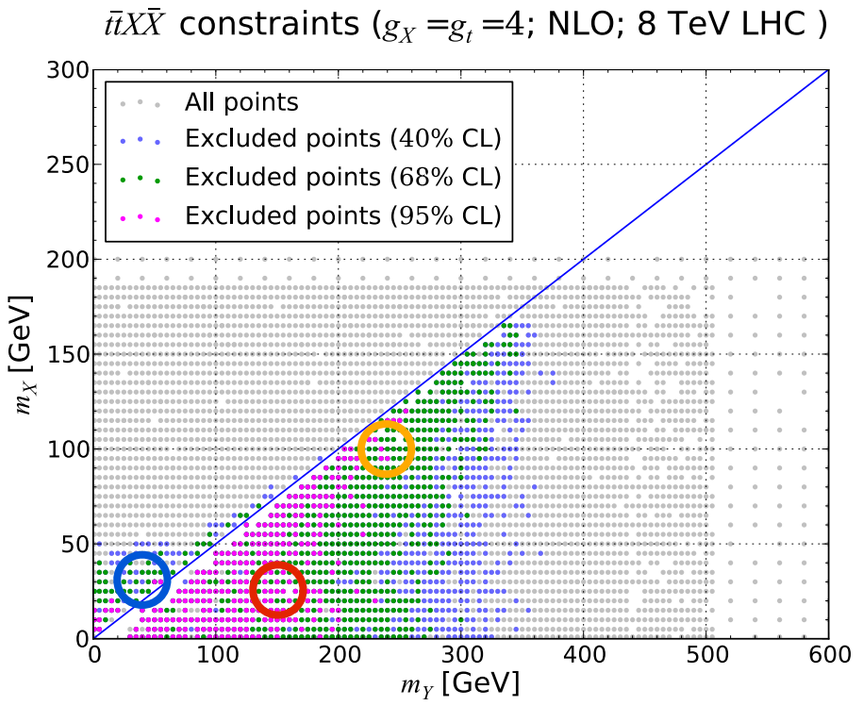
$t\bar{t}t\bar{t}$	$\sigma < 32\,\text{fb}$	CMS [1409.7339]	Upper limit on the SM cross section

MET searches

MET+top-quark pair (NLO)

- Recasting of CMS 1504.03198 *tt*+MET(semi-leptonic) in MA5
- 3 benchmark scenarios: moderate *K*-factor, reduced scale uncertainies

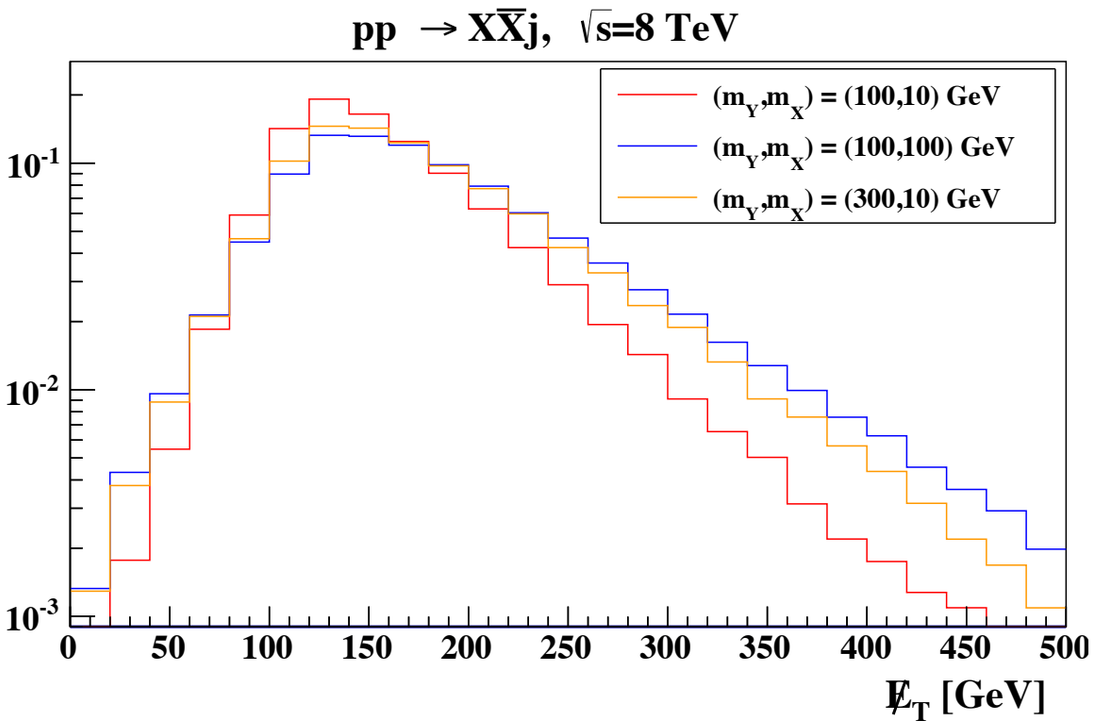


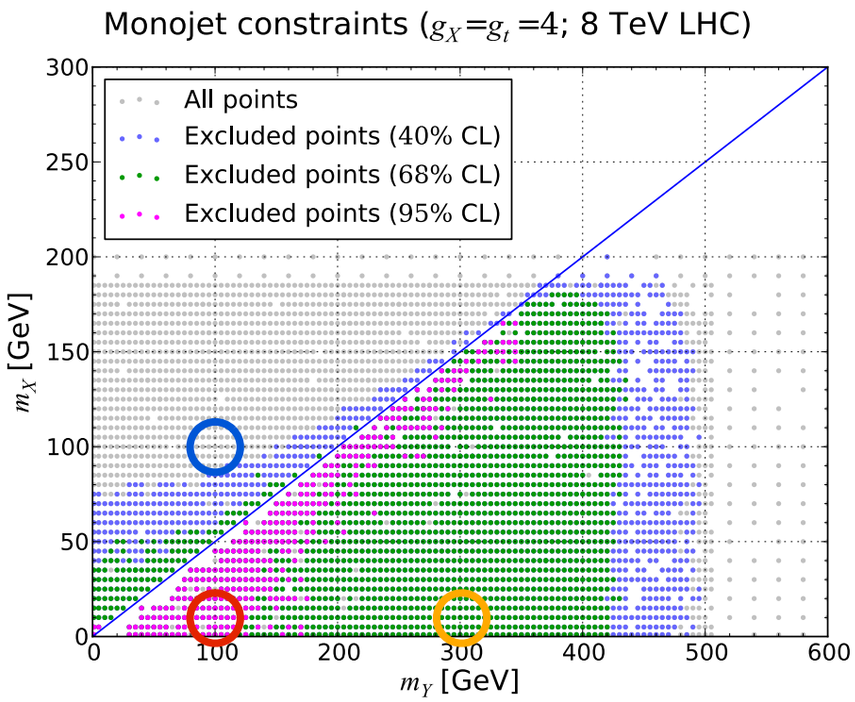


	(m_Y, m_X)	$\sigma_{\rm LO}$ [pb]	$\mathrm{CL}_{\rm LO}$ [%]	$\sigma_{\rm NLO}$ [pb]	$\mathrm{CL}_{\rm NLO}$ [%]
I	(150, 25) GeV	$0.658^{+34.9\%}_{-24.0\%}$	$98.7^{+0.8\%}_{-13.0\%}$	$0.773^{+6.1\%}_{-10.1\%}$	$95.0^{+2.7\%}_{-0.4\%}$
II	(40, 30) GeV	$0.776^{+34.2\%}_{-24.1\%}$	$74.7^{+19.7\%}_{-17.7\%}$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

MET+jet (LO loop-induced)

- Recasting of CMS 1408.3583 jet+MET in MA5
- 3 benchmark scenarios:



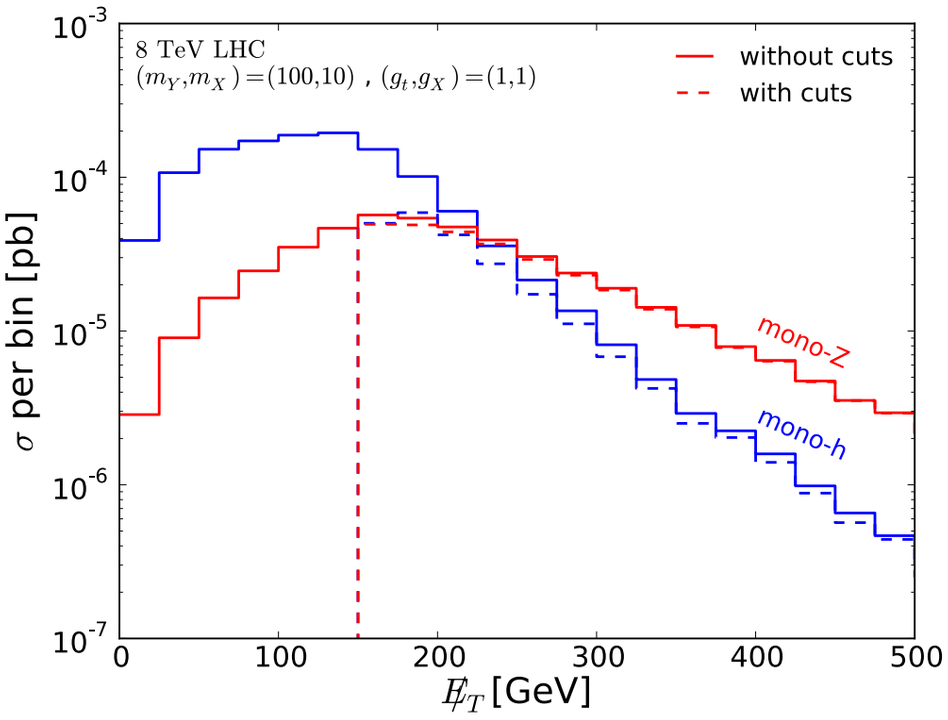


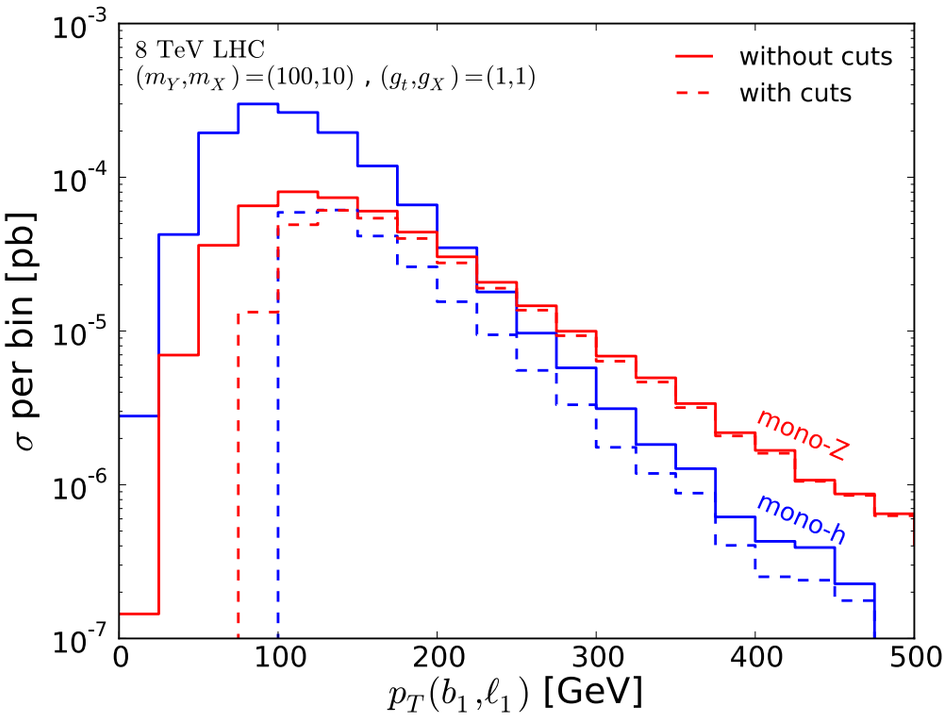
	(m_Y, m_X)	$\sigma_{\rm LO}$ [pb]
I	(100, 10) GeV	0.605
II	(100, 100) GeV	0.00261
III	(300, 10) GeV	0.194

- Higher senstivity for mono-jet than *tt*+MET
- *tt*+MET gains from higher CM Energies

Mono-Z and mono-Higgs

- Leptonic mono-Z search CMS [1511.09375]
- Mono-Higgs (*bb*) search ATLAS [1510.06218]
- Parton-level analysis compared to upper limits:





- Couplings $g_t > 2$ excluded for $m_Y > 2m_X$ with $m_Y < 100\,\mathrm{GeV}$
- Promising for future analysis

Mediator searches

Mediator searches

Final state	Imposed constraint	Reference	Comments
jj	$\sigma(m_Y = 500\ \text{GeV}) < 10\,\text{pb}$	CMS [1604.08907]	Only when $m_Y > 500\,\text{GeV}$
$\gamma\gamma$	$\sigma(m_Y = 150\ \text{GeV}) < 30\,\text{fb}$	CMS [1506.02301]	Only when $m_Y > 150\,\text{GeV}$
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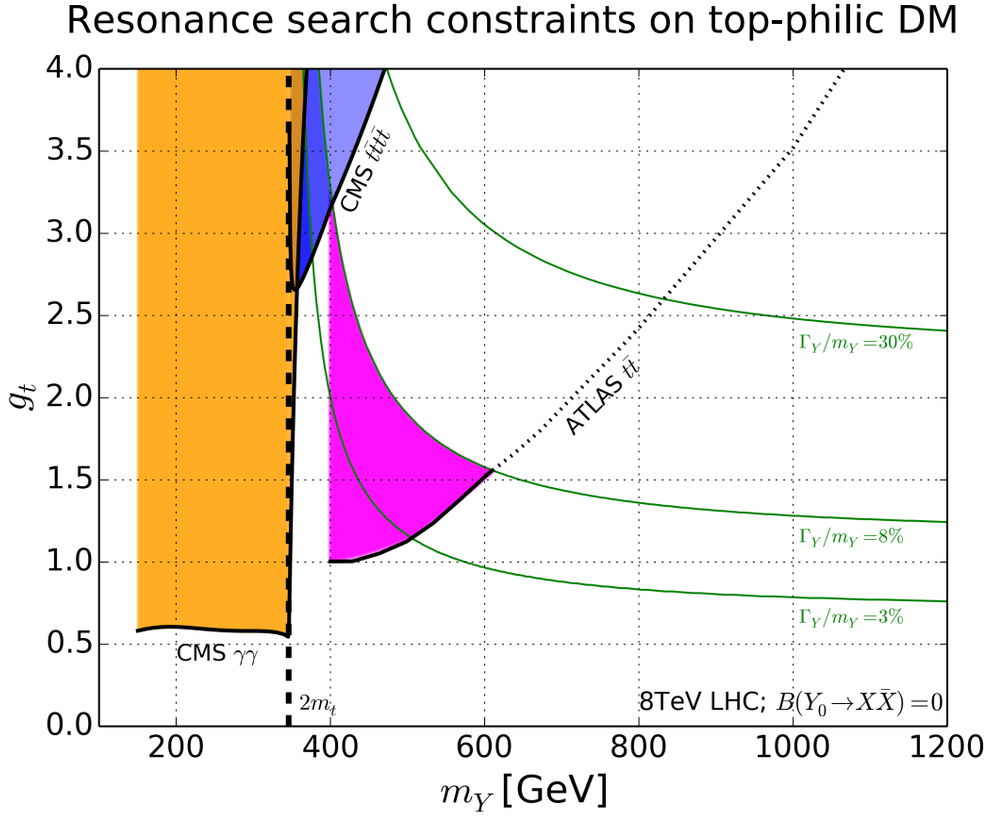
$t\bar{t}t\bar{t}$	$\sigma < 32\,\text{fb}$	CMS [1409.7339]	Upper limit on the SM cross section

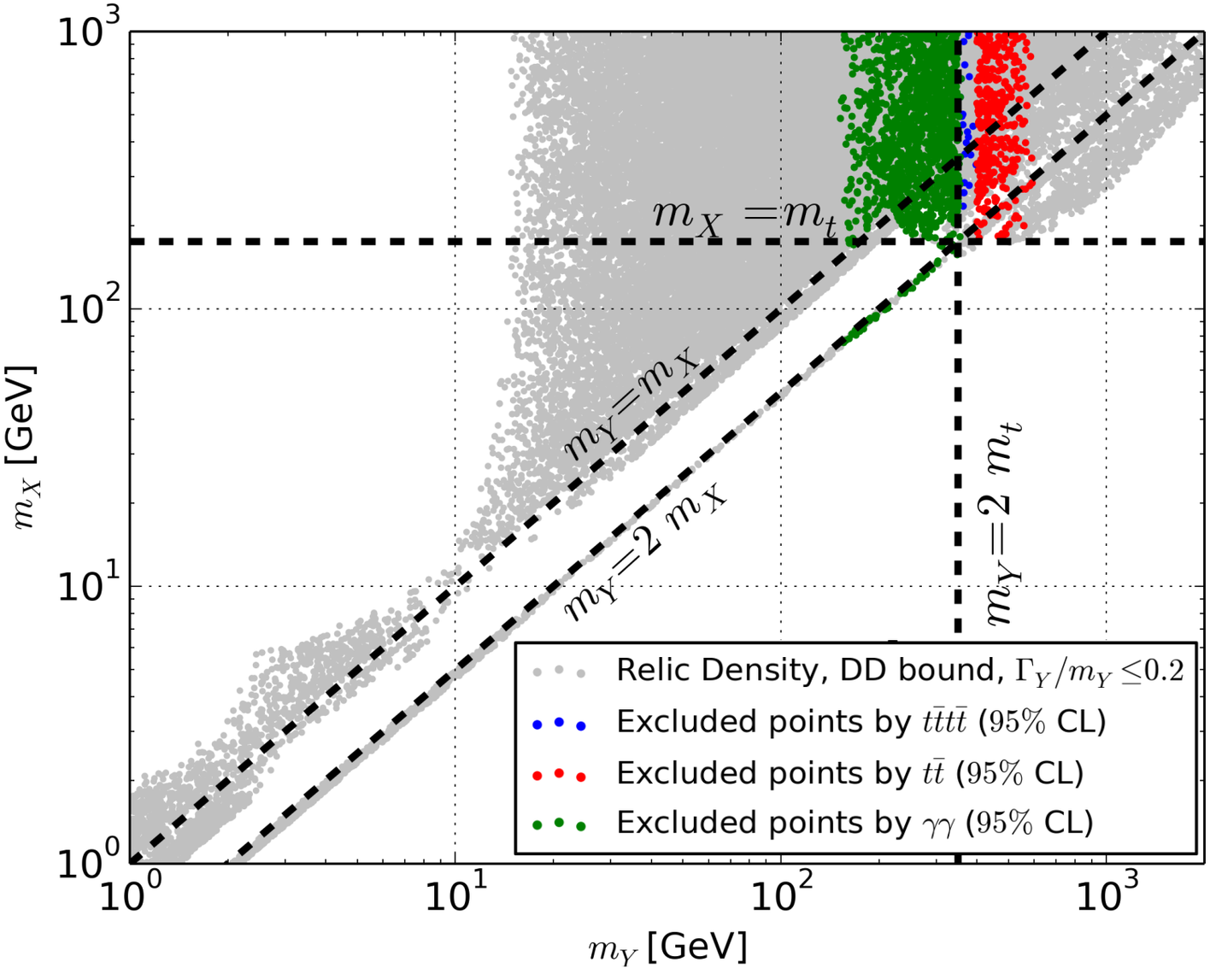
- Photon BR always suppressed by

$$\frac{\Gamma(Y_0 \to \gamma\gamma)}{\Gamma(Y_0 \to gg)} \sim \frac{8}{9}\frac{\alpha_e^2}{\alpha_s^2} \approx 10^{-3}$$

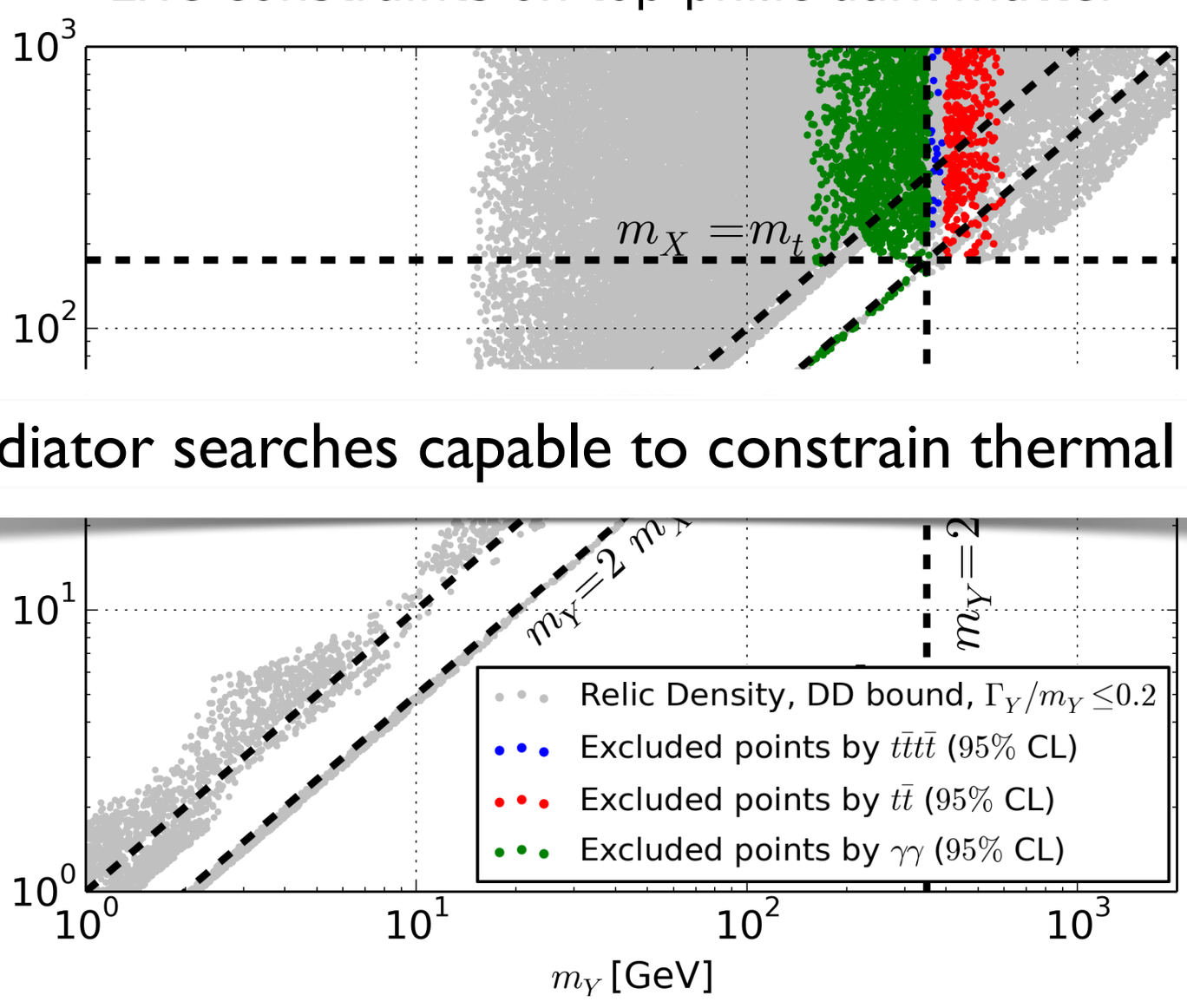
- Nevertheless: di-photon more relevant than di-jet
- Low mass range required



Combined constraints



Combined constraints



Only mediator searches capable to constrain thermal relic DM!

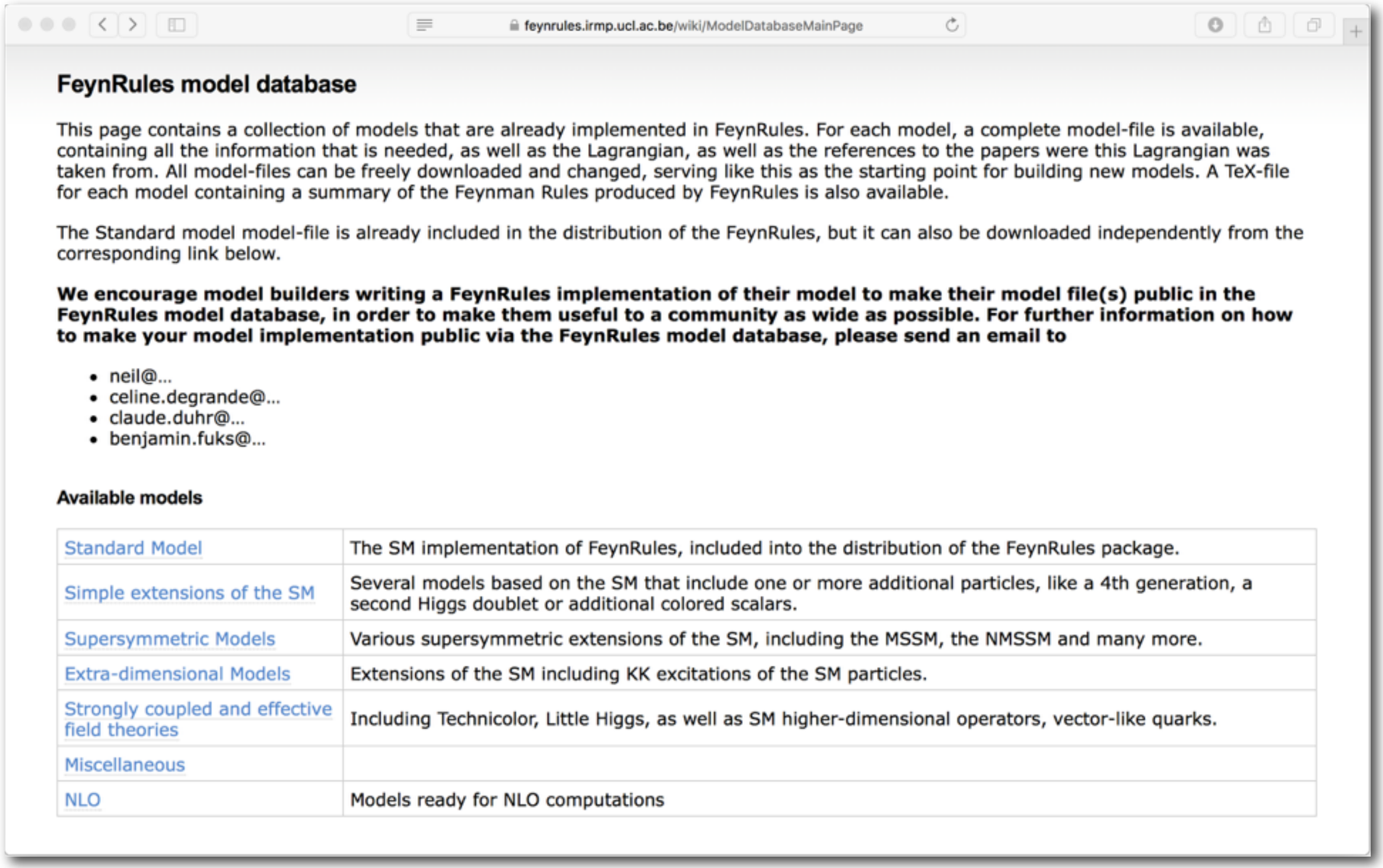
Summary

- Comprehensive analysis of collider physics and DM observables within FeyRules-MadGraph framework + MultiNest
- Considered Top-philic scalar mediator model
- Striking complementarity between various constraints
- Relic density constraint:

  ➔ Resonant region $m_Y \sim 2m_X$ or light mediator $m_Y < m_X$

  ➔ Low sensitivity for MET searches
- Mediator searches promising, however, low masses unchallenged

http://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage



http://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

feynrules.irmp.ucl.ac.be/wiki/DMsimp

wiki: DMsimp

Start Page | Index | History

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Simplified dark matter models

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

Authors

- s-channel
  - Antony Martini (Université catholique de Louvain) & Kentarou Mawatari (LPSC Grenoble)
    - Emails: kentarou.mawatari @ lpsc.in2p3.fr
- s-channel (electroweak)
  - Jian Wang (Johnnas Gutenberg University of Mainz) & Cen Zhang (Brookhaven National Laboratory)
    - Emails: cenzhang @ bnl.gov

Description of the model

This is simplified dark matter models for NLO. Our lagrangian consists of different types of DM:

- Xr (real scalar DM)
- Xc (complex scalar DM)
- Xd (Dirac spinor DM)
- Xm (Majorana spinor DM) (to be done.)
- ...

and different types of mediators:

- s-channel
  - Y0 (spin-0)
  - Y1 (spin-1)
  - Y2 (spin-2) [to be done.]
  - ...
- t-channel [to be done.]

One can find the model lagrangian in the note. See more details in

- 1508.00564 : O. Mattelaer, E. Vryonidou, "Dark matter production through loop-induced processes at the LHC: the s-channel mediator case".
- 1508.05327 : M. Backovic, M. Kramer, F. Maltoni, A. Martini, K. Mawatari, M. Pellen, "Higher-order QCD predictions for dark matter production at the LHC in simplified models with s-channel mediators".
- 1509.05785 : M. Neubert, J. Wang, C. Zhang, "Higher-order QCD predictions for dark matter production in mono-Z searches at the LHC".