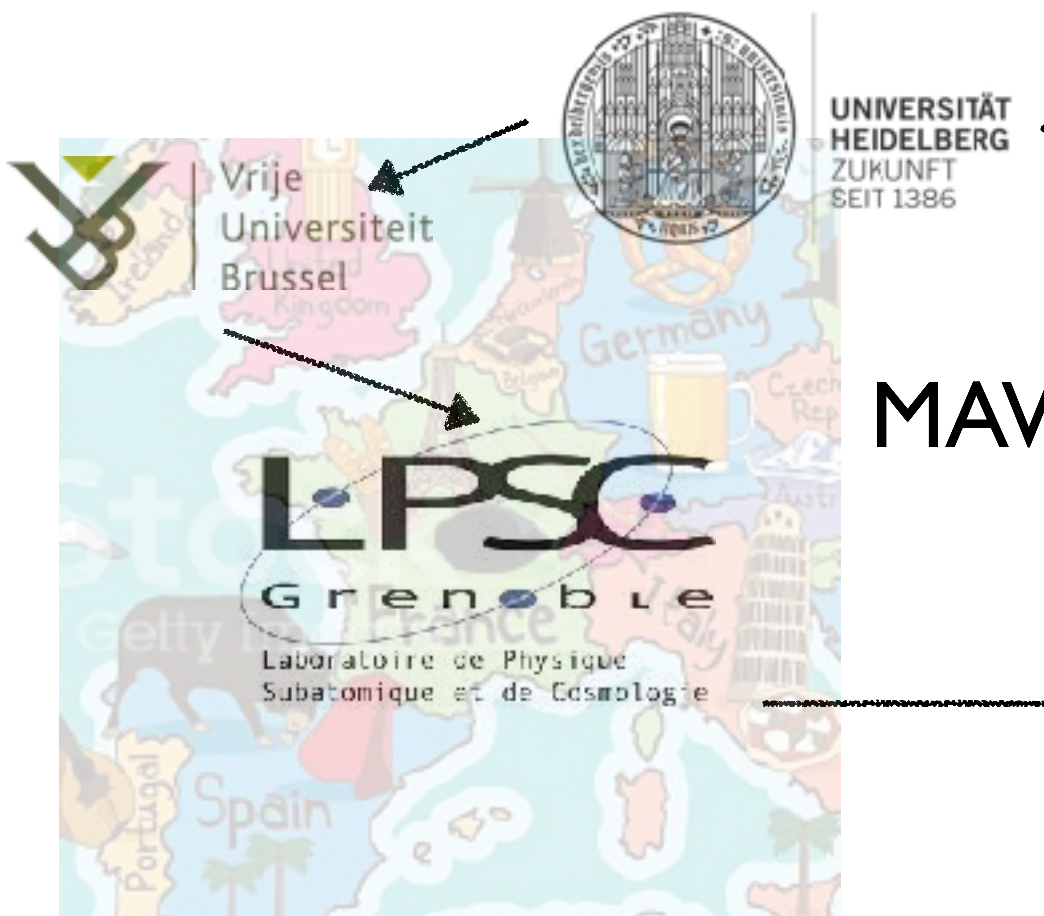
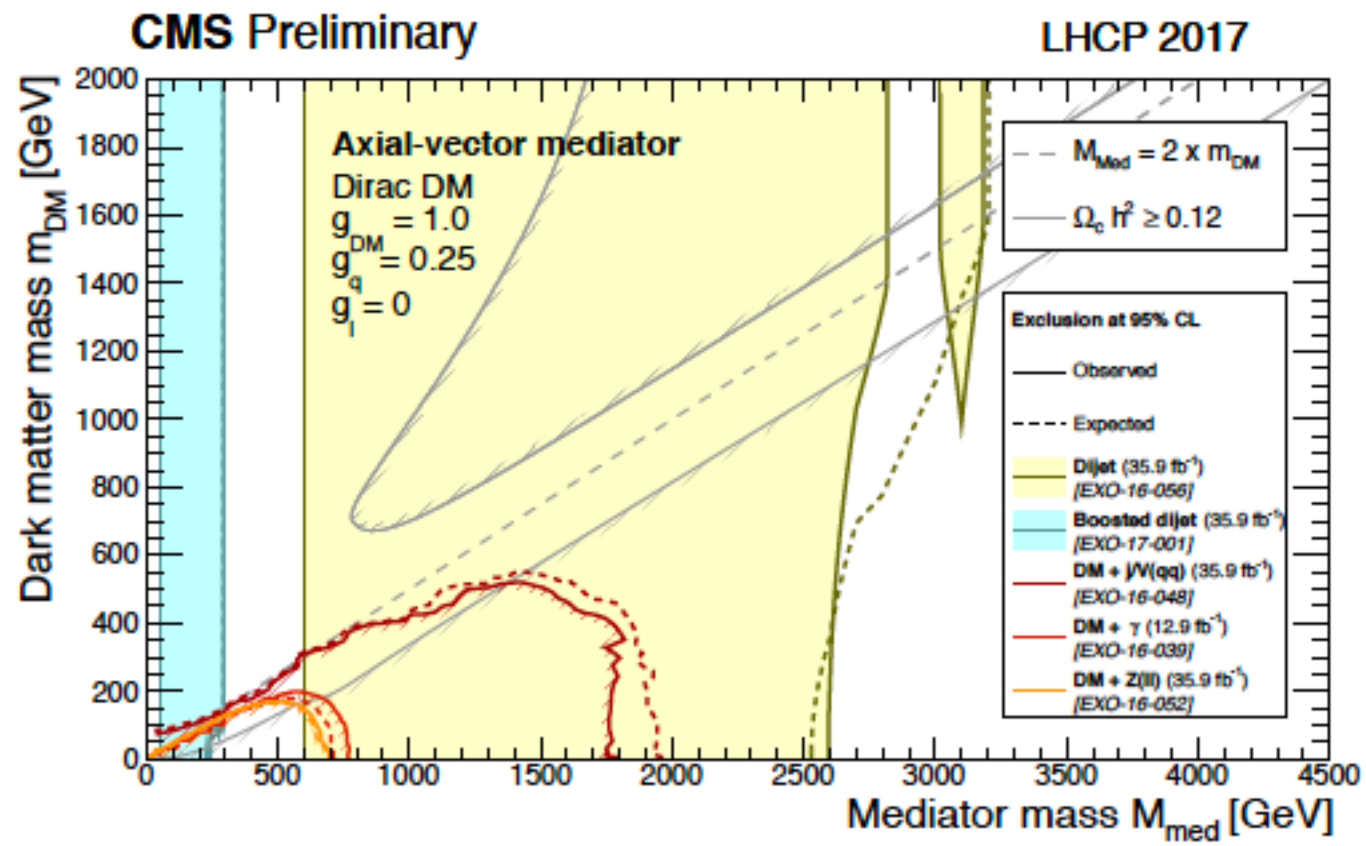
# Seeking dark matter at the interface of collider physics, astrophysics and cosmology

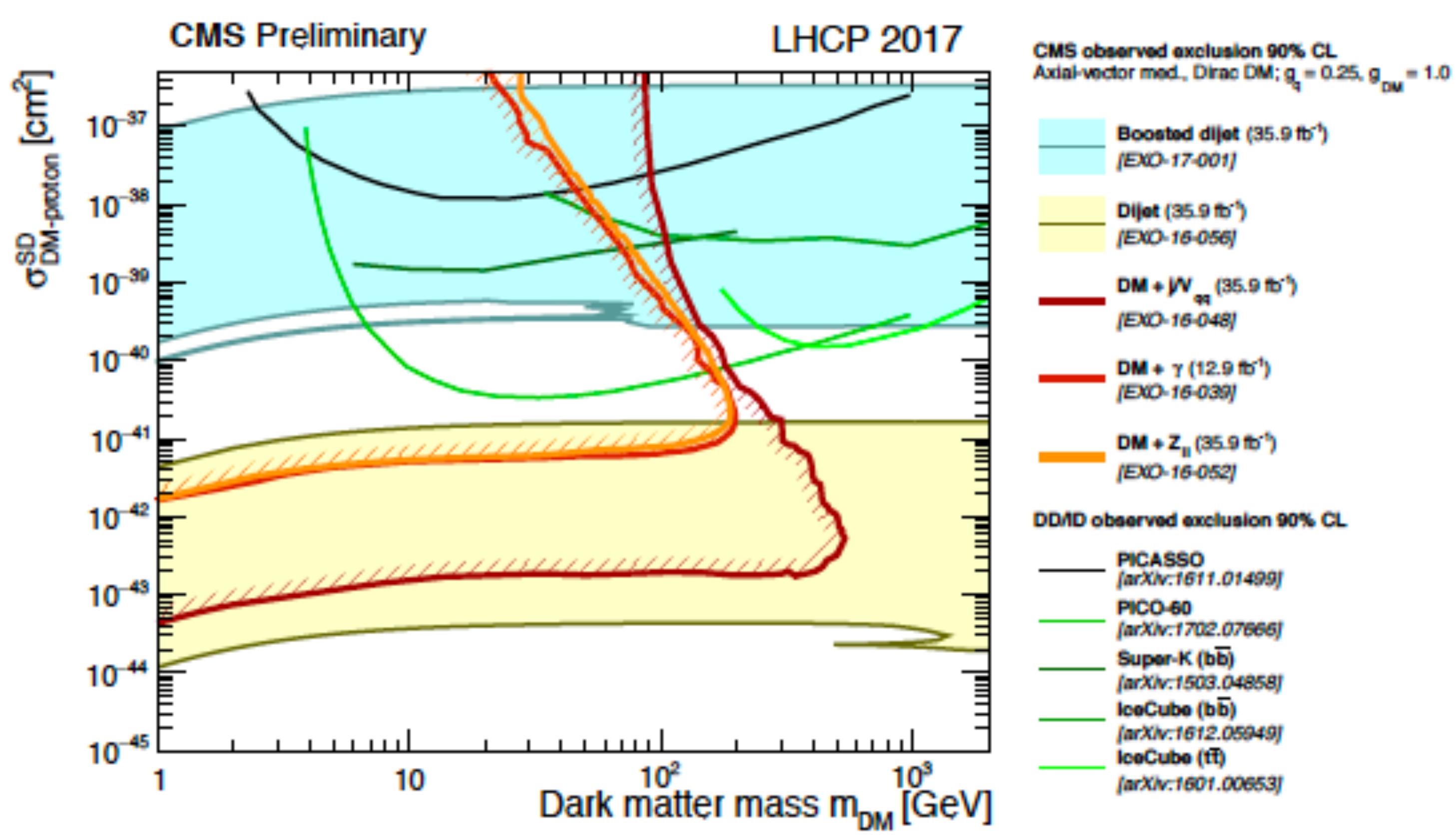




MAWATARI, Kentarou
馬渡 健太郎


# LHC Dark Matter Working Group
# (LHC DM WG)


CMS Preliminary
LHCP 2017
Axial-vector mediator
Dirac DM
g_DM = 1.0
g_q = 0.25
g_l = 0
M_Med = 2 x m_DM
Ω_c h² ≥ 0.12
Exclusion at 95% CL
Observed
Expected
Dijet (35.9 fb⁻¹) [EXO-16-056]
Boosted dijet (35.9 fb⁻¹) [EXO-17-001]
DM + j/V(qq) (35.9 fb⁻¹) [EXO-16-048]
DM + γ (12.9 fb⁻¹) [EXO-16-039]
DM + Z(ll) (35.9 fb⁻¹) [EXO-16-052]
Dark matter mass m_DM [GeV]
Mediator mass M_med [GeV]


CMS Preliminary
LHCP 2017
CMS observed exclusion 90% CL
Axial-vector med., Dirac DM; g_q = 0.25, g_DM = 1.0
Boosted dijet (35.9 fb⁻¹) [EXO-17-001]
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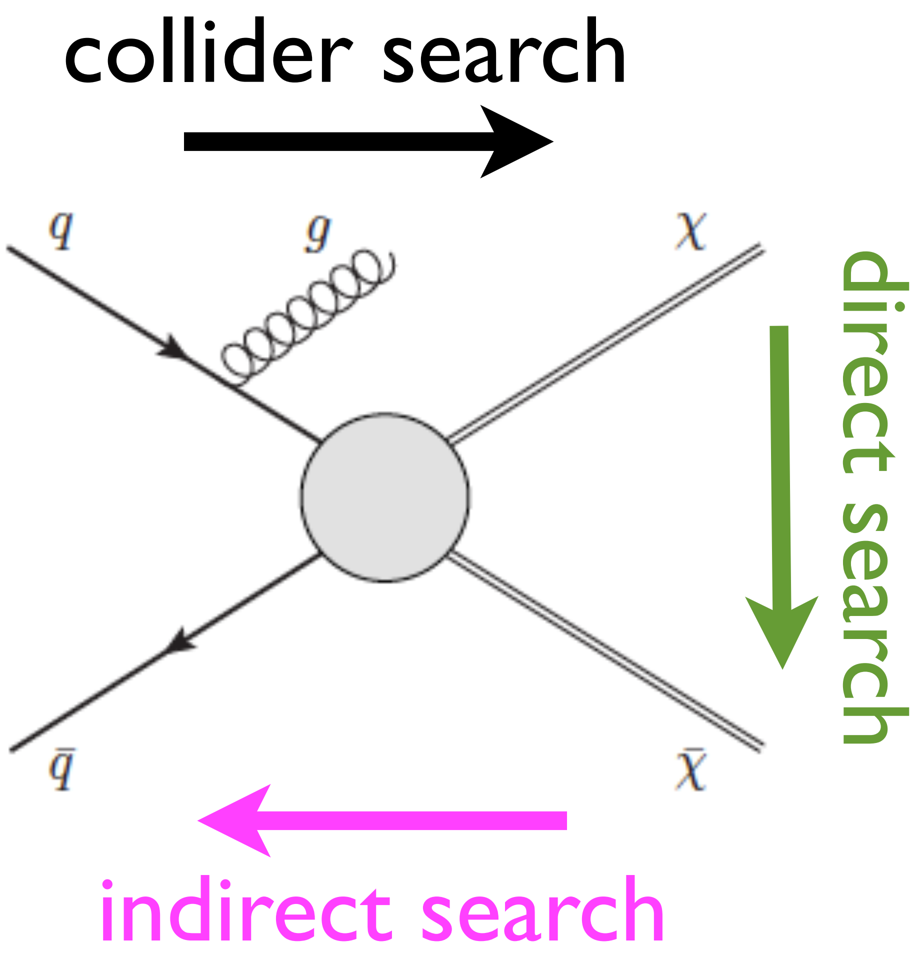
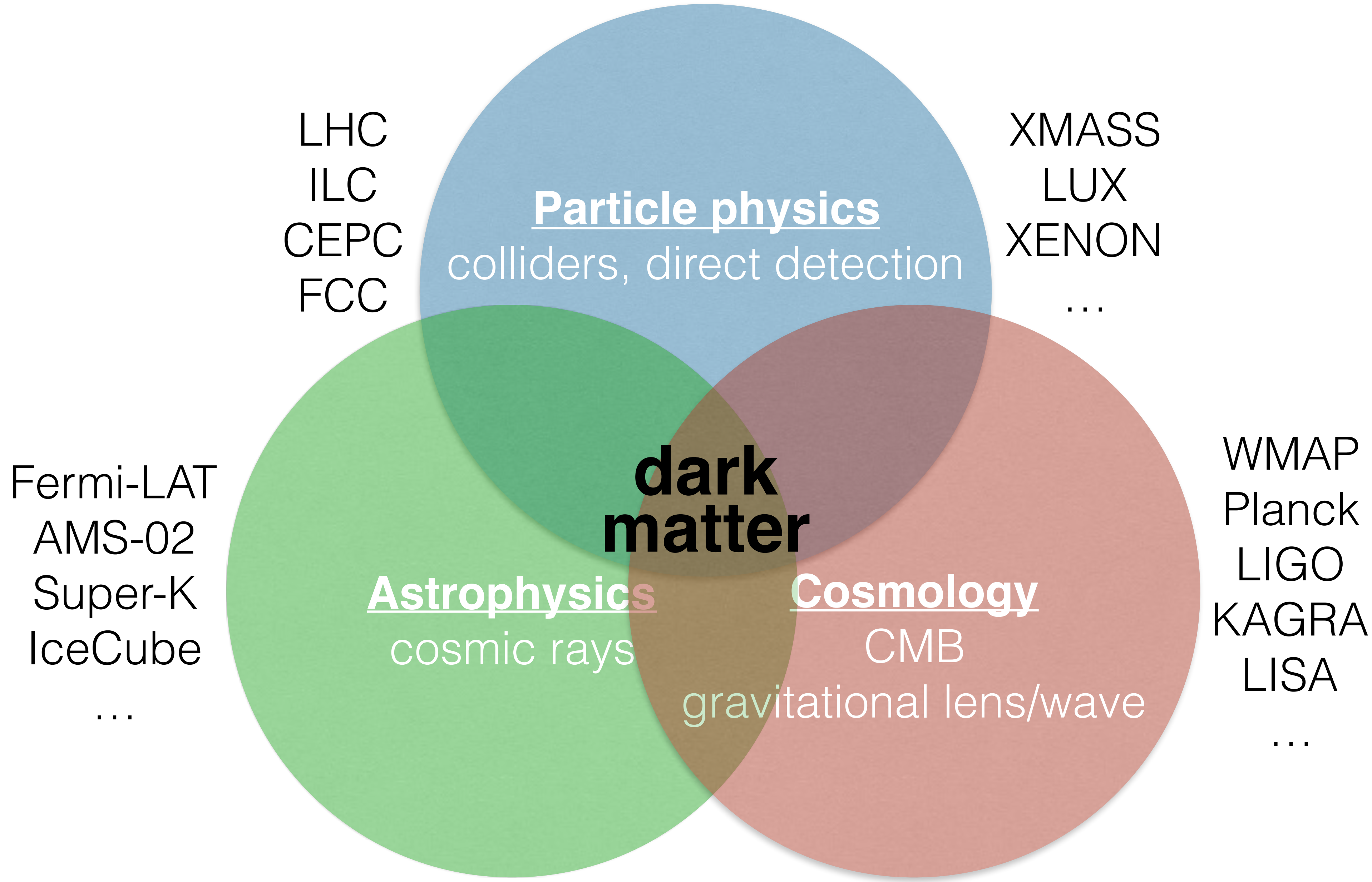
DM + γ (12.9 fb⁻¹) [EXO-16-039]
DM + Z_ll (35.9 fb⁻¹) [EXO-16-052]
DD/ID observed exclusion 90% CL
PICASSO [arXiv:1611.01499]
PICO-60 [arXiv:1702.07666]
Super-K (bb̄) [arXiv:1503.04858]
IceCube (bb̄) [arXiv:1612.05949]
IceCube (tt̄) [arXiv:1601.00653]
σ^SD_DM-proton [cm²]
Dark matter mass m_DM [GeV]

# Looking for dark matter

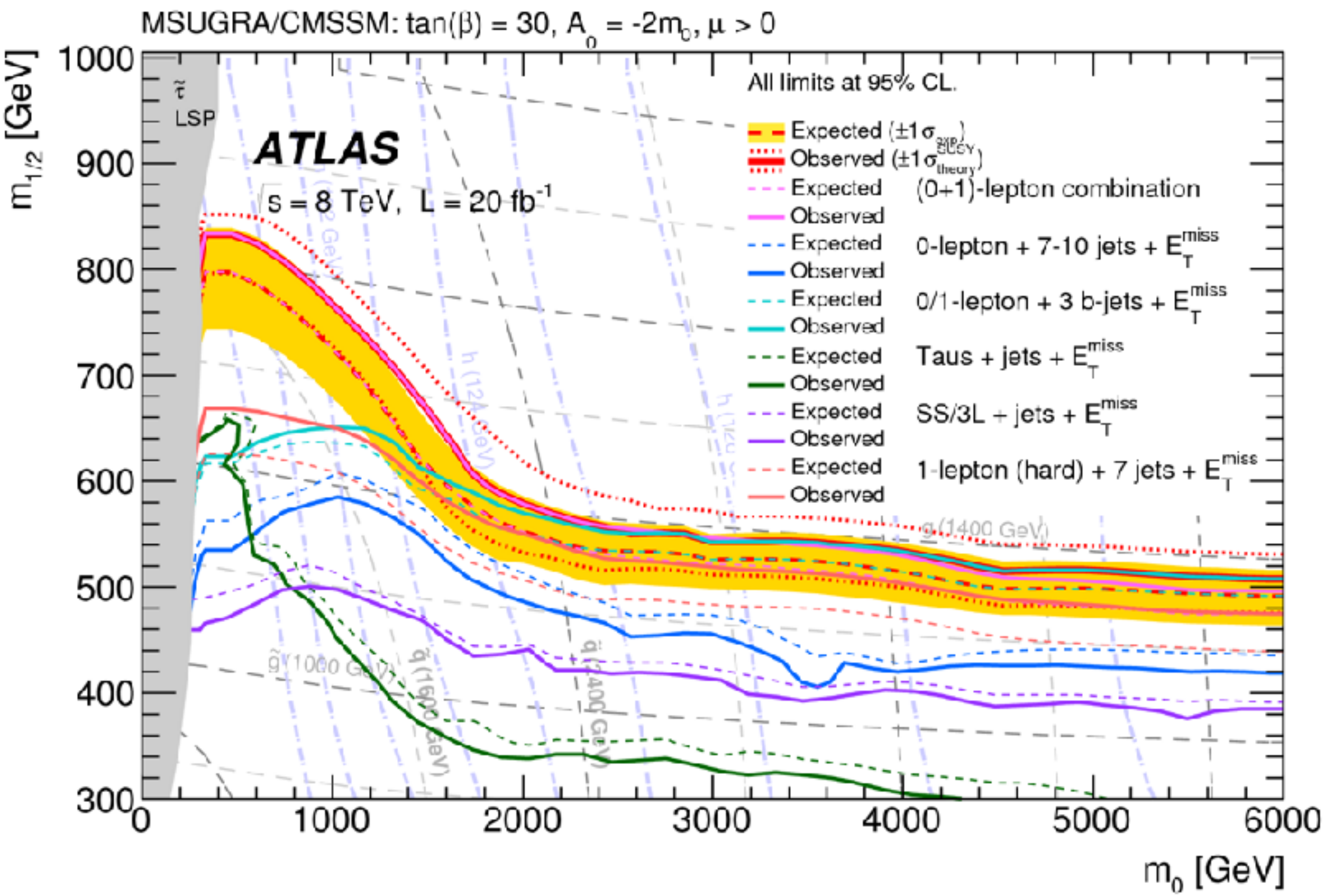
- If dark matter has non-gravitational interactions with ordinal matter, we can observe it directly and/or indirectly.
- Indeed, many types of dark matter search experiments are currently on-going all over the world.



# Dark matter Venn diagram



# Dark matter searches at LHC Run-I: top-down (e.g. Supersymmetry)

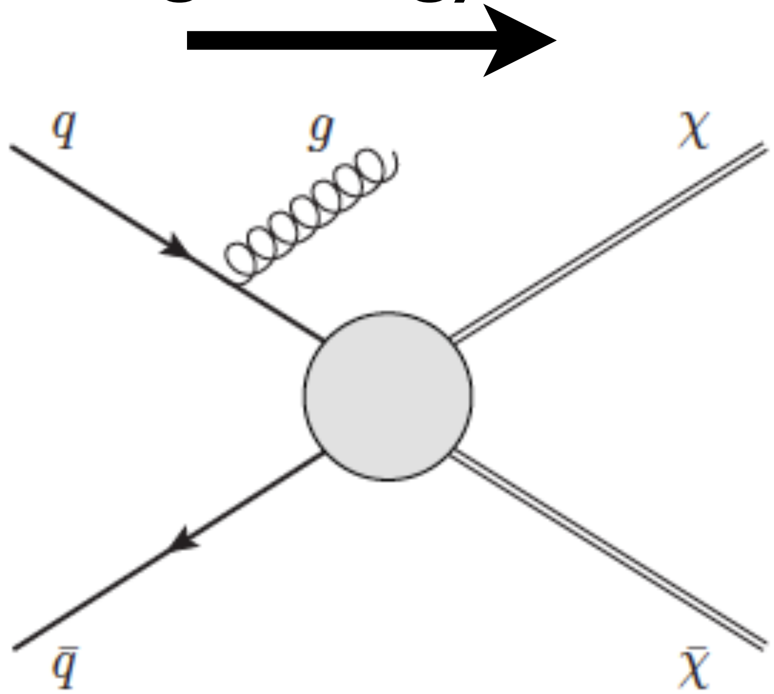


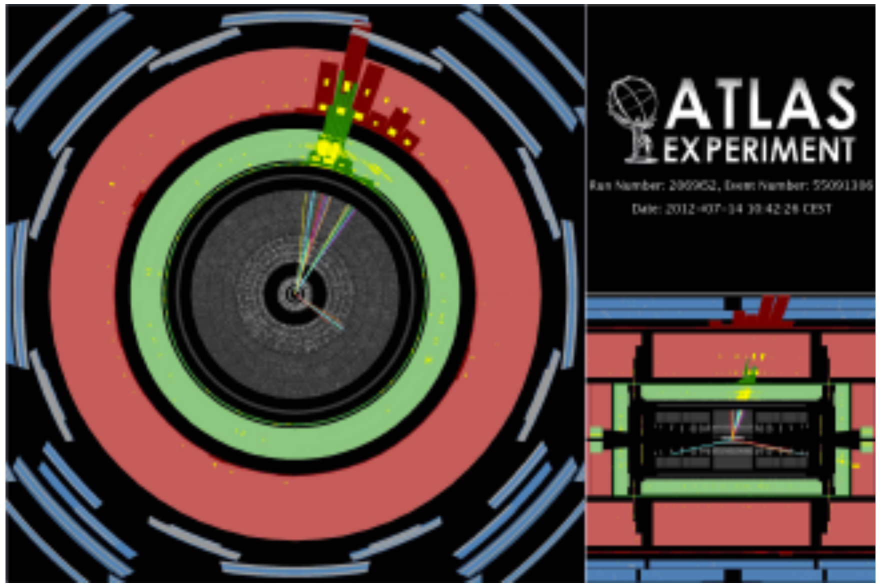
# Dark matter searches at LHC Run-I: bottom-up (Effective field theory)

missing-energy search

- employed contact interaction operators in EFTs (effective field theories).
- vector $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$

  axial-vector $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
- The signal is determined by the Lorentz structure, the DM mass, and the overall coupling (or the cutoff scale).
- easy interpretation to non-collider DM searches
- EFT validation; $M_\star$ ≦ (LHC accessible energy)



# Dark matter searches at LHC Run-I: bottom-up (Effective field theory)

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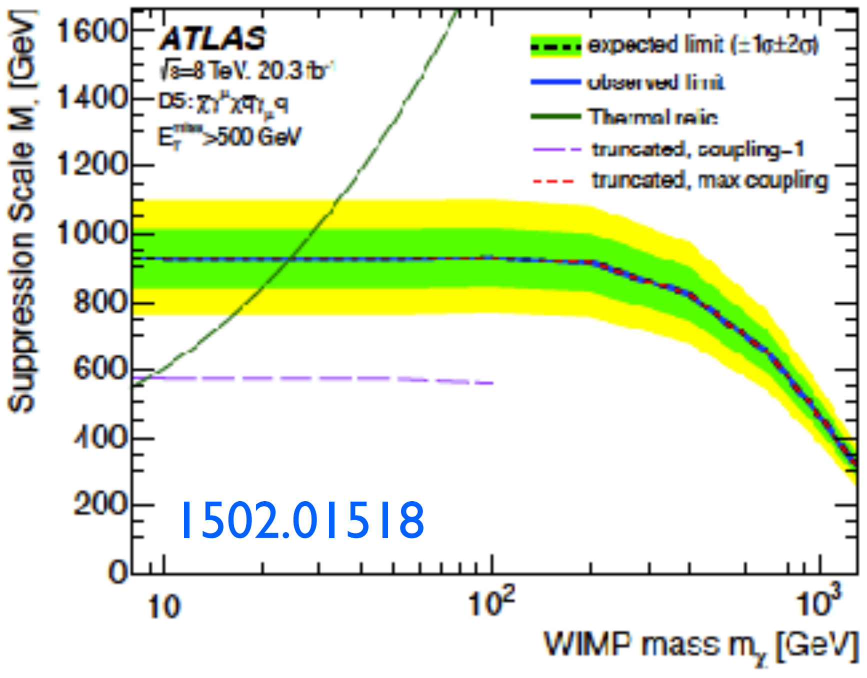

since 2015/12

LPCC: LHC Physics Centre at CERN

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# LHC DM WG: WG on Dark Matter Searches at the LHC

To subscribe to the general WG mailing list, used to distribute announcements about meetings and available documents, go to
http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg

A second mailing list is used for more technical exchanges related to the ongoing work of the WG. To subscribe, go to
http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg-contributors

The LHC Dark Matter Working Group (LHC DM WG) brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC. As examples, the group develops and promotes well-defined signal models, specifying the assumptions behind them and describing the conditions under which they should be used. It works to improve the set of tools available to the experiments, such as higher- precision calculations of the backgrounds. It assists theorists with understanding and making use of LHC results.
The LHC DM WG develops and maintains close connections with theorists and other experimental particle DM searches (e.g. Direct and Indirect Detection experiments) in order help verify and constrain particle physics models of astrophysical excesses, to understand how collider searches and non-collider experiments complement one another, and to help build a comprehensive understanding of viable dark matter models.

LHC WORKING

- Dark Matter WG
  - WG Meetings
  - WG documents
- Electroweak WG
  - WG Documents
  - WG meetings
- Forward Physics W
  - WG TWIKI PAGE
  - WG documents
  - WG meetings
- Heavy Flavour WG
  - WG Documents
  - WG Meetings
- MB & UE WG
  - WG meetings
  - WG documents
- Machine Learning

# Search for dark matter produced with an energetic jet or a hadronically decaying W or Z boson at $\sqrt{s} = 13$ TeV

The CMS Collaboration*



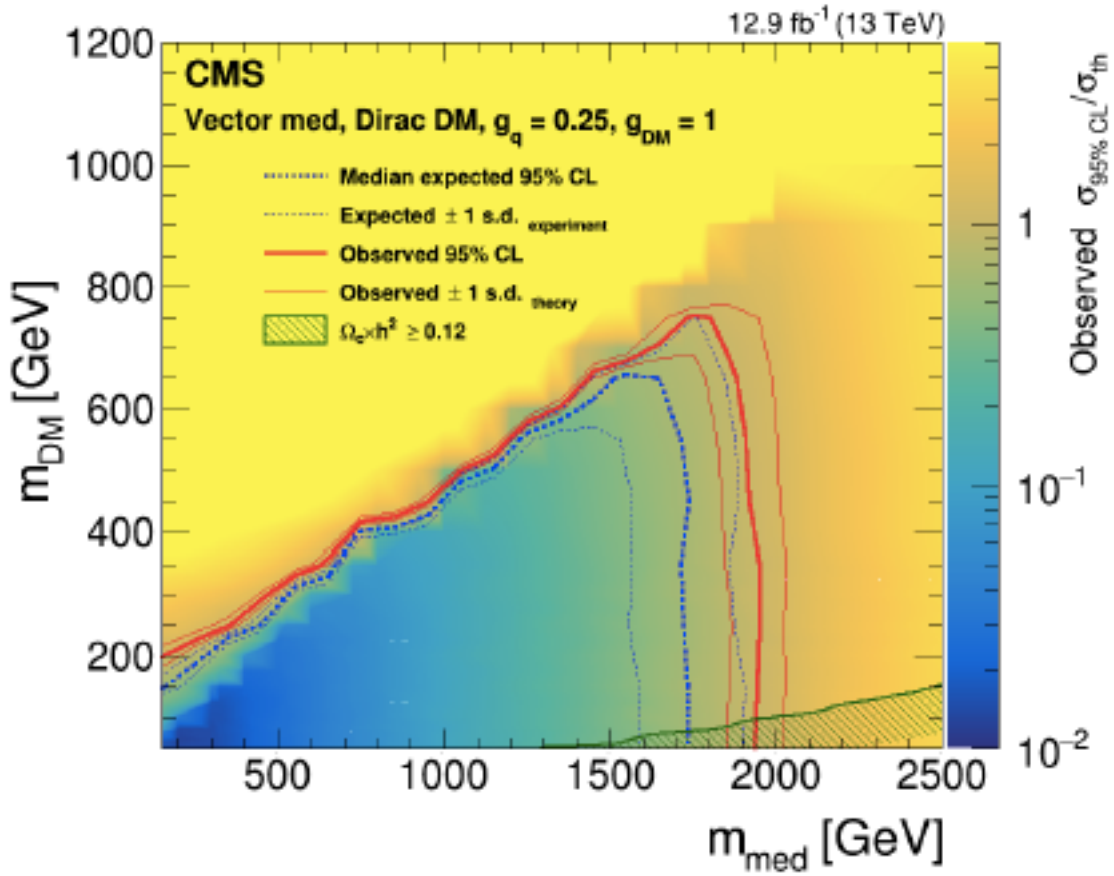
## Abstract

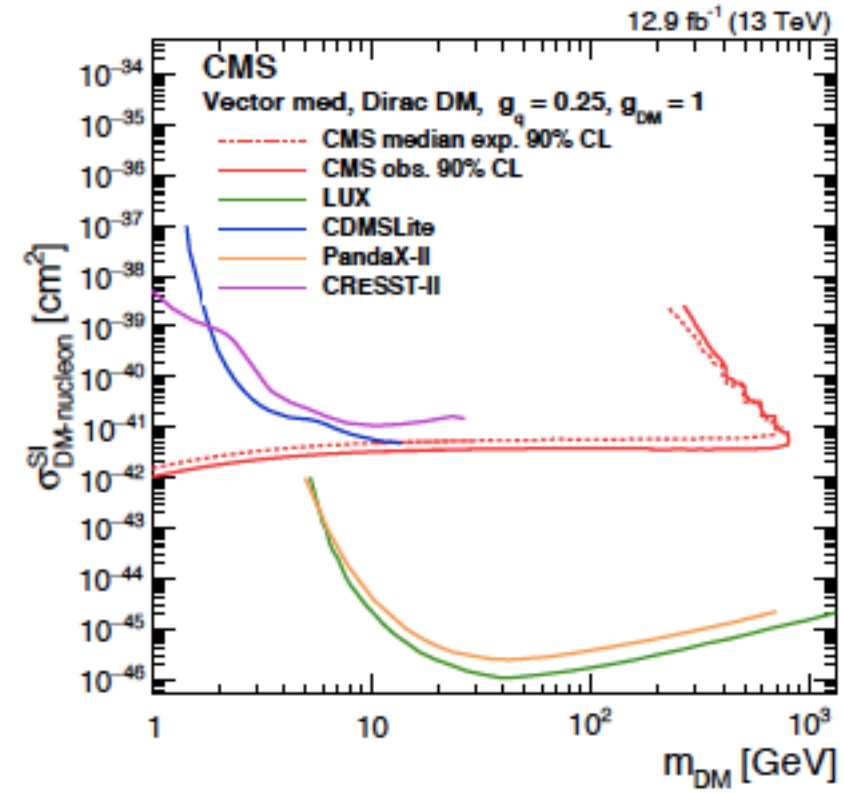
A search for dark matter particles is performed using events with large missing transverse momentum, at least one energetic jet, and no leptons, in proton-proton collisions at $\sqrt{s} = 13$ TeV collected with the CMS detector at the LHC. The data sample

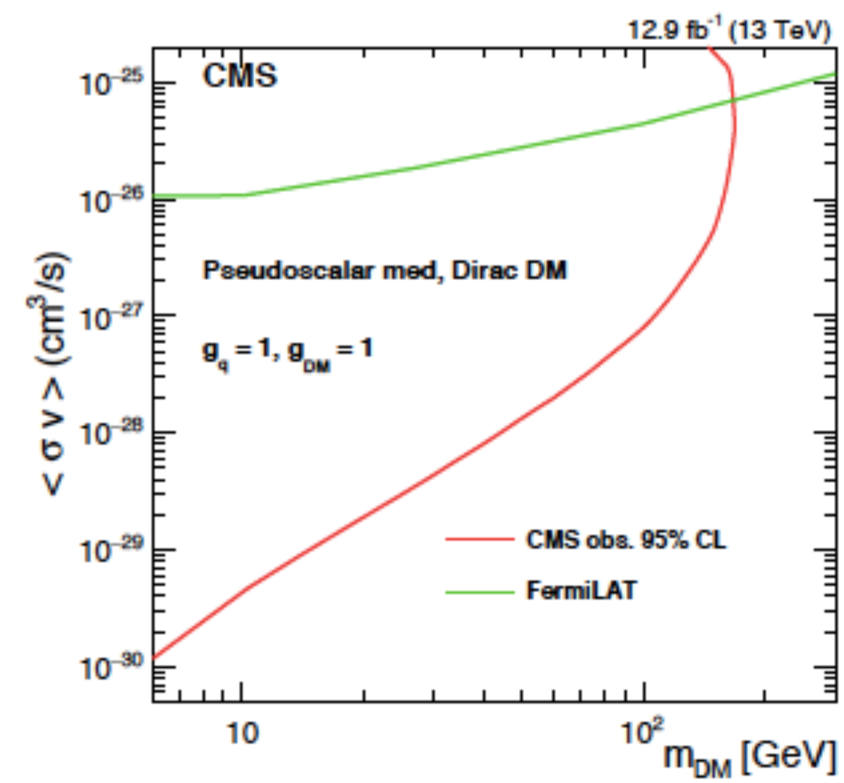
• • •

ing fraction. The results of this search provide the strongest constraints on the dark matter pair production cross section through vector and axial-vector mediators at a particle collider. When compared to the direct detection experiments, the limits obtained from this search provide stronger constraints for dark matter masses less than 5, 9, and 550 GeV, assuming vector, scalar, and axial-vector mediators, respectively. The search yields stronger constraints for dark matter masses less than 200 GeV, assuming a pseudoscalar mediator, when compared to the indirect detection results from Fermi–LAT.

# Constraints from LHC, direct, and indirect searches



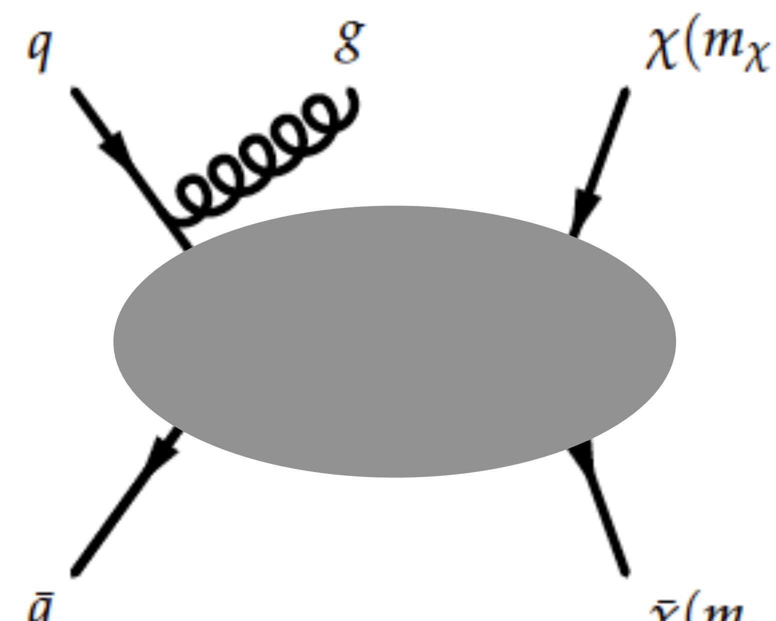



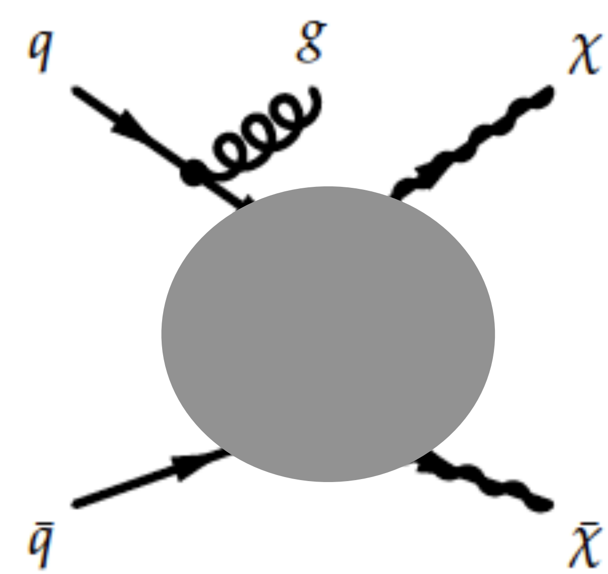
# DM searches at LHC Run-II

LHC DM WG 1507.00966

- is employing simplified DM models.
- $$\mathcal{L}_{\text{vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$
  $$\mathcal{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi$$
- The signal is determined by the mediator type, the DM and mediator masses, and the two couplings.
- Richer phenomenology
- Interpretations to non-collider DM searches are complicated.



s-channel mediator



t-channel mediator

# s-channel simplified DM models

LHC DM WG [1507.00966, 1603.04156]

- Simplified DM models (s-channel):
  - spin-1 mediator

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

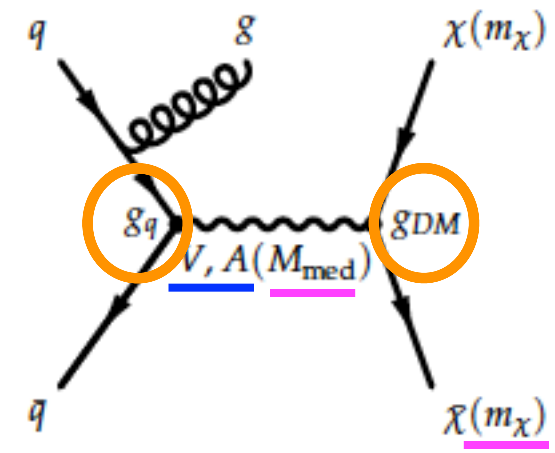
$$\mathcal{L}_{\rm axial\text{-}vector} = -g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma_5 q\,.$$

  - spin-0 mediator

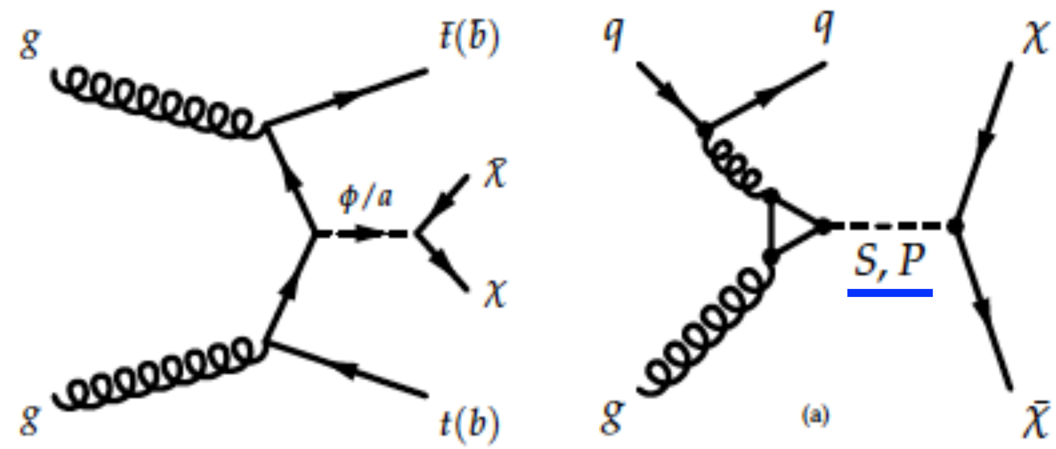
$$\mathcal{L}_{\rm scalar} = -g_{\rm DM}\,\phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q\,,$$

$$\mathcal{L}_{\rm pseudo\text{-}scalar} = -i g_{\rm DM}\,\phi\bar{\chi}\gamma_5\chi - i g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}\gamma_5 q\,,$$

- The signal is determined by
  - the mediator type (V, A, S, P)
  - the DM and mediator masses
  - the two couplings




spin-1 mediator




spin-0 mediator

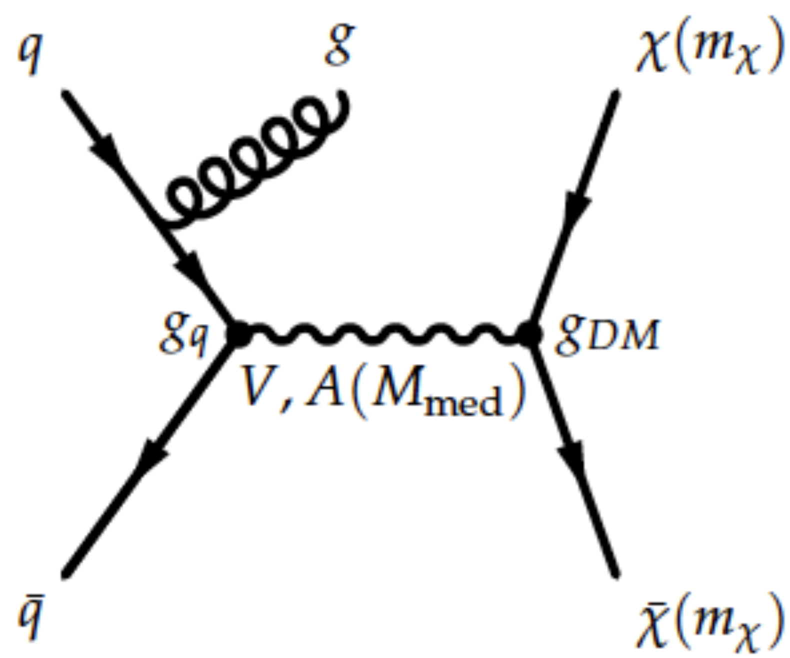
👉 Top-philic DM models

# Signatures of simplified DM models

LHC DM WG [1507.00966, 1603.04156]

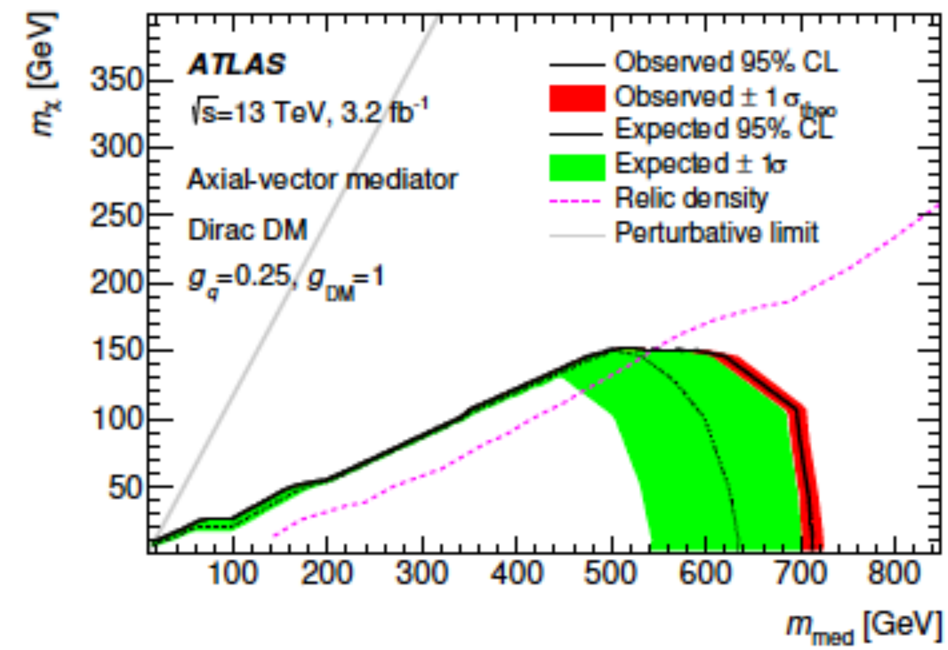
[ATLAS 1604.01306]

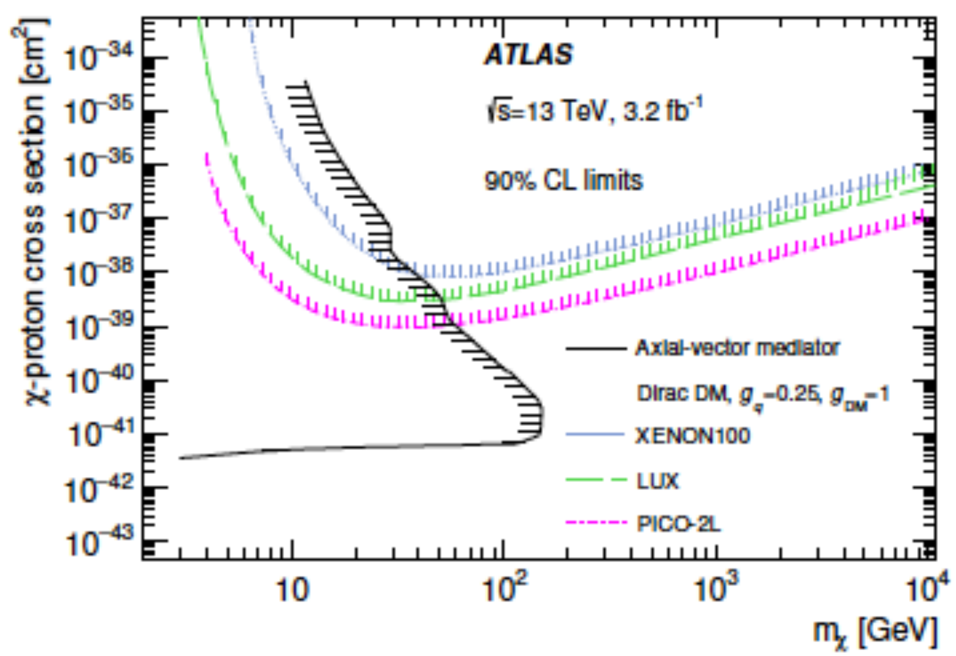
missing-energy search




direct detection

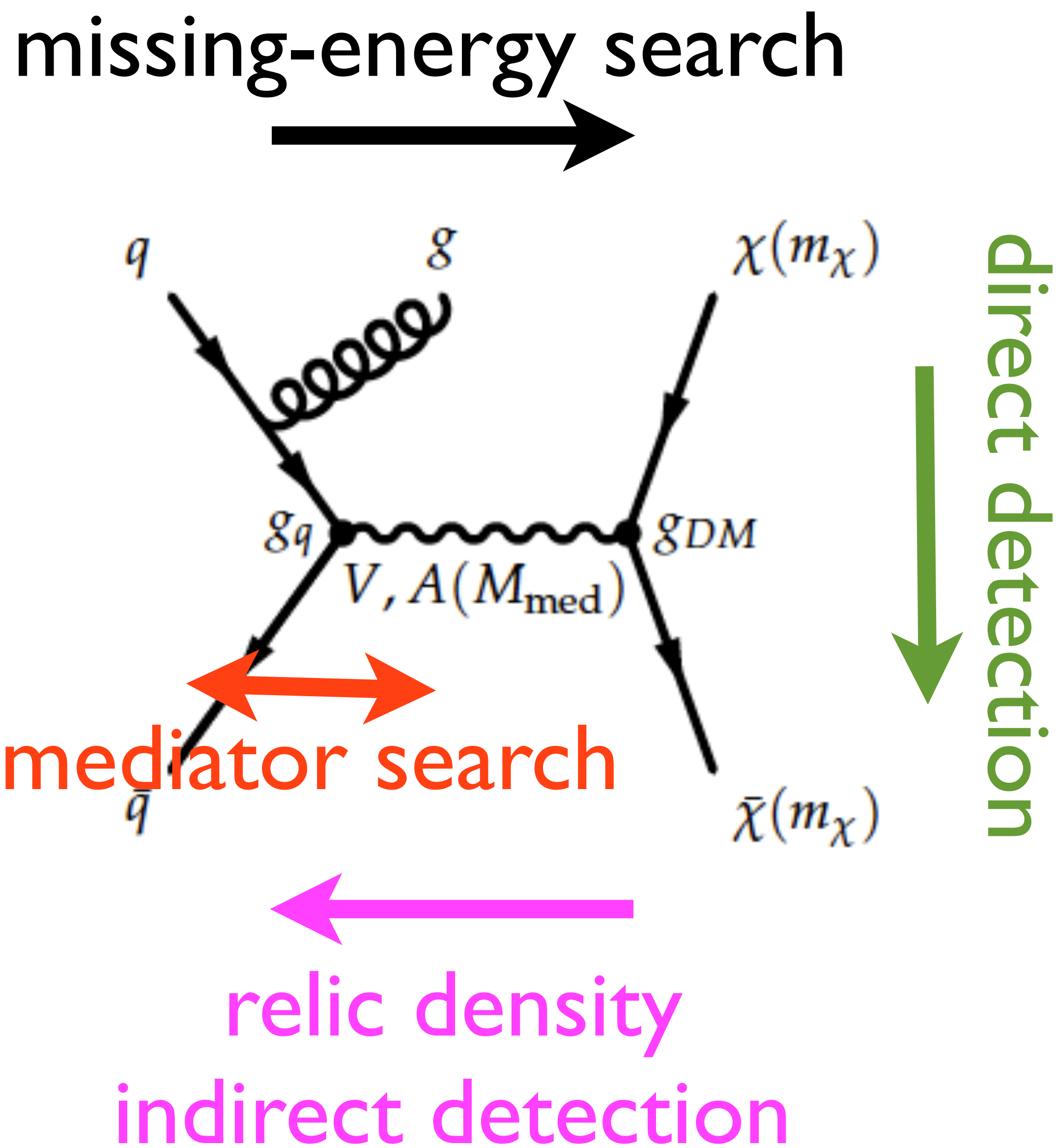
relic density
indirect detection

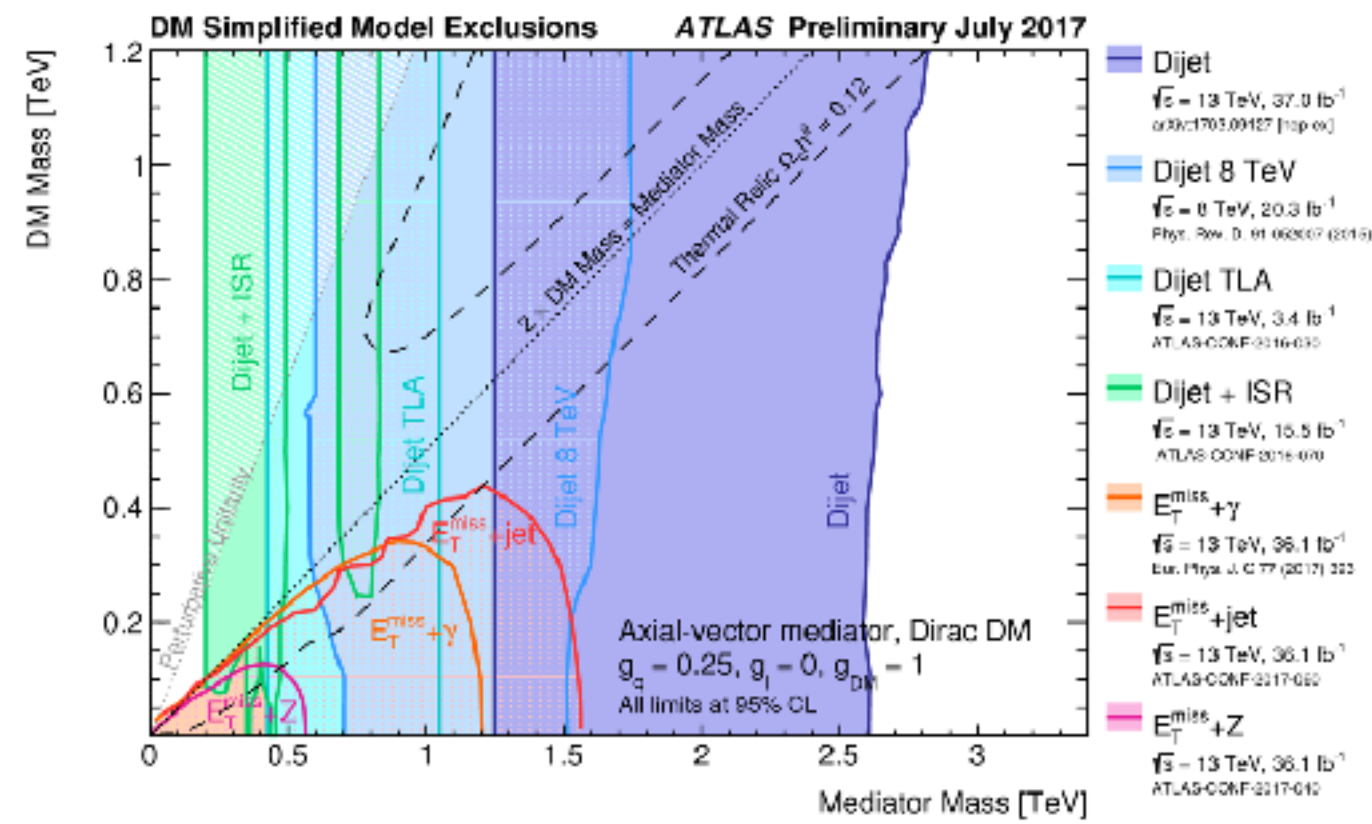


# Signatures of simplified DM models

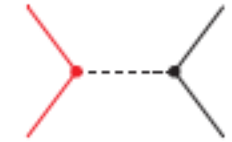
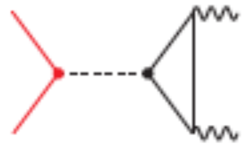
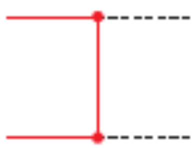
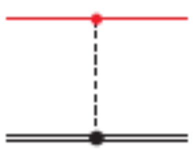
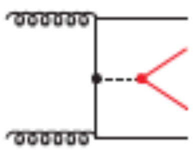
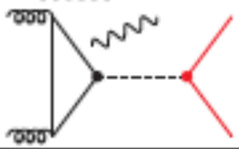
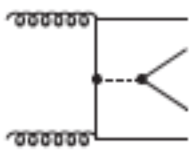
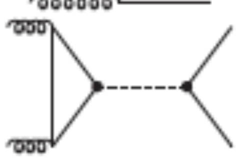
LHC DM WG [1507.00966, 1603.04156]



# A comprehensive approach to DM studies: simplified top-philic models

[1605.09242, JHEP]
52 pages, 23 figs, 8 tables

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

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

X=DM
Y=mediator

Kraemer, Maltoni

Arina, Backovic, Heisig

Conte, Fuks, Guo
Martini, Vryonidou
Mawatari

Hespel
Pellen

# BSM phenomenology workflow

- take a BSM model (symmetry, particle contents,…), i.e. Lagrangian
  - derive the Feynman rules — Model provider
    - draw Feynman diagrams for our interesting processes
      - compute the amplitude (squared)
        - generate parton-level events

      Matrix-element Generator
          - parton-shower/hadronisation — Shower Monte-Carlo programs
            - detector effect — Detector simulation tool
              - analysis — Recasting tool

DM physics tool

DM annihilation
DM-N cross section

# BSM phenomenology workflow

- take a BSM model (symmetry, particle contents,…), i.e. Lagrangian
  - derive the Feynman rules FeynRules
    - draw Feynman diagrams for our interesting processes
      - compute the amplitude (squared) MadGraph
        - generate parton-level events
          - parton-shower/hadronisation Herwig, Pythia, Sherpa
            - detector simulation Fastjet, Delphes
              - analysis GAMBIT, Checkmate, FastLim, MadAnalysis

micrOMEGAs
MadDM

# MC tools for Run-2 DM searches

LHC DM WG [1507.00966]

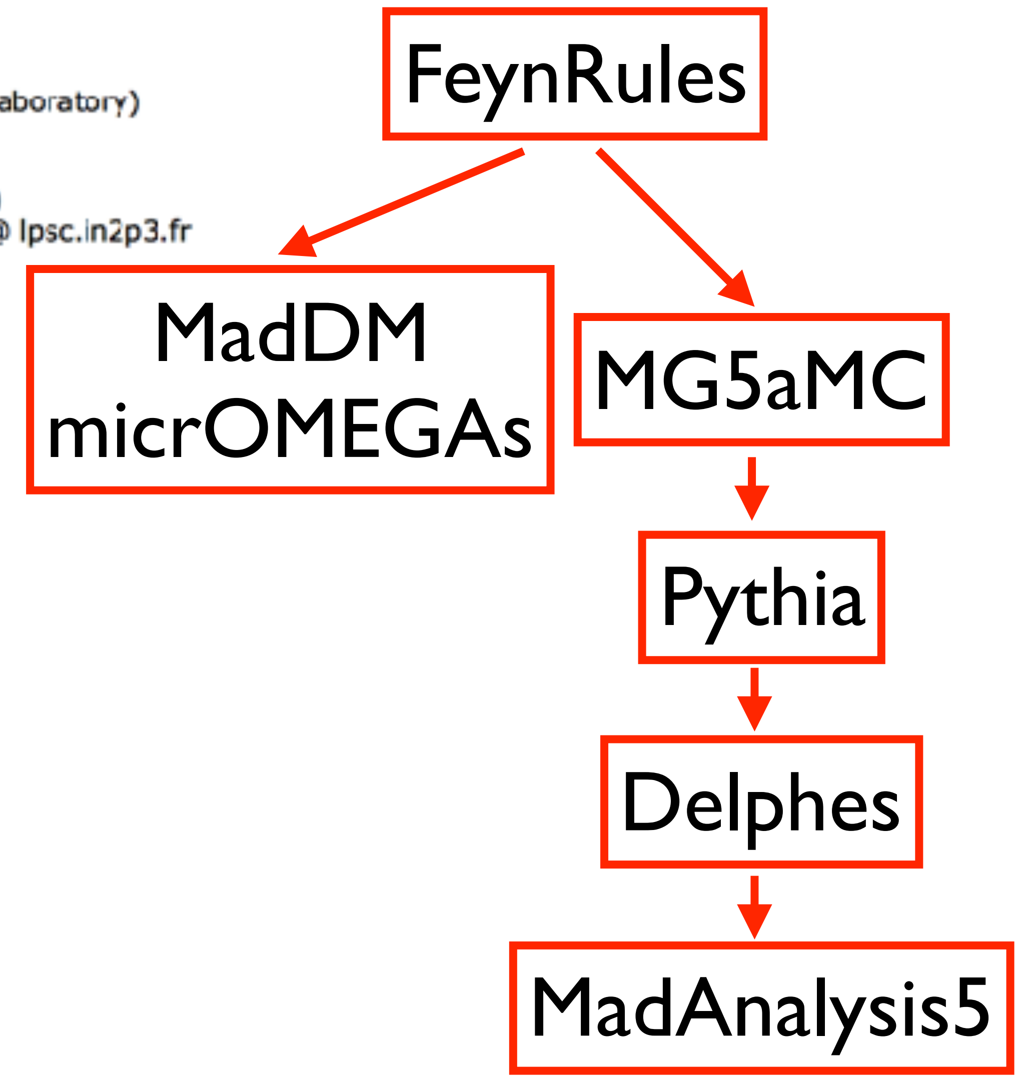
| Benchmark models for ATLAS and CMS Run-2 DM searches | | |
|---|---|---|
| | vector/axial vector mediator, $s$-channel (Sec. 2.1) | |
| Signature | State of the art calculation and tools | Implementation |
| jet + $\not{E}_T$ | **NLO+PS (powheg, SVN r3059)** | [ForI; Foro] |
| | NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0) | [New] |
| | NLO (MCFM v7.0) | Upon request |
| $W/Z/\gamma + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Fora] |
| | NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0) | [New] |
| | scalar/pseudoscalar mediator, $s$-channel (Sec. 2.2) | |
| Signature | State of the art calculation and tools | Implementation |
| jet + $\not{E}_T$ | **LO+PS, top loop (powheg, r3059)** | [Forn; Form] |
| | LO+PS, top loop (*DMsimp* UFO + MadGraph5_aMC@NLO v.2.3.0) | [New] |
| | LO, top loop (MCFM v7.0) | Upon request |
| $W/Z/\gamma + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | |
| $t\bar{t}, b\bar{b} + \not{E}_T$ | **LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)** | [Ford] |
| | NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0) | [New] |

Backovic, Kramer, Maltoni, Martini, KM, Pellen [1508.05327, EPJC] feynrules.irmp.ucl.ac.be/wiki/DMsimp

# Simplified dark matter models

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

$$\{g_t,\ g_X,\ m_X,\ m_Y\}$$




## Authors

- s-channel (spin-0 and spin-1)
  - Antony Martini (Université catholique de Louvain) & Kentarou Mawatari (LPSC Grenoble)
    - Emails: kentarou.mawatari @ lpsc.in2p3.fr
- s-channel (spin-0 and spin-1 electroweak)
  - Jian Wang (Johnnas Gutenberg University of Mainz) & Cen Zhang (Brookhaven National Laboratory)
    - Emails: cenzhang @ bnl.gov
- s-channel (spin-2)
  - Goutam Das (Saha Inst.), Celine Degrande (CERN) & Kentarou Mawatari (LPSC Grenoble)
    - Emails: goutam.das @ saha.ac.in, celine.degrande @ cern.ch, kentarou.mawatari @ lpsc.in2p3.fr

## 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.]
- Xv (vector DM)
- ...

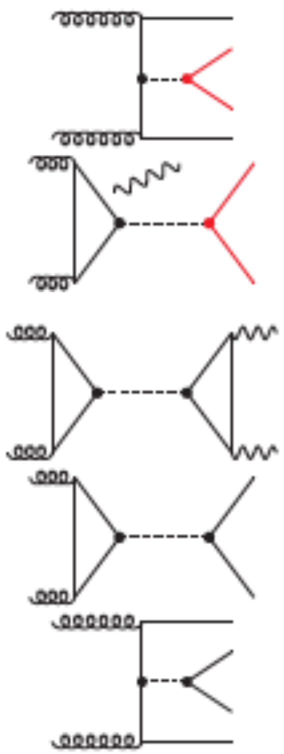
and different types of mediators:

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

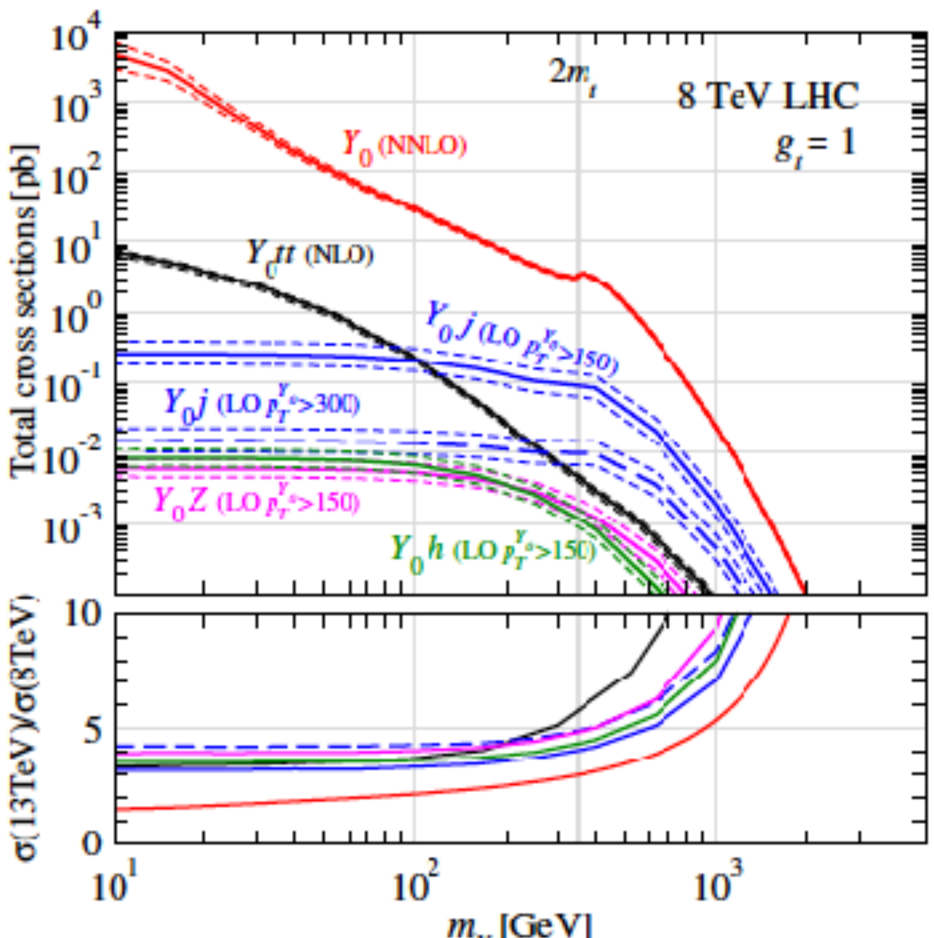
See more details in

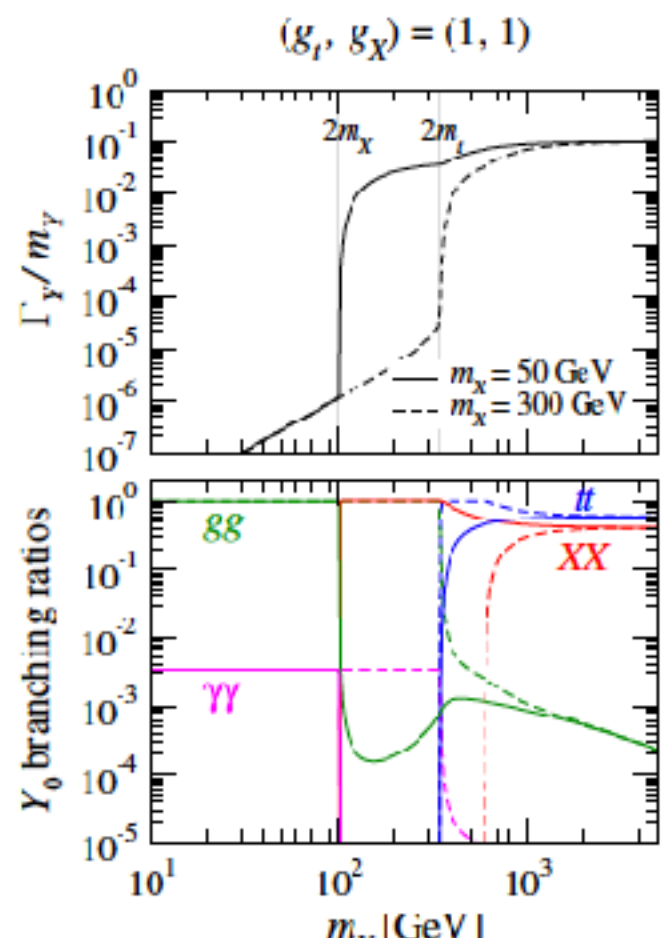
- 1508.00564 : O. Mattelaer, E. Vryonidou, "Dark matter production through loop-induced processes at the LHC: the s-channel mediator case" (EPJC75(2015)436).
- 1508.05327 : M. Backovic, M. Kramer, F. Maltoni, A. Martini, K. Mawatari, M. Pellen, "Higher-order QCD predictions for dark matter production at the LHC in simplified models with s-channel mediators" (EPJC75(2015)482).
- 1509.05785 : M. Neubert, J. Wang, C. Zhang, "Higher-order QCD predictions for dark matter production in mono-Z searches at the LHC" (JHEP1602(2016)082).
- 1605.09359 : G. Das, C. Degrande, V. Hirschi, F. Maltoni, H. Shao, "NLO predictions for the production of a spin-two particle at the LHC"
- 1701.07008 : S. Kraml, U. Laa, K. Mawatari, K. Yamashita, "Simplified dark matter models with a spin-2 mediator at the LHC".

# LHC(8TeV) constraints for top-philic DM

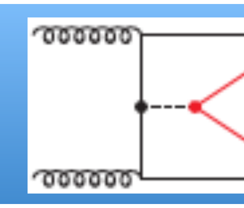


| Final state | Imposed constraint | Reference | Comments |
|---|---|---|---|
| $\not{E}_T + t\bar{t}$ | MadAnalysis5 PAD (new) | CMS [1504.03198] | Semileptonic top-antitop decay |
| $\not{E}_T + j$ | MadAnalysis5 PAD (new) | CMS [1408.3583] | |
| $\not{E}_T + Z$ | $\sigma(\not{E}_T > 150\text{ GeV}) < 0.85\text{ fb}$ | CMS [1511.09375] | Leptonic $Z$-boson decay |
| $\not{E}_T + h$ | $\sigma(\not{E}_T > 150\text{ GeV}) < 3.6\text{ fb}$ | ATLAS [1510.06218] | $h \to b\bar{b}$ decay |
| $jj$ | $\sigma(m_Y = 500\text{ GeV}) < 10\text{ pb}$ | CMS [1604.08907] | Only when $m_Y > 500$ GeV |
| $\gamma\gamma$ | $\sigma(m_Y = 150\text{ GeV}) < 30\text{ fb}$ | CMS [1506.02301] | Only when $m_Y > 150$ GeV |
| $t\bar{t}$ | $\sigma(m_Y = 400\text{ GeV}) < 3\text{ pb}$ | ATLAS [1505.07018] | Only when $m_Y > 400$ GeV |
| $t\bar{t}t\bar{t}$ | $\sigma < 32\text{ fb}$ | CMS [1409.7339] | Upper limit on the SM cross section |



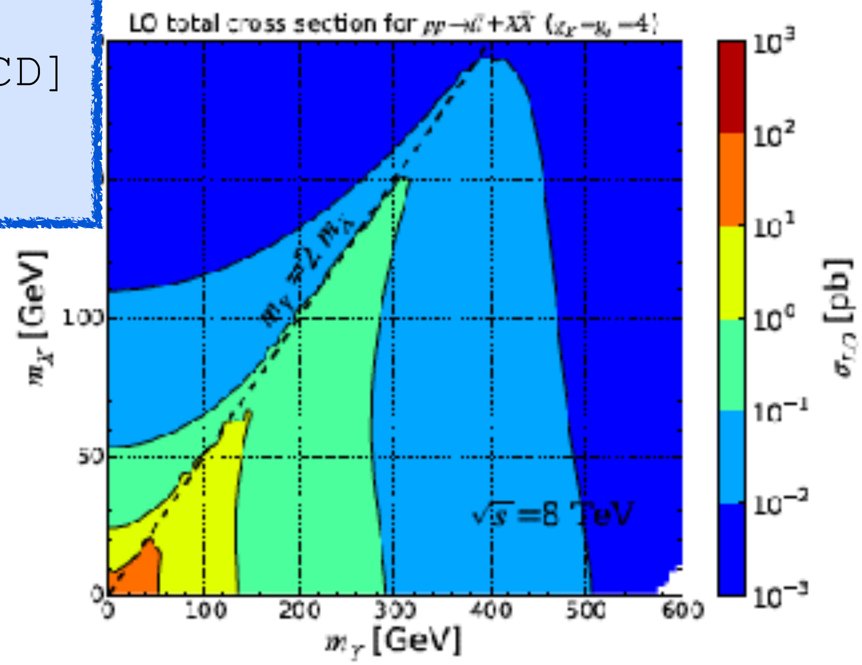



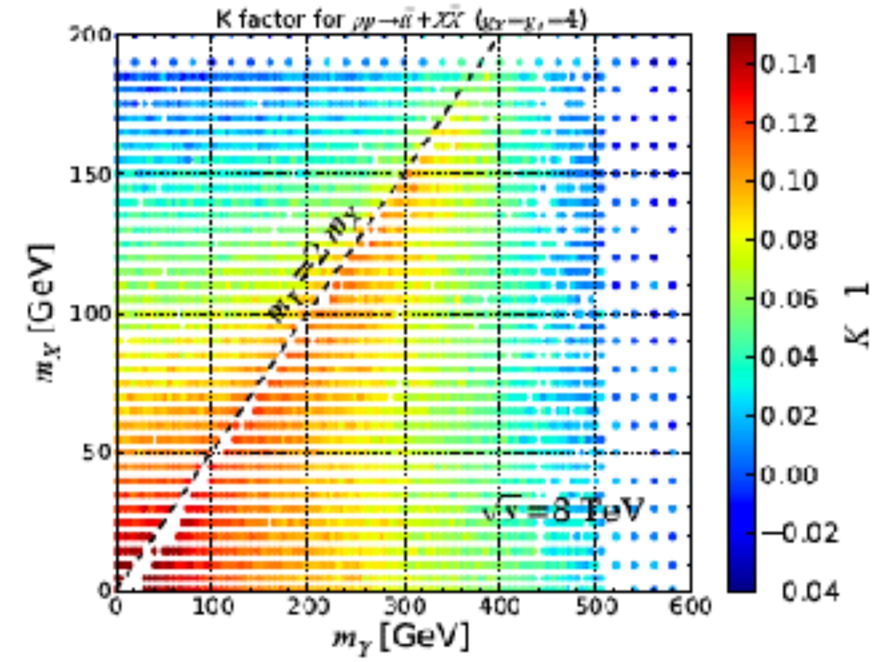
# MET + a top-quark pair (NLO)

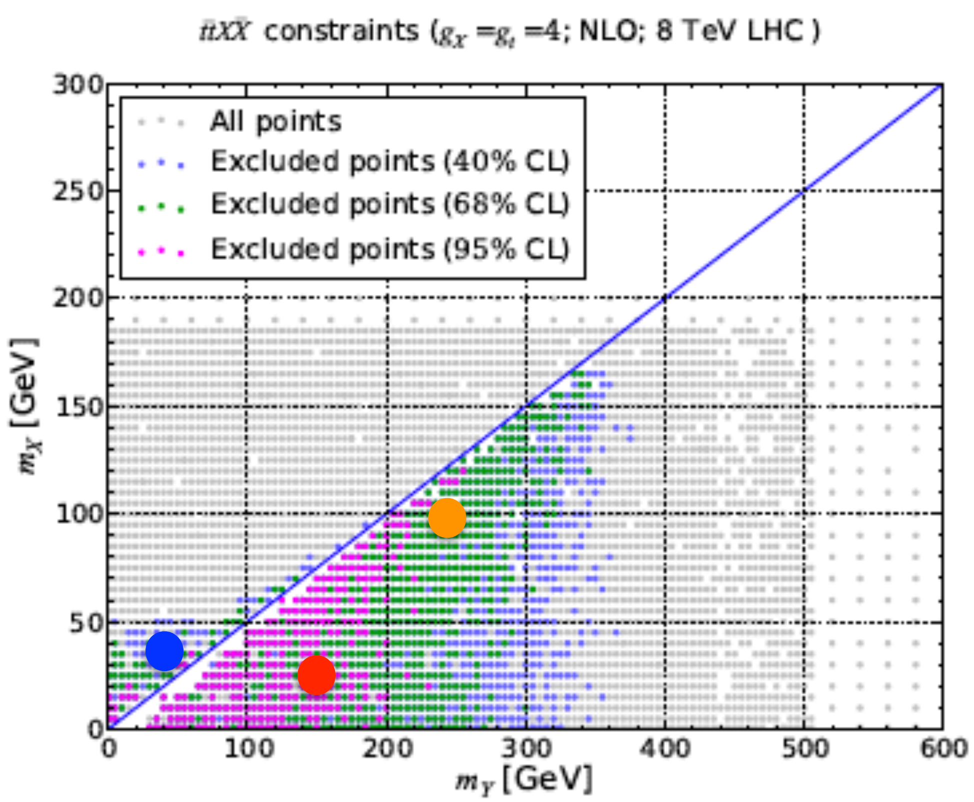


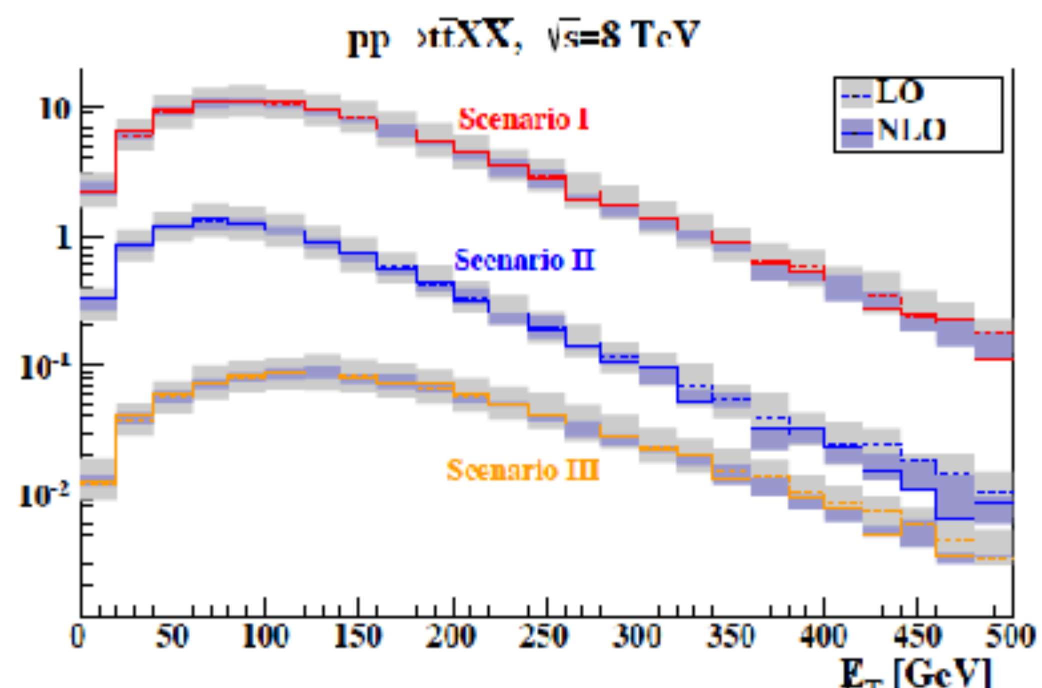
```
./bin/mg5_aMC
>import model DMsimp_s_spin0
>generate p p > t t~ xd xd~ [QCD]
>output
>launch
```

| $(m_Y, m_X)$ | $\sigma_{\rm LO}$ [pb] | $\sigma_{\rm NLO}$ [pb] |
|---|---|---|
| (150, 25) GeV | $0.658^{+34.9\%}_{-24.0\%}$ | $0.773^{+6.1\%}_{-10.1\%}$ |
| (40, 30) GeV | $0.776^{+34.2\%}_{-24.1\%}$ | $0.926^{+5.7\%}_{-10.4\%}$ |
| (240, 100) GeV | $0.187^{+37.1\%}_{-24.4\%}$ | $0.216^{+6.7\%}_{-11.4\%}$ |



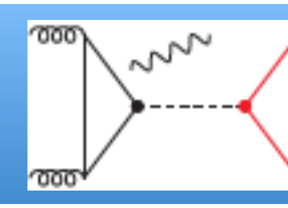



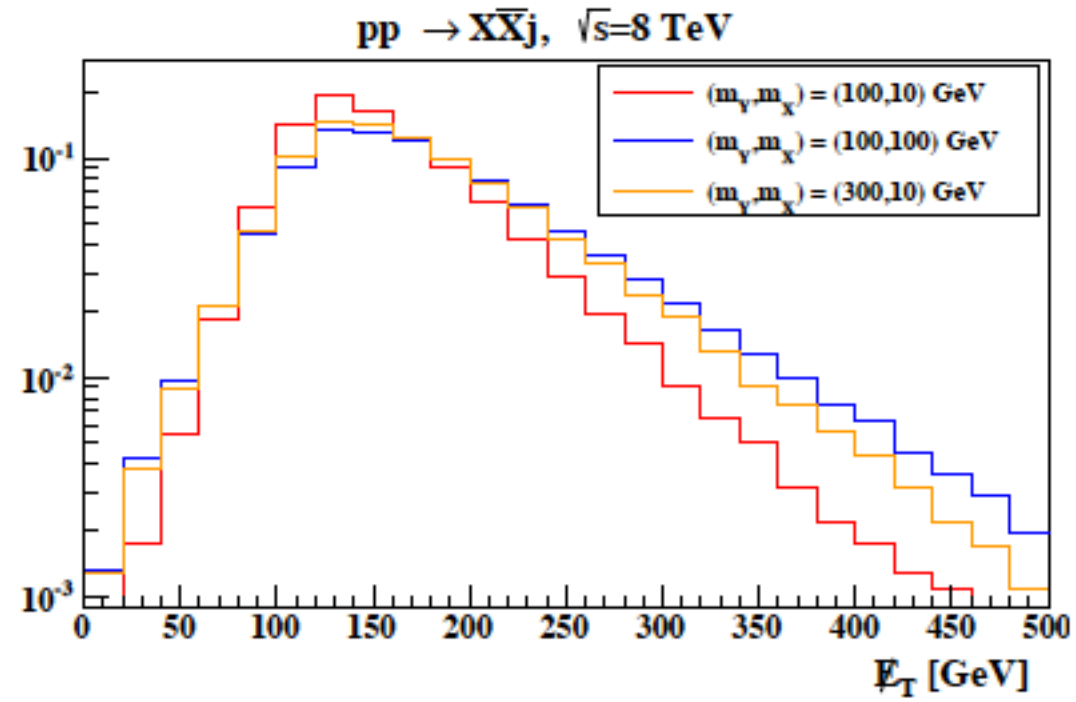




NLO predictions reduce the theoretical uncertainty.

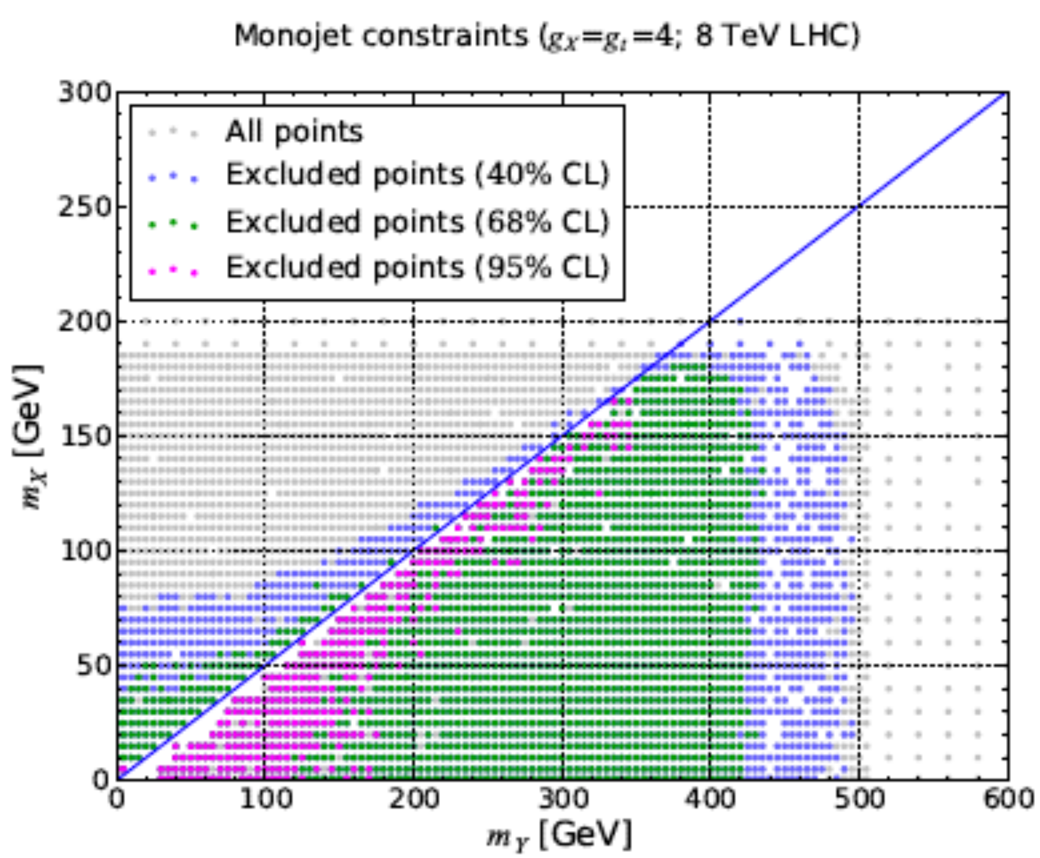
# Mono-jet (LO loop-induced)

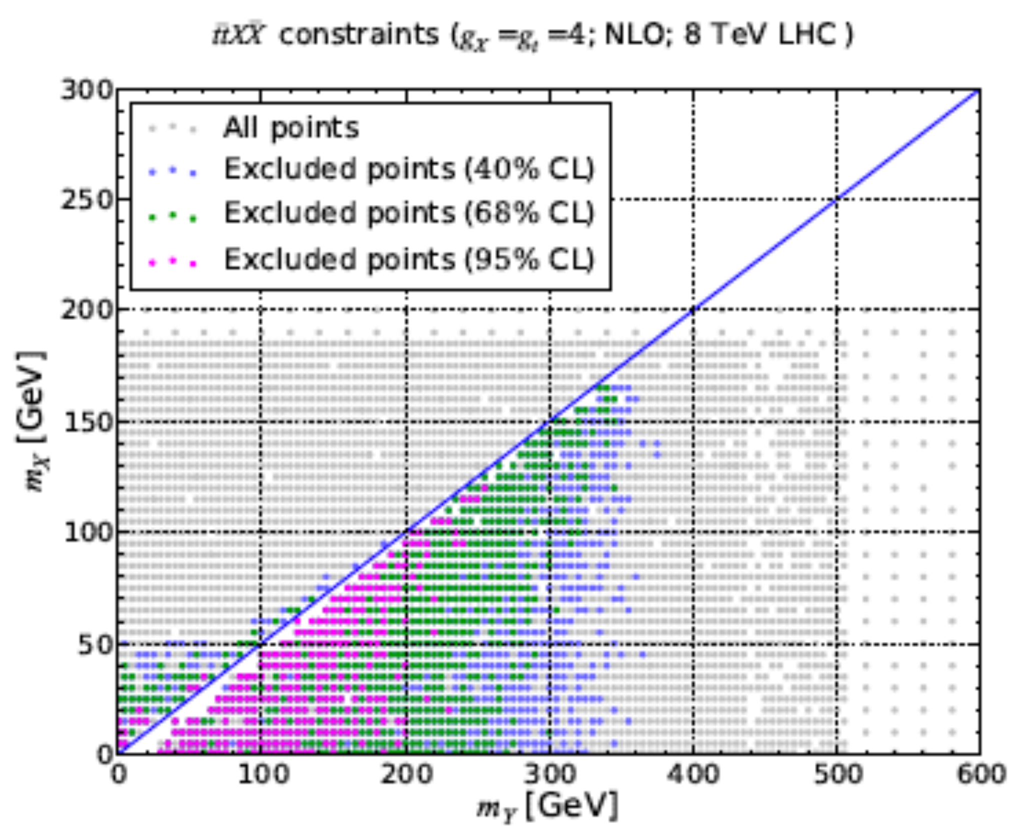


```
./bin/mg5_aMC
>import model DMsimp_s_spin0
>generate p p > j xd xd~ [QCD]
>output
>launch
```

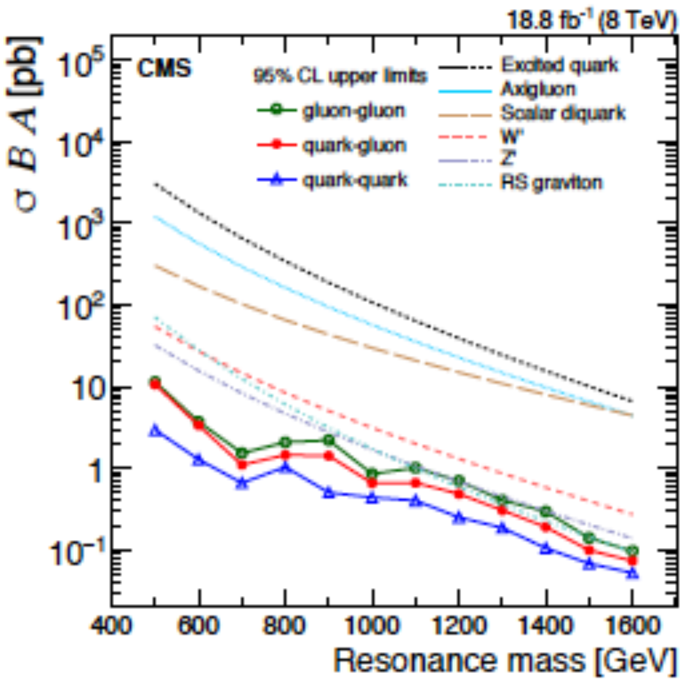


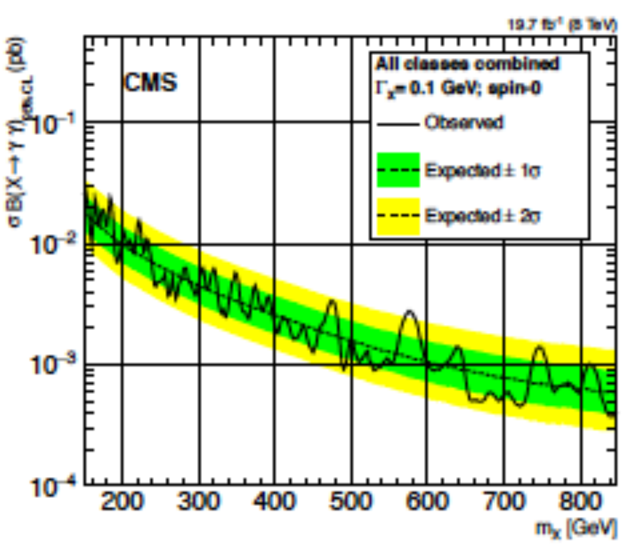

Complementarity between the different searches.

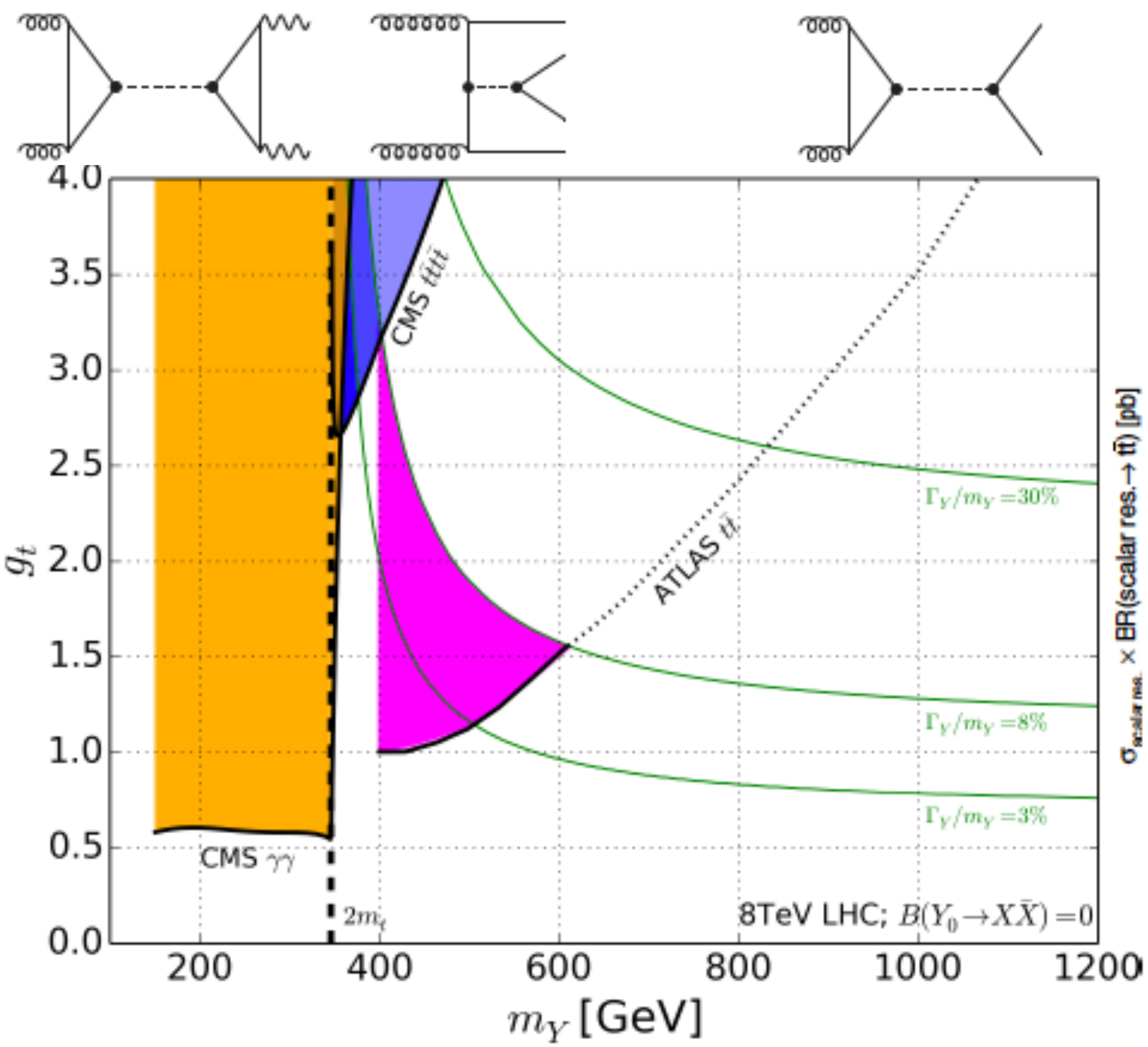


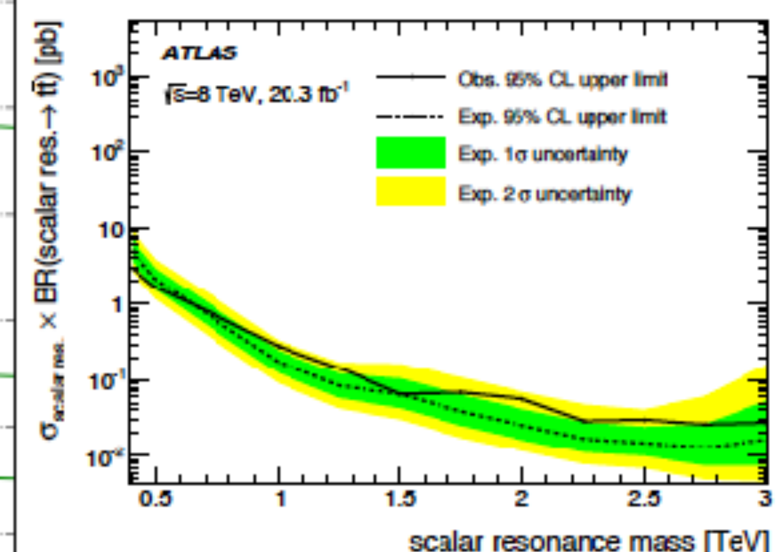
# Resonance search constraints




Extension of the search range is desirable.




| | | | |
|---|---|---|---|
| $jj$ | $\sigma(m_Y = 500\text{ GeV}) < 10\,\text{pb}$ | 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 $m_Y > 150\,\text{GeV}$ |
| $t\bar{t}$ | $\sigma(m_Y = 400\text{ GeV}) < 3\,\text{pb}$ | 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 |

# Relic vs. Direct detection vs. LHC

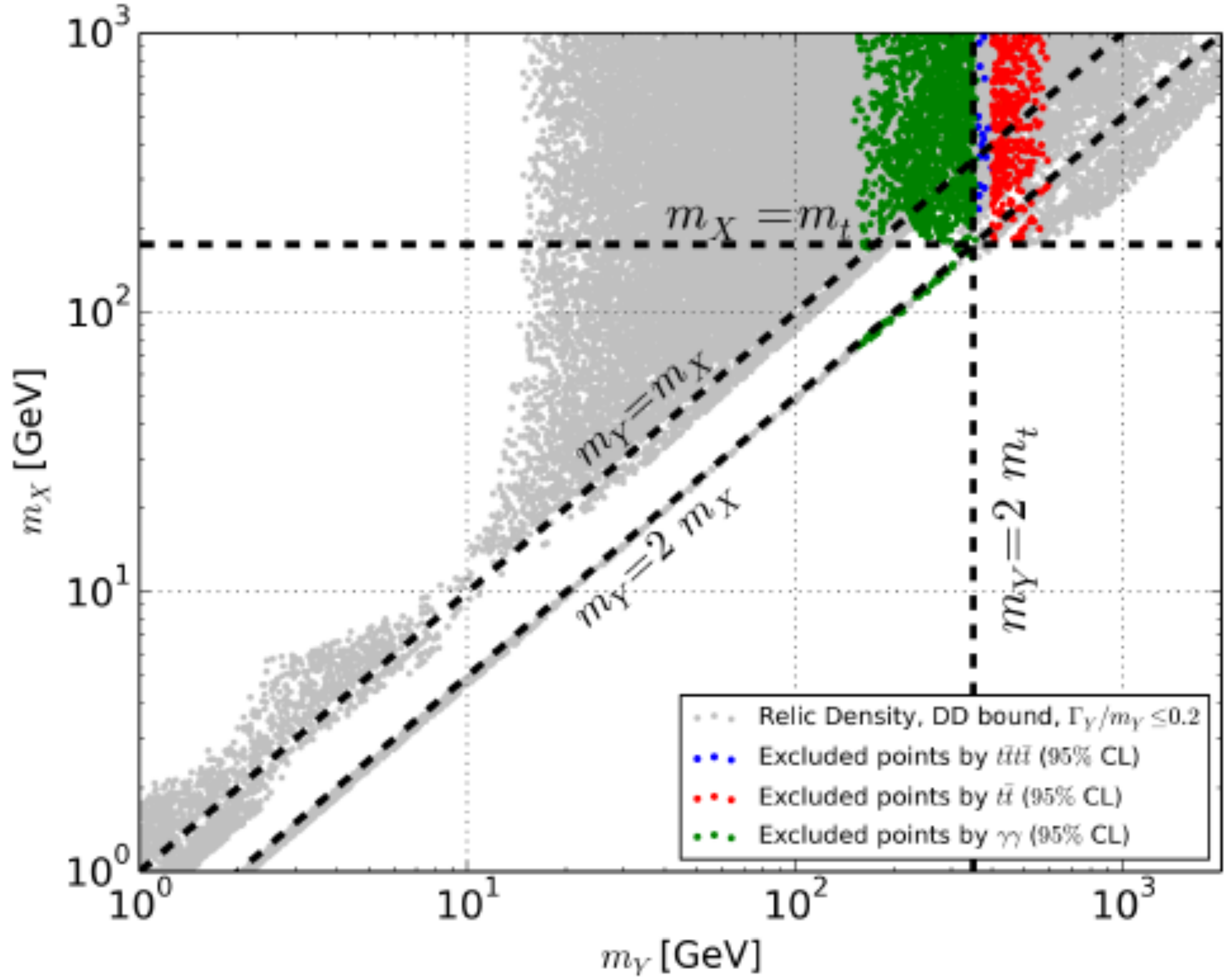
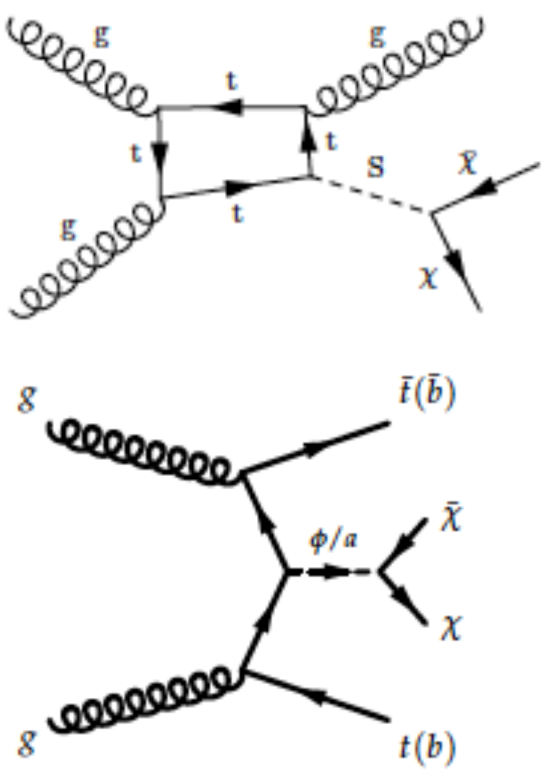
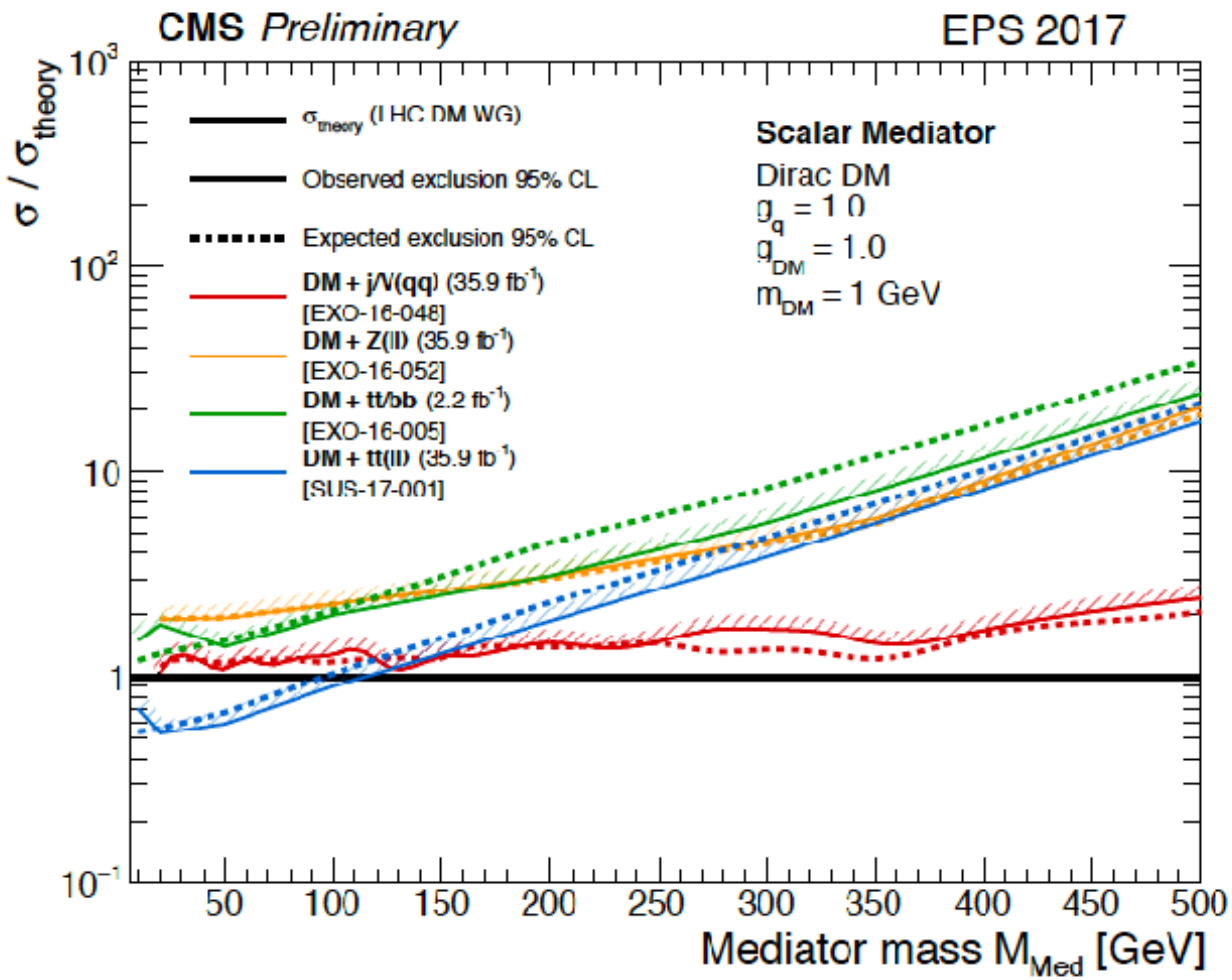



**Figure 14.** Results of our four-dimensional parameter scan projected onto the $(m_Y, m_X)$ plane once constraints set from the LHC results are imposed. The points excluded by the diphoton, the $t\bar{t}$ and the four-top considered searches all satisfy the relic density, narrow width and direct detection constraints.

# 13TeV MET constraints on top-philic DM



# Towards the next generation of simplified Dark Matter models

arXiv:1607.06680

# Spin-2 mediated simplified DM models

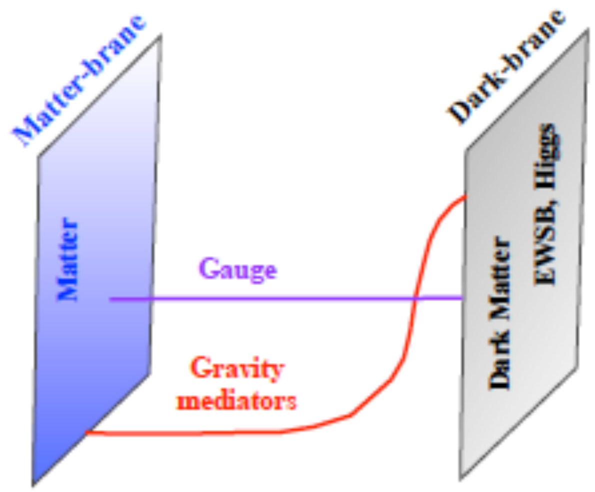
Gravity-mediated DM:
Lee, Park, Sanz [1306.4107, 1401.5301]
Rueter, Rizzo, Hewett [1706.07540]

$$\mathcal{L}_X^{Y_2} = -\frac{1}{\Lambda} g_X^T \, T_{\mu\nu}^X Y_2^{\mu\nu}$$

Kraml, Laa, KM, Yamashita [1701.07008, EPJC]

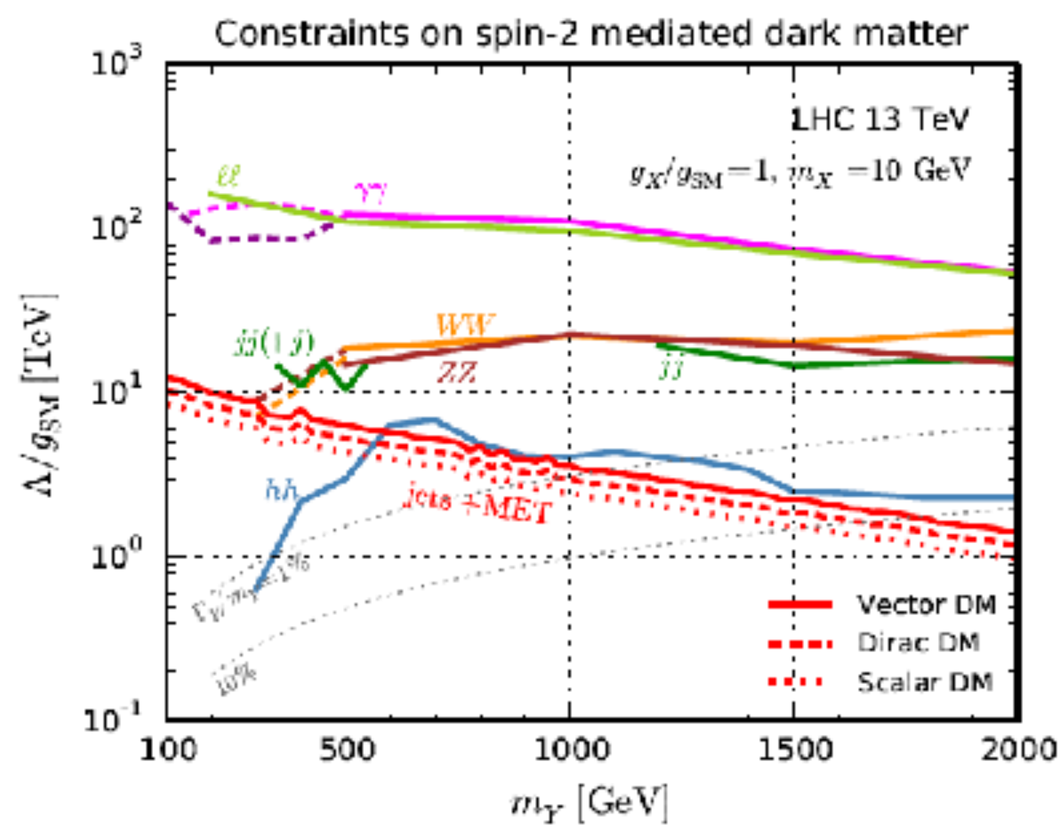
$$\mathcal{L}_{\rm SM}^{Y_2} = -\frac{1}{\Lambda} \sum_i g_i^T \, T_{\mu\nu}^i Y_2^{\mu\nu}$$

$$g_{\rm SM} \equiv g_H^T = g_q^T = g_\ell^T = g_g^T = g_W^T = g_B^T$$




$$\{m_X, \, m_Y, \, g_X/\Lambda, \, g_{\rm SM}/\Lambda\}$$

- Which analyses can constrain the model at the LHC ?
- Which analyses can provide the best constraint ?
- Can we find some interesting parameter space ?



# Summary and outlook

- 暗黒物質探索(collider + non-collider)のための系統的シミュレーションフレームワークが発展している。
  - LHC Dark Matter Working Group
  - EFT ↔ Simplified models ↔ UV-completed models (e.g. SUSY)
- 高次補正の重要性
  - 信頼できる生成断面積、理論の不定性の縮小
- 一つのDMモデルを多角的に攻める。
- Recasting/reinterpretation の重要性