# Dark Matter @ Colliders

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**BSM lectures @ NPAC**

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# Outline

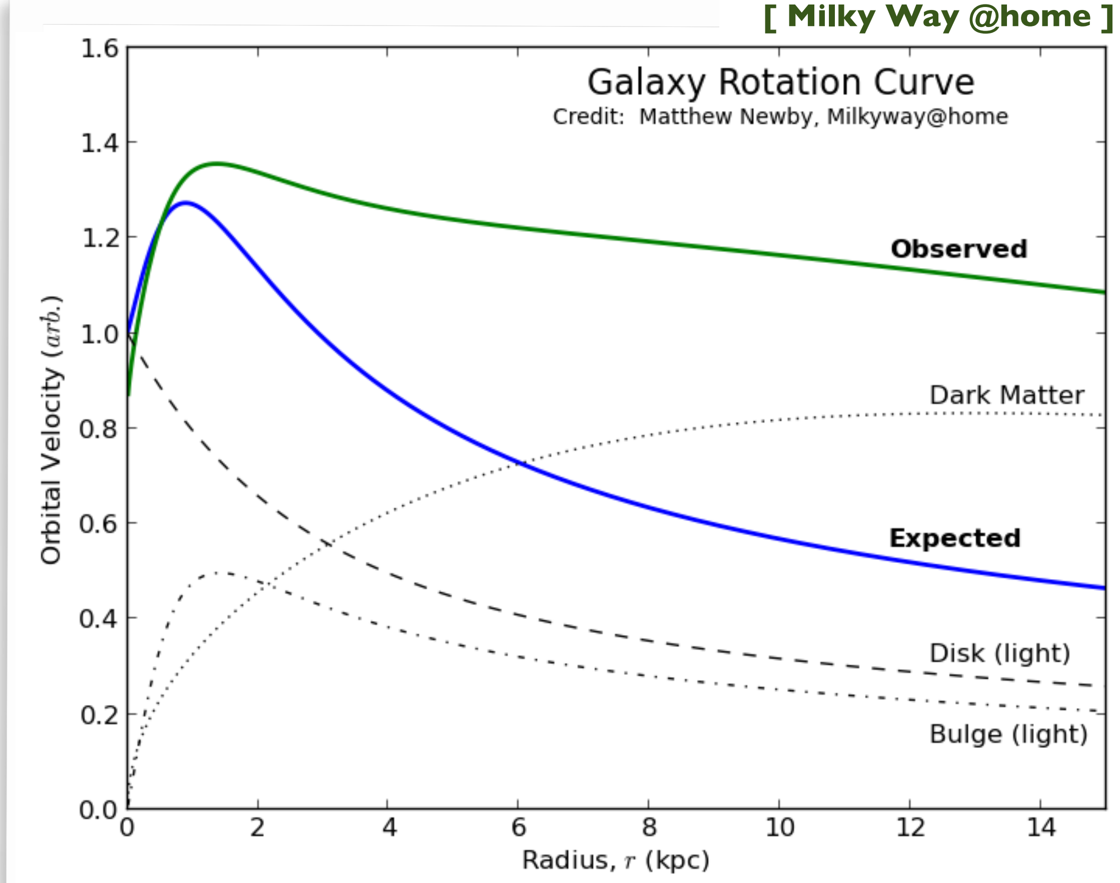
1. Dark matter from a collider perspective
2. Interpretation of dark matter collider search results
3. Summary

# New physics and dark matter

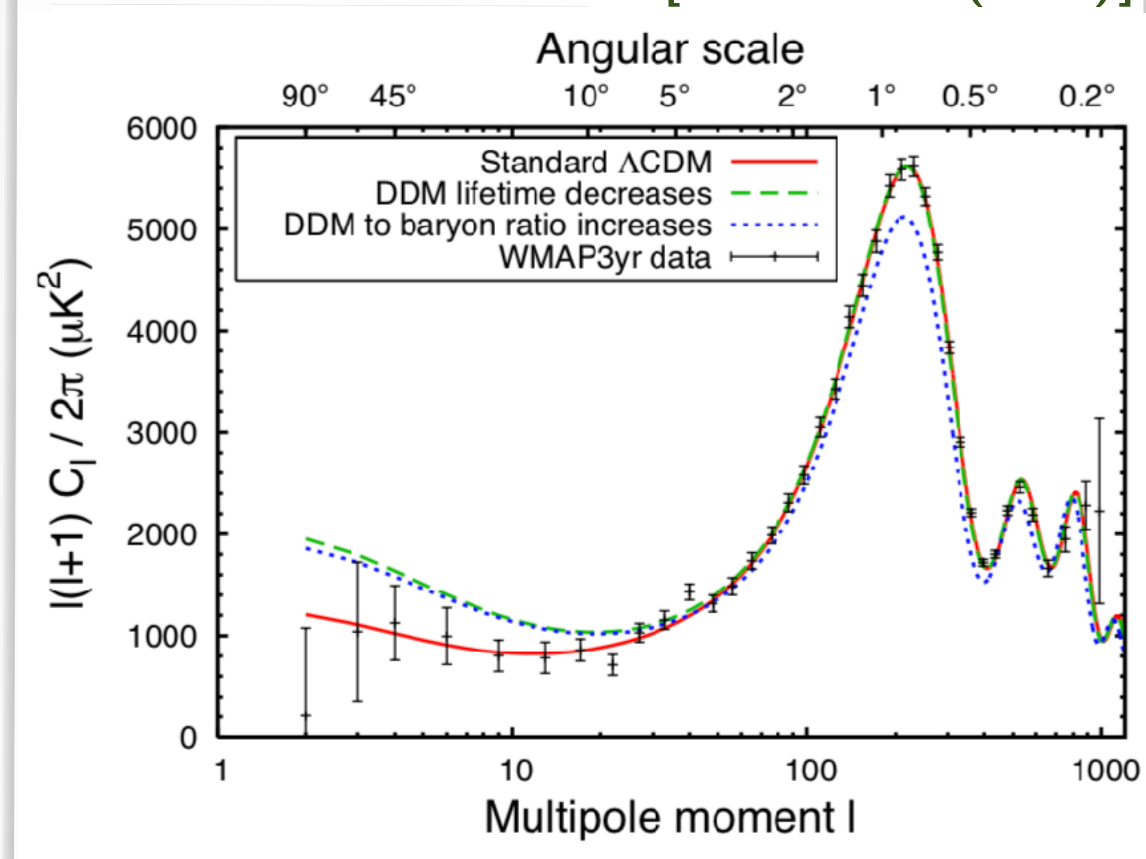
- ✦ Dark matter is an important motivation for new physics
  - ✤ Flattening of the galaxy rotation curves
  - ✤ Gravitational lensing
  - ✤ Cosmic microwave background
  - ✤ Structure formation

Enormous endeavour to detect dark matter

[ Milky Way @home ]




[ Lattanzi & Valle (PRL`07) ]

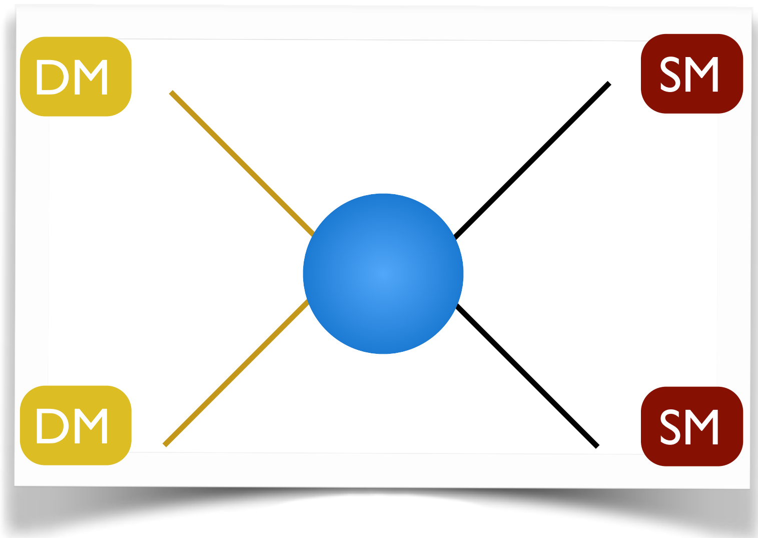


# Dark matter in cosmology and at colliders

✦ Dark matter is searched for directly, indirectly and at colliders

✤ This huge experimental effort offers a strategy to constrain models

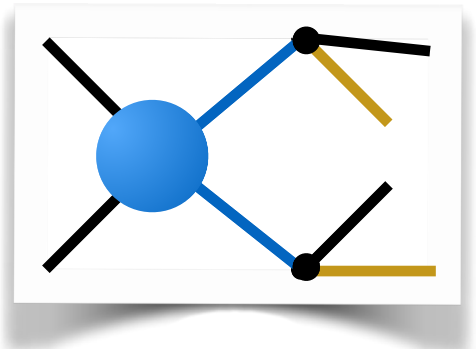
✦ Complementary between colliders and cosmology




✤ Dark matter relic abundance must be reproduced

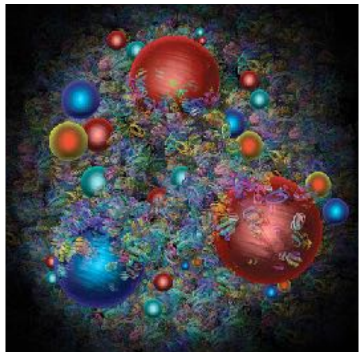
✤ Dark matter direct/indirect detection constraints

✤ Direct production at (hadron) colliders
(or from the decay of heavier states)



# From dark matter to missing transverse energy

- Hadron collisions: scattering of the proton constituents
  - Unknown *partonic* centre-of-mass energy $\sqrt{\hat{s}}$
    - Larger $\sqrt{\hat{s}}$ ➢ heavier new particles
  - Unknown longitudinal momenta
    - Use of quantities invariant under longitudinal boosts ($p_T$, *etc.*)



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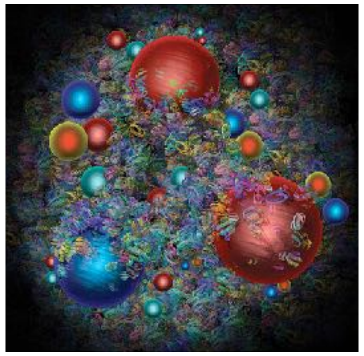

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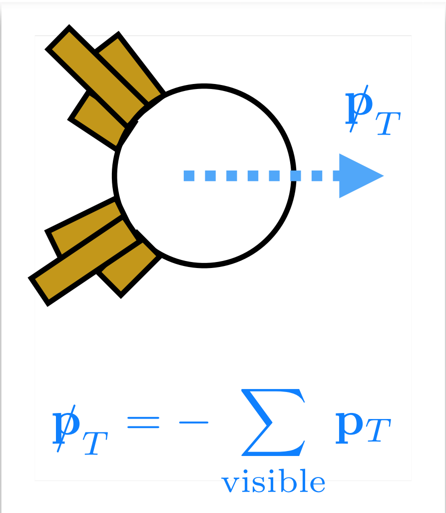


## ✦ Energy-momentum conservation (in the transverse plane)

- ✤ The initial-state total transverse momentum is zero
  - ➢ the final-state total $p_T$ is zero
- ✤ Invisible particles (DM in particular) ≡ missing momentum
  - ★ Weakly interacting and neutral ➢ detector is transparent
  - ★ Presence inferred from momentum imbalance

$$\not{E}_T = ||\not{\mathbf{p}}_T|| = \left|\left| - \sum_{\text{visible}} \mathbf{p}_T \right|\right|$$

- ✤ Beware: MET ≠ DM
  - ★ MET could originate from neutral long-lived states, or even neutrinos
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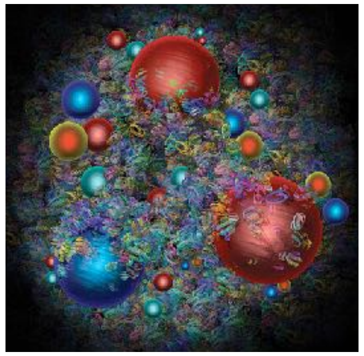

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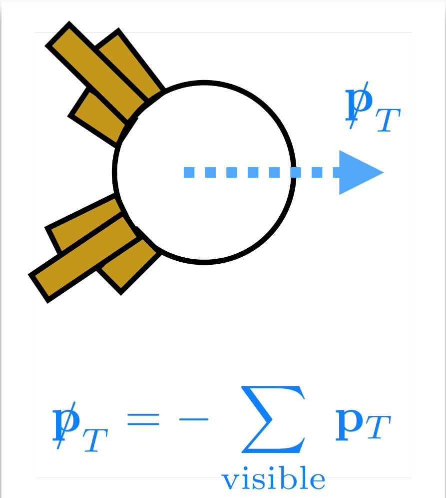


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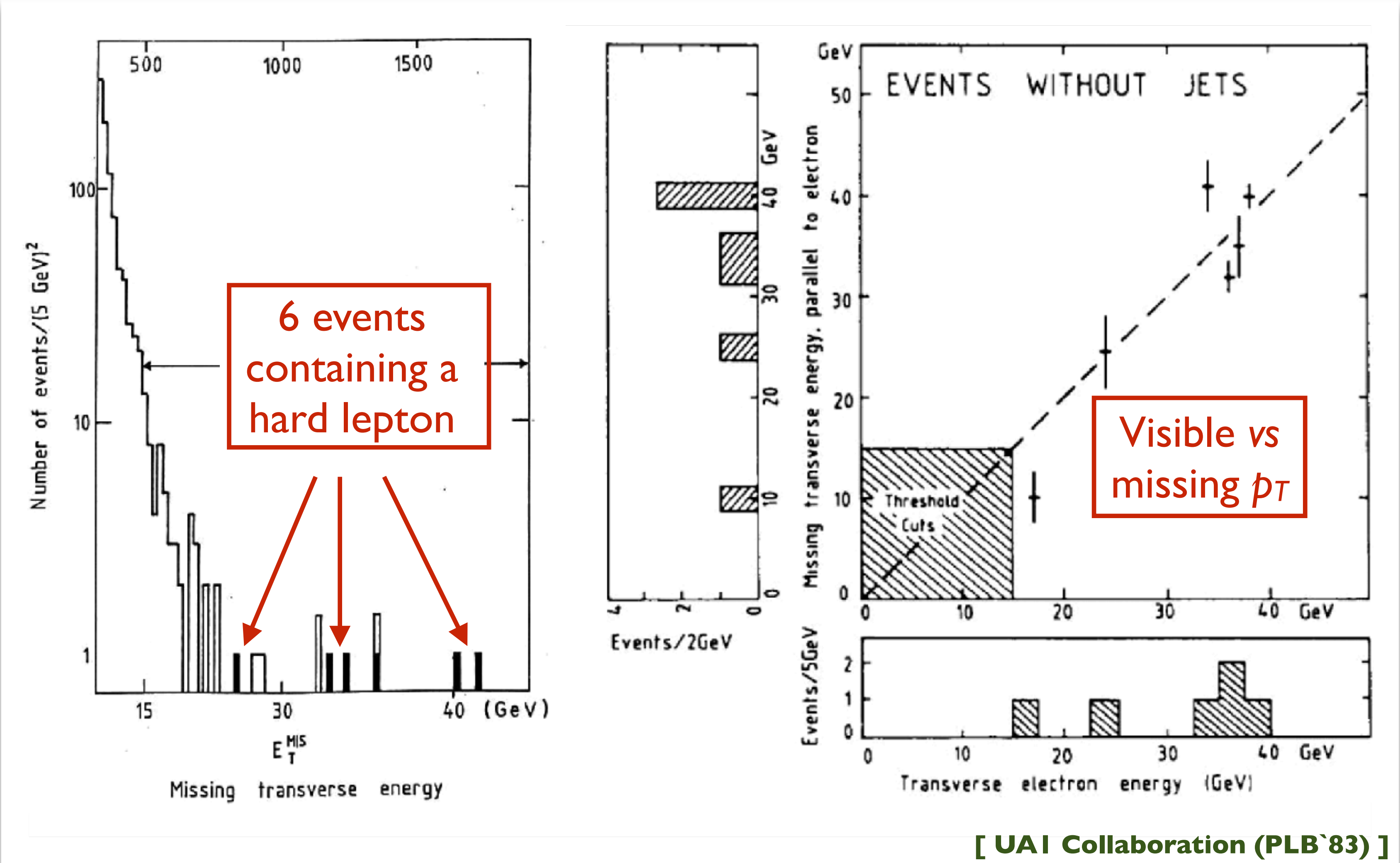
**How to detect missing energy?**

# Detecting missing energy at colliders (I)

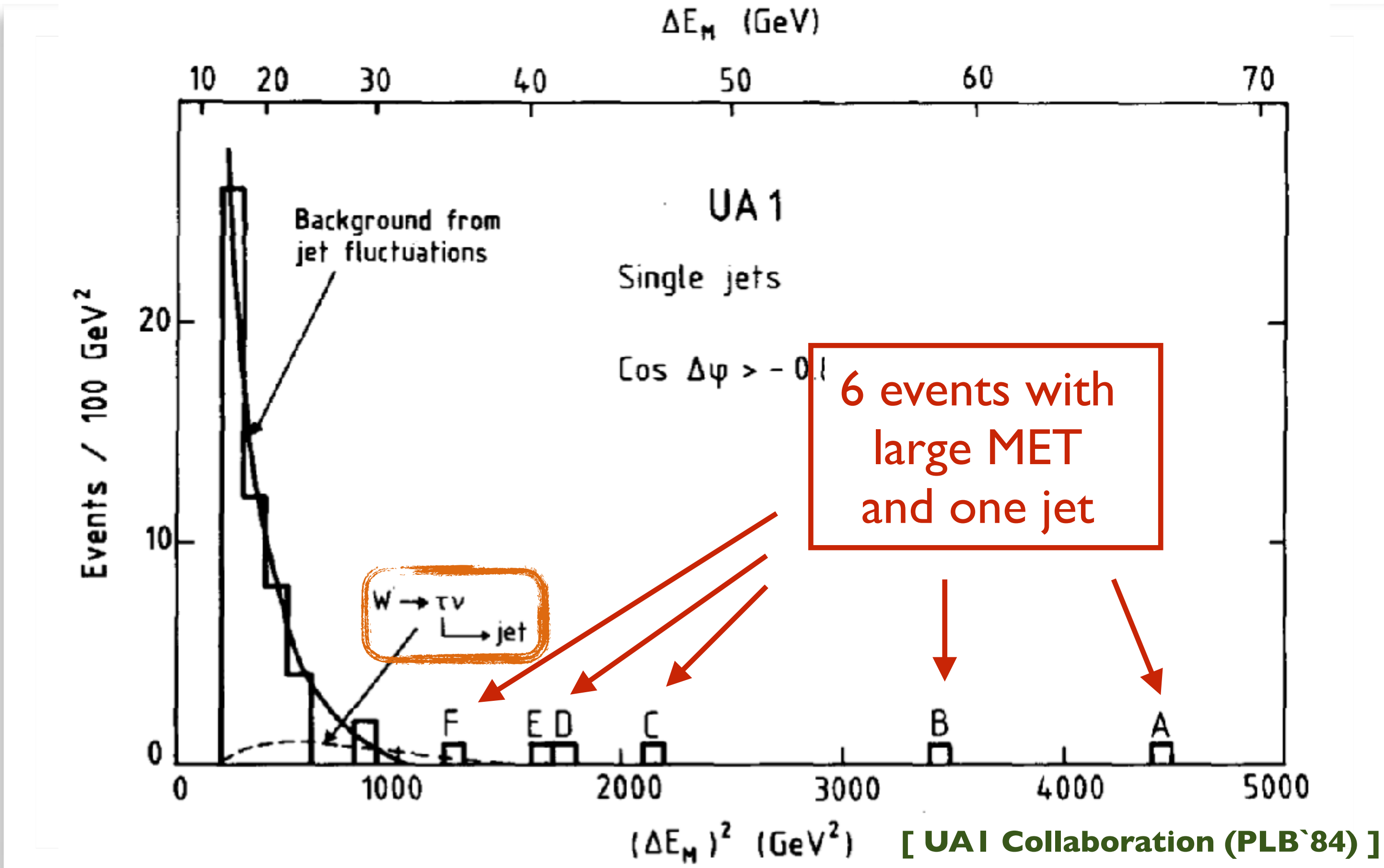
- Missing transverse energy detection 40 years ago
  - This neither new nor typical of modern colliders
  - W-boson discovery in 1983 (with 6 events) ➢ $M_W = 81 \pm 5$ GeV




[ UA1 Collaboration (PLB`83) ]

# Detecting missing energy at colliders (2)

- Missing transverse energy detection 40 years ago
  - Jets and missing energy in UA1
  - Not considered DM-related at that time
  - No SM explanation → *W*+jets (in orange) , invisible *Z*+jets, *etc.*

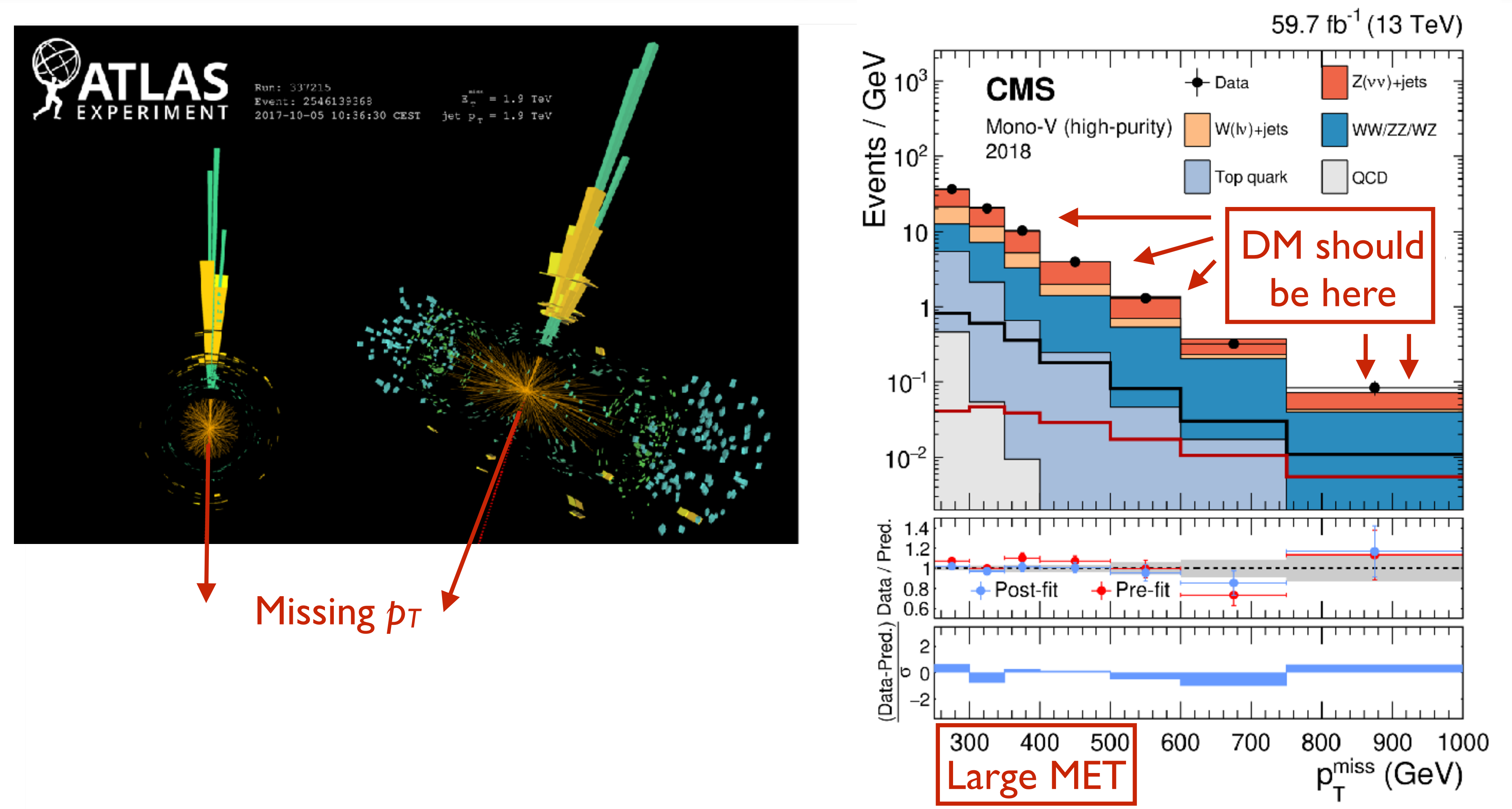



[ UA1 Collaboration (PLB`84) ]

# Detecting missing energy at colliders (3)

✦ Missing transverse energy at the LHC: 40 years fast forward

- Searching for a signal with a lot of missing energy
- The missing momentum recoils against visible objects




[ CMS-EXO-20-004 ]

# Dark matter signatures at the LHC

- ✦ Dark matter signatures
  - ✤ Missing transverse energy (carried away by the DM particles)
  - ✤ Visible stuff (triggers, handles for background rejection, *etc.*)
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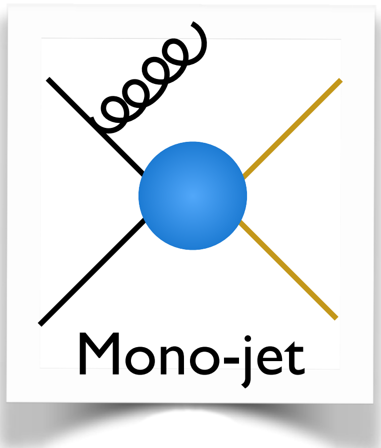

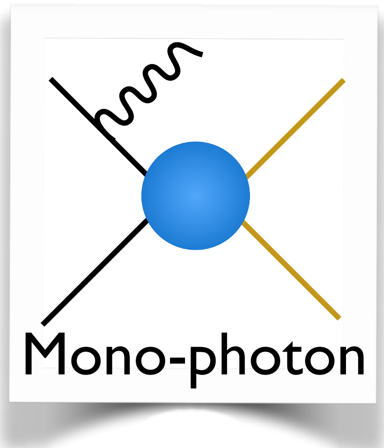

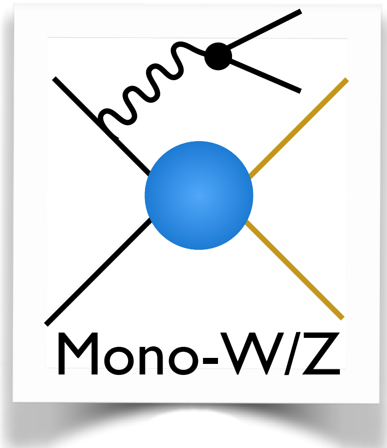

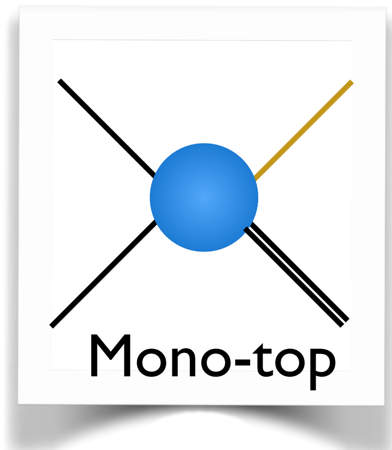

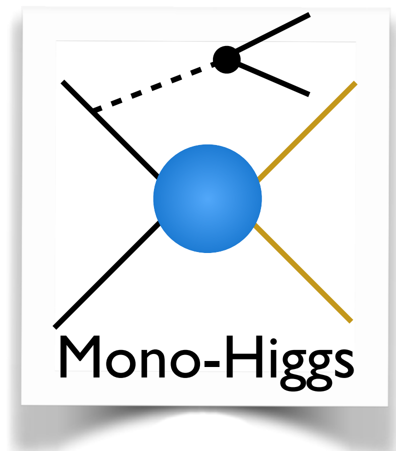

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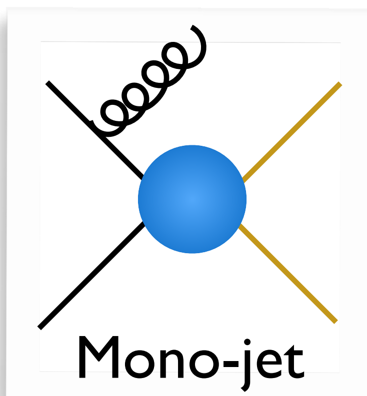
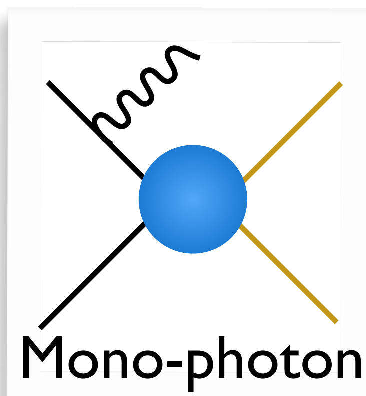
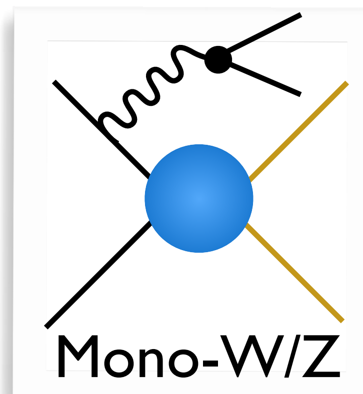
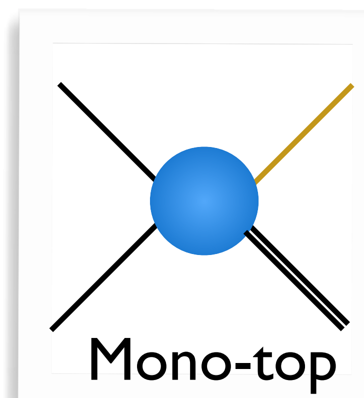
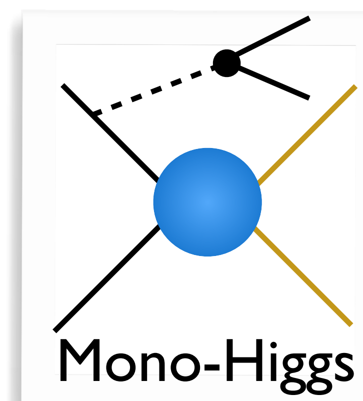


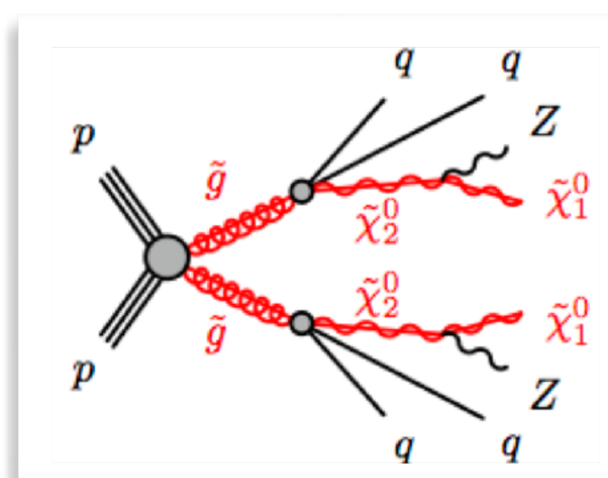




- ✤ More complicated signals also considered
  - ★ Multi-jets and missing energy
  - ★ Multiple leptons, jets and missing energy
  - ★ Top-antitop pair and missing energy
  - ★ *etc.*



# Almost two decades of mono-X searches…

✦ The mono-X (DM) story is almost 20 years old
- ✤ The problem was to trigger on DM signals → need for a visible object
- ✤ Introduced first as mono-photons in lepton collisions [ Birkedal, Matchev & Perelstein (PRD`04) ]
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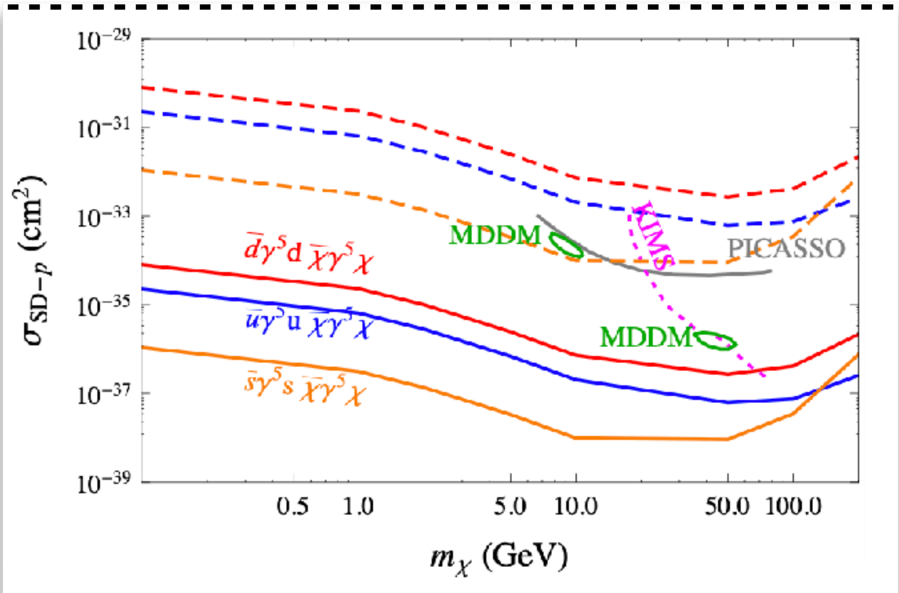
## ✦ Colliders meet direct detection

- ✤ Applied to the LEP and Tevatron case
- ✤ Limits set in the same parameter space
- ✤ Light DM becomes accessible through mono-jets and mono-photons

**[ Bai, Fox & Harnik (JHEP`10) ]**

**[ Fox, Harnik, Kopp & Tsai (PRD`11) ]**



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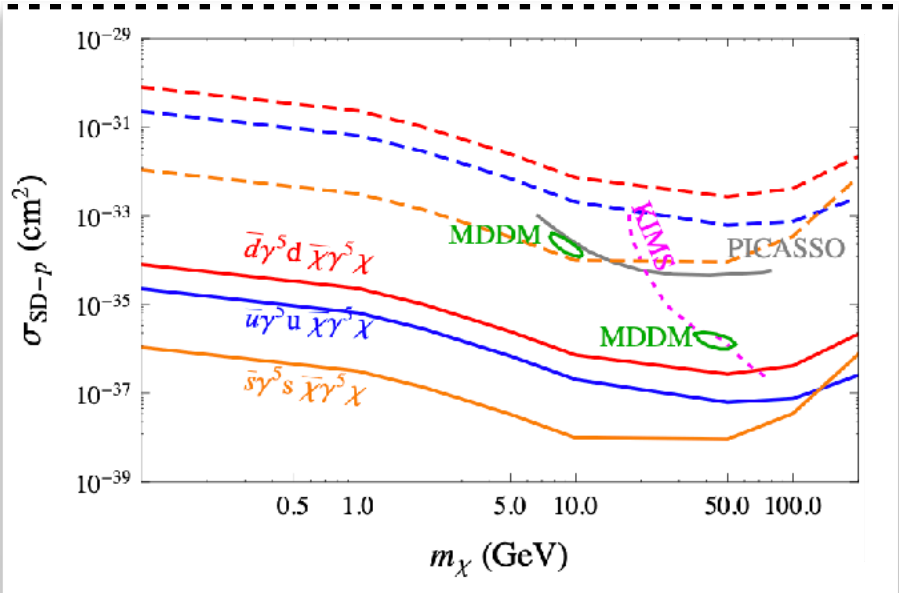


## ✦ Towards the modern epoch

- ✤ New dark signals: mono-top, mono-Z, mono-lepton & mono-Higgs

[ Andrea, BF & Maltoni (PRD`11); Bell, Dent, Galea, Jacques, Krauss & Weiler (PRD`12); Bai & Tait (PLB`13); Petrov & Shepherd (PLB`14) ]

- ✤ First experimental studies: CDF, and then ATLAS/CMS

# A dark matter search strategy at the LHC

- A typical LHC dark matter search strategy
  - Requirement of a significant amount of missing transverse energy
  - Requirement of a significantly hard visible object (jet, di-lepton pair, photon, *etc.*)
  - Extra constraints (angular correlations, vetoes, *etc.*) to reduce the backgrounds
  - Cut and count and looking for excesses over the background

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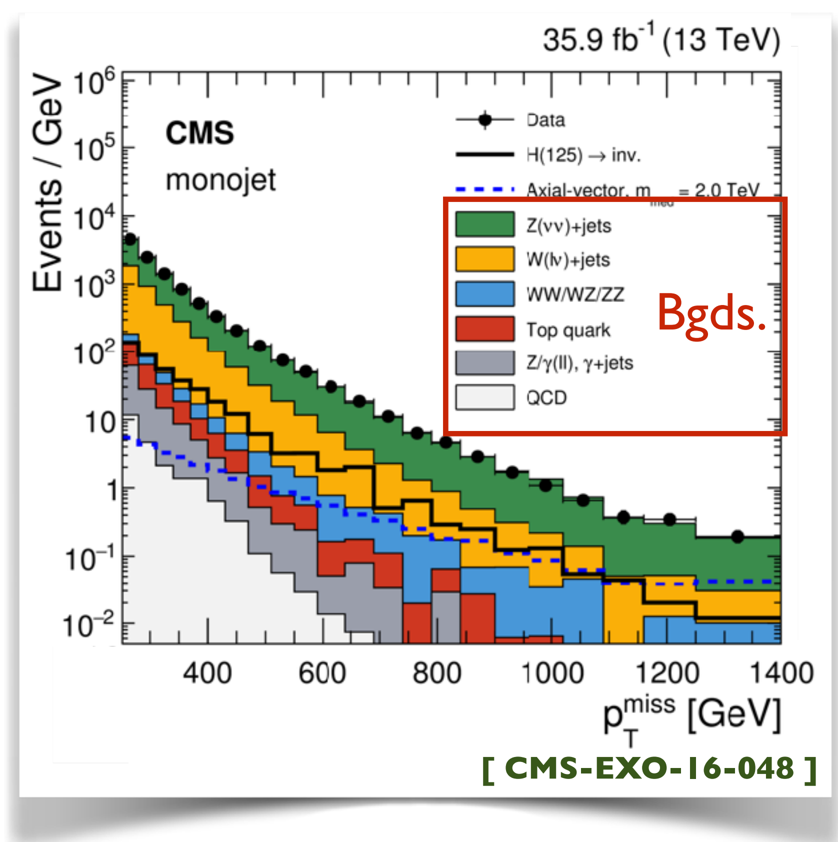
## ✦ Backgrounds - the mono-jet case

- ✤ Invisible *Z* decays
  - → irreducible backgrounds
- ✤ W decays with a lost lepton
  - → not very frequent but large (total) rate
- ✤ Mis-measurements in multi-jet production
  - → rare, but huge QCD total rate
  - → steeply falling with the MET value

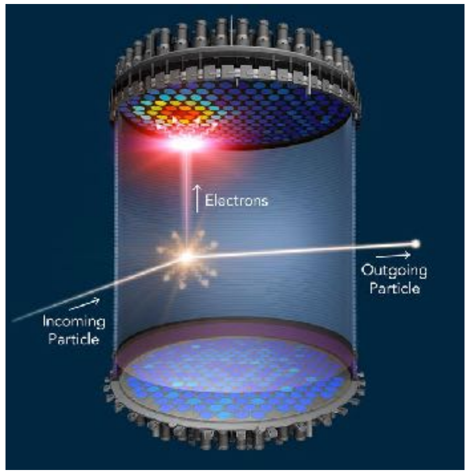


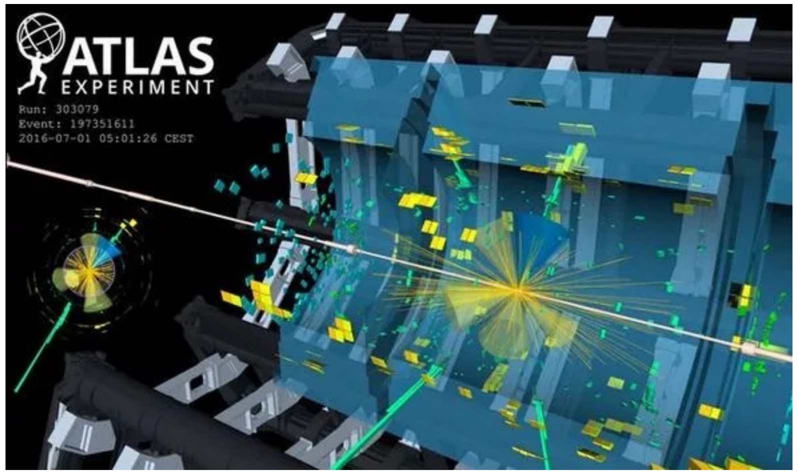
# Outline

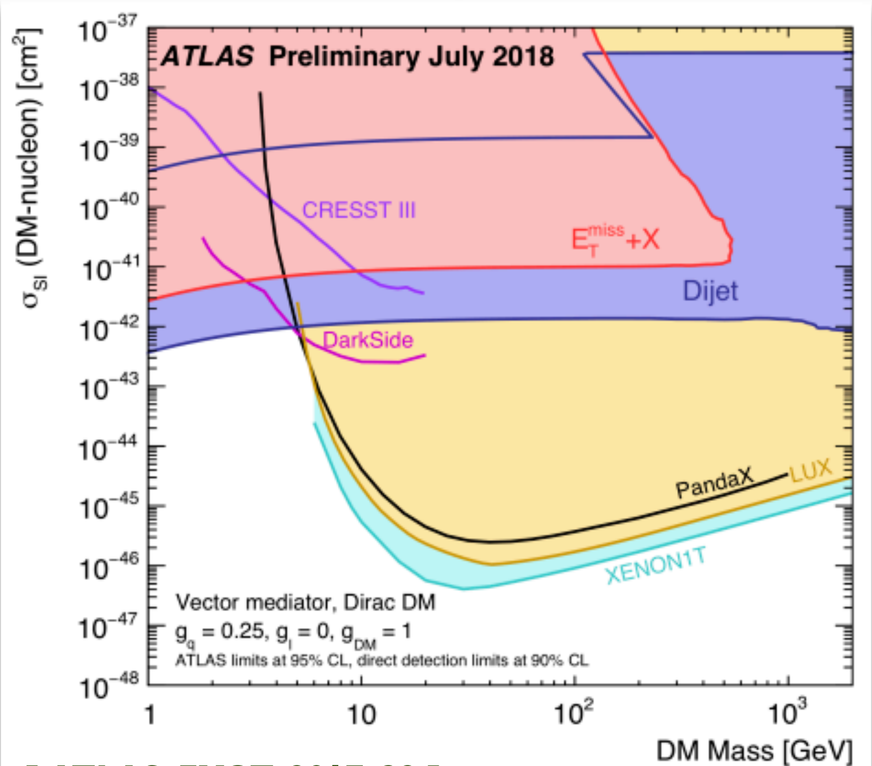
# An EFT interpretation

# Connecting direct detection and colliders

✦ No mono-X excess wrt the SM background
- ✤ Limits can be set on DM and its properties
  - ➢ in the same plane as for direct detection




[ ATLAS-EXOT-2017-32 ]

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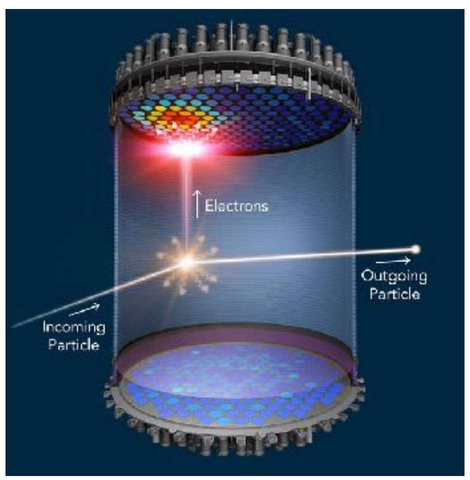


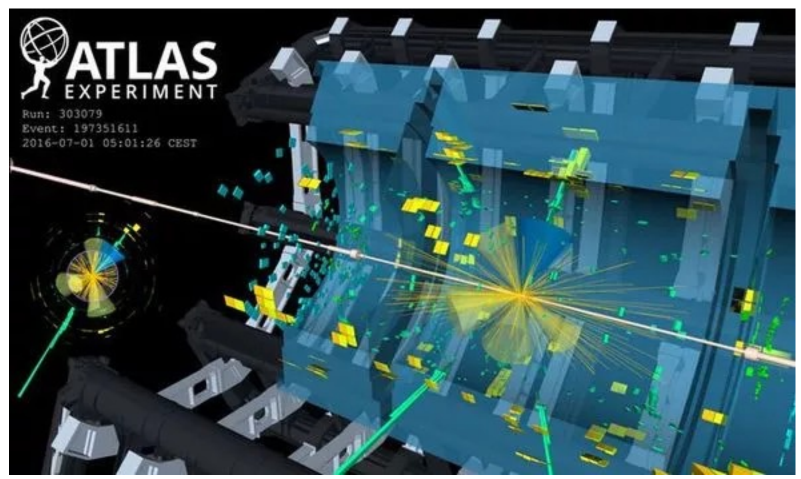


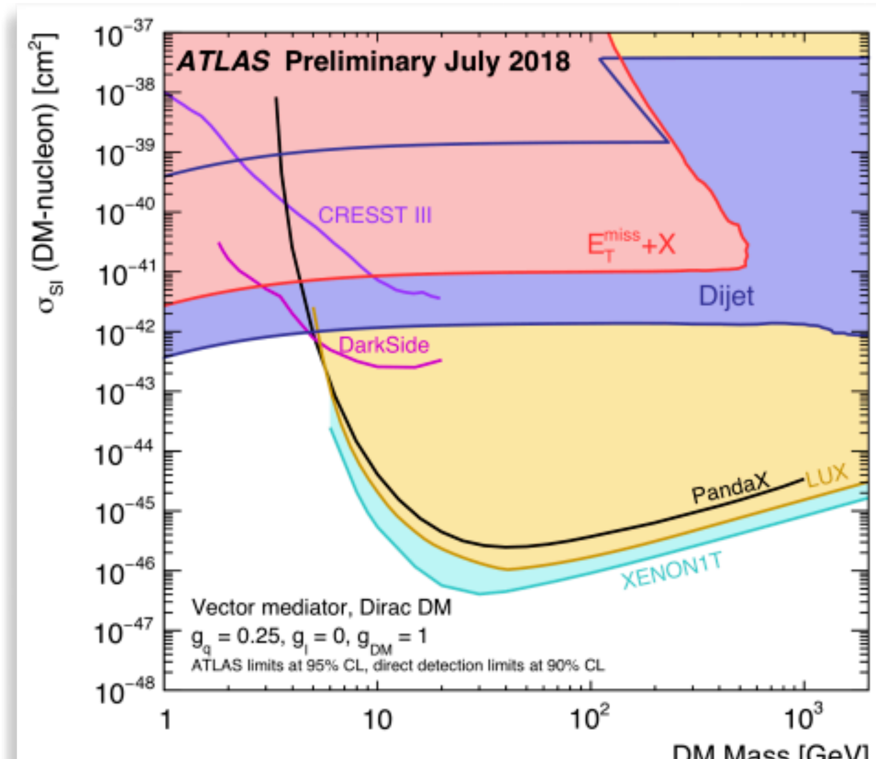


[ ATLAS-EXOT-2017-32 ]

✦ Direct detection in a nutshell

✤ Cross sections ⇔ nucleon-DM couplings ⇔ DM-quark/gluon couplings

✤ Effective field theory approach

★ LHC constraints on the effective couplings and scale

# DM direct detection in a nutshell

[ Drees & Nojiri (PRD`93); Hisano, Nagai & Nagata (JHEP`15) ]

- Effective field theory to model DM-nucleon interactions

| | | | | |
|---|---|---|---|---|
| $\mathcal{L}_\chi = f_N\ \bar\chi\chi\bar N N$ | or | $\mathcal{L}_\phi = f_N\ \phi^2\bar N N$ | or | $\mathcal{L}_X = f_N\ X_\mu X^\mu \bar N N$ |
| Majorana DM | | Real scalar DM | | Real vector DM |

- $f_N$ originates from nucleon matrix elements and the underlying new physics

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✦ The nucleon matrix elements: expectation values of quark/gluon bilinears

$$\langle N|\ m_q\bar q q\ |N\rangle, \quad \langle N|\ \frac{\alpha_s}{\pi}G_{\mu\nu}G^{\mu\nu}\ |N\rangle, \quad \langle N|\ \bar q\gamma_\mu\gamma_5 q\ |N\rangle, \quad \ldots$$

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## ✦ Connection with the UV: Wilson coefficients

- Integration out of heavy UV states → DM-quark/gluon effective interactions

$$\begin{aligned}
\mathcal{L}_{\mathrm{EFT},\chi} &= \frac{C^q_\chi}{\Lambda^2}\,[\bar\chi\chi]\,[m_q\bar q q] + \frac{C^q_{\chi,\mathrm{AV}}}{\Lambda^2}\,[\bar\chi\gamma_\mu\gamma_5 q]\,[\bar q\gamma^\mu\gamma_5 q] + \ldots \\
\mathcal{L}_{\mathrm{EFT},\phi} &= \frac{C^q_\phi}{\Lambda^2}\phi^2\,[m_q\bar q q] + \frac{C^g_\phi}{\Lambda^2}\,\frac{\alpha_s}{\pi}\phi^2\,[G_{\mu\nu}G^{\mu\nu}] + \ldots \\
\mathcal{L}_{\mathrm{EFT,X}} &= \frac{C^q_X}{\Lambda^2}\,[X_\mu X^\mu]\,[m_q\bar q q] + \frac{C^g_X}{\Lambda^2}\,\frac{\alpha_s}{\pi}\,[X_\mu X^\mu]\,[G_{\mu\nu}G^{\mu\nu}] + \ldots
\end{aligned}$$

The Wilson coefficients depend on the UV physics

# Complementary constraints

✦ Constraints from both directions

**Dark matter direct detection cross section** ⟷ **DM EFT** $\mathcal{L}_{\rm EFT} = \frac{C}{\Lambda^2}\,\mathcal{O}(q,g,{\rm DM})$ ⟷ **UV model (with heavy states)**

✤ Direct detection constraints translated into bounds on the UV parameters

✤ LHC bounds on the UV model translated into bounds on $C/\Lambda^2$ (and DD rates)

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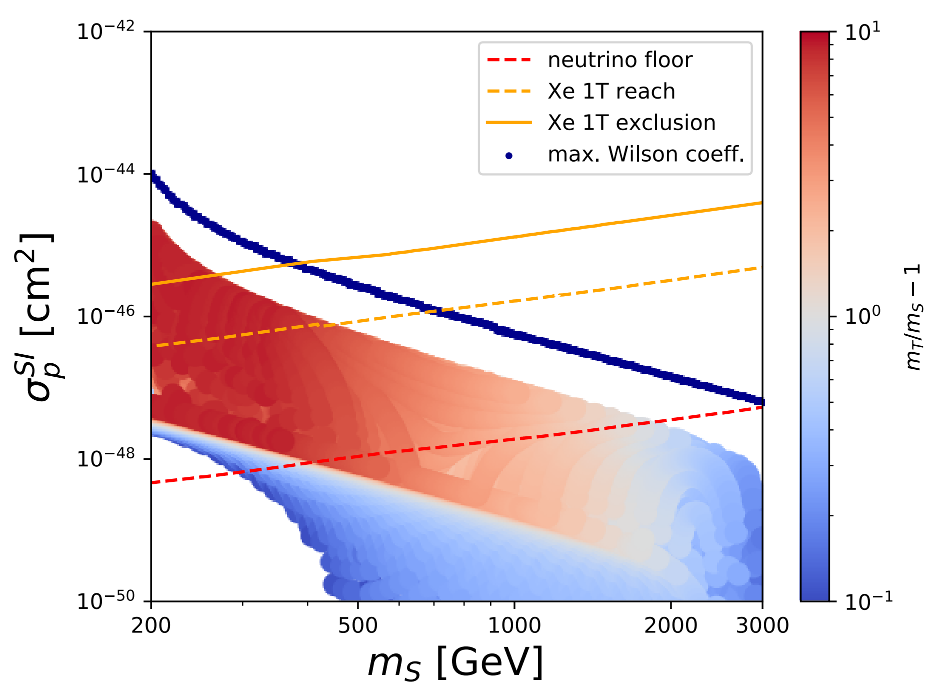
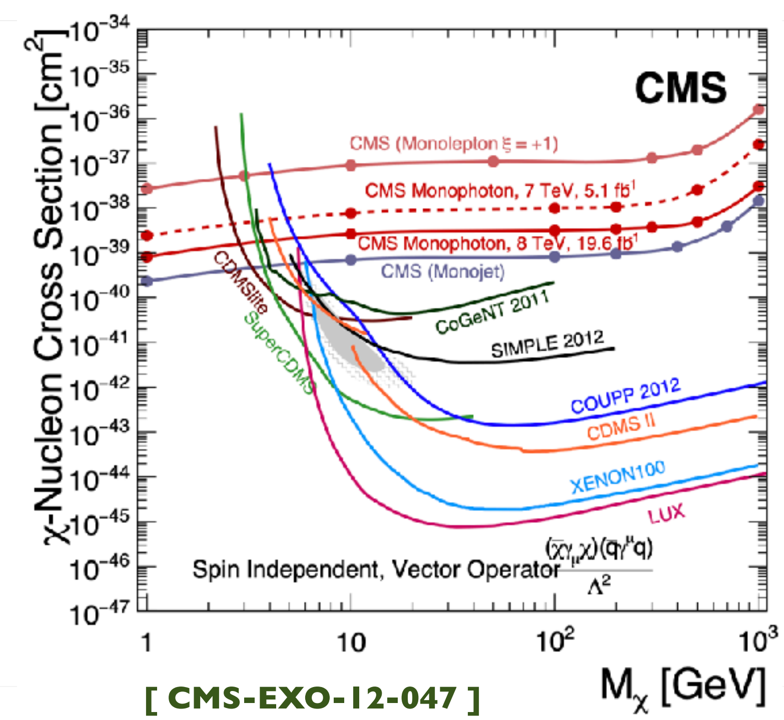
## ✦ Illustration of the complementarity

✤ Top-philic scalar DM from direct detection to bounds on the UV model

✤ Direct detection bounds from mono-photon searches at the LHC (run 1)




[ Cornell, Deandrea, Flacke, BF & Mason (JHEP`21) ]

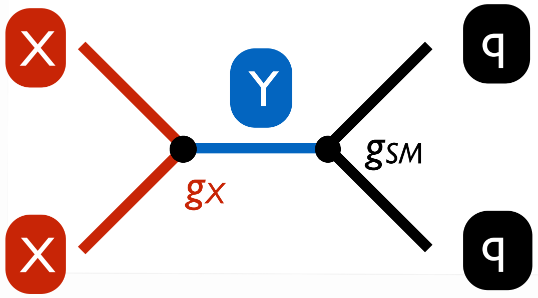



[ CMS-EXO-12-047 ]

# The failure of the EFT interpretation

## ✦ Using an EFT

- Integration out of heavy UV states → relating UV parameters to the EFT scale $\Lambda$
- Example: *s*-channel axial-vector mediator *Y* coupling to a dark matter *X*




$$\Rightarrow \frac{C}{\Lambda}\, \bar{X}\gamma^\mu\gamma_5 X\ \bar{q}\gamma_\mu\gamma_5 q \qquad \text{with} \qquad \frac{\Lambda}{C} = \frac{m_Y}{g_X\, g_{\rm SM}}$$

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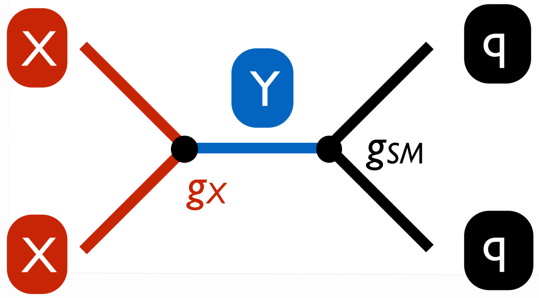


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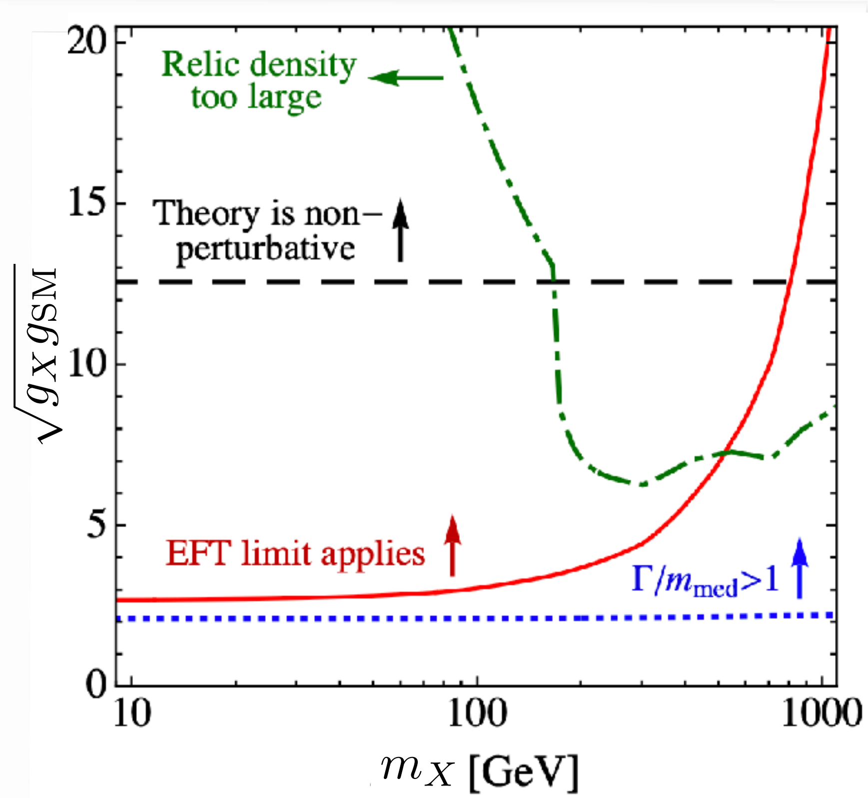


[ Buchmueller, Dolan & McCabe (JHEP`14) ]

## ✦ An ill-defined interpretation

- ✤ $m_Y$ is fixed for the EFT to be valid
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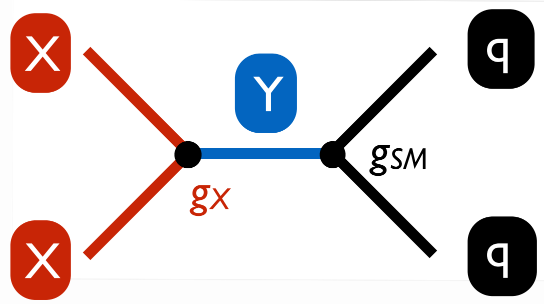
- ✤ Derivation of minimum couplings (red line)
  - → from LHC run I mono-jet searches
- ✤ The mediator is not even a particle ($\Gamma > m_Y$)
  - ★ Large (not extreme) widths interesting too
- ✤ Perturbativity issues for $m_X > 800$ GeV
  - ★ Predictions unreliable, new techniques needed

# The failure of the EFT interpretation

## ✦ Using an EFT

- ✤ Integration out of heavy UV states → relating UV parameters to the EFT scale $\Lambda$
- ✤ Example: *s*-channel axial-vector mediator *Y* coupling to a dark matter *X*

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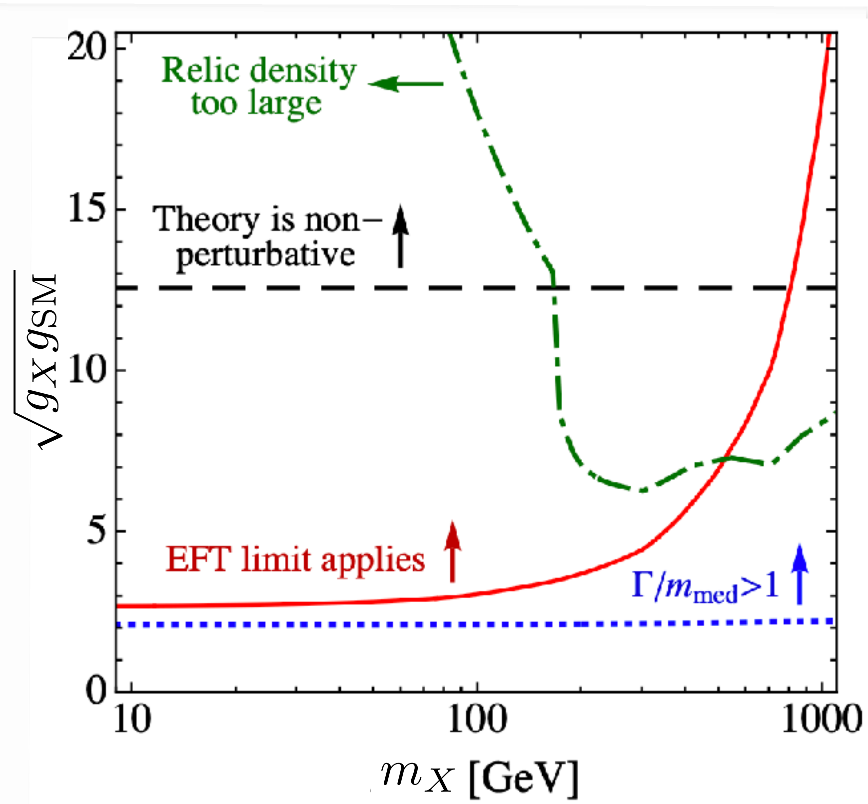

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**Constraints on baroque setups**

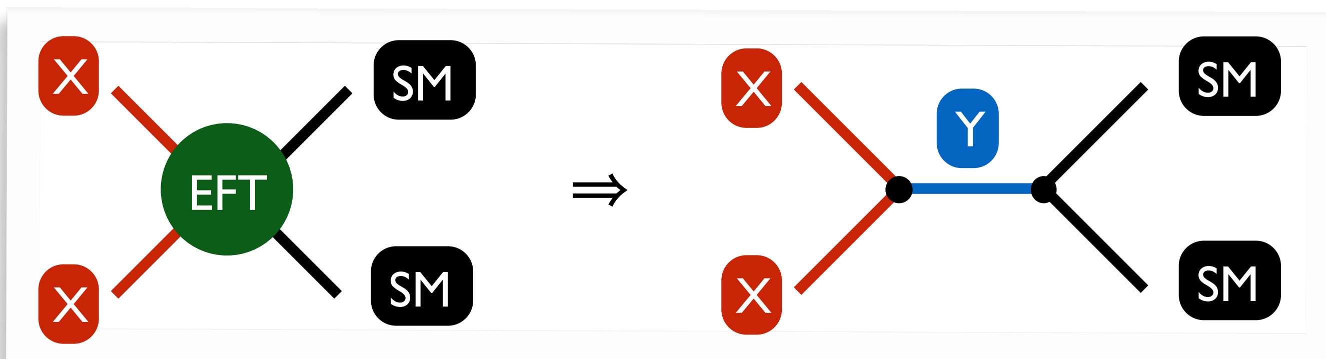
# Dark Matter simplified models

# The *s*-channel case

# From EFT to simplified model interpretations

✦ Resolution of the EFT interactions in a minimal way

- Simplified models as a tool for generic DM search interpretations
- Sizeable LHC rates, few assumptions on the model
- A small number of free parameters



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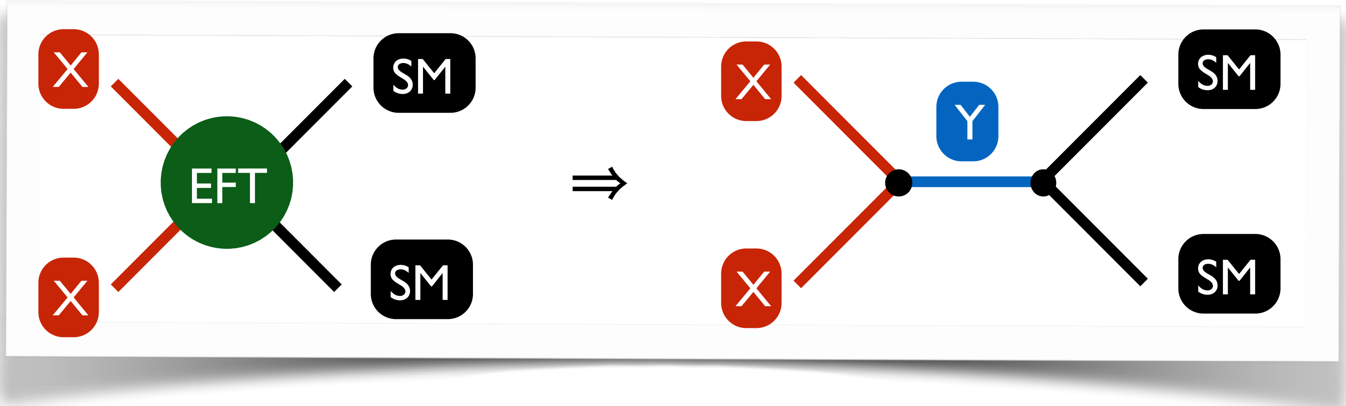


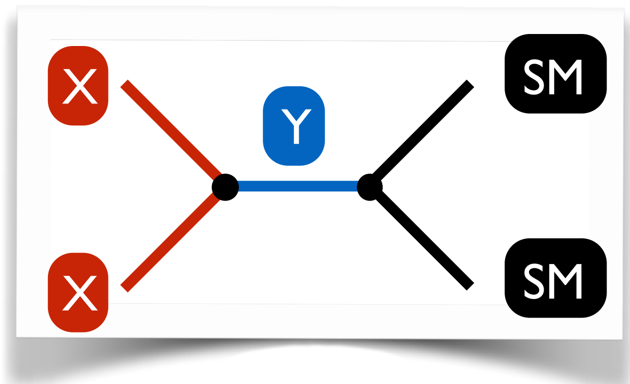

✦ Generic simplified models for dark matter @ LHC

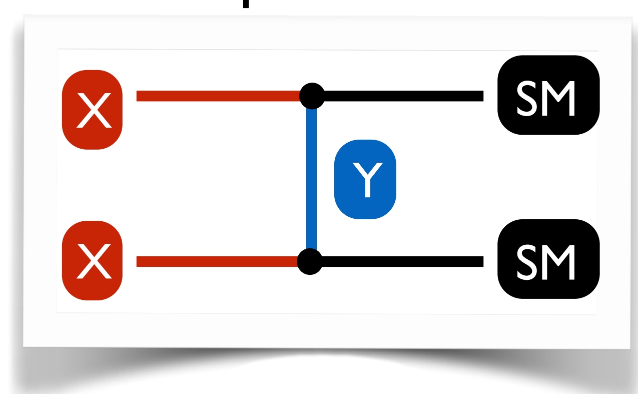
- Minimality: SM + 1 DM candidate + 1 mediator (coupling to quarks and gluons)
  - ★ Representative of different theoretically-motivated new physics scenarios
  - ★ Lack non-minimal features (multiple mediators, multi-component DM, *etc.*)
  - ★ Beware: non-minimality can change the picture

# Simplified dark matter models @ LHC

## ✦ Basic properties of the simplified DM models

- ✤ DM (X) is stable
  - ⤳ Odd under some $\mathbb{Z}_2$ discrete symmetry
  - ⤳ SM states even under the same symmetry
- ✤ The mediator (Y) connects DM to 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




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

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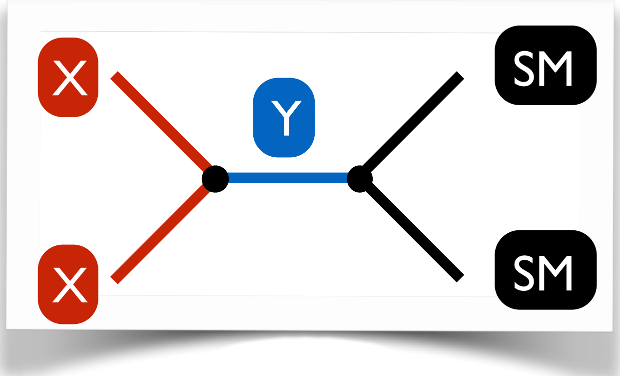


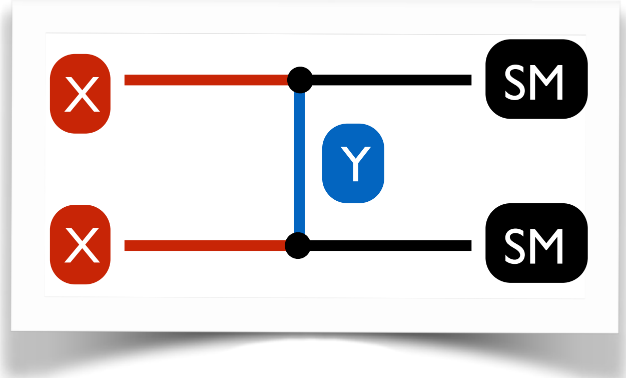


[ Arina, BF & Mantani (EPJC`20) ]
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## ✦ Free parameters

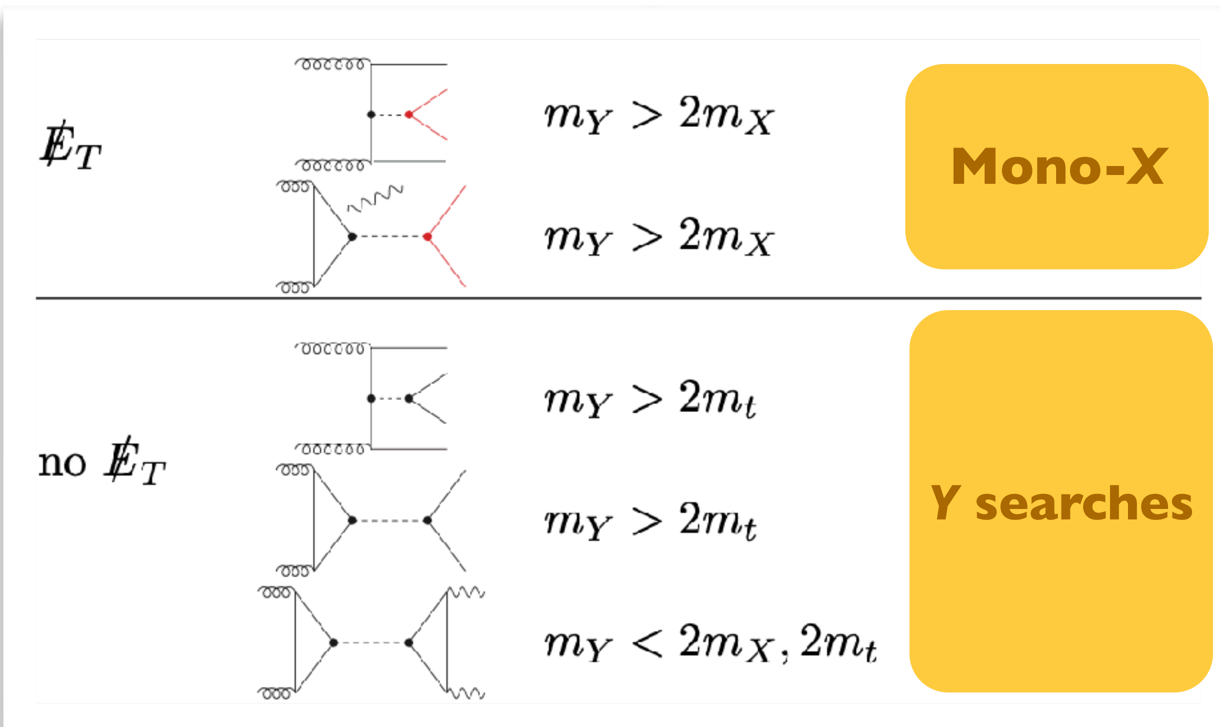
✤ 2 spins: $J_X, J_Y$

✤ O(10) masses
- ★ 1 DM mass: $m_X$
- ★ Several mediators (coupling to different SM generations)

✤ Many couplings in the flavour space

# *s*-channel models at colliders

✦ Simplified models ⇔ richer phenomenology than expected




- ✤ Two classes of processes
  - ★ With missing energy (mono-X)
  - ★ Without missing energy (mediator)
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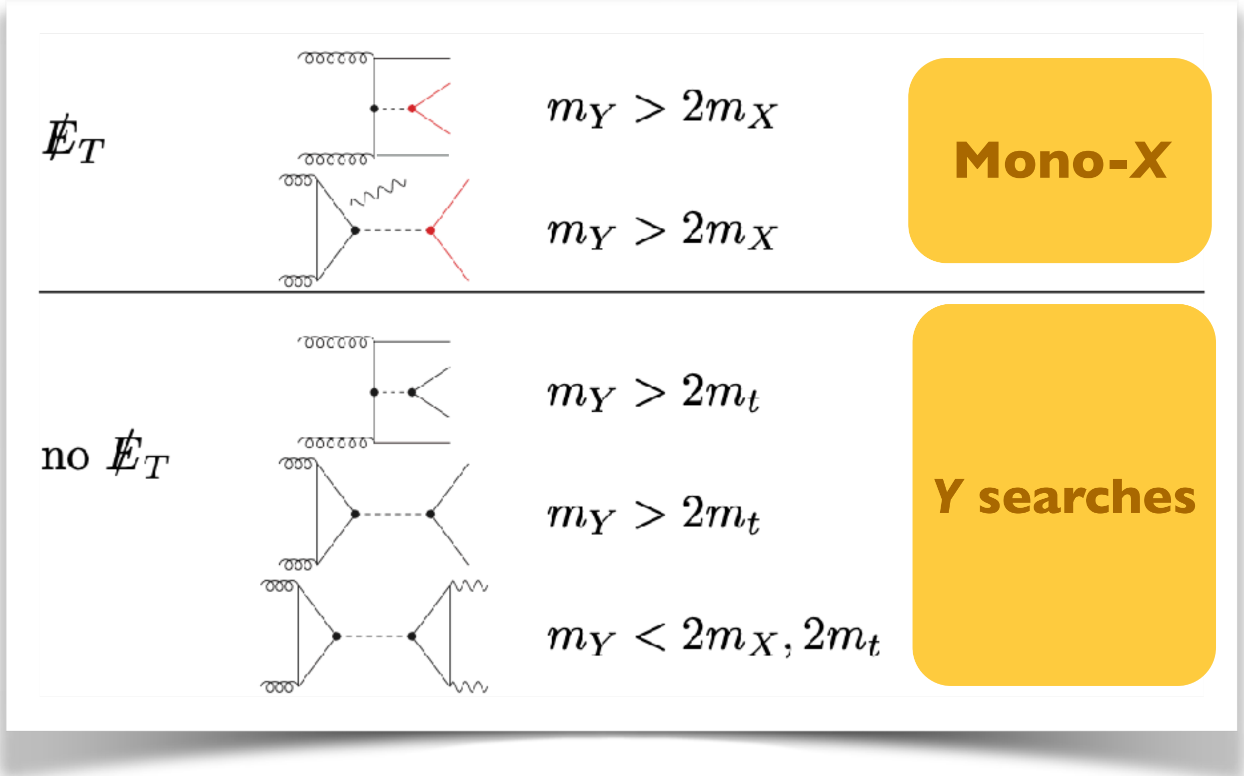


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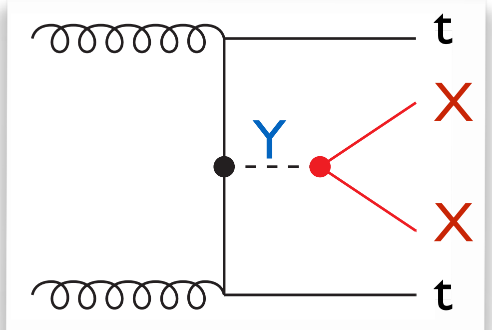
## ✦ Complementary DM model probes at colliders

- ✤ With DM searches
- ✤ Through resonance searches

# Example: top-philic fermion DM / scalar mediator

- A simplified model for top-philic dark matter
  - A dark sector with a fermionic dark matter candidate X
  - A (scalar) mediator Y linking dark matter and the top
    - MFV ≡ fermion-Y couplings proportional to the SM Yukawas




$$\mathcal{L} = -\frac{g_t y_t}{\sqrt{2}} \, [\bar{t}t] \, Y - g_X \, [\bar{X}X] \, Y$$

4 parameters: 2 masses and 2 couplings

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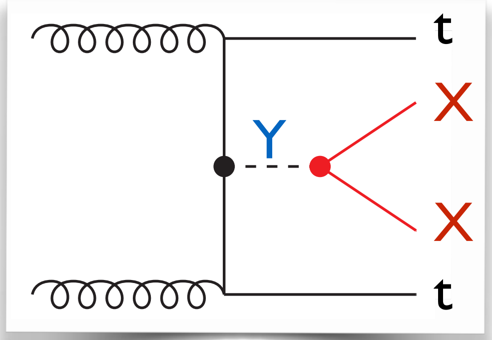


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## ✦ Scanning procedure

- ✤ Masses
  - ★ 1 GeV < $m_Y$ < 5 TeV
  - ★ 1 GeV < $m_X$ < 1 TeV
- ✤ Perturbative couplings: 0.01 < $g_X, g_t$ < $2\pi$
- ✤ Flat likelihood functions in all dimensions
- ✤ LHC Run 1 constraints are imposed, no cosmology bounds

# Collider constraints on top-philic s-channel DM

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

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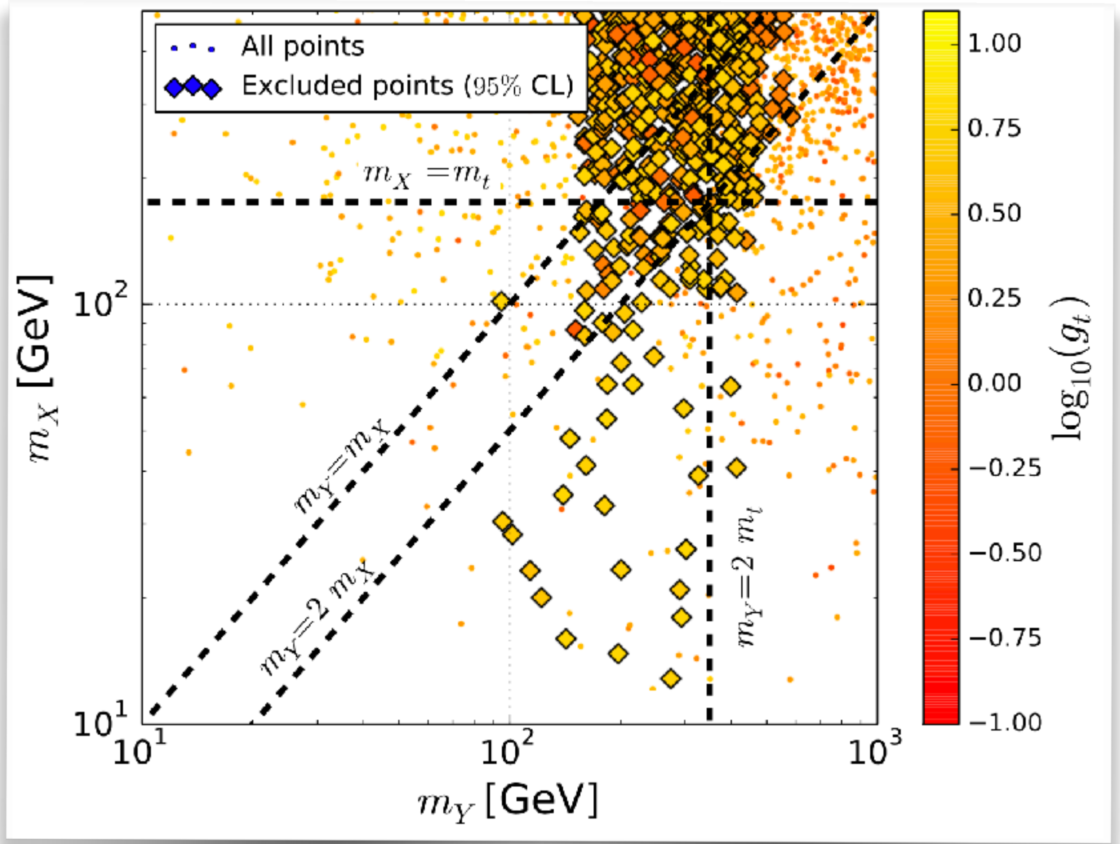

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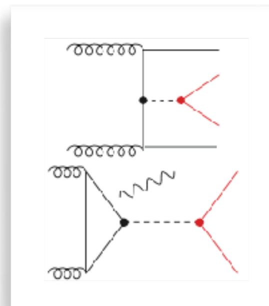

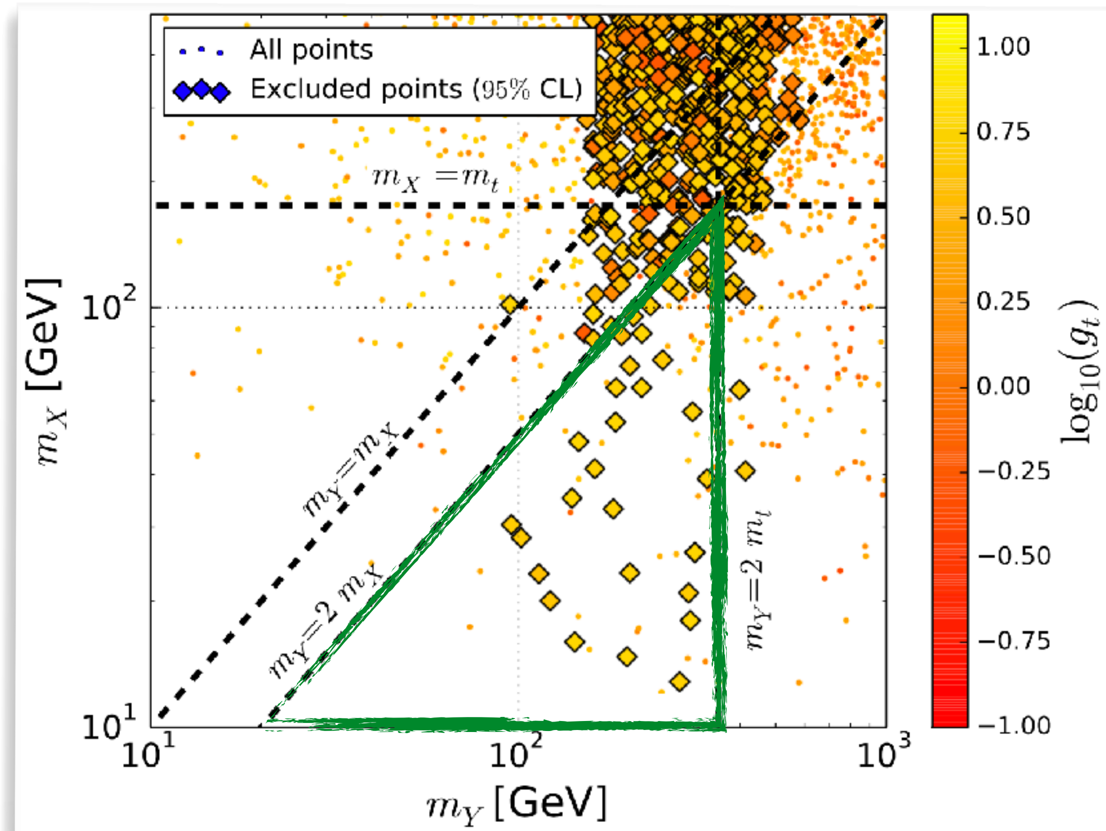

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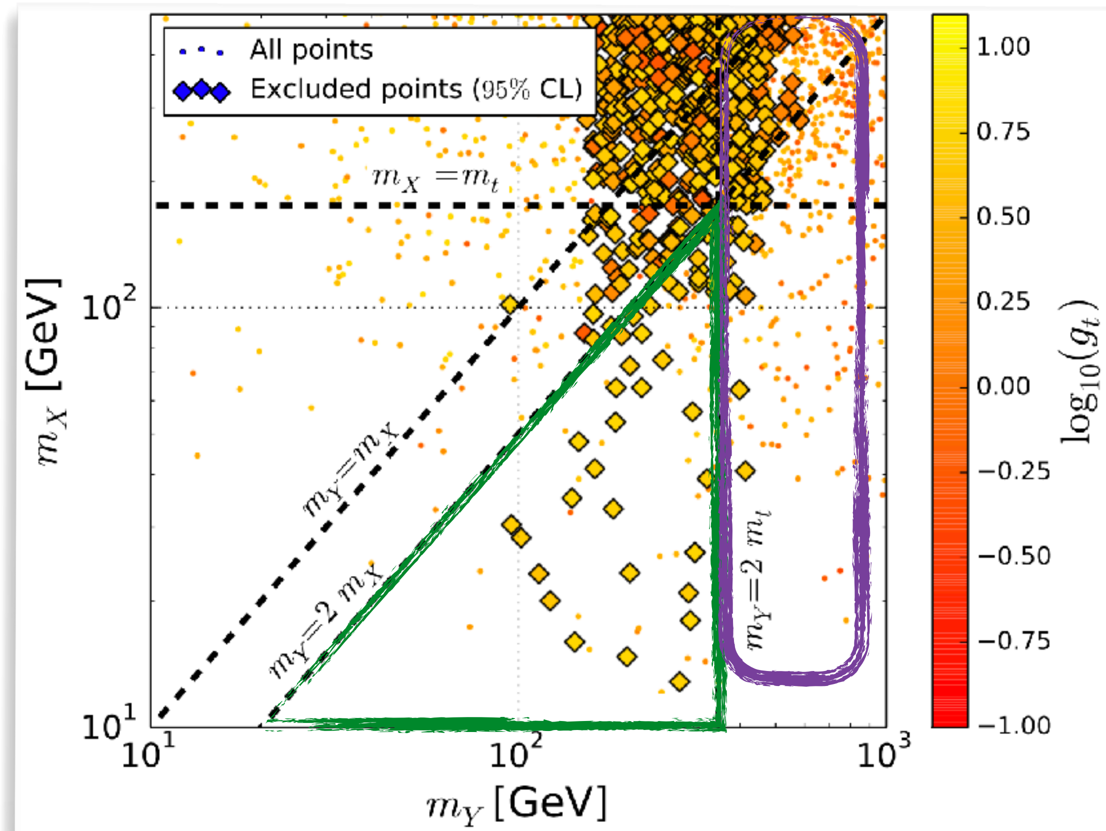


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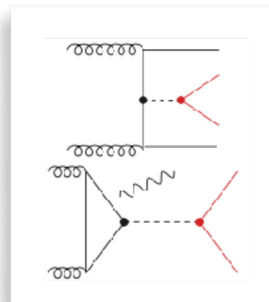

- $t\bar{t}/t\bar{t}t\bar{t}$ production
  - $Y$ decays in tops open and dominant
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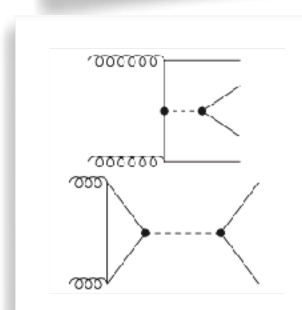

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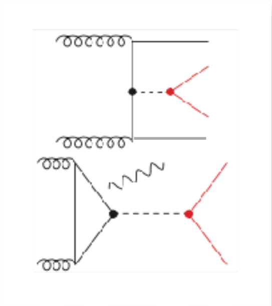

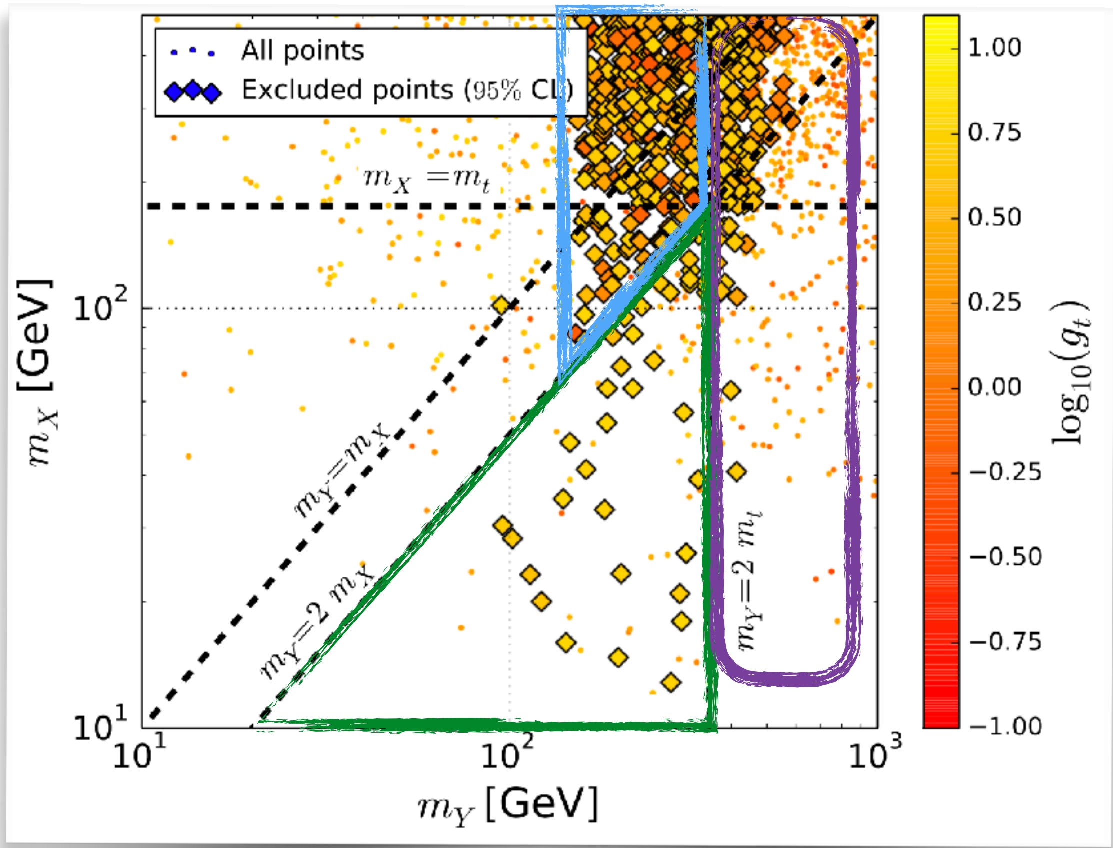


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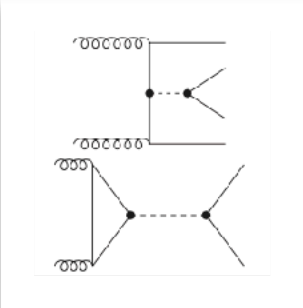

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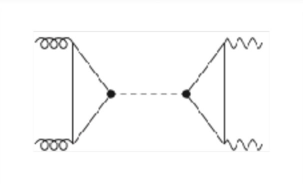

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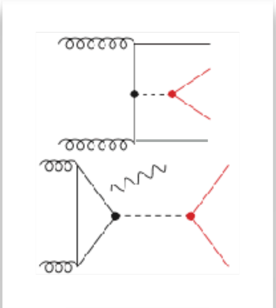

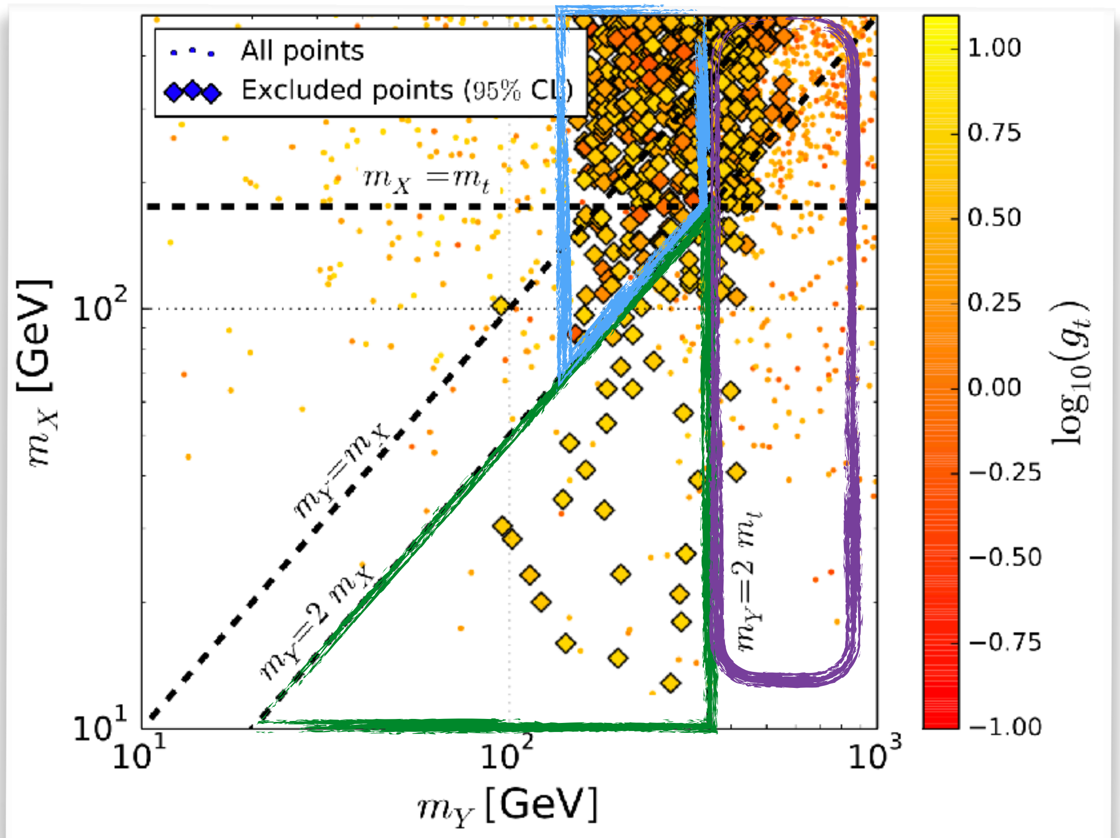


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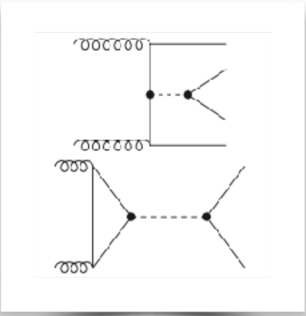

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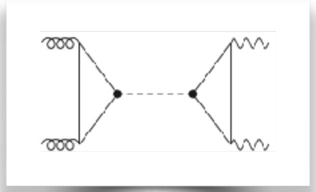


**Large complementarity between all LHC searches**

# Details on the simulations

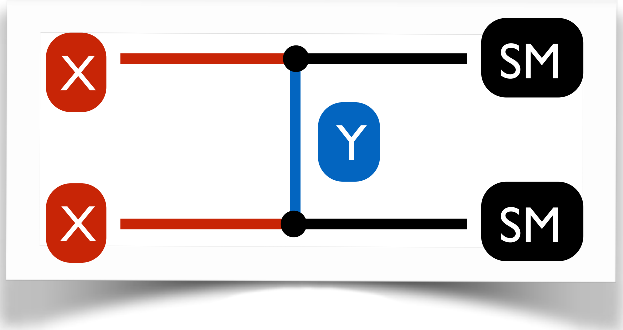
- ✦ Several key aspects behind the previous results
  - ✤ Simulations at the NLO-QCD accuracy → precision predictions
  - ✤ Recasting with public tools
    - ★ Many ATLAS and CMS searches for new physics
    - ★ Interpretation within popular frameworks and simplified models
    - ★ Need for interpretations in all kind of models

# Dark matter simplified models

# The *t*-channel case

# *t*-channel models at colliders

- Very different from *s*-channel models
  - The mediator couples to one DM and one SM particle
    - ★ *Y* decay into one invisible (→ MET) and one visible state
  - Relevant for the LHC: couplings to (light) quarks



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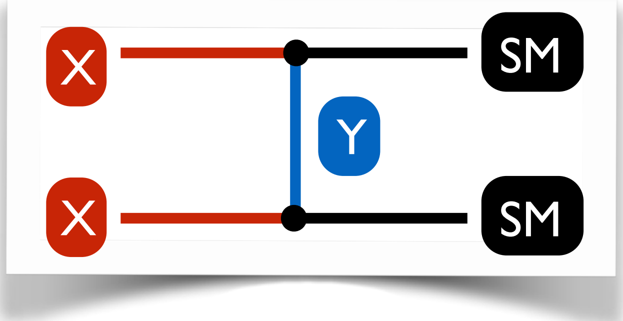
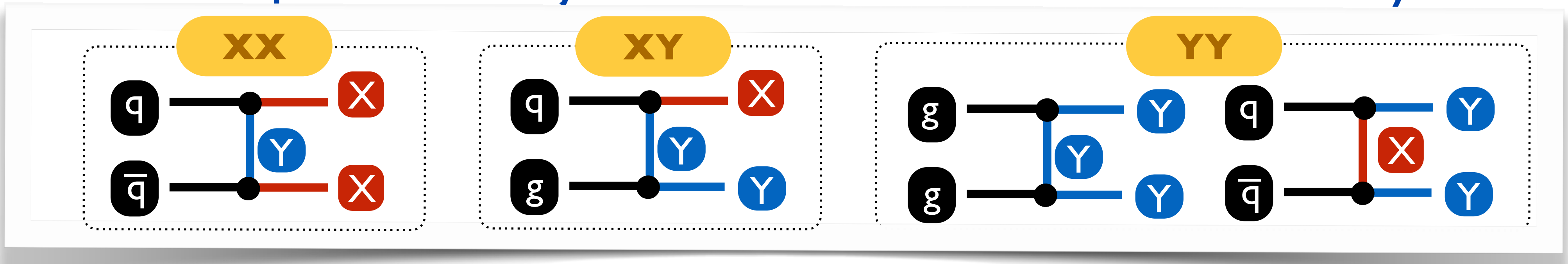



✦ 3 classes of processes ↝ jets from radiation or mediator decays




✤ 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

★ Interference issue

# Recasting ATLAS mono-jet search (36/fb)

✦ CLs exclusion from the best region (1 TeV mediator; 150 GeV DM)

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

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

✤ NLO simulations are crucial
- ★ Modification of the rates (larger yields) and shapes (different best region)
- ★ Better control of the theory errors

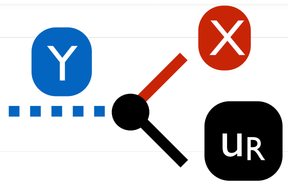
✤ Considering all signal components is crucial
- ★ One component alone is not sufficient to exclude the scenario

# $1^{st}$ 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 | $\varphi_{u_1}$ | 0 |

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

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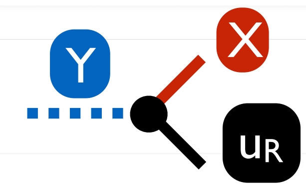


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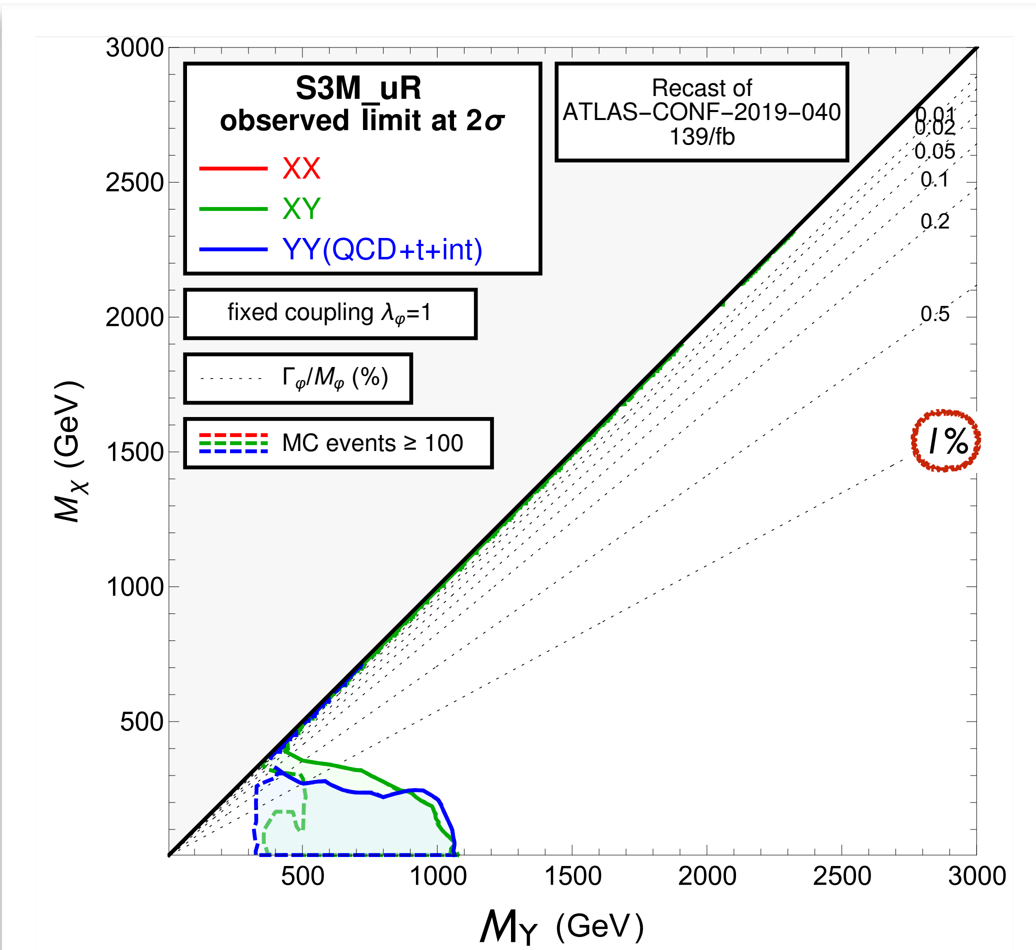



[ Arina, BF, Mantani, Mies, Panizzi & Salko (PLB`20) ]

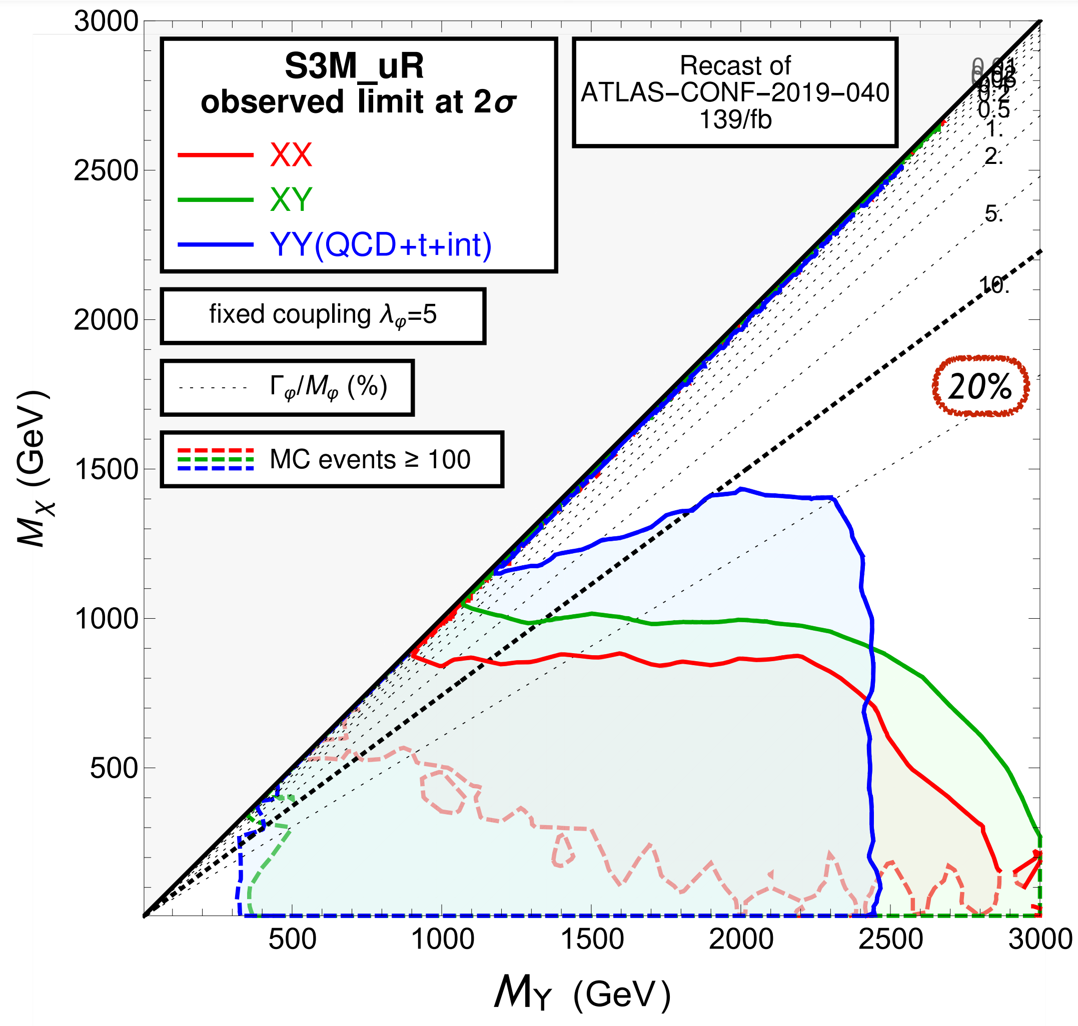
## ✦ Recast: ATLAS multi-jet + MET search

- ✤ 139/fb
- ✤ Mono-jet-like and multi-jet + 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 $\lambda$ values

# More strongly coupled dark matter




[ Arina, BF, Mantani, Mies, Panizzi & Salko (PLB`20) ]

- $\lambda = 5$
  - All channels contribute (larger rates)
    - ★ XX ~ $\lambda^4$
    - ★ XY ~ $\lambda^2$
    - ★ YY ~ $\lambda^4 + \lambda^2 + \lambda^0$

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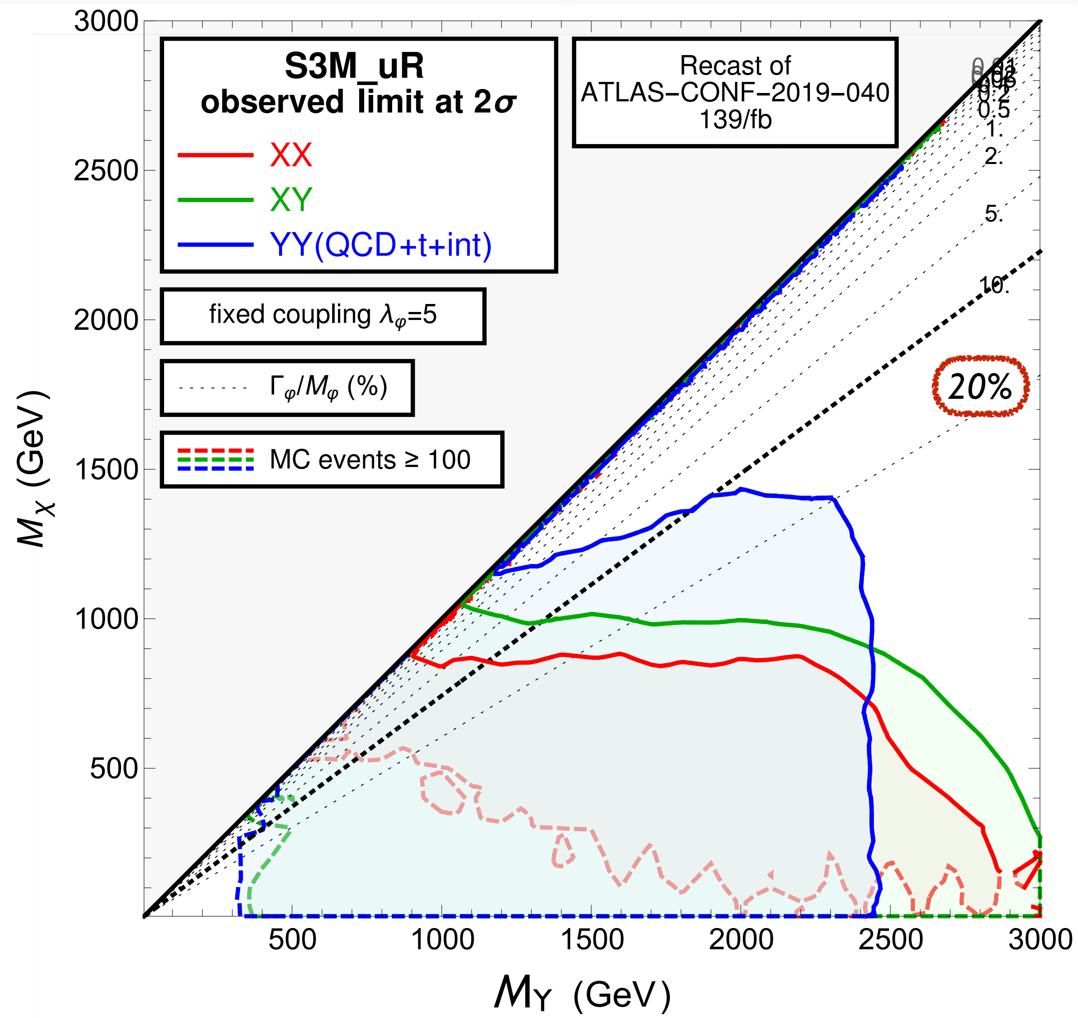


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- ★ The NWA breaks down
- ★ $\Gamma_Y/M_Y > 10\%$ or compressed spectrum
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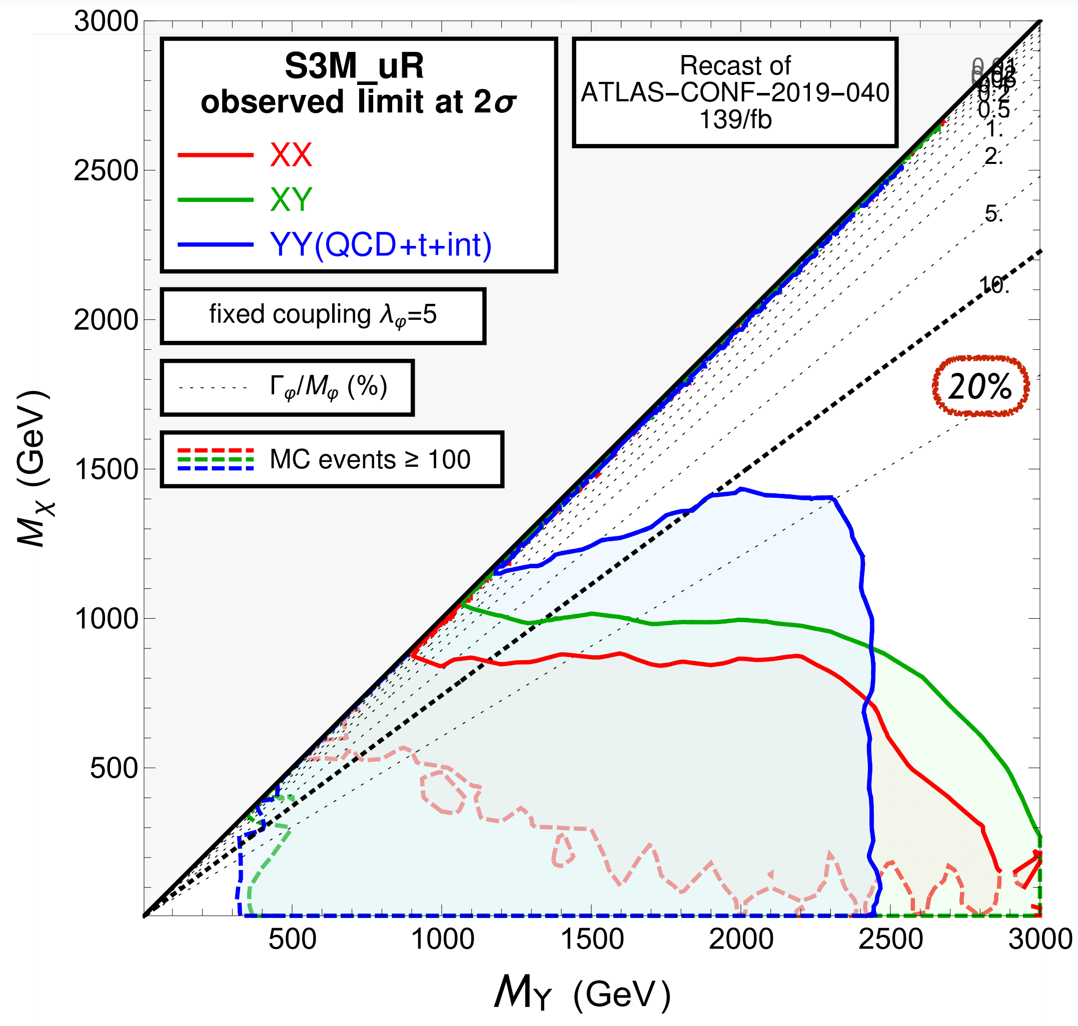


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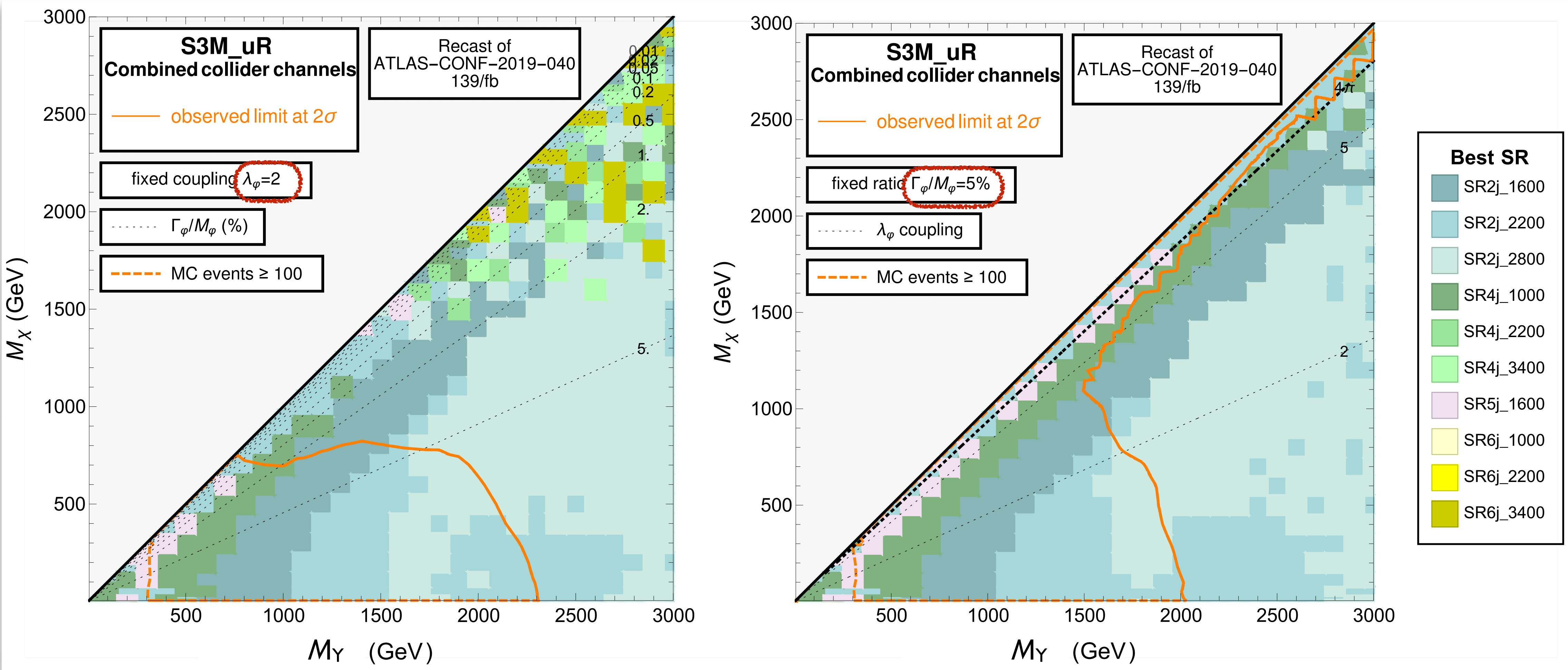
  - $\Gamma_Y$ plays a role for large $\lambda$ values
- Sensitivity to all channels
  - Different jet properties
    - → XX: small $N_j$, mostly soft jets
    - → XY: medium $N_j$, hard and softer jets
    - → YY: large $N_j$, hard jets
  - Dedicated regions for all cases

# Fixed coupling *vs* fixed width

[ Arina, BF, Mantani, Mies, Panizzi & Salko (PLB`20) ]




- $\lambda = 2$ *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 $\Gamma_Y/M_Y$: compressed spectrum ≡ non-perturbative regime
    - ★ Fixed $\lambda$: split spectrum ≡ broad mediator

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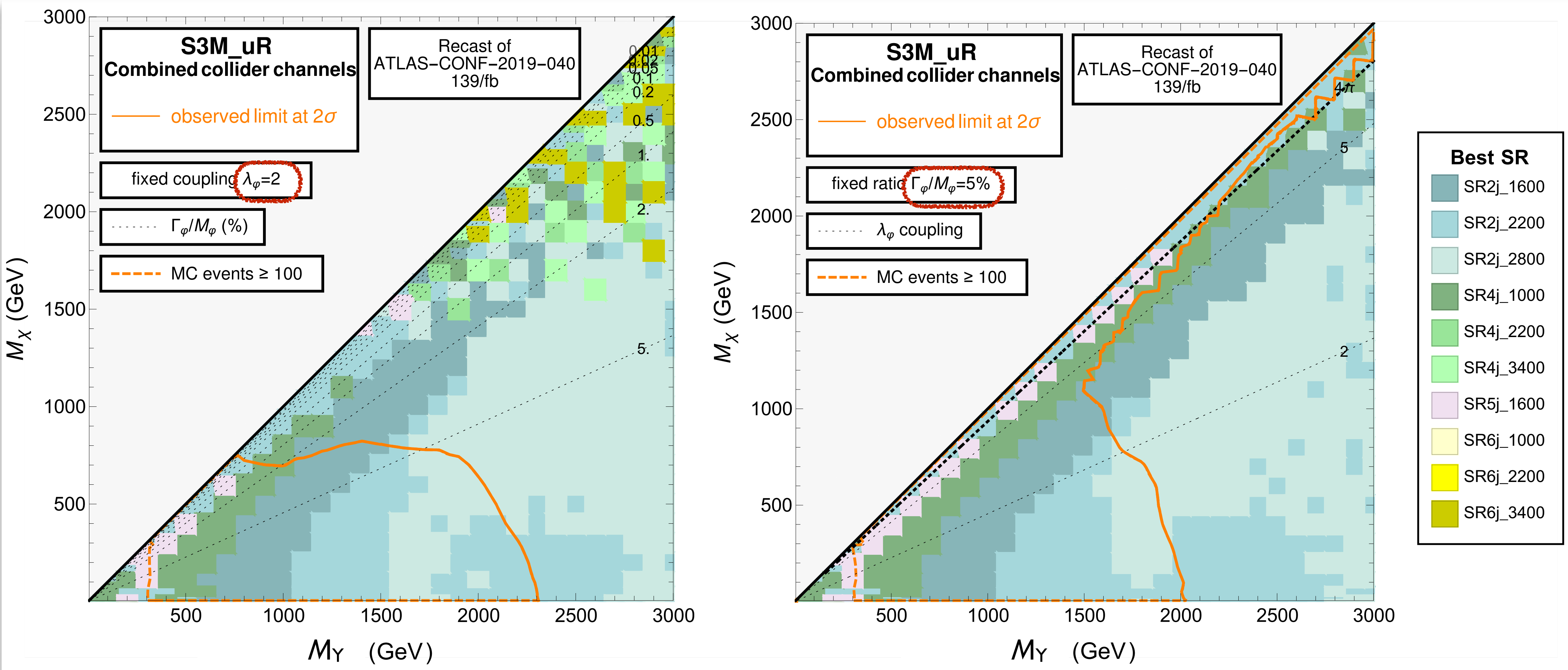


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**Care to be taken with baroque setups**

# Beyond simplified models

# Benchmark models

- ✦ More complex than simplified models
  - ✤ A large set of models exist → focus on few benchmarks (e.g. supersymmetry)
  - ✤ Dedicated searches for those specific benchmarks
    - ★ Simplified models encapsulate characteristics of varied theories

- ✦ 3 (subjective) examples
  - ✤ The Higgs portal model (very few parameters and one new state)
  - ✤ Dilaton-induced DM (very few parameters and two new states)
  - ✤ Supersymmetry (lots of parameters and new states)
- ✦ There are many more: dark photons, axions, *etc.* (not covered here)

# I. The Higgs portal

[ Arcadi, Djouadi & Raidal (PhysRept`19) ]

- The Higgs boson connects DM to the SM
  - DM interacts with the Higgs boson via effective couplings
  - The Higgs can decay into a pair of DM particles
    - For instance, Majorana DM:

$$\mathcal{L}_\chi = \frac{i}{2}\bar\chi \partial\!\!\!/ \chi - \frac{m_\chi}{2}\bar\chi\chi - \frac{1}{4}\frac{C}{\Lambda}\Phi^\dagger\Phi\bar\chi\chi$$

Economical (few states and params)
Simplest way to connect DM to the SM

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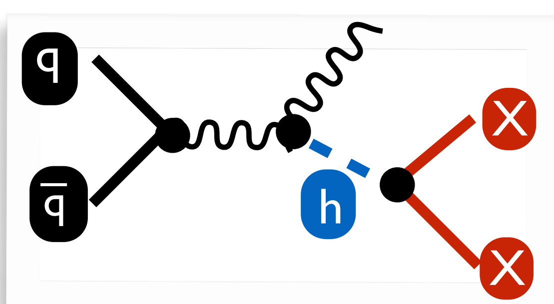
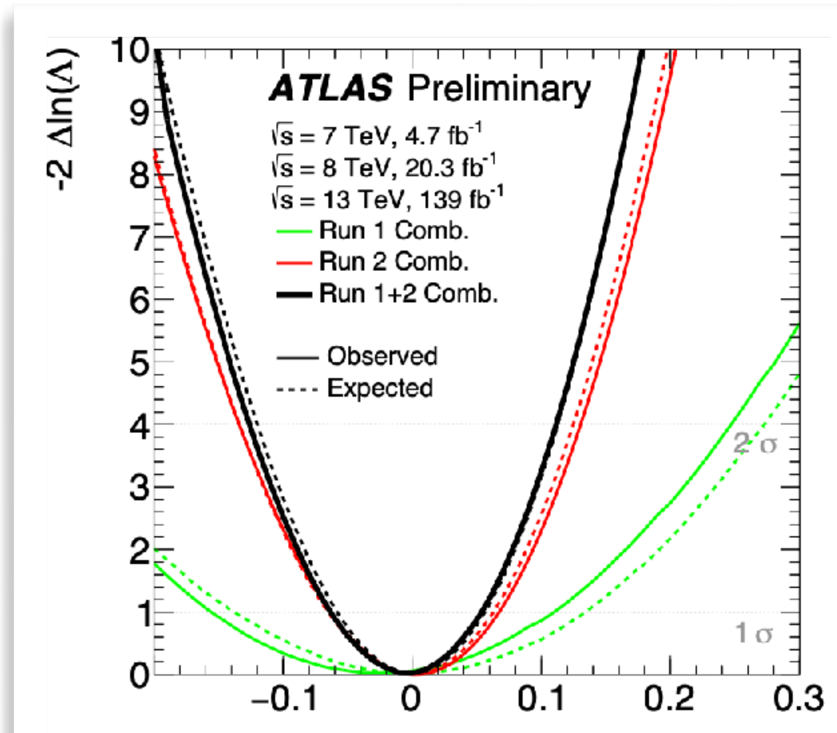
## ✦ LHC searches for invisible Higgs decays

- ✤ No sign of new physics
- ✤ All SM production modes considered (VBF, VH,…)
- ✤ BR(H→ inv) < 0.11 @ 95%CL
  - ★ Full run 2 dataset




[ ATLAS-CONF-2020-052 ]

# 2. Dilaton induced DM

## ✦ A dilaton portal between the SM and dark sector

[ Bai, Carena & Lykken (PRL`09) ]

- Scale invariance is imposed → compensator field → dilaton
- Dilaton couplings proportional to the mass
  - ★ 3 parameters: the dilaton and DM masses, scale invariance breaking scale *f*
  - ★ Example: vector DM

$$\mathcal{L}_\sigma = \left(\frac{\sigma}{f} + \frac{\sigma^2}{2f^2}\right) m_V^2 X_\mu X^\mu$$

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## ✦ Mono-X searches apply

- Solid exclusions (hashed = HL-LHC)

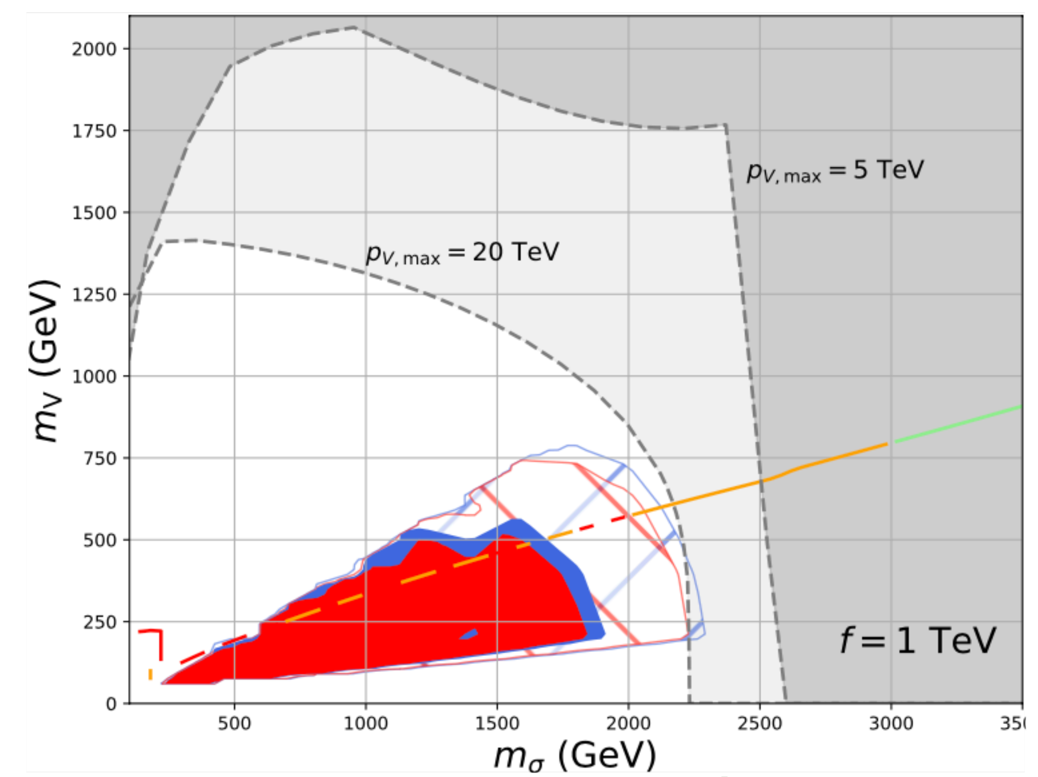
## ✦ Heavy Higgs searches & correct relic

- Orange line (excluded)
- Green line (allowed)

## ✦ The EFT must be valid

- Cutoff on the momentum transfers
- Grey exclusions

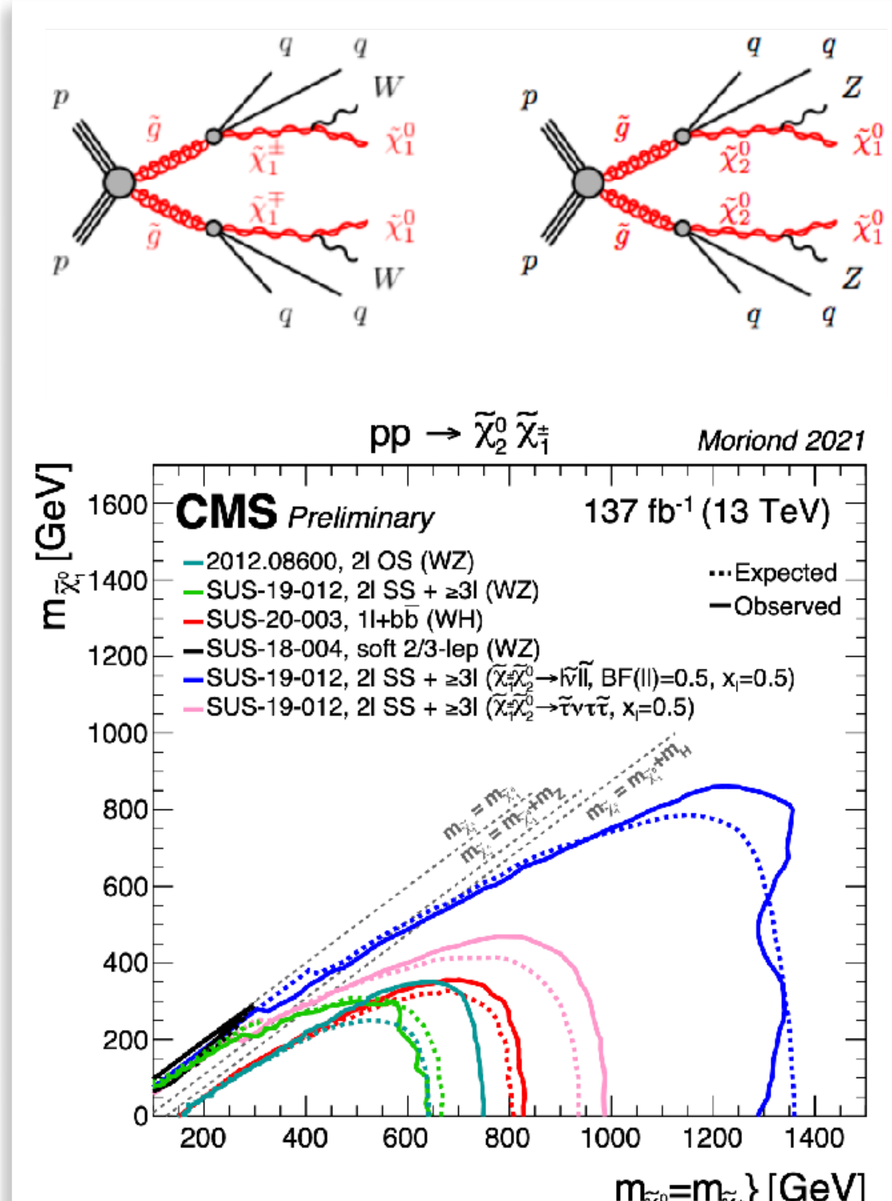
**f=1 TeV is ruled out!**




[ BF, Goodsell, Kang, Ko, Lee & Utsch (JHEP`20) ]

# 3. Supersymmetry (I)

- Pair production of heavy states cascade-decaying into leptons, jets and MET
  - Inspiring many simplified model searches
  - Neutralino ≡ typical WIMP candidate
  - Strong limits exist
  - Holes in the SUSY space exist too




[ CMS Moriond Update ]

- Specific variables
  - Transverse variables ($M_{T2}$, …)
  - Hadronic quantities ($H_T$, $m_{\rm eff}$, …)
  - *etc.*

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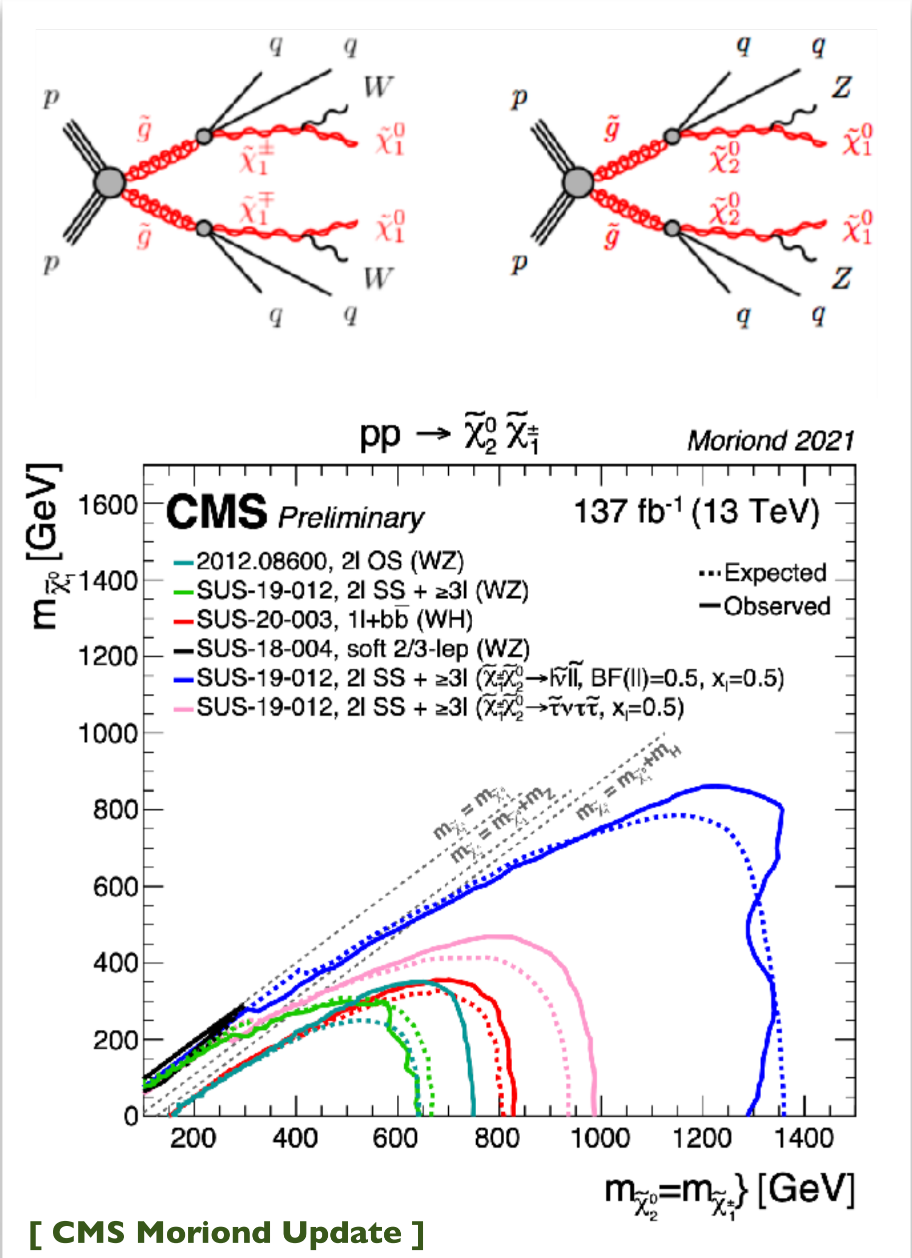


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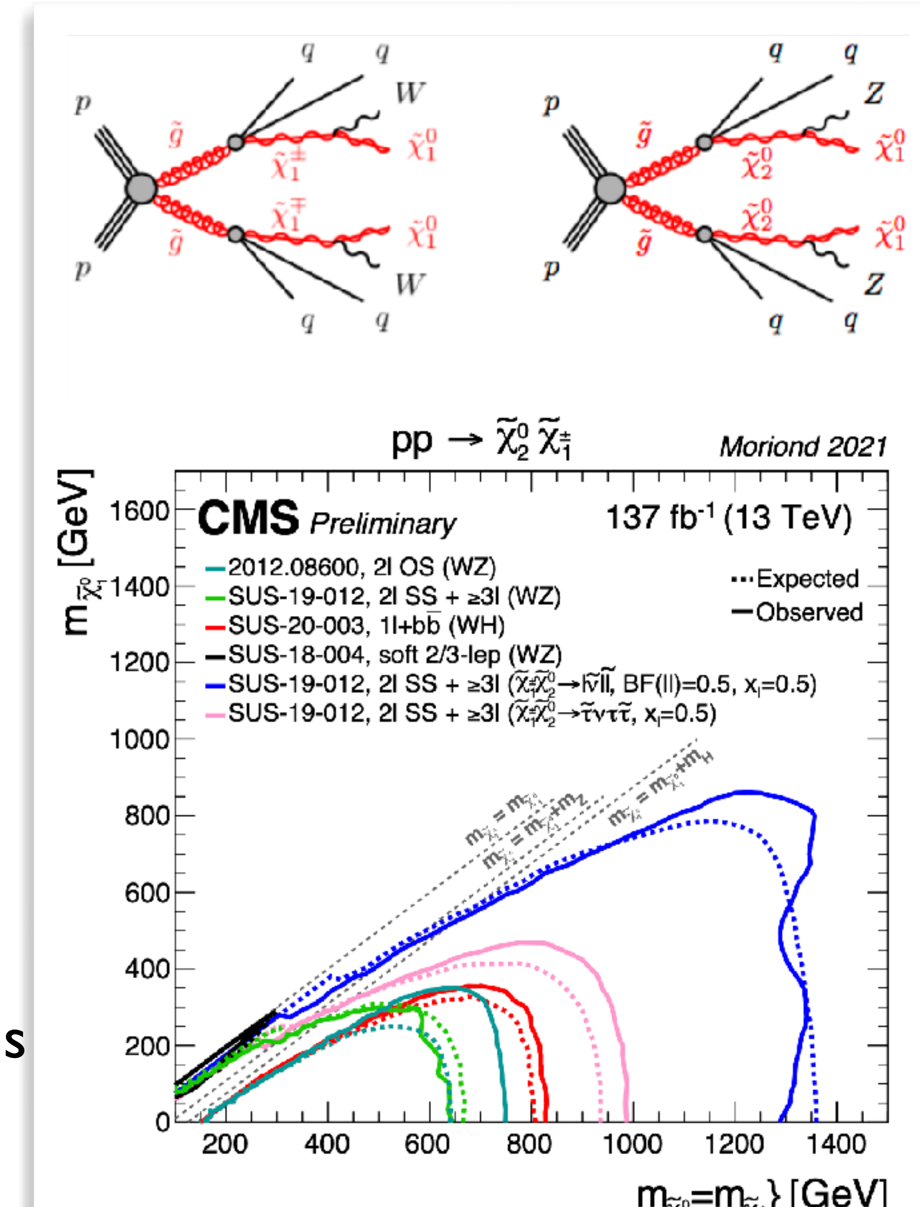
**Is SUSY ruled out? NO…**
**But will it ever be? 😀**

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# 3. Supersymmetry (2)

- Supersymmetry could be non-minimal
  - Left-right SUSY, SUSY VLQ, SUSY GUTs, sneutrino DM, *etc*.
- Non-minimal supersymmetry ≡ great playground to test new signals
  - Example: UMSSM (SUSY + Z')

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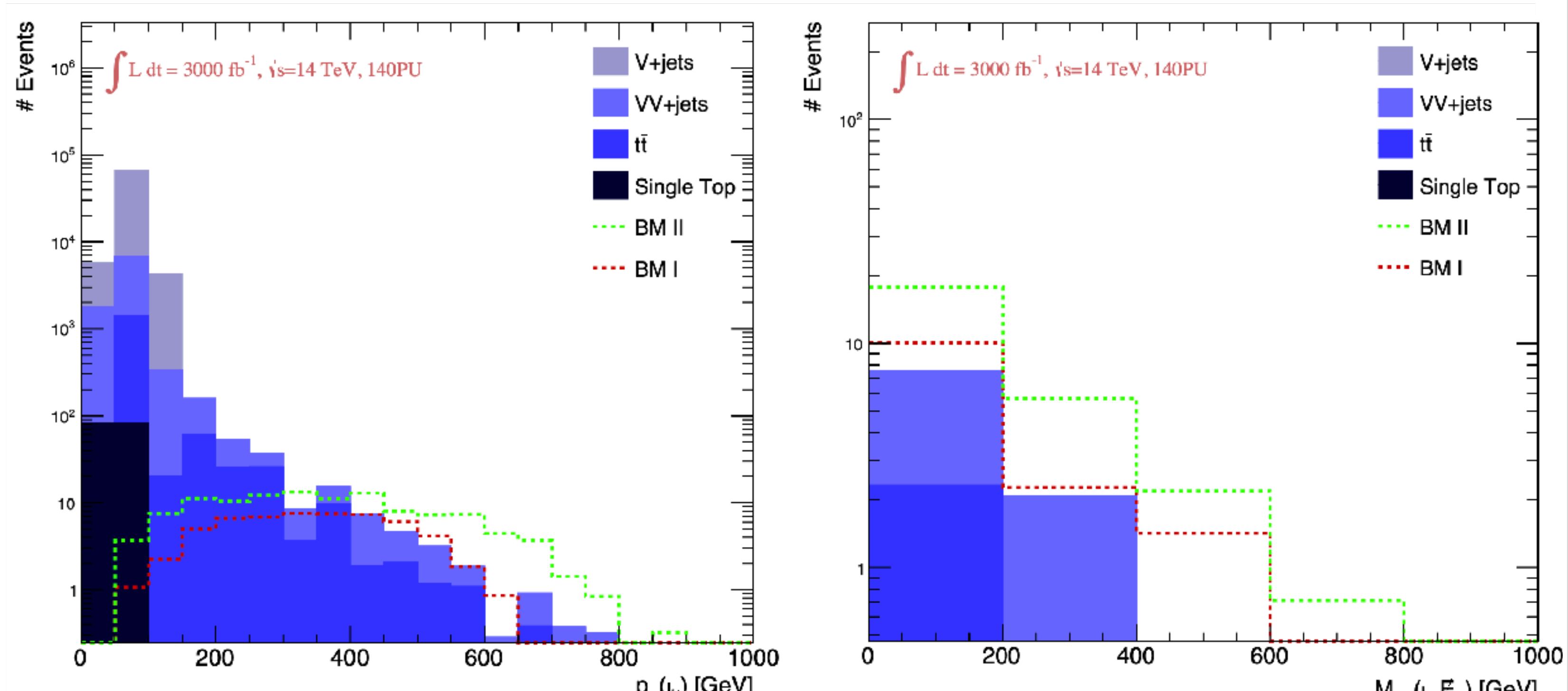
- ✦ Hard to miss signals




[ Araz, Corcella, Frank & BF (JHEP '18) ]

- ✤ Very hard probes
- ✤ Special variables
- ✤ Visible at HL-LHC

# Outline

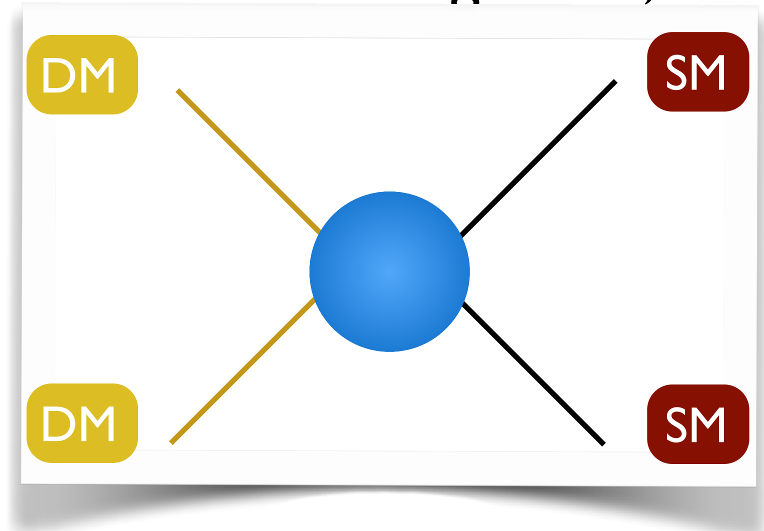
1. Dark matter from a collider perspective

2. Interpretation of dark matter collider search results

3. **Summary**

# New physics and dark matter

- ✦ Dark matter is an important motivation for new physics
  - ✤ Galaxy rotation curves, gravitational lensing, cosmic microwave background, …
- ✦ Searched for in a complementary way
  - ✤ Dark matter relic abundance must be reproduced
  - ✤ Dark matter direct/indirect detection constraints
  - ✤ Production at (hadron) colliders

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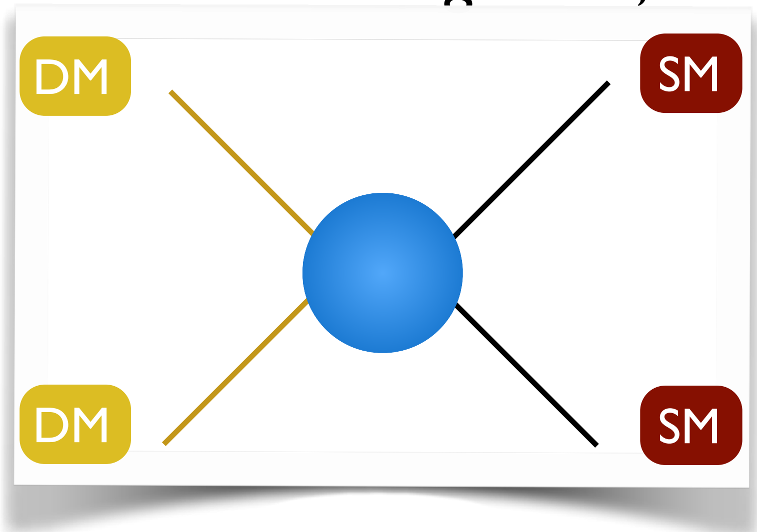


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**A lot of fun is planned for the next decades**