Dark matter search at ATLAS with top quarks

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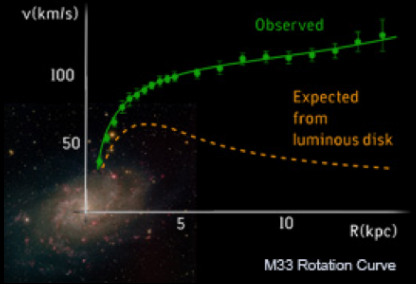
Top LHC France 2019

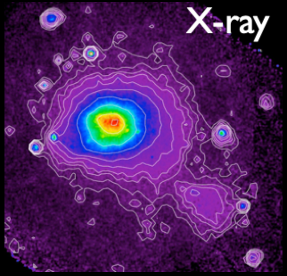
Dark matter: observations

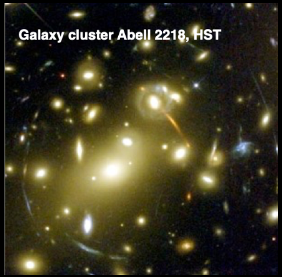
Evidence for dark matter from astrophysics and cosmology observations at **different scales**

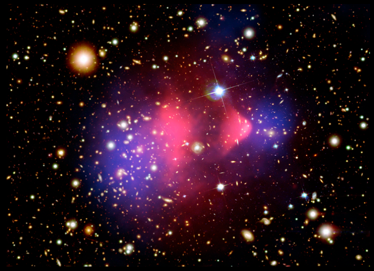
Galaxy rotation



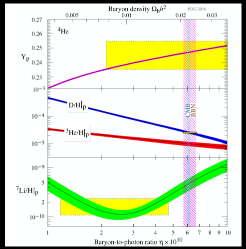
Galaxy clusters via Xrays and gravitational lensing, collisions





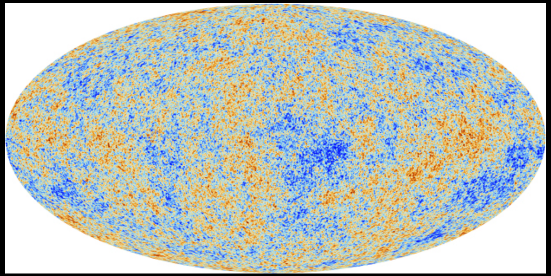


Nucleosynthesis



(Schramm & Turner 1998)

Cosmic microwave background



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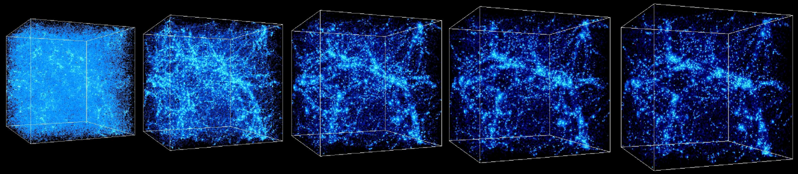
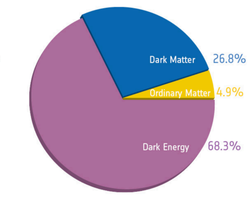
Large scale structure formation



© simulations were performed at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University).
Visualisations by Andrey Kravtsov.

Dark matter: what do we know about it ?



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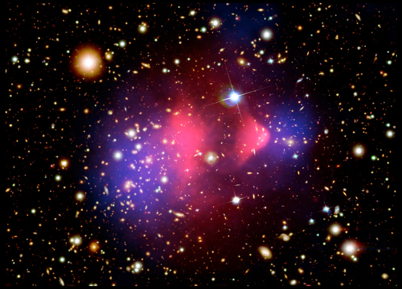
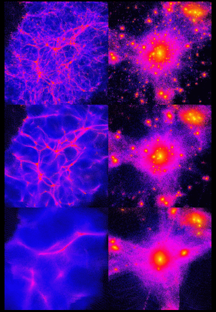
Properties

- It makes up 85% of the matter in the Universe today
  - It is massive
- It interacts weakly with ordinary matter (at least through gravitation)
  - It is neutral
- It interacts weakly with itself
- It is stable (a minima very long-lived, order of the age of the universe)
  - ➪ Ruled out SM Z and Higgs
  - Need a symmetry to prevent it to decay ex T-parity
- It is "cold" ie non relativistic
  - ➪ ruled out SM neutrinos (also not enough massive)



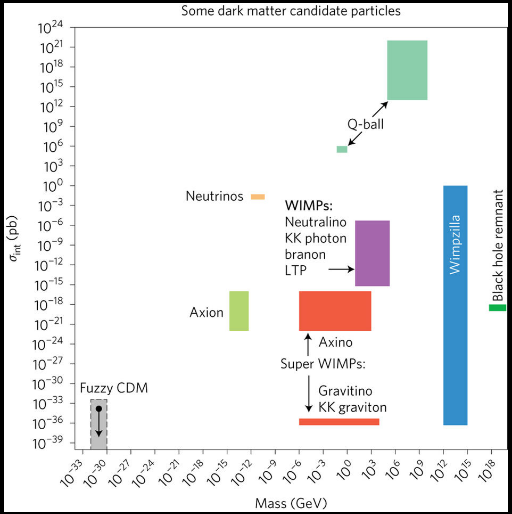


© Cold, Warm, and Hot dark matter simulations, credit ITP, University of Zurich.

Dark matter: which candidates ? Associated theories ?

Candidates

- WIMPs = Weakly Interacting Massive Particles
  - ➜ WIMP "miracle" : weak cross-section + particle mass ~1 TeV ~ relic density
  - Lightest Susy particle
  - Kaluza-Klein photon
- Very Weak Interacting Massive Particles
  - gravitinos
  - Axions: to solve the strong CP problem, unstable but long lived
  - Sterile neutrinos: to explain neutrino masses
  - Kaluza Klein gravitons
  - …
- Could be also a more complex sector with several particles and interactions



https://science.energy.gov/~/media/hep/pdf/files/pdfs/dmsagreportjuly18_2007.pdf

Associated theories

- Supersymmetry (R-parity)
- Extra dimensions (KK parity)
- Little Higgs (T-parity)
- QCD axions
- …

Dark matter: how to detect it ?

Indirect detection

- Search for charged cosmic rays, gamma rays or neutrinos

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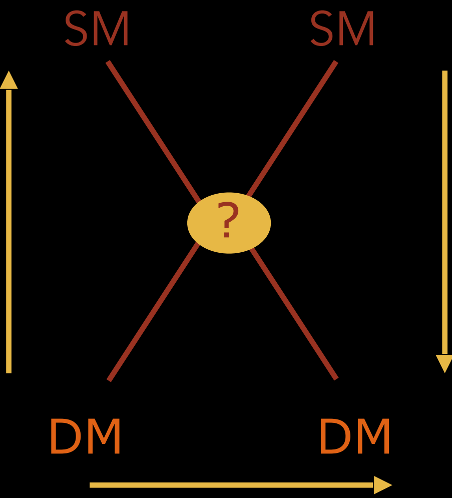
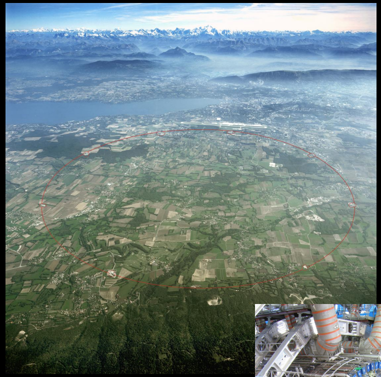
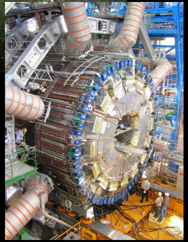
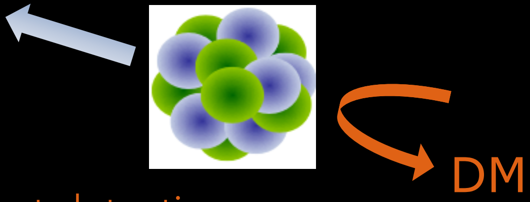


Collider search

- Produce DM particles from SM particles collisions







Direct detection

- Use scattering of DM on a nucleus

Dark matter search at LHC

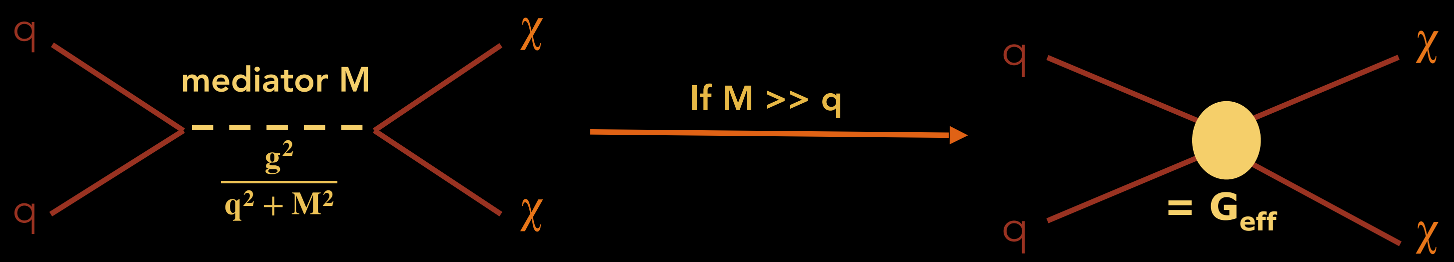
Search for particles from (UV) complete theories

➜ simulate particles decays, dark matter reconstructed as missing ET

- Supersymmetry
- Extra dimensions
- Little Higgs

Use of effective Field theory

➜ more general search, many theories show common low energy behaviour



➜ describe new interactions with few operators

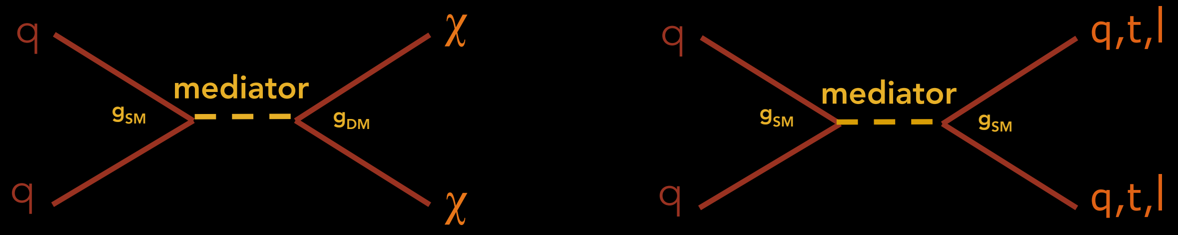
➜ but EFT valid only if M >> q ➪ Run 1 LHC limits M ~1 TeV => should not use energy > 1 TeV => not used at Run 2

Dark matter search at LHC

Simplified models

- In between EFT (used at run 1) and complete theory: add a single DM candidate (Dirac fermion) and a mediator
  - ➜ Allow to relax the q^2 limit but more model dependent
  - ➜ Few free parameters: additional masses and couplings
  - ➜ Allow to use other signatures to probe mediator and thus constrains the model

- mediator that can be scalar, vector or axial-vector, neutral or charged



- more complex two Higgs doublet models and a dark matter particle also studied

Dark matter search at ATLAS

Rich phenomenology leading to a lot of different constraints

➩ using simplified models allows to measure these constraints in the same framework and shows their complementarity

Results using simplified models gathered in one paper: arXiv:1903.01400

- « Constraints on mediator-based dark matter and scalar dark energy models using $\sqrt{s}$=13 TeV pp collision data collected by the ATLAS detector »

Common model and scenarios

- ATLAS/CMS + theory Dark Matter forum defined the DMSimp model (arXiv:1507.00966)
- Recommendations for benchmark scenarios (arXiv:1703.05703)
- Madgraph implementation (LO/NLO)

➜ Next slides focuses on these results (Susy constraints not shown here)

Simplified models with top quarks in final state

ATLAS summary paper

- List of considered models
- Analyses with top quarks contribute almost everywhere

Short description	Acronym	Symbol	J^P	Charge	Signatures
Vector/axial-vector mediator	V/AV	Z'_V/Z'_A	$1^{\mp}$	-	jet/γ/W/Z+E_T^{miss}, difermion resonance
Vector baryon-number-charged mediator	VBC	Z'_B	1^-	baryon-number	$h + E_T^{miss}$
Vector flavour-changing mediator	VFC	Z'_{VFC}	1^-	flavour	tt, $t + E_T^{miss}$
Scalar/pseudo-scalar mediator	S/PS	ϕ/a	$0^{\pm}$	-	jet+E_T^{miss}, $t\bar{t}/b\bar{b}$+E_T^{miss}
Scalar colour-charged mediator	SCC$_{q/b/t}$	$\eta_{q/b/t}$	0^+	colour, 2/3 electric-charge	jet+E_T^{miss}, $b + E_T^{miss}$, $t + E_T^{miss}$
Two-Higgs-doublet plus vector mediator	2HDM+Z'_V	Z'_V	1^-	-	$h + E_T^{miss}$
Two-Higgs-doublet plus pseudo-scalar mediator	2HDM+a	a	0^-	-	$W/Z/h + E_T^{miss}$, $t\bar{t}/b\bar{b}$+E_T^{miss}, h(inv), $t\bar{t}t\bar{t}$
Dark energy	DE	ϕ_{DE}	0^+	-	jet+E_T^{miss}, $t\bar{t}$ +E_T^{miss}

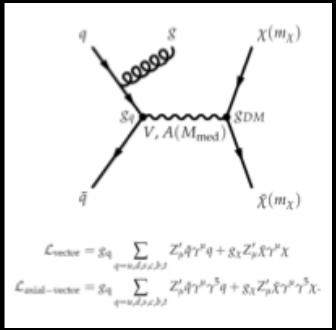
Top final states

- opposite sign top pair
- same sign top pair
- 4 top quarks
- single top + MET
- top pair + MET

(axial-)vector mediator

Model:

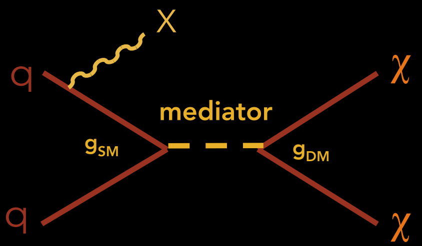
- Free parameters: m(χ), m(mediator), g_{DM} and g_q, g_l
- Minimal width computed according to couplings and considered particles mass
  - mediator decays considered = ones strictly necessary to maintain model self-consistency

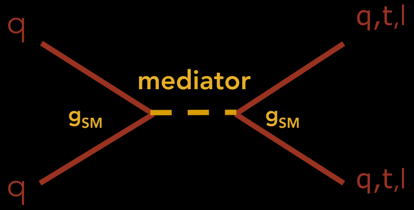


Scenarios:

- Chosen to show the complementarity of the DM production analyses (mono X + MET) and the mediator-to-visible analyses (di X)

Scenarios	g_q	g_{DM}	g_l
V1: vector model with only couplings to quarks	0.25	1.0	0.
V2: vector model with small couplings to leptons	0.1	1.0	0.01
A1: axial-vector model with only couplings to quarks	0.25	1.0	0.
A2: axial-vector model with equal coupling to quarks & leptons	0.1	1.0	0.1





Top analysis: ttbar resonance search

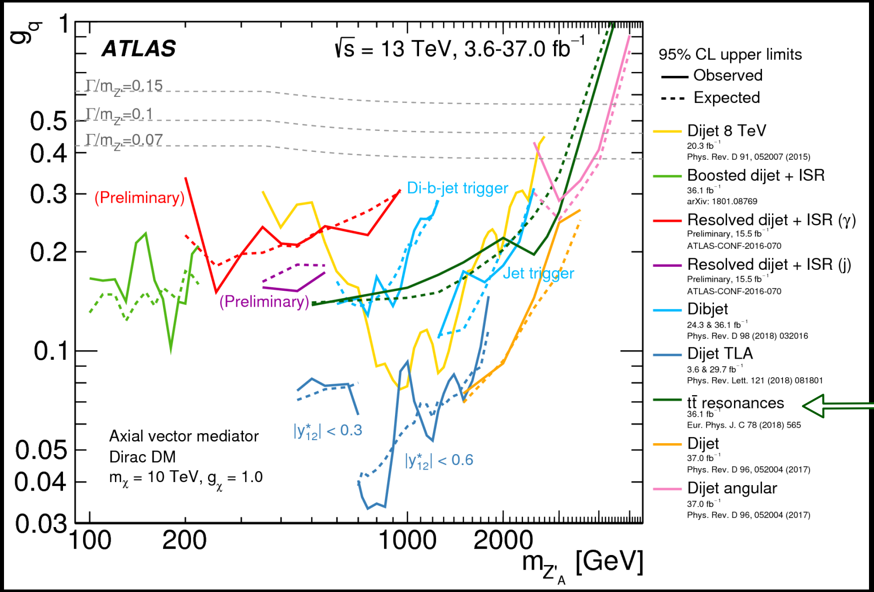
- l+jets final state used (Eur. Phys. J. C 78 (2018) 565)

Complementarity between di-X analyses

Limits in the coupling to quark - mediator mass plane, for di-X analysis

- Different di-jet analyses strategies allow to cover mediator mass from 100 GeV to 5 TeV
- Good di-top sensitivity, particularly at high mass despite the lower BR wrt to light quarks

➜ Scalar mediator analysis not available, ttbar final state will be dominant there



Caveat: for dijets analyses backgrounds are fitted on data using a sliding-window fit of the m(jj) distribution

➜ Limits are only valid if the mediator width fraction $\Gamma/m_{Z'}$ is below the corresponding threshold

- $\Gamma/m_{Z'} < 50\%$ for di-jet angular
- $\Gamma/m_{Z'} < 15\%$ for di-jet
- $\Gamma/m_{Z'} < 10\%$ for di-jet TLA |y*|<0.3
- $\Gamma/m_{Z'} < 7\%$ for di-jet TLA |y*|<0.6

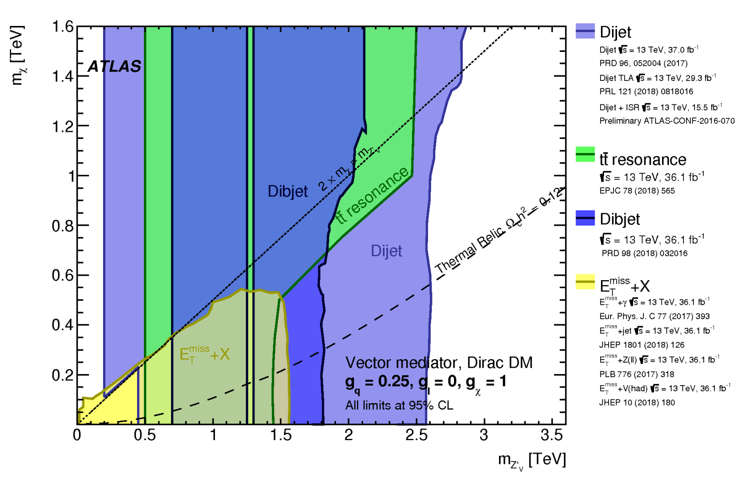
➜ This does not apply to the ttbar analysis where the backgrounds were constrained with simulations and control regions

Complementarity: vector mediator

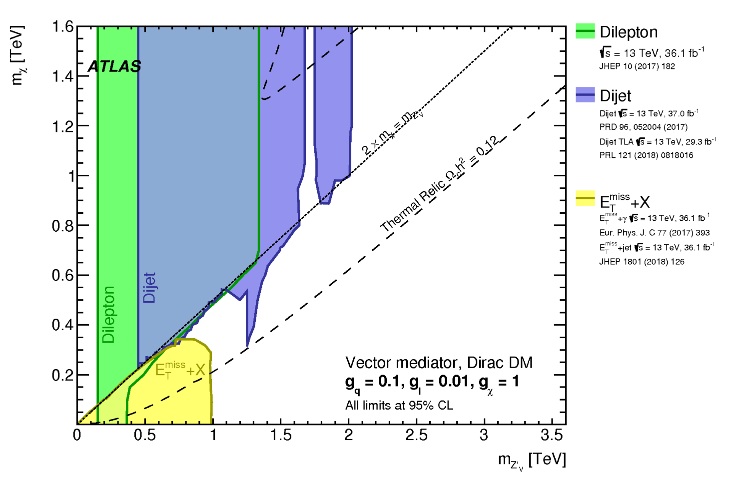
MET+X, di-jet, di-top, di-lepton analyses

- di-X analyses limits ~ don't depend on DM mass
- Note: couplings dependence is important
  - good complementarity between MET+X and di-X

g_q=0.25, g_l=0, g_{DM}=1



g_q=0.10, g_l=0.01, g_{DM}=1

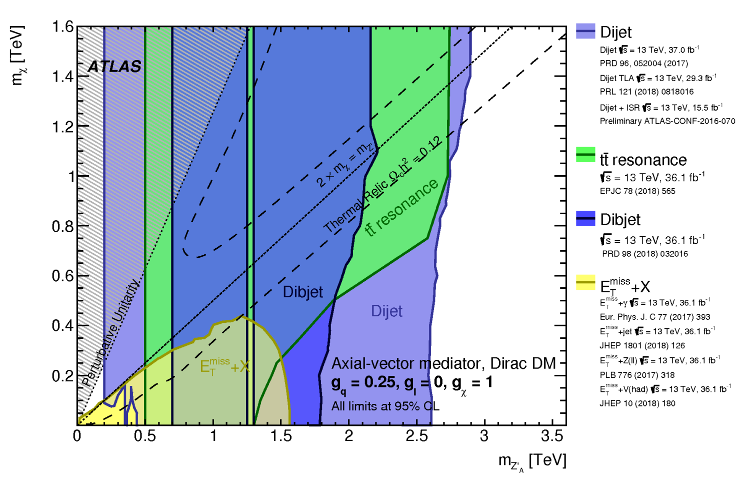


Complementarity: axial-vector

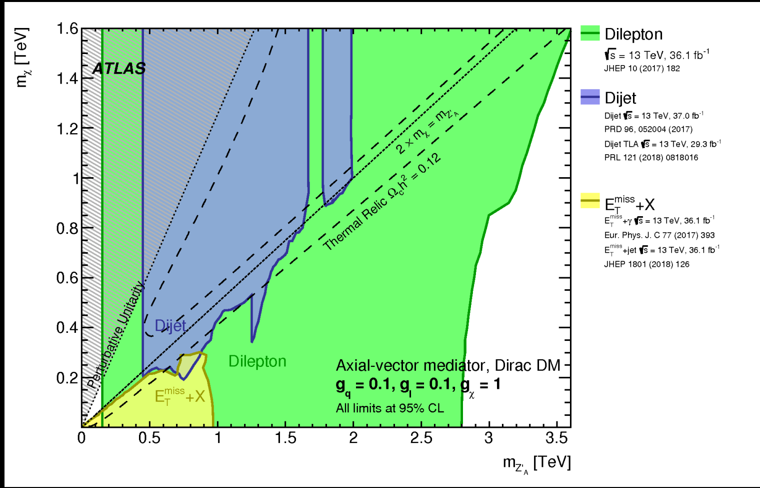
MET+X, di-jet, di-top, di-lepton analyses

- Sensitivity depends also on the mediator coupling type

g_q=0.25, g_l=0, g_{DM}=1



g_q=0.10, g_l=0.1, g_{DM}=1

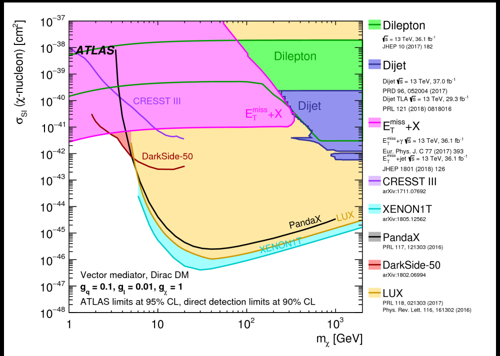


Complementarity with direct detection

ATLAS limits can be translated in the cross-section-DM mass plane used for direct detection experiment (arXiv:1603.04156)

- LHC uses 95% CL level for limits, direct detection experiment 90% CL
- Limits valid only for the coupling hypothesis indicated

Spin independent = vector mediator

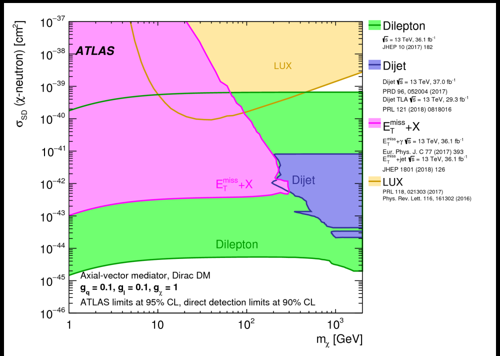


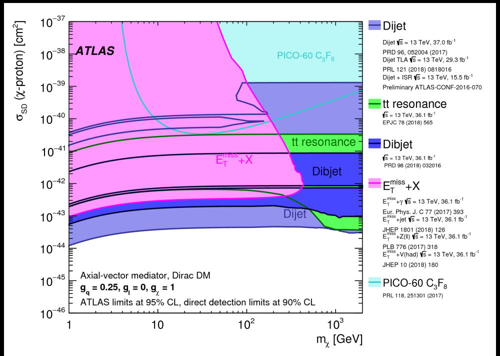
$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}$$

$$f(g_q) = 3 g_q$$

$$\mu_{n\chi} = m_n m_{\rm DM}/(m_n + m_{\rm DM})$$

Spin dependent = axial-vector mediator





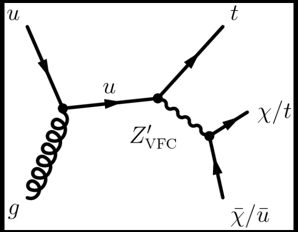
$$\sigma_{\rm SD} = \frac{3 f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}$$

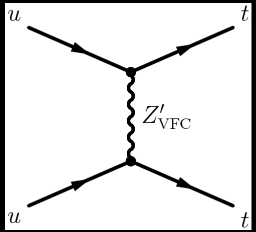
$$f(g_q) = 0.32 g_q$$

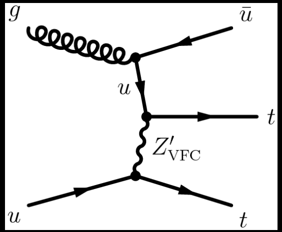
Flavour changing interaction

Also a vector mediator model but with flavour changing interaction of the DM with ordinary matter

- allows DM interaction with top quarks (right handed field only)







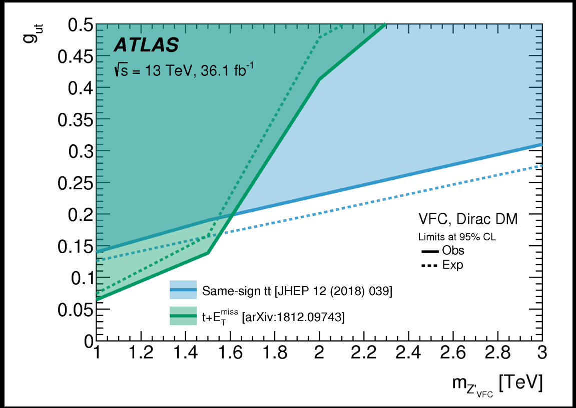
- parameters: mediator mass, g_{ut}, g_{DM}
  - DM mass has low impact on kinematics if $m_{Z'} > 2\,m_\chi$ => m_χ fixed to 1 GeV

Top analyses

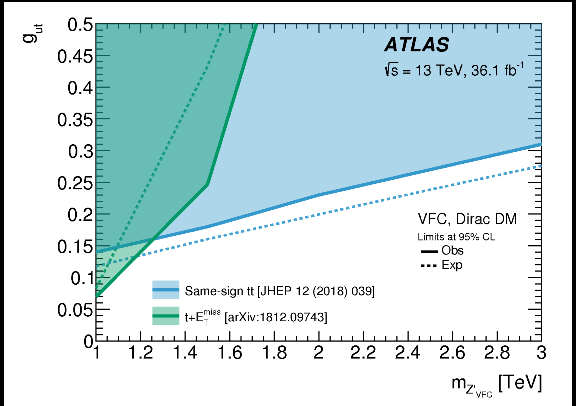
- same sign top: arXiv:1812.09743
- top + MET: arXiv:1812.09743

Flavour changing interaction

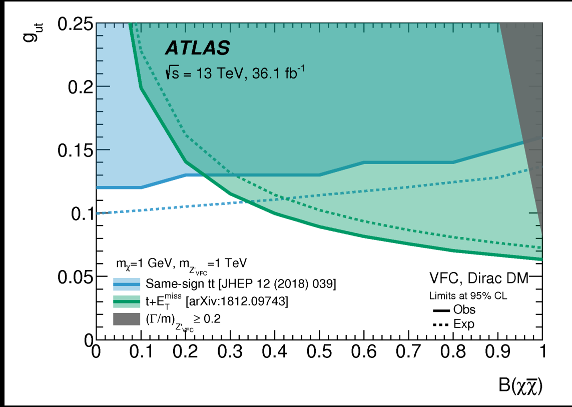
$g_{DM} = 0.5$



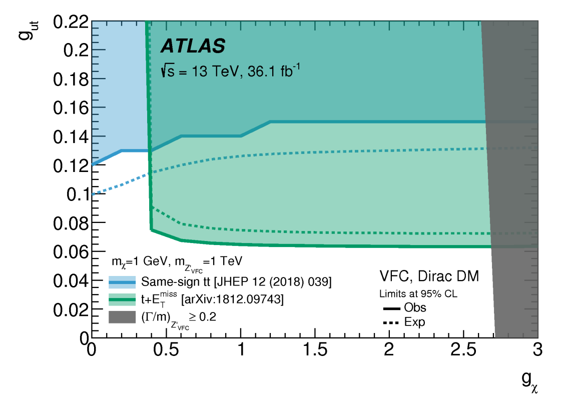
$g_{DM} = 1$



$m_{Z'} = 1$ TeV



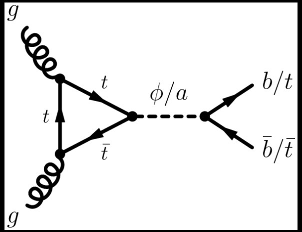
$m_{Z'} = 1$ TeV

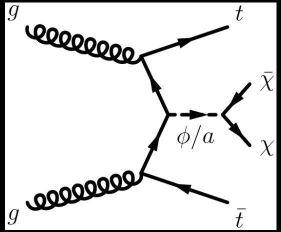


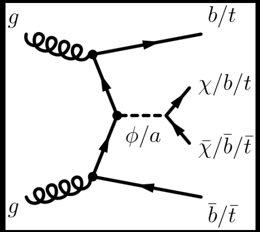
(pseudo) Scalar, colour-neutral

DM particle produced through the exchange of a spin-0 mediator

- colour-neutral scalar φ or pseudoscalar particle a
- parameters: m(φ/a), m(χ), g_χ, and the flavour-universal g_q coupling that multiplies the SM-Yukawa coupling to obtain the mediator coupling to fermions
  - ⇨ Minimal Flavour Violation, allows to be compatible with precision flavour measurements
  - ⇨ top quark final states
- Minimal width assumed taking into account only couplings and considered particles mass







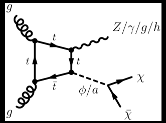
Top analyses

- Top pair+MET
- ttbar production through spin0 resonance will be very interesting but difficult because interference with SM ttbar, not available, tttt too low number of events

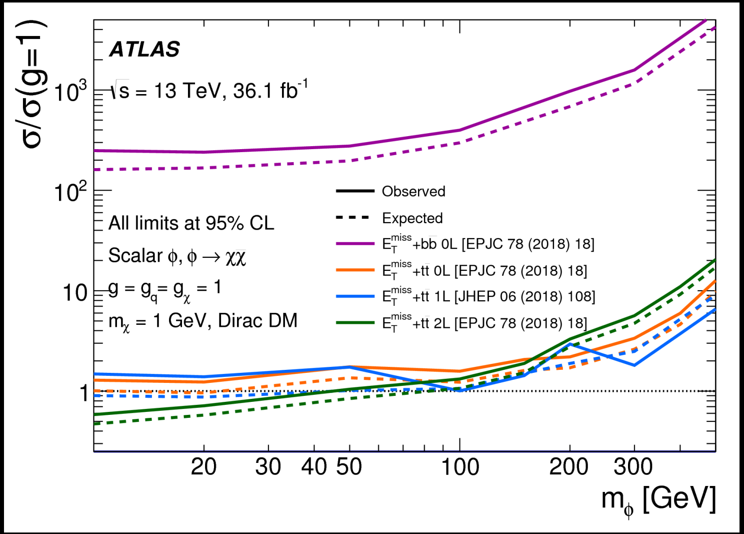
(pseudo) Scalar, colour-neutral

Limits on the cross-section ratio between signal production and nominal

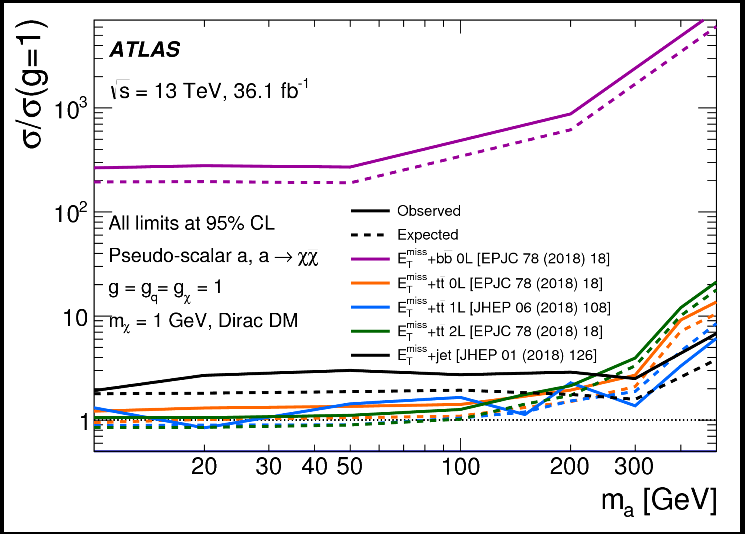
- $g_\chi = g_q = 1$, $m_\chi = 1$ GeV (valid for higher mass if decay to DM allowed)
- bbbar and ttbar + MET analyses, and jet+MET



Scalar



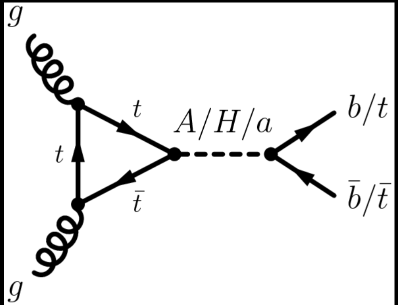
Pseudo-scalar

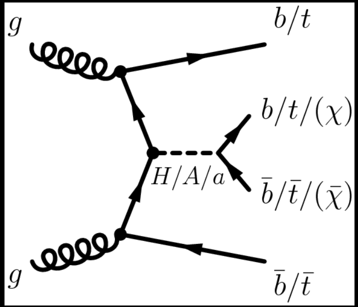


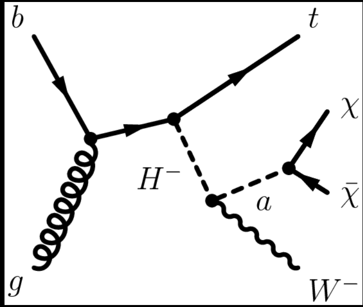
Two Higgs doublet model with pseudo-scalar

Model

- 2HDM model (type II) + pseudo-scalar a that couples to DM
- a mixes with the pseudo-scalar partner of SM Higgs boson
- 14 parameters: 5 Higgs masses, DM mass, 3 quartic couplings between scalar doublets and a, y_χ coupling between a and DM, EW VEV, ratio of VEV of 2 H doublets, mixing angles
  - hyp: h=SM H, quartic coupling λ=3 for H potential stability, $m_A=m_{H^+}=m_H$, $y_\chi=1$
  - free parameters: ma, mA, tanβ, sinθ and m_χ







Top analyses

- Top pair+MET, 4 top quarks, top + MET

Two Higgs doublet model with pseudo-scalar

Scenarios:

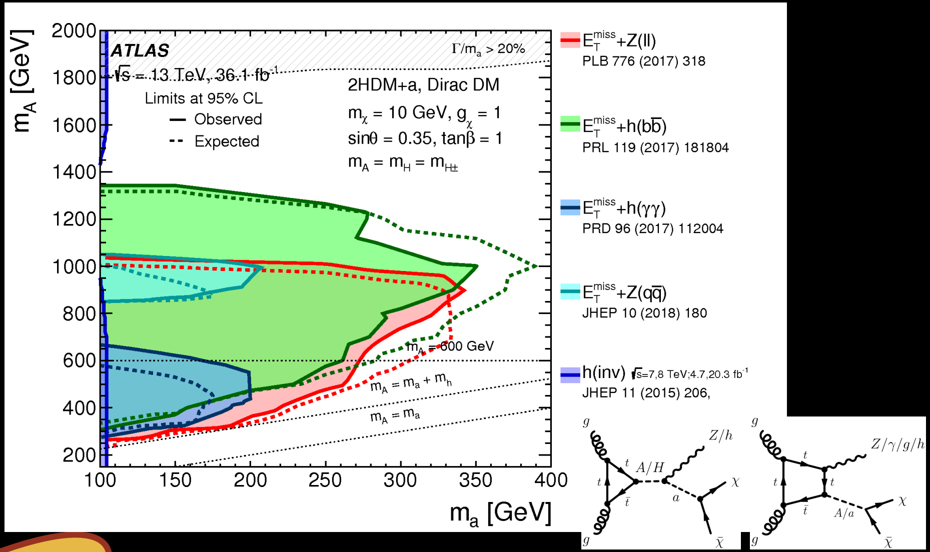
1 - (m_a, m_A) plane
tanβ=1, sinθ=0.35

2 - (ma, tanβ) plane
mA=600 GeV, sinθ=0.35

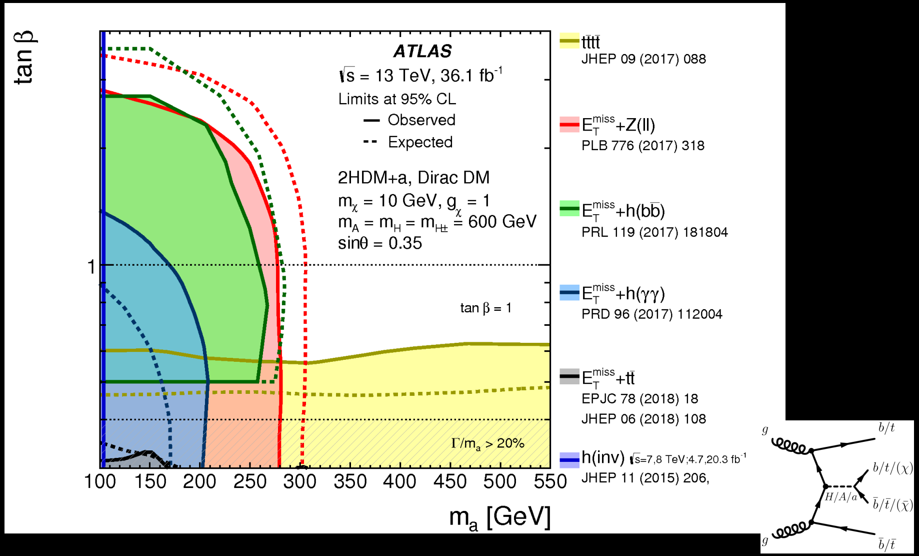
3 - sinθ scan
m_A=600 (1000) GeV, m_a=200 (350) GeV, tanβ=0.5, 1, 50 (0.5, 1)

4 - m_χ scan
m_A=600 GeV, m_a=250 GeV, tanβ=1, sinθ=0.35

Scenario 1

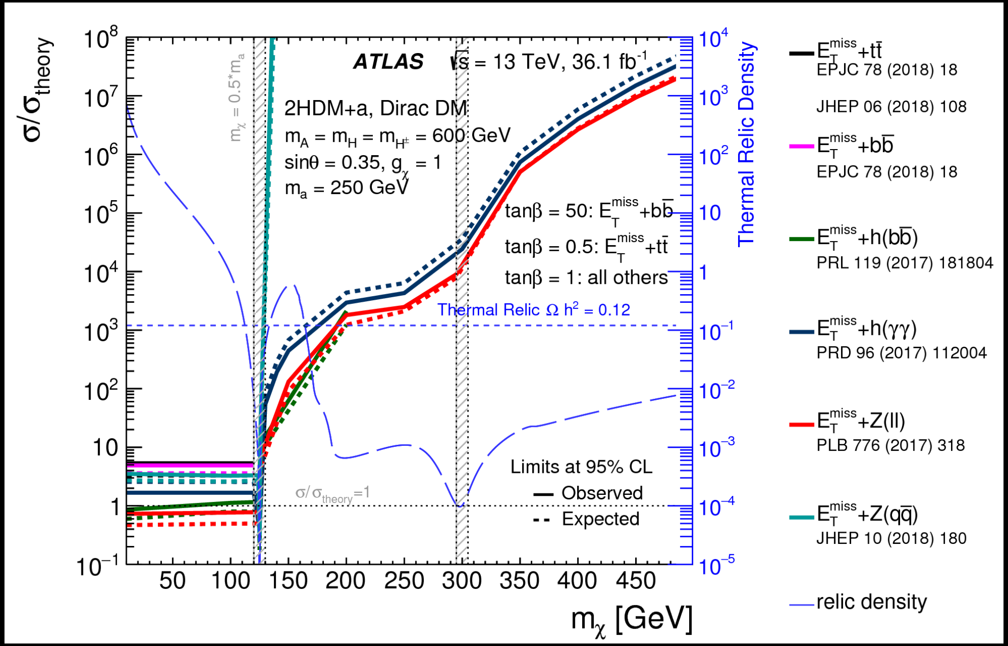


Scenario 2



Two Higgs doublet model with pseudo-scalar

Scenario 4 - mχ scan with m_A=600 GeV, m_a=250 GeV, tanβ=1, sinθ=0.35



View as a function of DM mass

- sensitivity of X+MET analyses independent of m_χ if a can decay in $\chi\chi$ at low m_χ, the region is excluded by Z+MET
- above not enough sensitivity to exclude the parameter space

EFT model of scalar dark energy

EFT implementation of Horndeski theories that introduce a dark energy scalar which couples to gravity

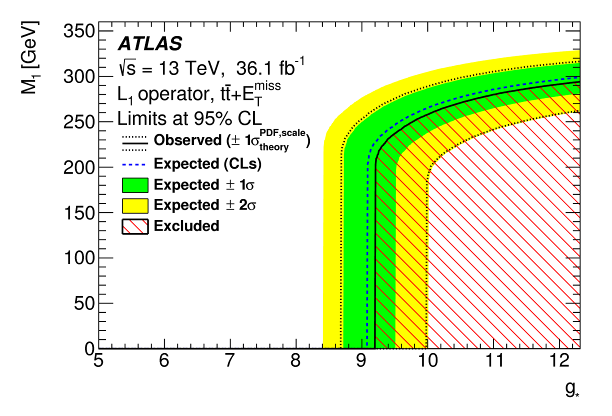
- where T is the energy-momentum tensor corresponding to the SM Lagrangian

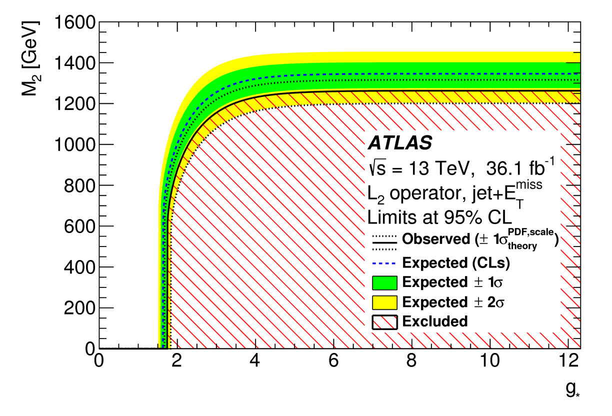
  for $\mathcal{L}1$, T = m$\bar{\psi}\psi$ for a Dirac field and is therefore proportional to the mass of the SM fermions ⇨ ttbar+MET

- M characteristic energy scale

$$\mathcal{L}_1 = \frac{\partial_\mu \phi_{\rm DE} \partial^\mu \phi_{\rm DE}}{M_1^4} T_\nu^\nu$$

$$\mathcal{L}_2 = \frac{\partial_\mu \phi_{\rm DE} \partial_\nu \phi_{\rm DE}}{M_2^4} T^{\mu\nu},$$





Conclusion

DM search is a very active field

General searches using simplified models are quite powerful

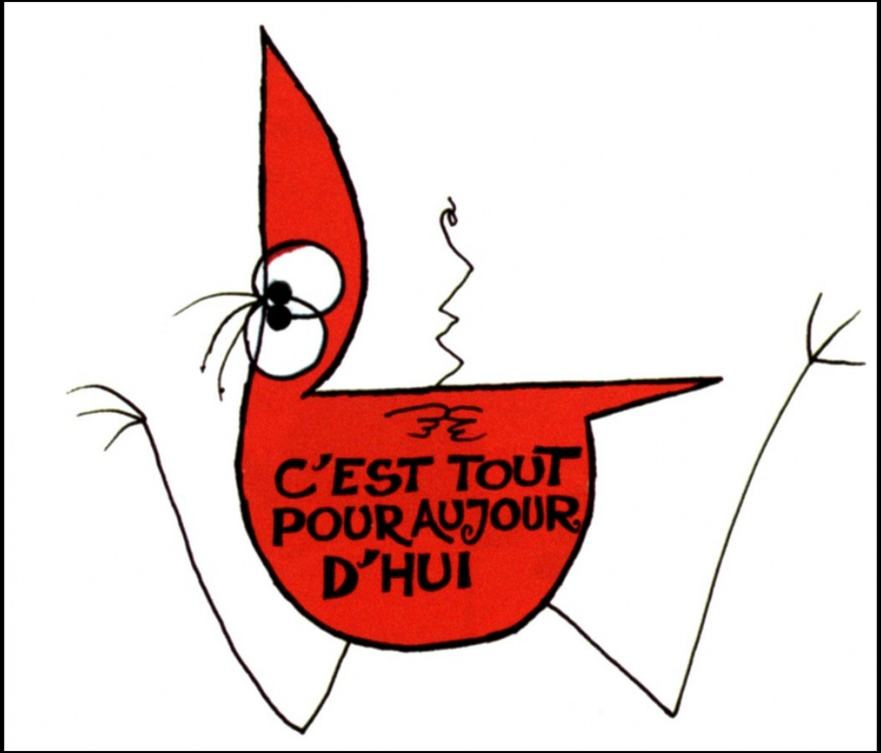
- Allow to take advantage of the wide analyses sensitivities at LHC to constrain models using the analyses with and without DM particle in the final state
- Common benchmark model defined at DM forum help to focus in interested regions
- Allow to show complementarity between searches at LHC and collider search and direct detection experiments

Top quark is an interesting tool in that frame

- in almost all the cases studied and in particular with the presence of a (pseudo)scalar mediator

No signal so far

- next steps: full run 2 statistics to analyse, improved analyses

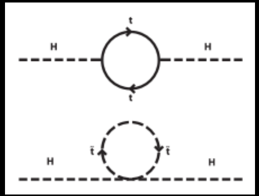

C'EST TOUT
POUR AUJOURD'HUI

TO GO FURTHER…

Collider Search: where does top quark join in ?

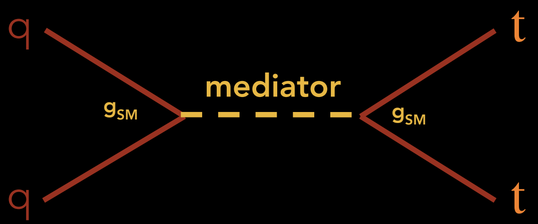
Supersymmetry

- Naturalness requires SUSY to have « light » stop (~TeV)
- Stop decays in top + MET, or similarly to top unless compressed scenario
- R-parity conservation ➯ stop produced by pair
- Top quarks found also in gluinos decays



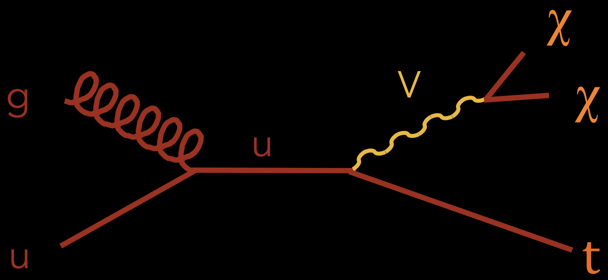
Simplified models

ttbar



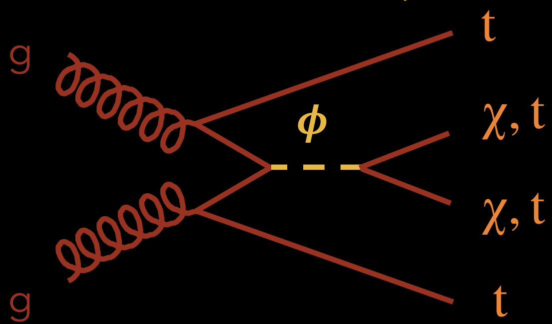
Mediator: (axial)vector, (pseudo)scalar

Single top + MET, FCNC



FCNC, colored charged scalar

ttbar + MET, 4 top

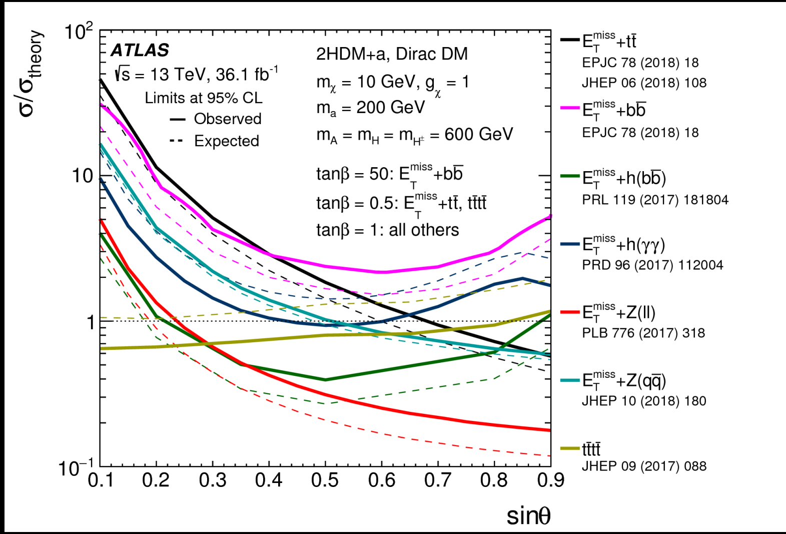


(pseudo)scalar, 2HDM + (pseudo)scalar

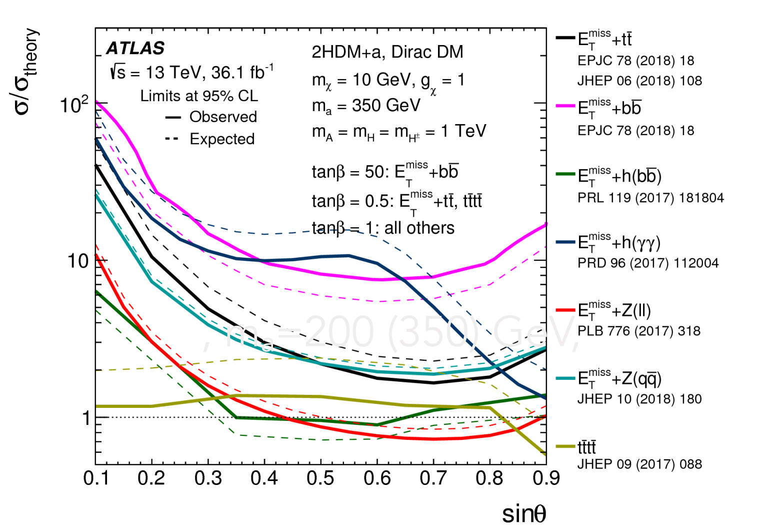
Two Higgs doublet model with pseudo-scalar

Scenario 3: $\sin\theta$ scan with $\tan\beta$=0.5, 1, 50 (0.5, 1)

m_a=200 GeV, m_A=600 GeV



m_a=350 GeV, m_A=1000 GeV



a → ttbar allowed