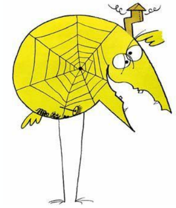
Dark matter search with top quarks

Sabine Crépé-Renaudin

Disclaimer



➜ Chose not to be exhaustive but more to show the strategy for the DM searches

➜ Very rich search field

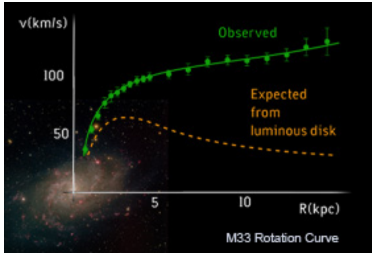
- will only show 13 TeV analysis results with at least 2015+2016 statistics
- Not enough time to describes in detail the analysis strategies

Dark matter: observations

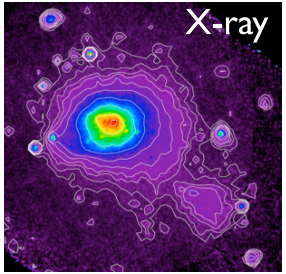
Evidence of dark matter

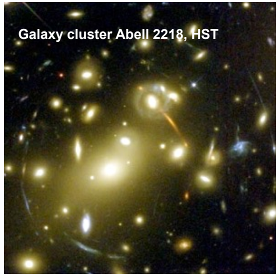
- From astrophysics and cosmology observations at **different scales**

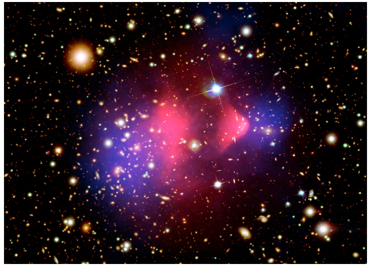
Galaxy rotation



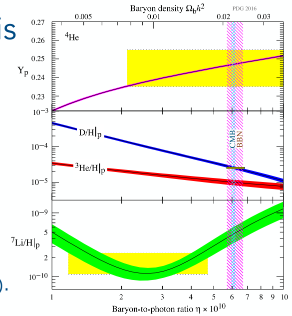
Galaxy clusters via Xrays and gravitational lensing, collisions





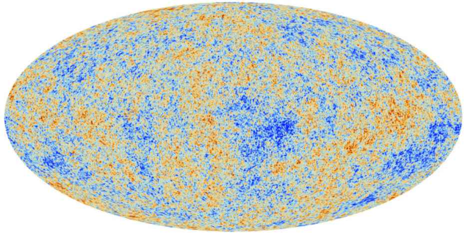


Nucleosynthesis



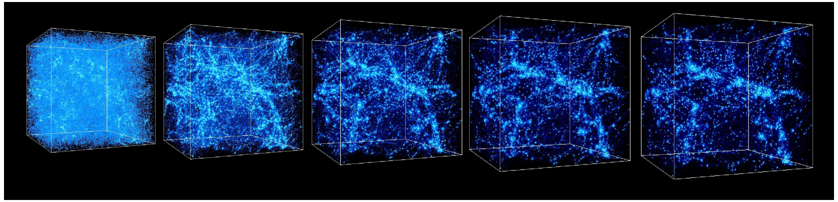
([Schramm & Turner 1998](#)).

Cosmic microwave background



Ⓒ ESA, Planck Collaboration

Large scale structure formation

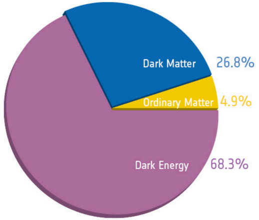


Ⓒ simulations were performed at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov.

➜ **Results consistent: need of a new kind of matter**

Dark matter: what do we know about ?

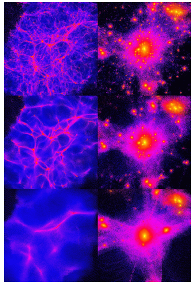
Properties



© Planck

- It makes up 85% of the matter in the Universe
  - 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 ?

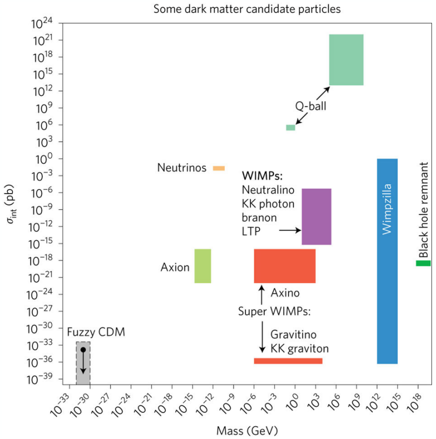
Candidates

- WIMPs = Weakly Interacting Massive Particles

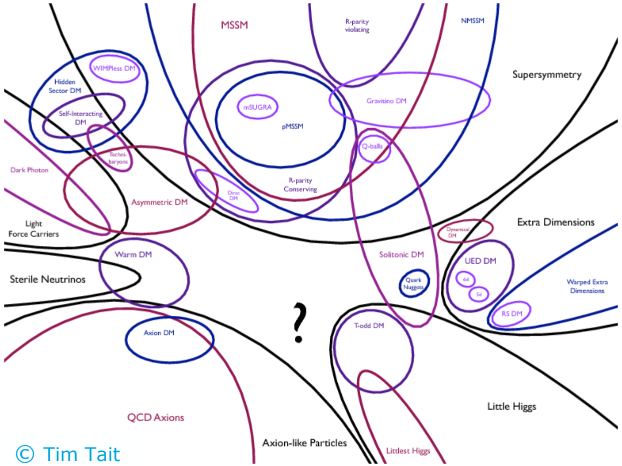
  ➜ WIMP "miracle" : weak cross-section + particle mass ~1 TeV ~ relic density
  - Susy neutralinos
  - Kaluza-Klein photon

- 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



© Tim Tait

Theories

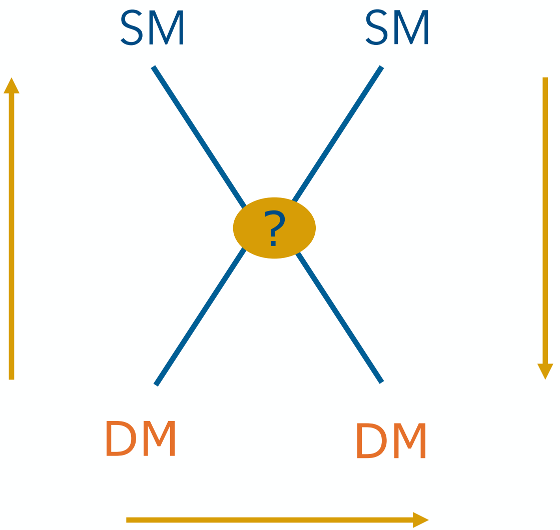
- Supersymmetry
  - Symmetry: R-parity
- Extra dimensions
  - Symmetry : KK parity
- Little Higgs
  - Symmetry: T-parity
- QCD axions
- …

Dark matter: how to detect it ?

Indirect detection

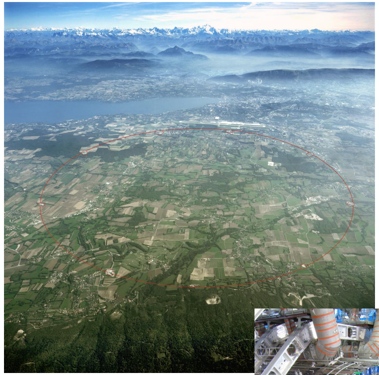
- Search for charged cosmic rays, gamma rays or neutrinos

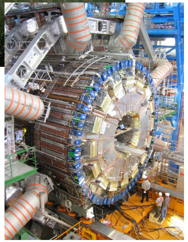
© NASA / Sonoma State University, Aurore Simonnet



Collider search

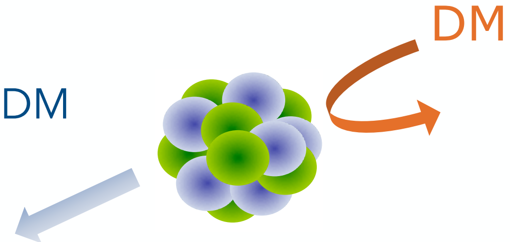
- Produce DM particles from SM particles collisions





Direct detection

- Use scattering of DM on a nucleus



Dark matter search at LHC

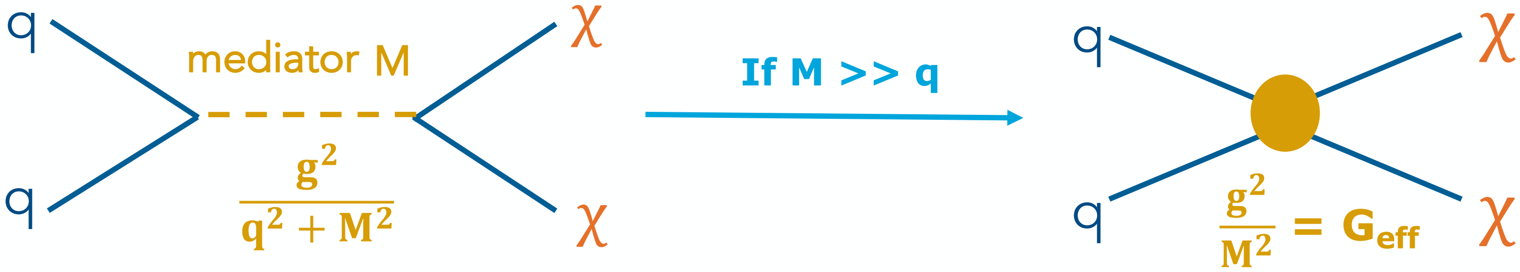
Search for particles from (UV) complete theories

➜ simulate particles decays, dark matter reconstructed as missing E_T

- Supersymmetry
- Extra dimensions
- Little Higgs

Use of effective Field theory

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

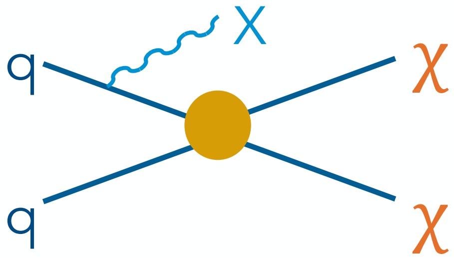


➜ describe new interactions with few operators

Dark matter search at LHC: effective theory

Use of effective Field theory

- Mono X search: use of a radiated particle to trigger the event



$X = \gamma$, jet, …
$\chi\chi$ = MET

➜ **LHC Run-1 focus**

- Advantages:
  - model independent
  - Allow to translate LHC results into (in)direct search frames (with some care on the hypothesis)
- Limitations:
  - EFT valid only if M >> q ⇨ Run 1 LHC limits M ~1 TeV => should not use energy > 1 TeV
  - Loose correlations that can be used in complete theory

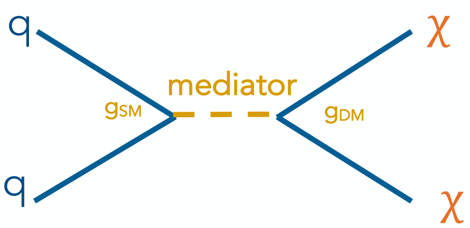
Dark matter search at LHC: simplified models

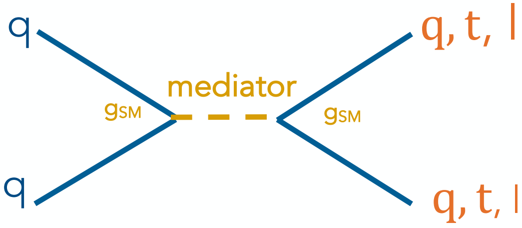
Simplified models

- In between EFT and complete theory: add a single DM candidate (Dirac fermion) and a mediator

➜ Allow to relax the q^2 limit but more model dependent

➜ Allow to use other signatures to probe mediator and thus constrains the model





Common model and scenarios

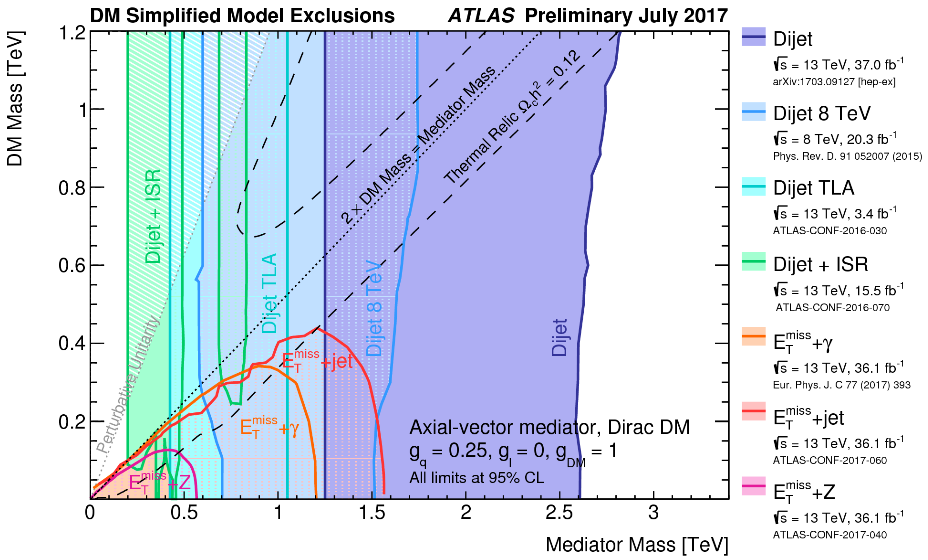
- ATLAS/CMS + theory Dark Matter forum defined the *DMSimp model* (arXiv:1507.00966)
- Recommendations for benchmark scenarios (arXiv:1703.05703)
- Madgraph implementation (LO/NLO)

Complementarity

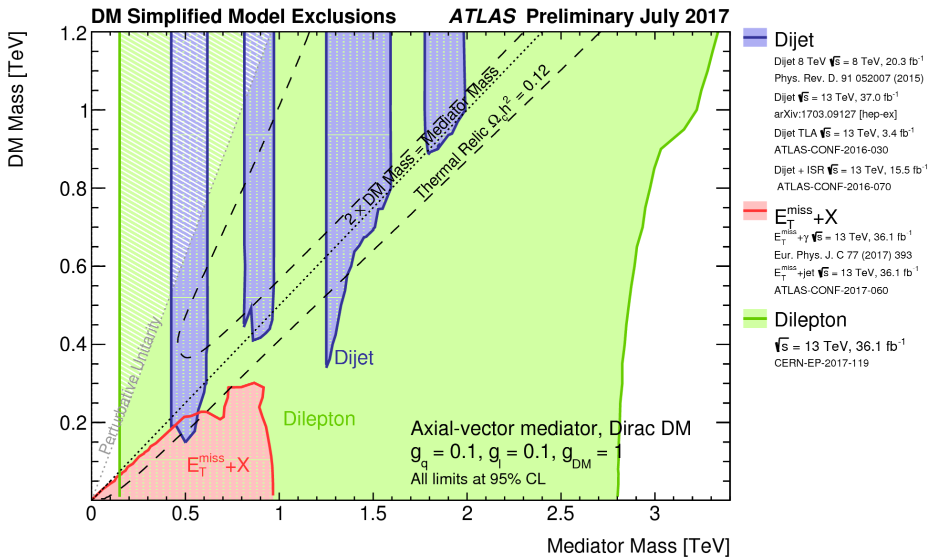
Combination of mono-jet, mono-photon and di-jets

- Note: couplings dependence is important

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



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

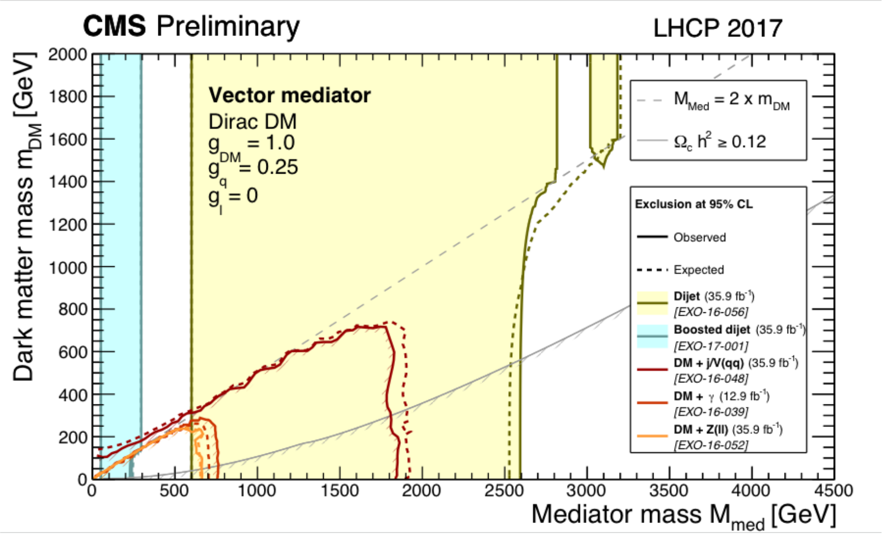


Complementarity

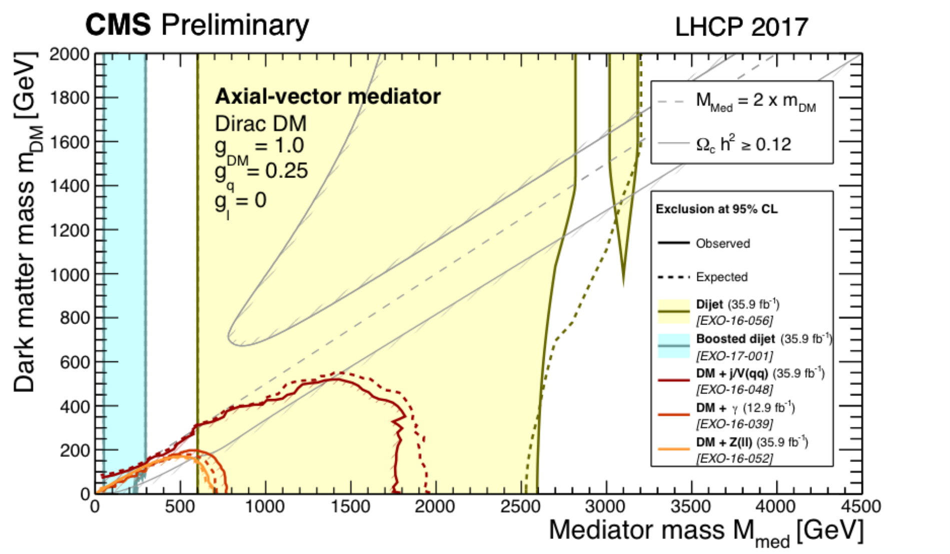
Combination of mono-jet, mono-photon and di-jets

- Sensitivity depends also on the mediator coupling type

Vector mediator



Axial-vector mediator

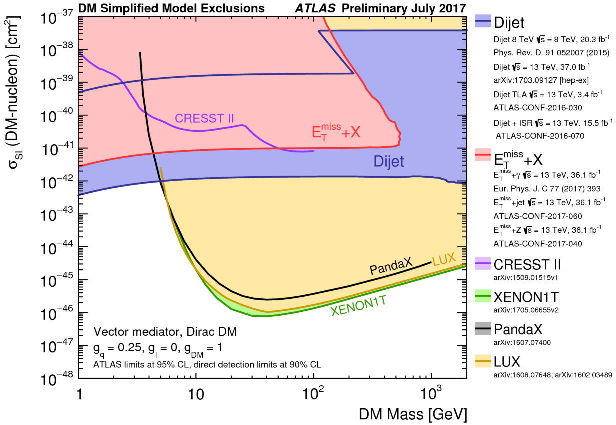


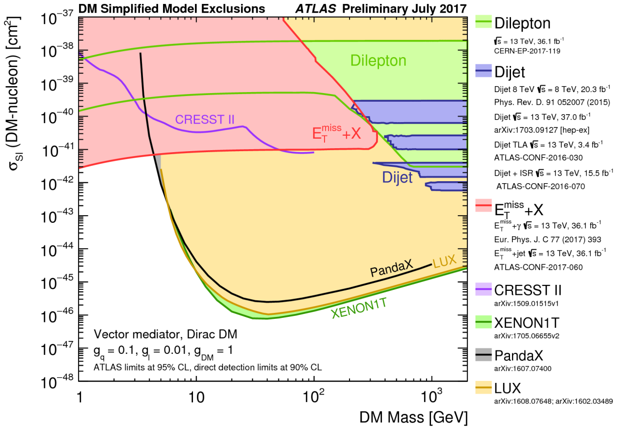
Comparison with direct detection

Vector mediator g_q=0.25, g_l=0

Vector mediator g_q=0.1, g_l=0.01

ATLAS

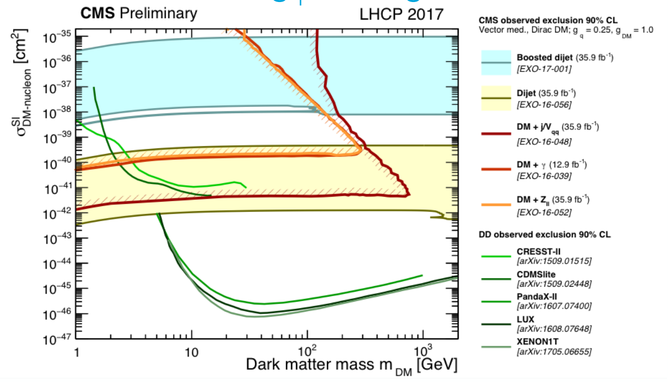


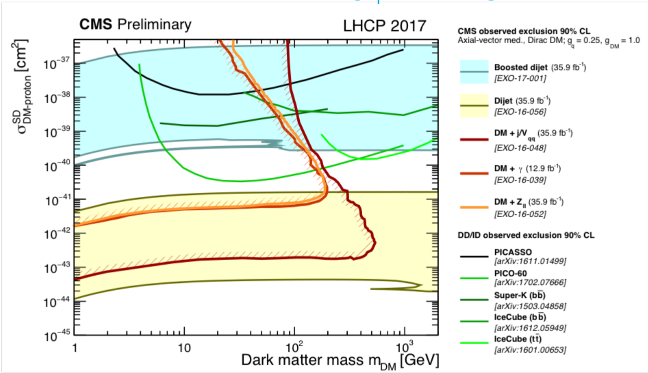


Vector mediator g_q=0.25, g_l=0

Axial-vector mediator g_q=0.25, g_l=0

CMS

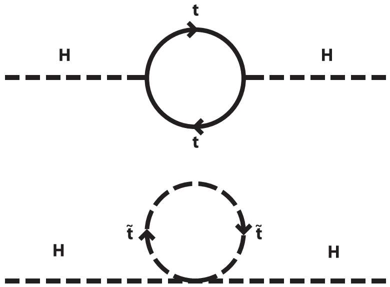




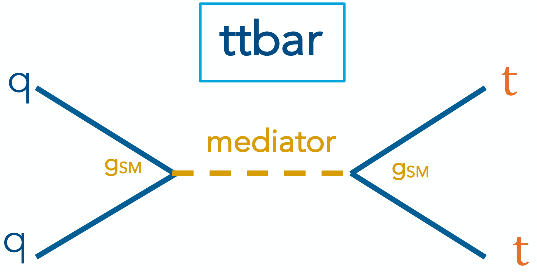
Collider Search: where does top quark join in ?

Supersymmetry

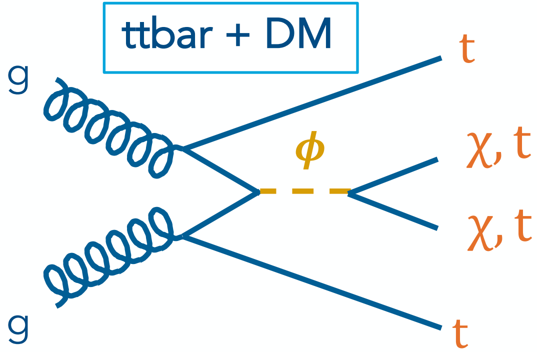
- Naturalness requires SUSY to have « light » stop (~TeV)
- Stop decays in top + MET, or similarly to top decay unless compressed scenario
- R-parity conservation ➪ stop produced by pair
- Top quarks found also in gluinos decays



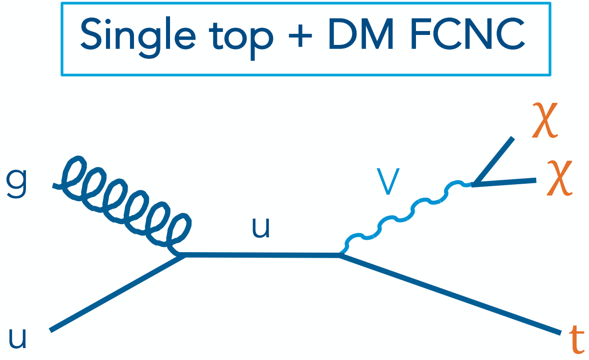
Simplified models



Mediator: (axial)vector, (pseudo)scalar



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



FCNC, coloured charged scalar

Supersymmetry: stop search

Top squarks

- Susy = symmetry between fermion and bosons
  ⇨ $\tilde{t}_L$ and $\tilde{t}_R$ superpartners of t_L and t_R,
  ⇨ mix in 2 mass eigenstates $\tilde{t}_1$ (the lightest) and $\tilde{t}_2$
- Significant mass-splitting between the 2 stops is possible due to the large top-quark Yukawa coupling + renormalisation group equations drive third-generation squarks masses to values significantly lower than those of the other generations.

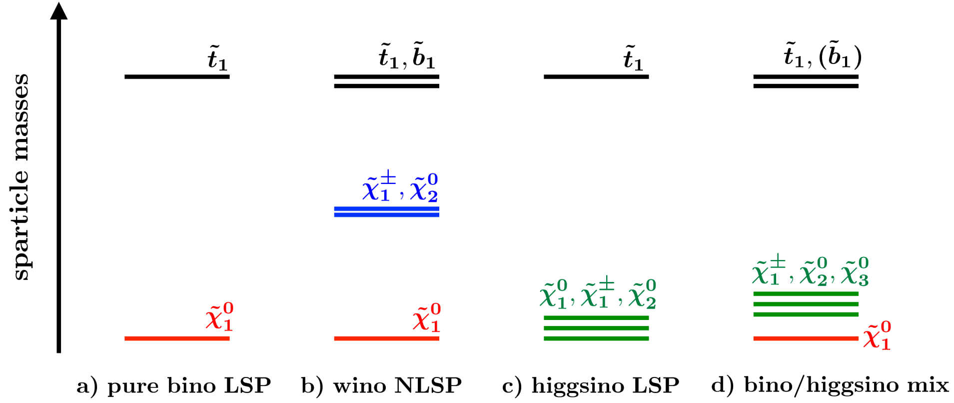
DM particle

- The charginos $\tilde{\chi}^{\pm}$ and neutralinos $\tilde{\chi}^{0}$ are the mass eigenstates formed from the superposition of the charged and neutral SUSY partners of the Higgs and electroweak gauge bosons
  ⇨ higgsino, wino and bino
- Neutralino is often considered as the Lightest Supersymmetric Particle (LSP)

Supersymmetry: stop search

Search for stop pairs

- Decays depends on the susy parameters via the particle mass hierarchy, the mixing between $\tilde{t}_L$ and $\tilde{t}_R$ and the nature of the neutralino (which mixture of higgsino, wino and bino)



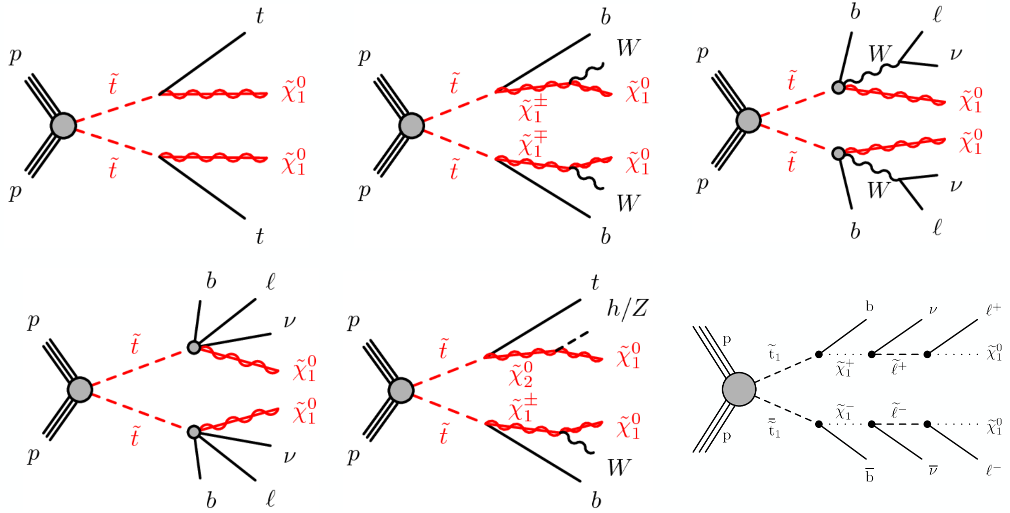
Example of mass spectra considered in the [ATLAS 1 lepton analysis]

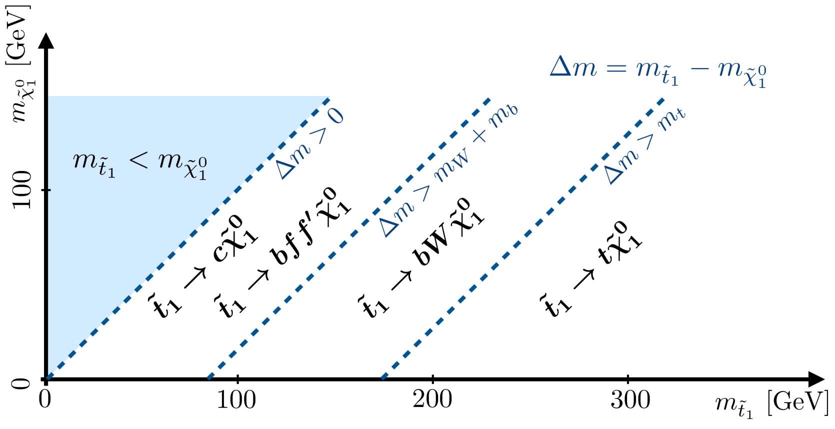
- Analyses divided
  - with respect to final states (0, 1, 2 leptons) as for any top pair analysis
  - and subdivided according to decay chain

Supersymmetry: stop search

Decay chain

- Different diagrams are taken into account to cover the largest possible space in the parameter phase space



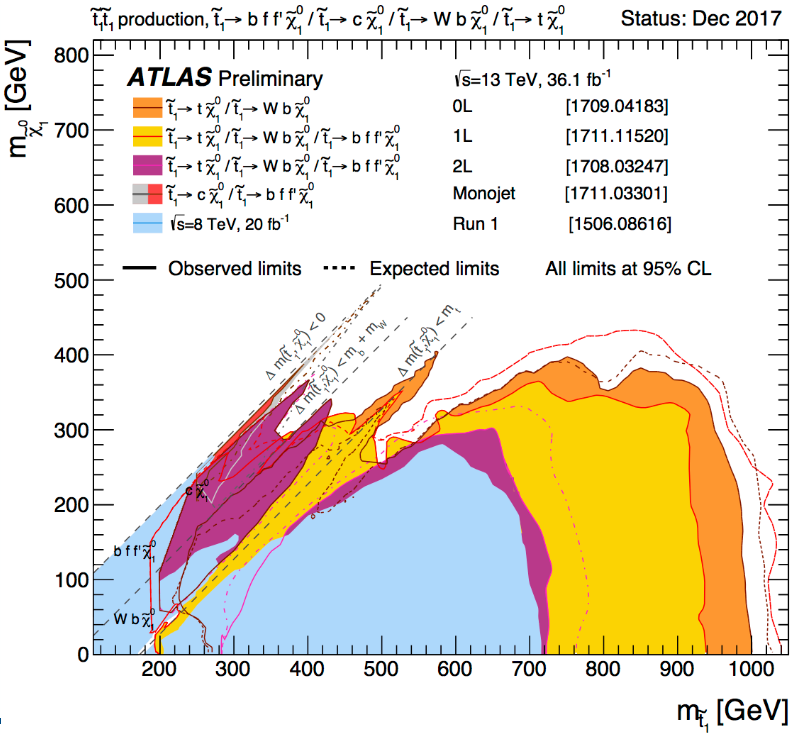


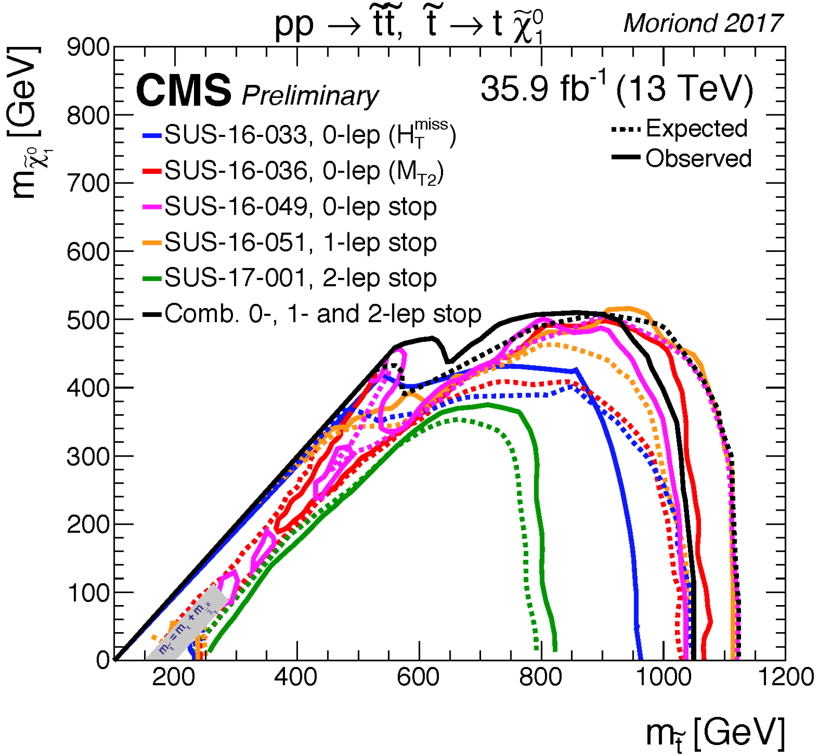
Example: considered decay chain in the pure bino LSP hypothesis (from ATLAS 1 lepton analysis)

- Note: in the boundary regions, sensitivity decrease because of the kinematics

Susy Stop pair search: summary

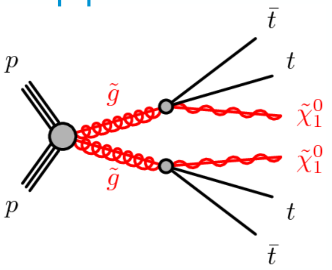
Latest summary plots with references of papers

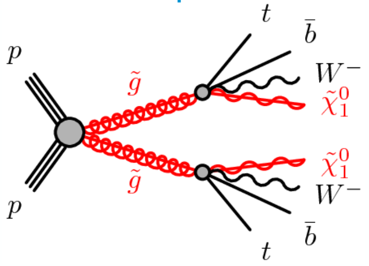


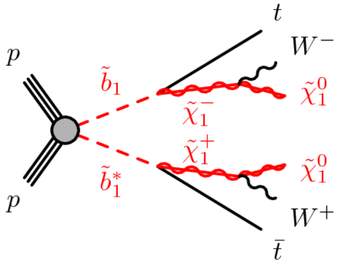


Gluinos searches

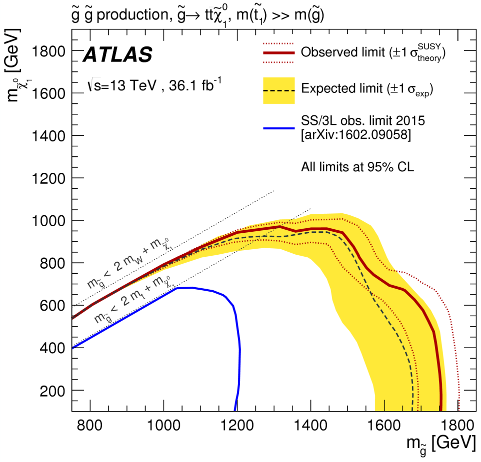
Top quarks appear also in gluinos/b squark decays

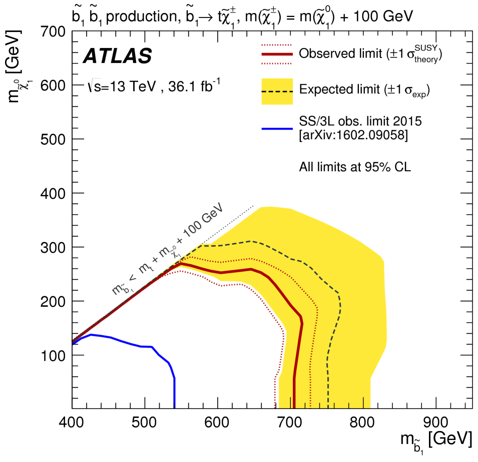






- Results obtained with an analysis using final states with two same-sign or three leptons and jets
  arXiv:1706.03731





Simplified model: top pair + DM

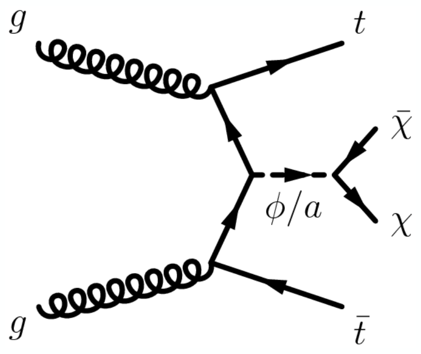
Fermionic DM particle produced through the exchange of a spin-0 mediator

- colour-neutral scalar ϕ or pseudo-scalar particle a
- Final state top pair + MET

⇨ Not far from susy searches but kinematics different

⇨ More complex models derived from 2HDM could be also considered:

– Choice of DM forum: 2HDM (type II) + pseudo-scalar ⇨ close kinematics, need however to add heavy pseudo-scalar A decays



Couplings

- couplings of the mediator to the SM fermions are constrained by precision flavour measurements

⇨ Minimal Flavour Violation assumed: same structure as in the Standard Model.

⇨ Interaction between ϕ/a and SM matter ∝ fermion mass via Yukawa coupling ⇨ top

Parameters:

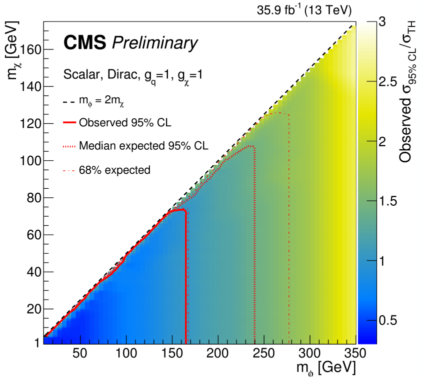
- m(ϕ/a), m(χ), g_χ, and the flavour-universal g_q coupling, to reduce parameter number: $g_\chi = g_q = g$
- Minimal width assumed taking into account only couplings and considered particles mass

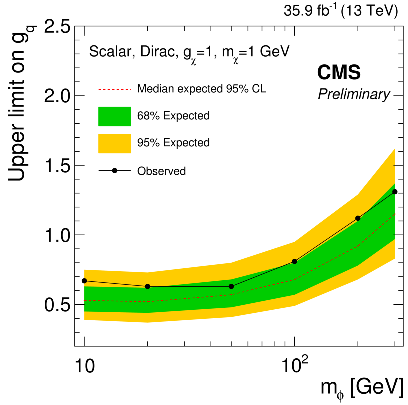
Simplified model: top pair + DM - CMS

➜ CMS 0,1,2 L combination CMS-PAS-EXO-16-049

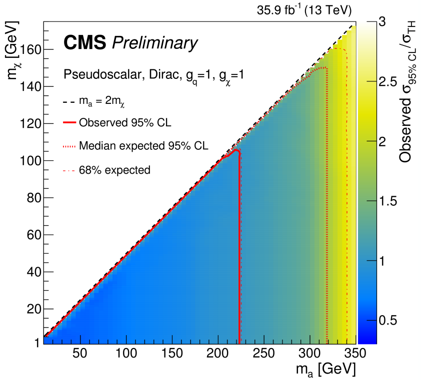
Limits on coupling

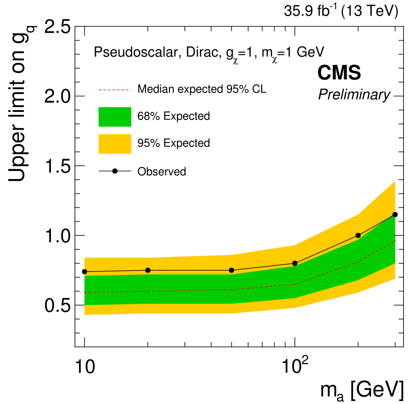
scalar





Pseudo-scalar



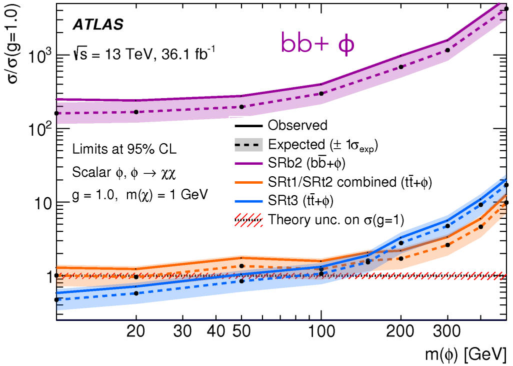


Simplified model: top pair + DM - ATLAS

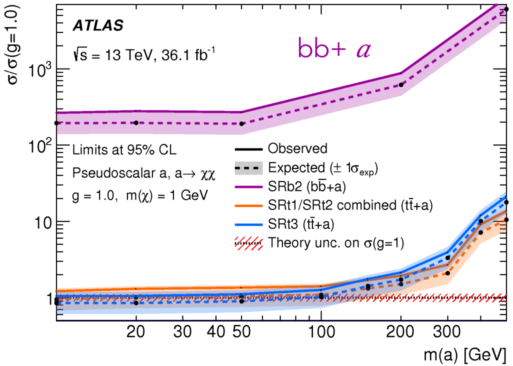
➜ ATLAS 2L 0L arXiv:1710.11412 + ATLAS 1L (susy) arXiv: 1711.11520

Vs mediator mass

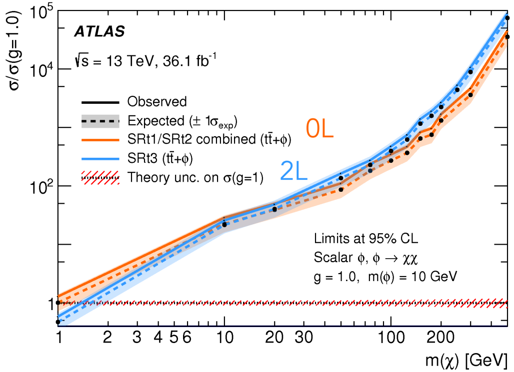
scalar

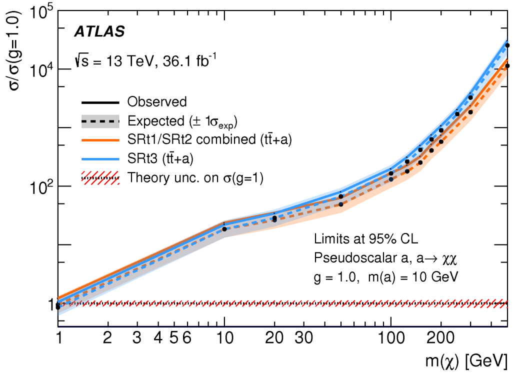


Pseudo-scalar

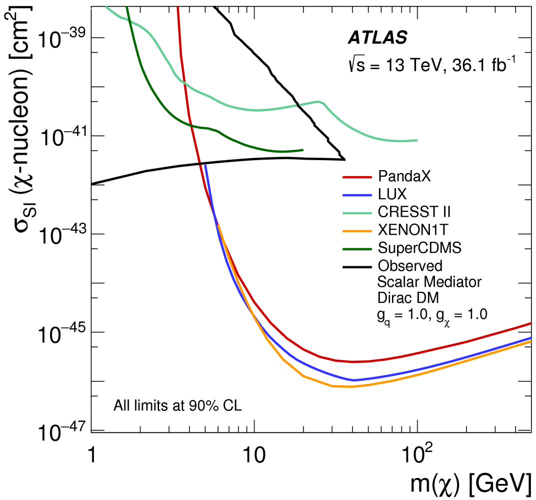


Vs DM mass





➜ Comparison (2L) with direct detection spin independent

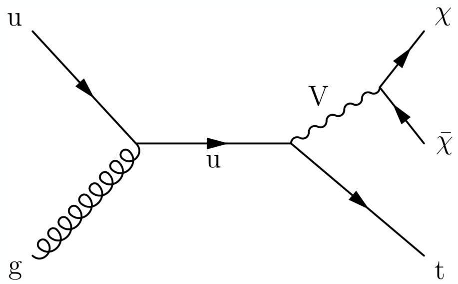


➜ Direct detection not competitive for pseudo-scalar mediator

Single top + DM

Models

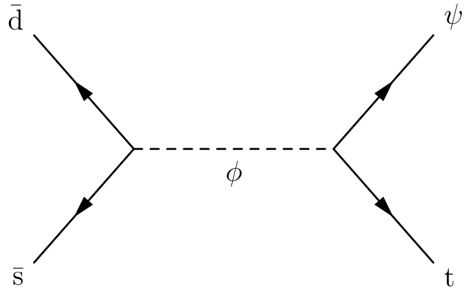
- "Non resonant": FCNC producing a top quark + a vector boson that decays to DM



Couplings:

- g_χ^V and g_χ^A V= vector, A=axial-vector
- g_u^V, g_u^A, g_d^V, g_d^A, are 3 × 3 flavour matrices
  - $g_u^V - g_u^A = g_d^V - g_d^A$ to preserve $SU(2)_L$
  - *Choice:* $g_u^V = g_d^V \equiv g_q^V$, and $g_u^A = g_d^A \equiv g_q^A$

- "Resonant": coloured charged scalar ϕ that decays to a top quark and a DM fermion ψ



Couplings:

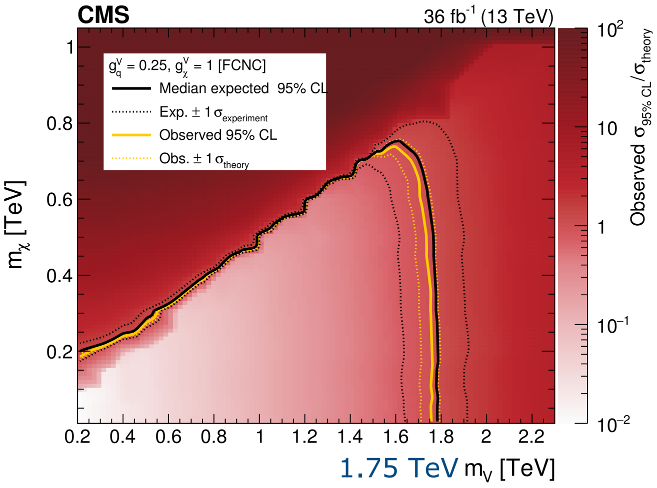
- ϕ to down-type quarks: a_q (scalar) and b_q (pseudo-scalar)
- ϕ to DM ψ*:* Similarly, a_ψ and b_ψ
- Hypothesis: $a_q = b_q = 0.1$ and $a_\psi = b_\psi = 0.2$.

Single top +DM

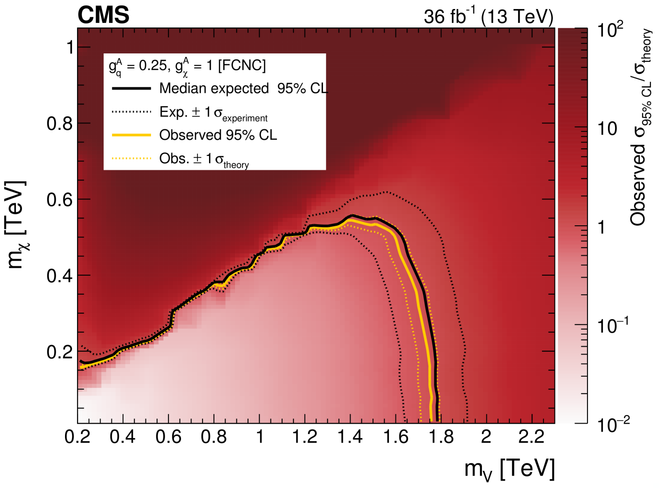
Analysis

- CMS, hadronic top decay arXiv:1801.08427
- Top-tagging: BDT with substructure variable to distinguish top from light jet (quark/gluon)

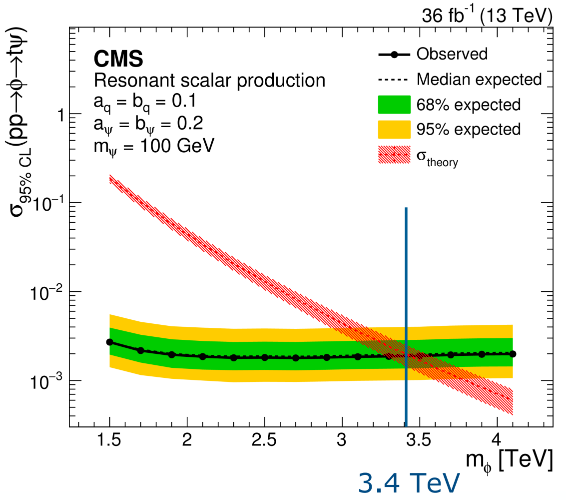
Non resonant: vector couplings



Non resonant: axial-vector couplings



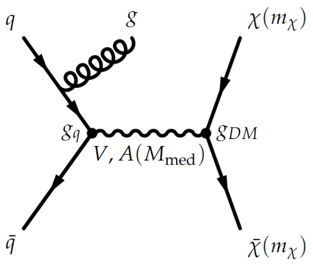
Resonant

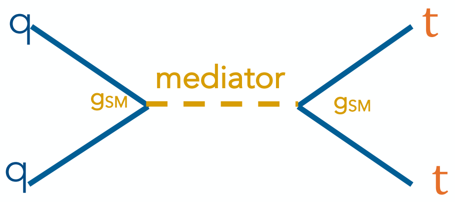


- Limits also given for couplings vs m(V)

Simplified model: (axial-)vector mediator

Model:





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

$$\mathcal{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi.$$

- Free parameters: m(χ), m(med), 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:

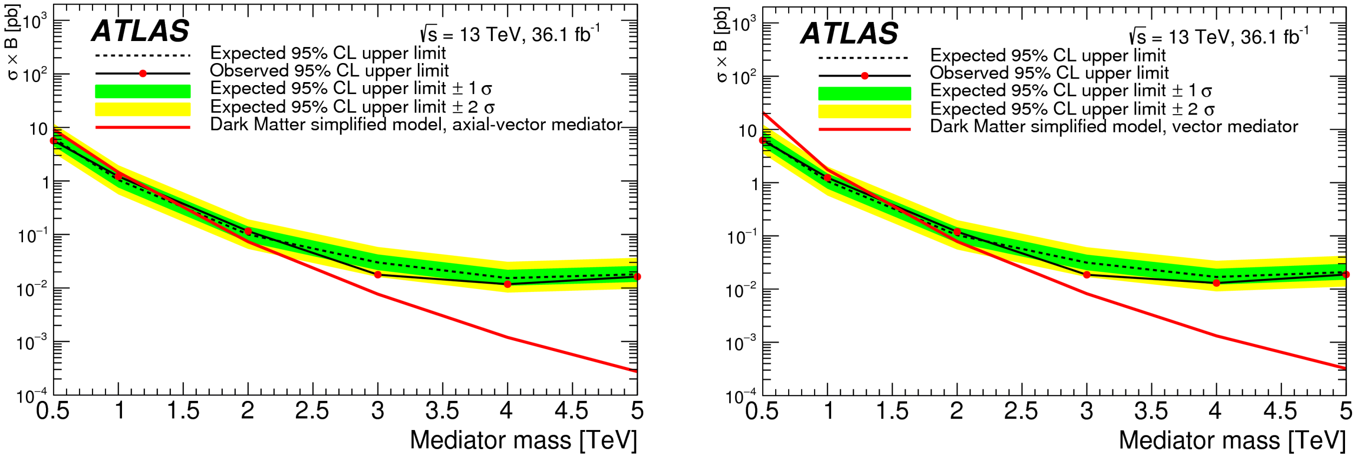
- Chosen to show the complementarity of the DM production analyses (mono X) and the mediator-to-visible analyses (di X)

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 pair

Analysis

- ATLAS, lepton+jets final state, resolved and boosted regimes arXiv:1804.10823



- Not competitive with dijets limits, because of the BR

➜ will be more interesting to look at (pseudo-)scalar mediators

Summary and conclusion

DM search is a very active field

Beyond search using complete model like Susy, strategy evolved from run1 to run 2 from EFT to quite general simplified models

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

Top quark is an interesting tool in that frame

- Already a lot of results and more to come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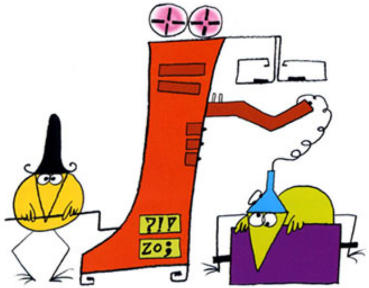
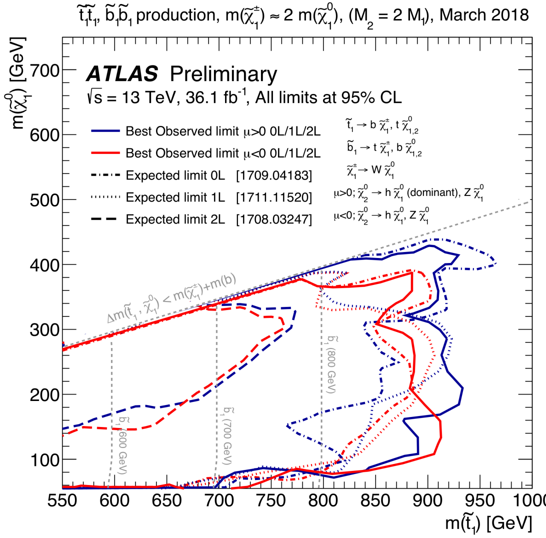
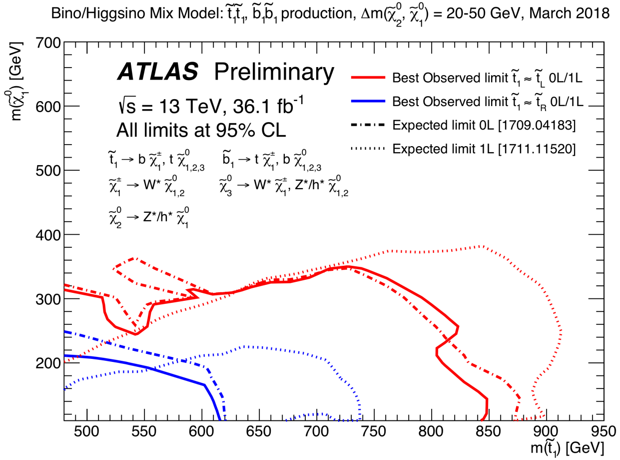


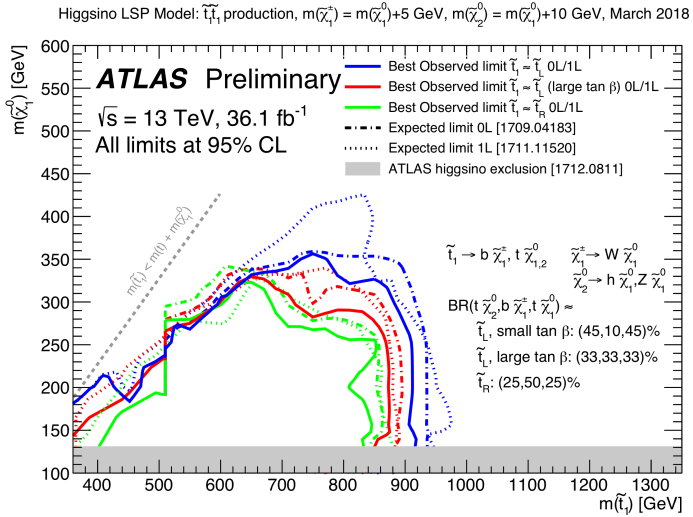
TO GO FURTHER…

Susy Stop pair search: summary

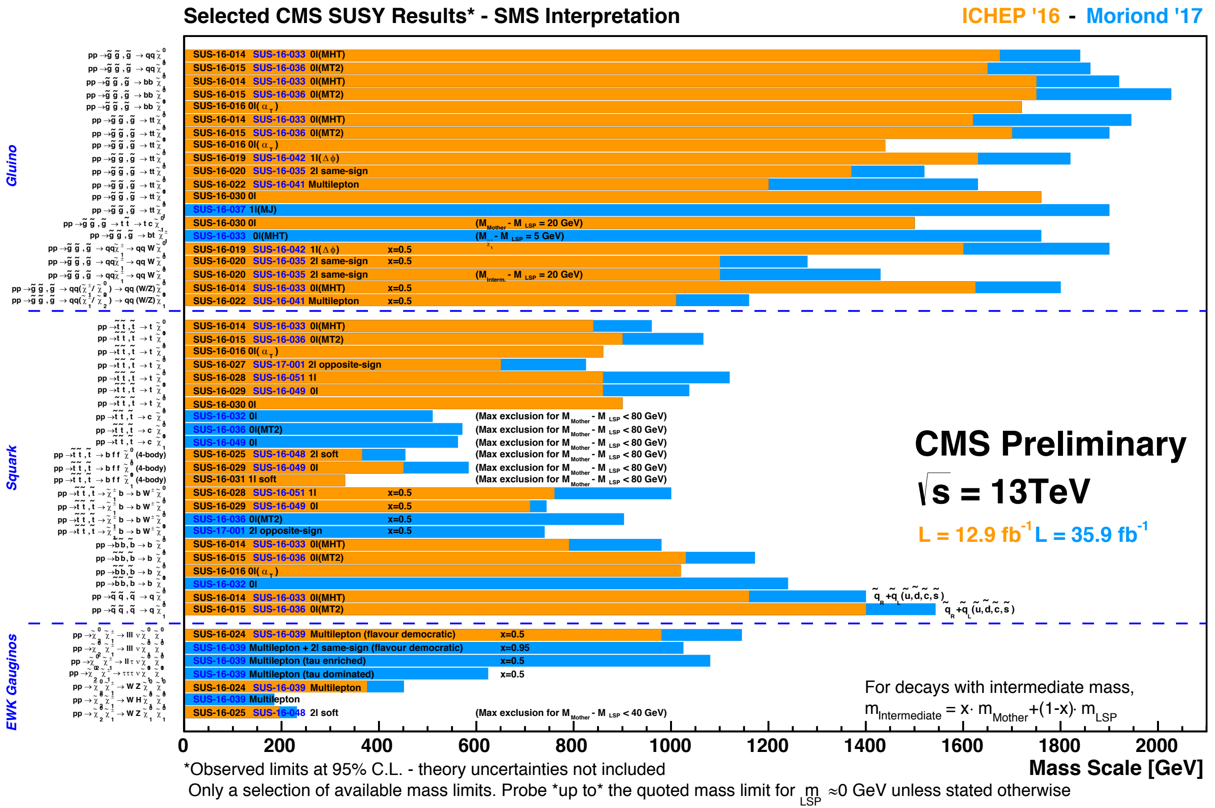
Other scenarii



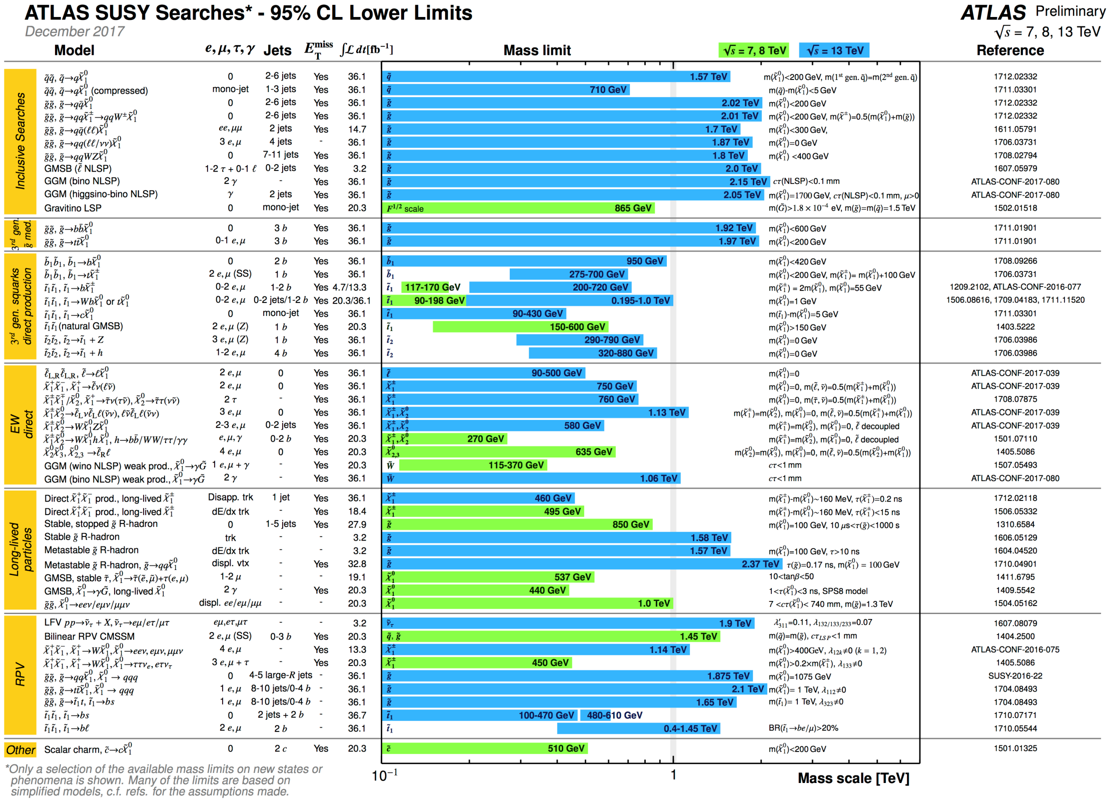




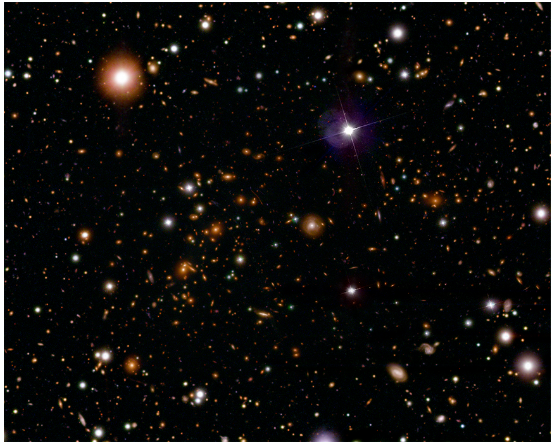
Susy CMS summary



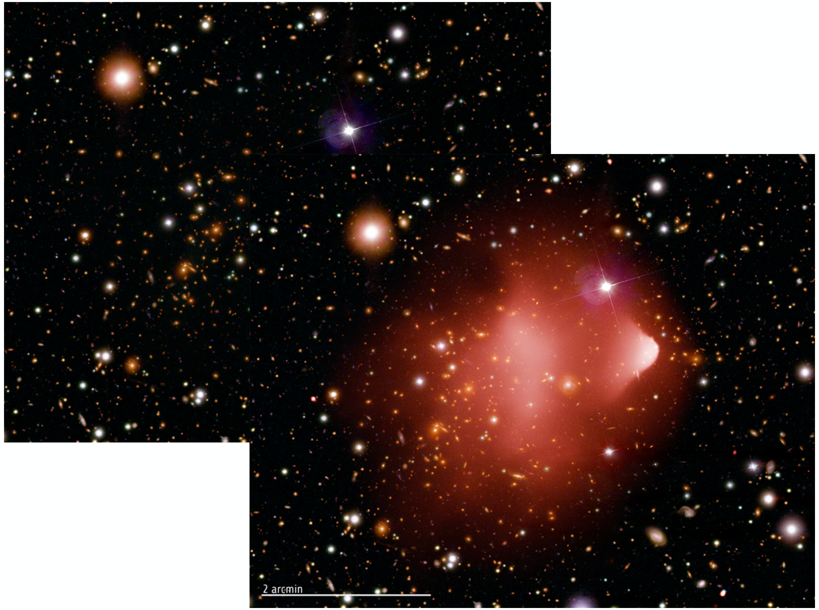
Susy ATLAS summary



Bullet cluster

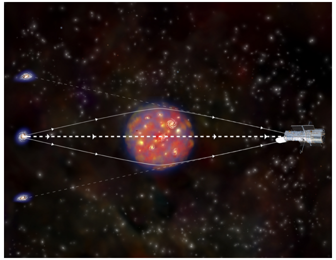


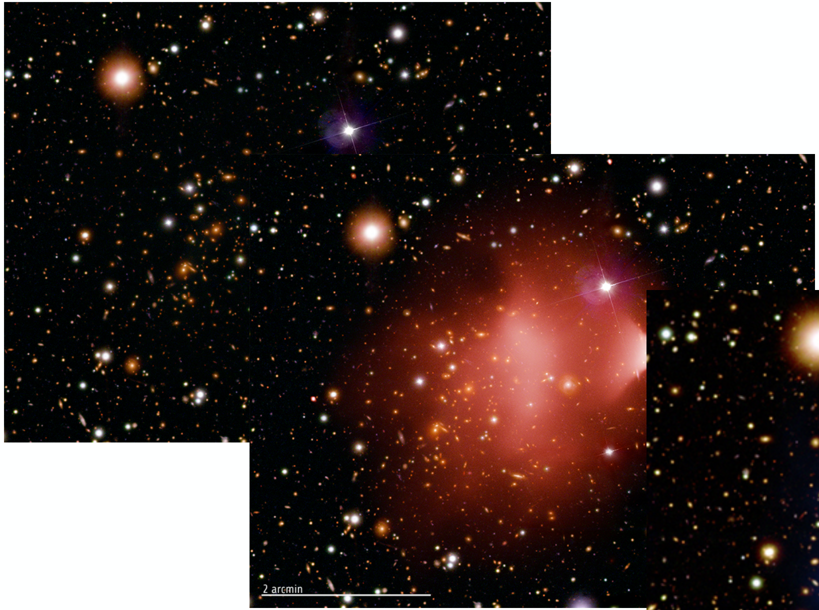
Bullet cluster



Hot gaz (X-ray)

Bullet cluster





Mass (gravitational lensing)

Bullet cluster