

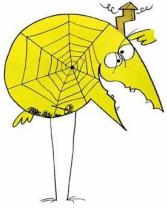


Dark matter search with top quarks

Sabine Crépé-Renaudin



Disclaimer



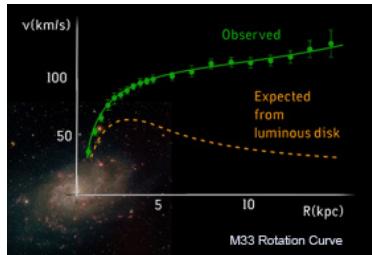
- Chose not to be exhaustive but more to show the strategy for the DM searches
- Very rich search field
 - will only show 13 TeV analysis results with at least 2015+2016 statistics
 - Not enough time to describes in detail the analysis strategies

Dark matter: observations

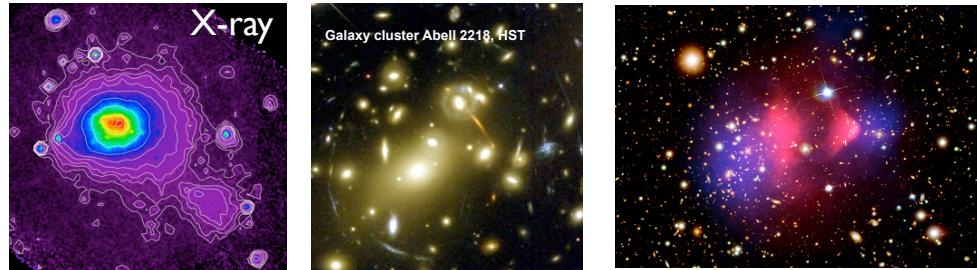
Evidence of dark matter

- From astrophysics and cosmology observations at different scales

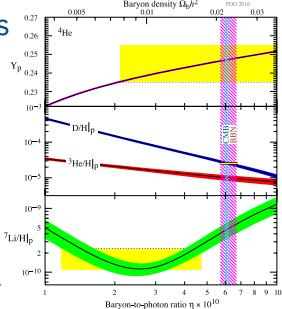
Galaxy rotation



Galaxy clusters via Xrays and gravitational lensing, collisions

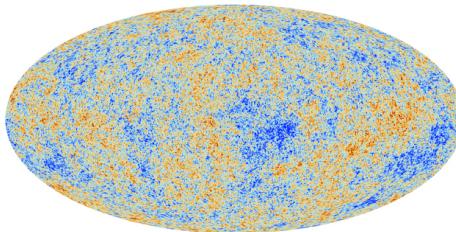


Nucleosynthesis



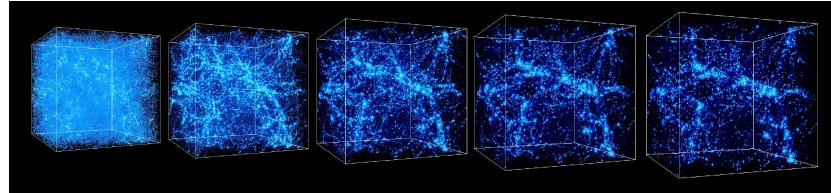
(Schramm & Turner 1998).

Cosmic microwave background



© ESA, Planck Collaboration

Large scale structure formation



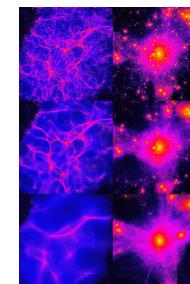
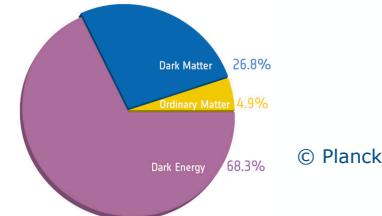
© simulations were performed at the [National Center for Supercomputer Applications](#) by [Andrey Kravtsov](#) ([The University of Chicago](#)) and [Anatoly Klypin](#) ([New Mexico State University](#)). Visualizations by [Andrey Kravtsov](#).

→ Results consistent: need of a new kind of matter

Dark matter: what do we know about ?

Properties

- 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)
 - \Rightarrow Ruled out SM Z and Higgs
 - Need a symmetry to prevent it to decay ex T-parity
- It is “cold” ie non relativistic
 - \Rightarrow ruled out SM neutrinos (also not enough massive)

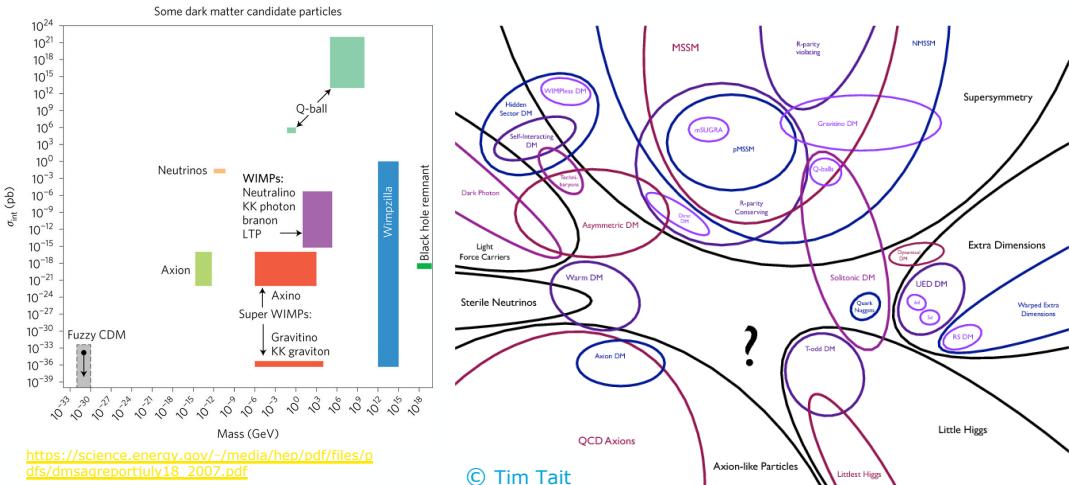


© Cold, Warm, and Hot dark matter simulations, credit ITP, University of Zurich.

Dark matter: which candidates ? Associated theories ?

Candidates

- WIMPs = Weakly Interacting Massive Particles
 - WIMP “miracle” : weak cross-section + particle mass ~ 1 TeV \sim 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



Theories

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

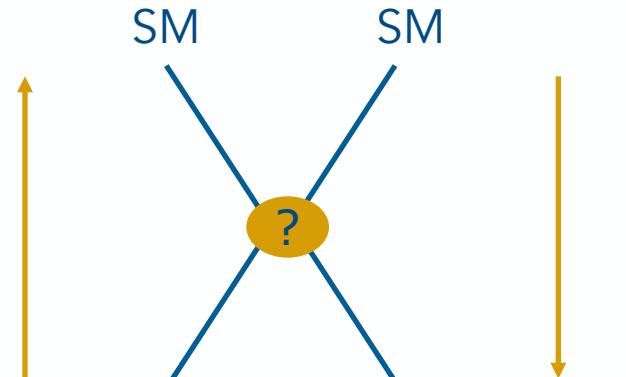
Dark matter: how to detect it ?

Indirect detection

- Search for charged cosmic rays, gamma rays or neutrinos

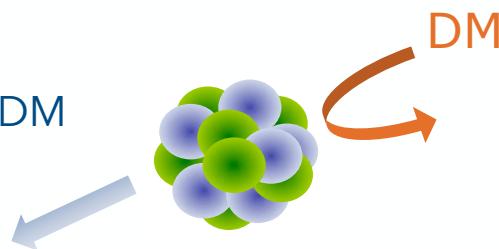


© NASA / Sonoma State University,
Aurore Simonnet



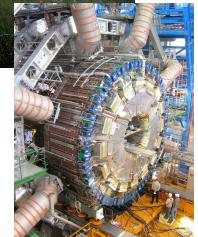
Direct detection

- Use scattering of DM on a nucleus



Collider search

- Produce DM particles from SM particles collisions



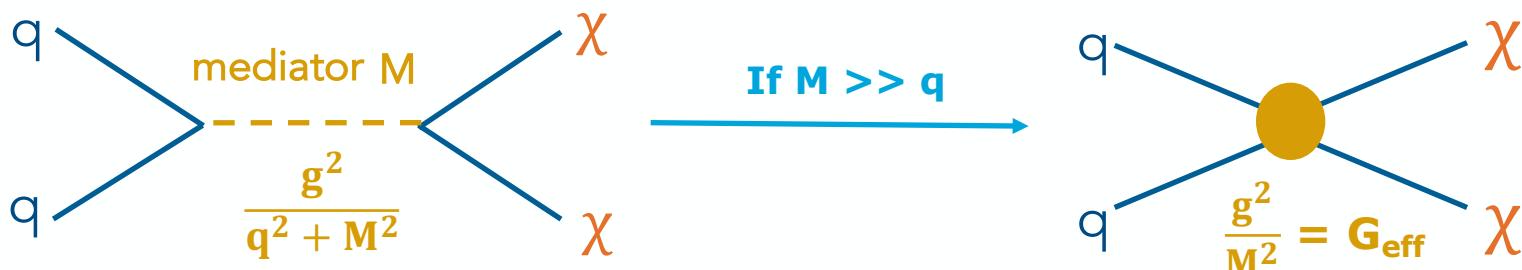
Dark matter search at LHC

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

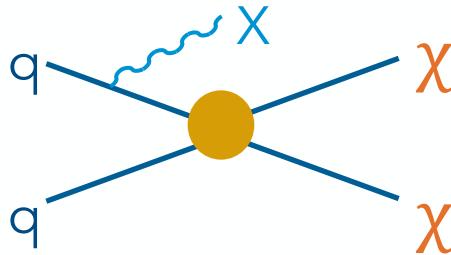


- describe new interactions with few operators

Dark matter search at LHC: effective theory

Use of effective Field theory

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



$$\begin{aligned} X &= \gamma, \text{jet}, \dots \\ XX &= \text{MET} \end{aligned}$$

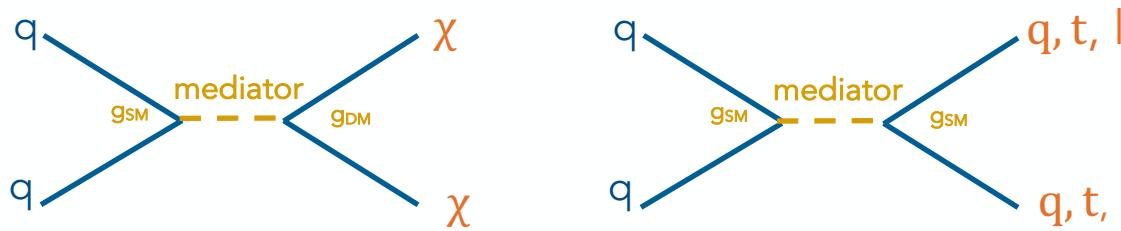
→ LHC Run-1 focus

- Advantages:
 - model independent
 - Allow to translate LHC results into (in)direct search frames (with some care on the hypothesis)
- Limitations:
 - EFT valid only if $M \gg q \Rightarrow$ Run 1 LHC limits $M \sim 1 \text{ TeV} \Rightarrow$ should not use energy $> 1 \text{ TeV}$
 - 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

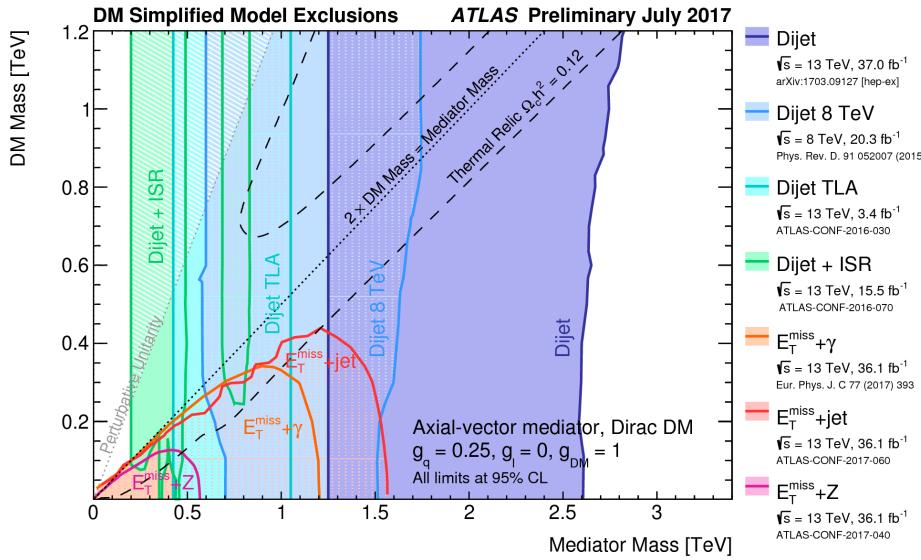
- ATLAS/CMS + theory Dark Matter forum defined the *DMSimp model* ([arXiv:1507.00966](https://arxiv.org/abs/1507.00966))
- Recommendations for benchmark scenarios ([arXiv:1703.05703](https://arxiv.org/abs/1703.05703))
- Madgraph implementation (LO/NLO)

Complementarity

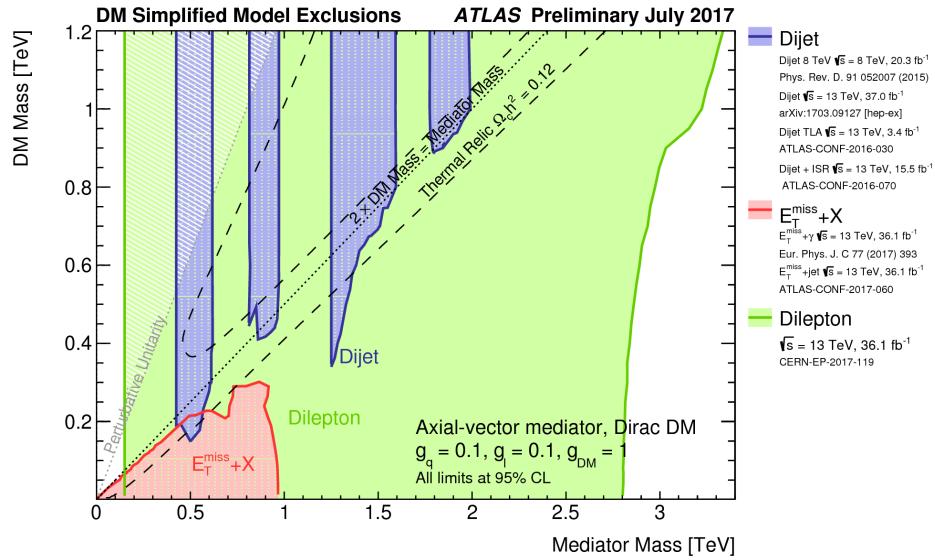
Combination of mono-jet, mono-photon and di-jets

- Note: couplings dependence is important

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



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

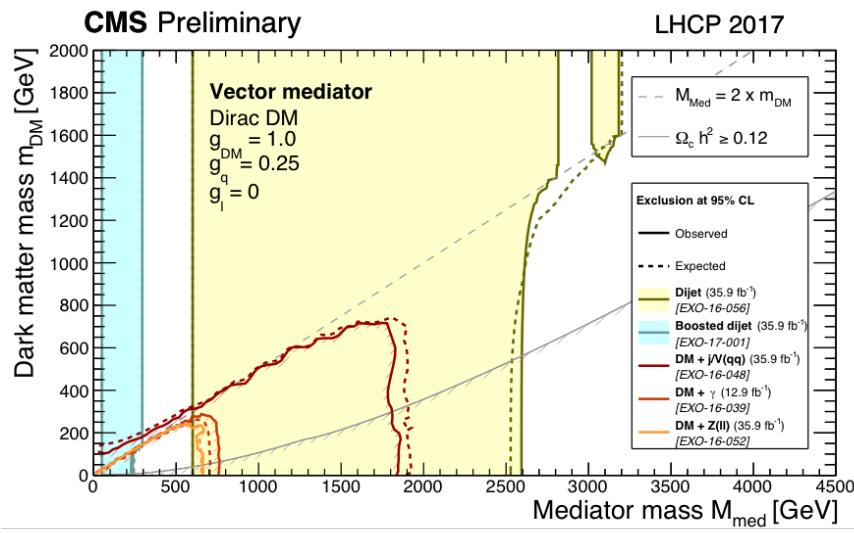


Complementarity

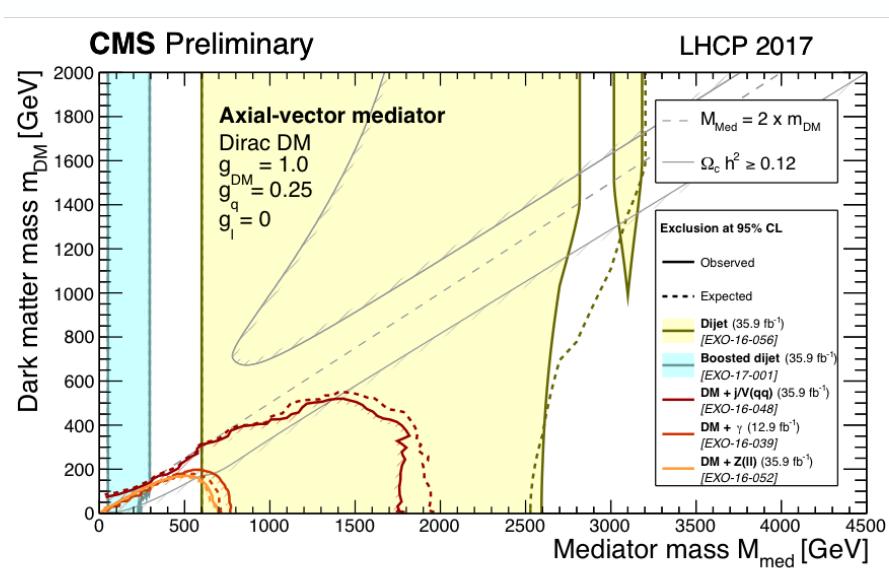
Combination of mono-jet, mono-photon and di-jets

- Sensitivity depends also on the mediator coupling type

Vector mediator



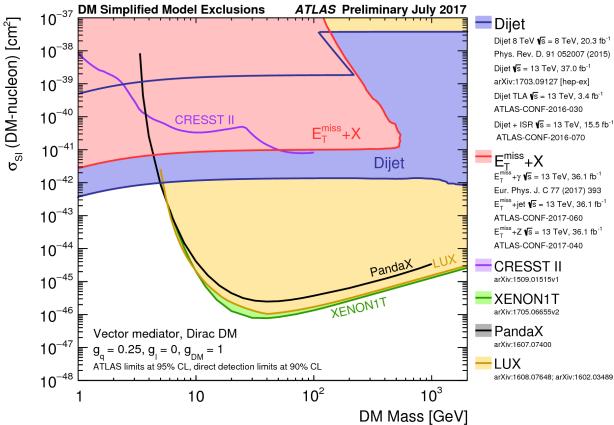
Axial-vector mediator



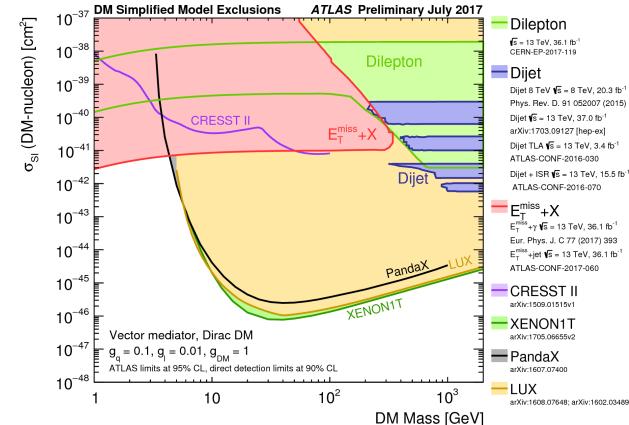
Comparison with direct detection

ATLAS

Vector mediator $g_q=0.25, g_l=0$

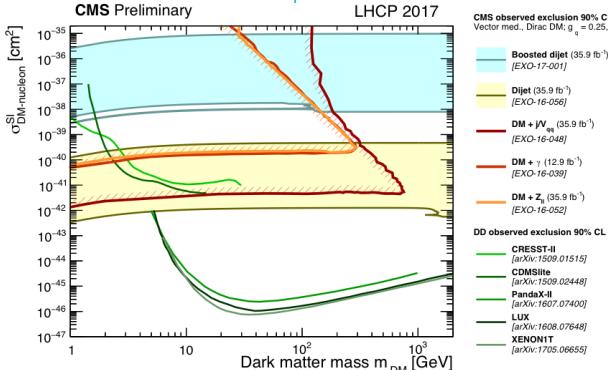


Vector mediator $g_q=0.1, g_l=0.01$

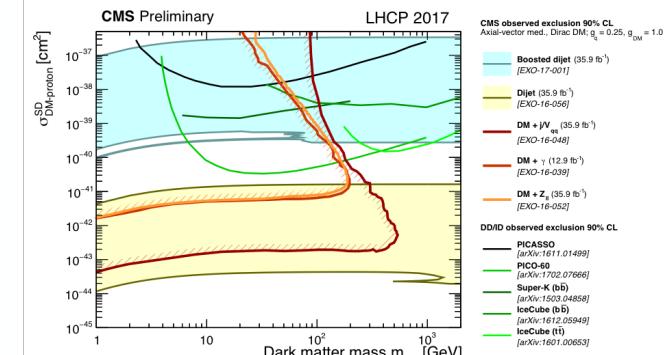


CMS

Vector mediator $g_q=0.25, g_l=0$



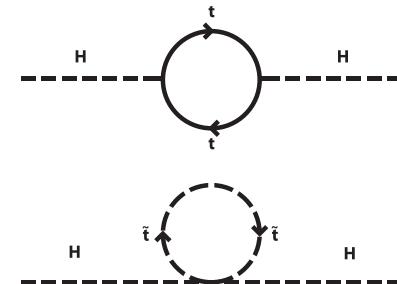
Axial-vector mediator $g_q=0.25, g_l=0$



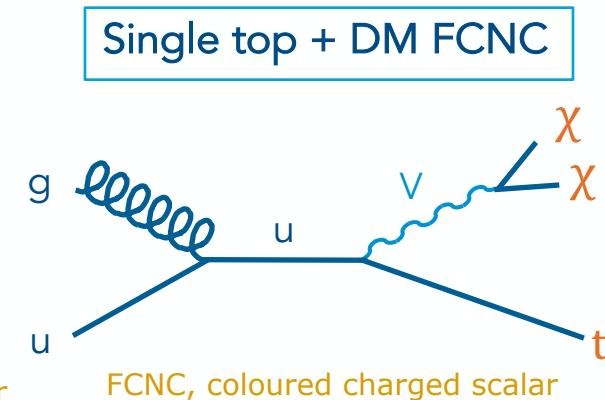
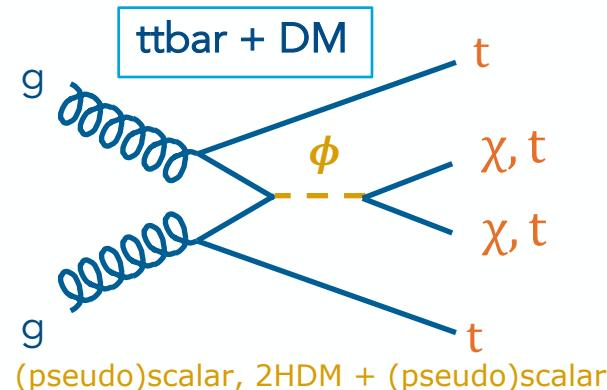
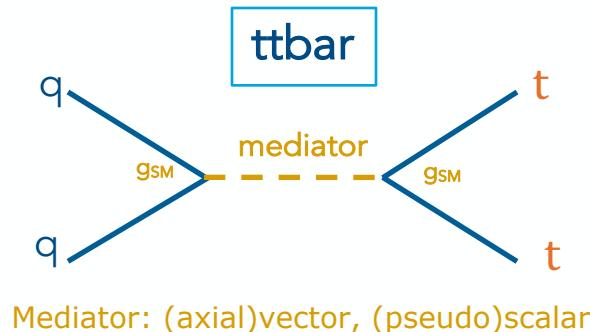
Collider Search: where does top quark join in ?

Supersymmetry

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



Simplified models



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.

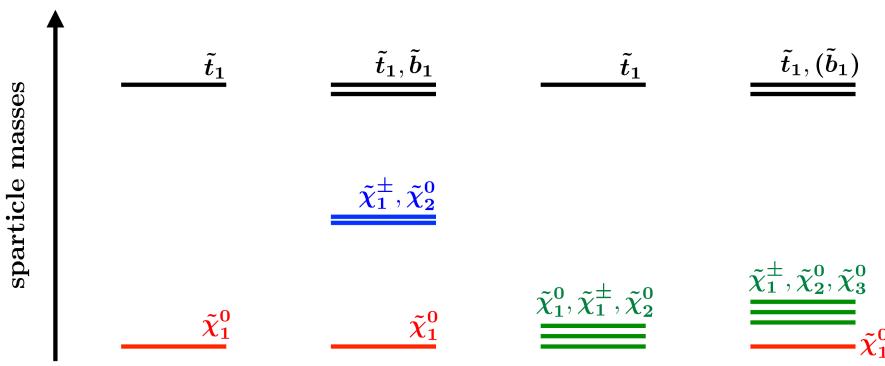
DM particle

- 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 t_L and 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](#)

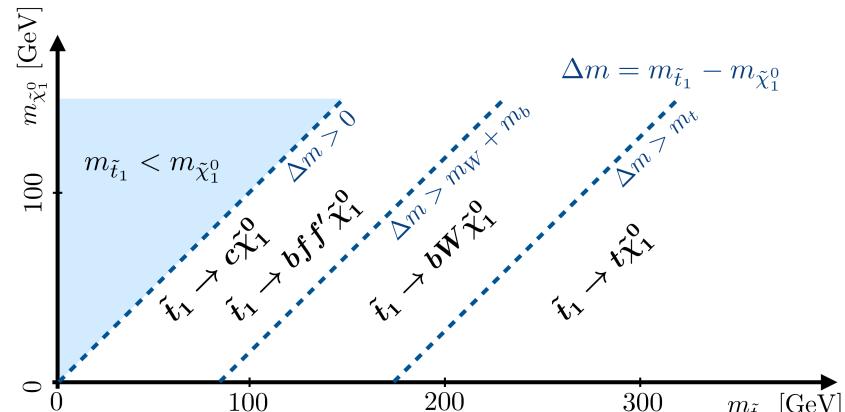
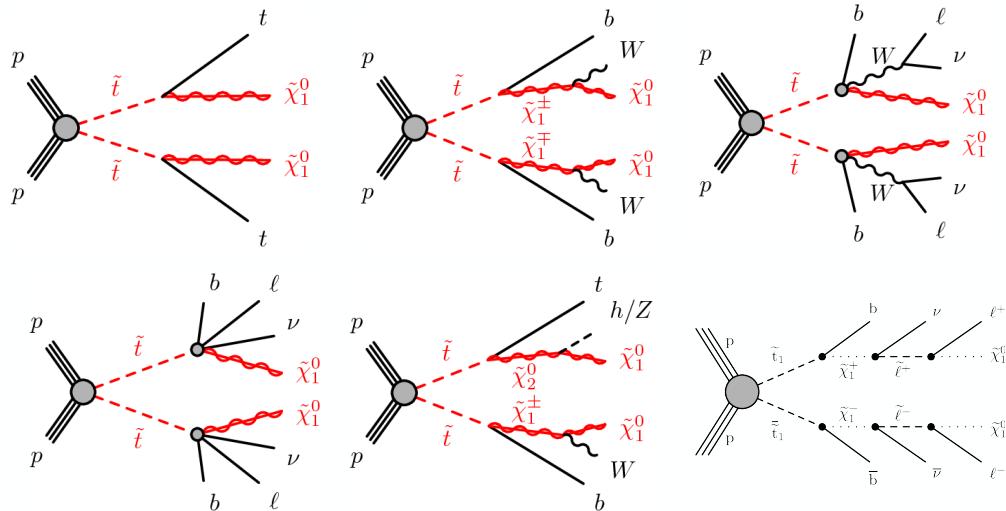
a) pure bino LSP b) wino NLSP c) higgsino LSP d) bino/higgsino mix

- 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

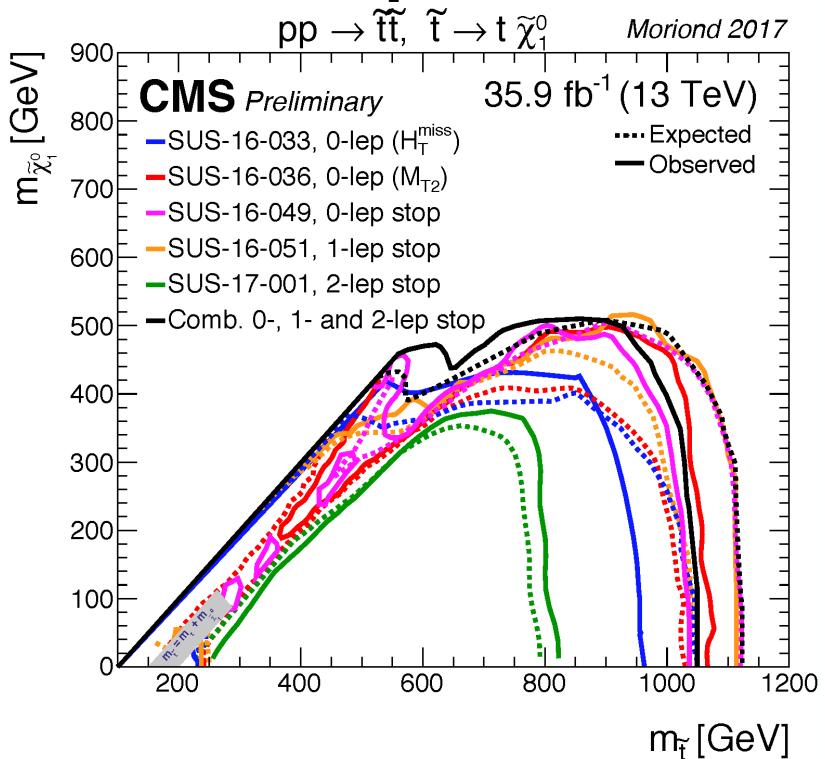
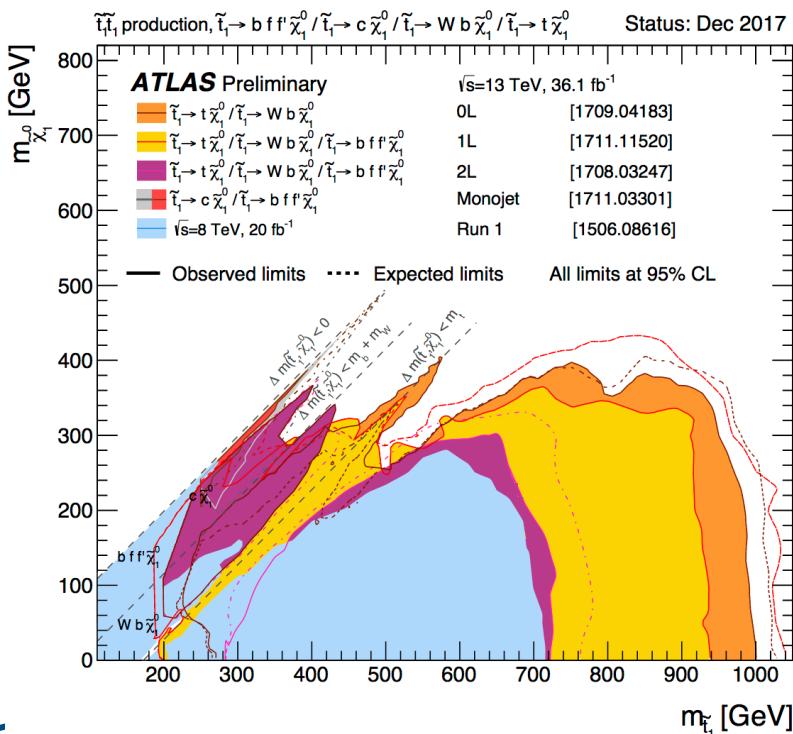


Example: considered decay chain in the pure bino LSP hypothesis
(from [ATLAS 1 lepton analysis](#))

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

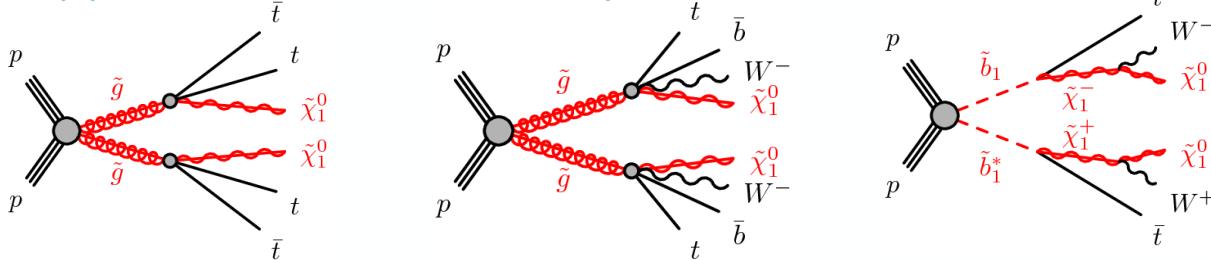
Susy Stop pair search: summary

Latest summary plots with references of papers

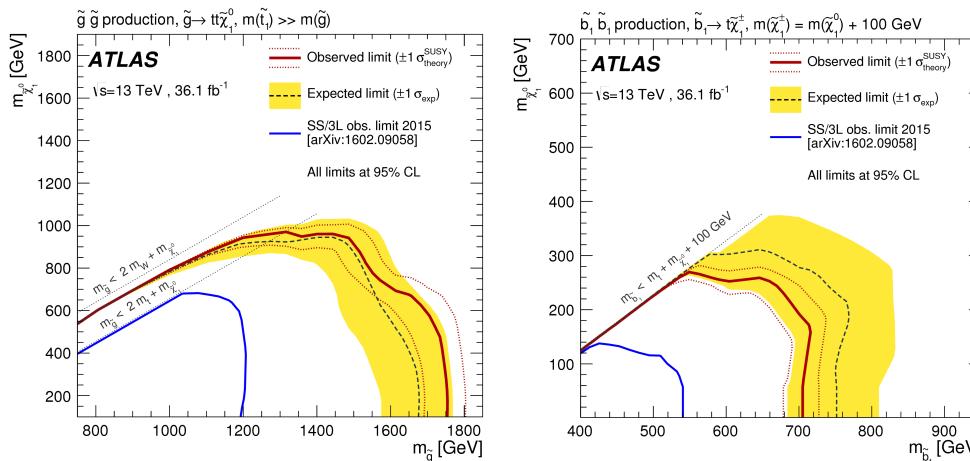


Gluinos searches

Top quarks appear also in gluinos/b squark decays



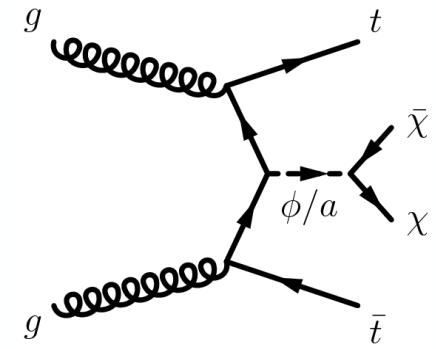
- Results obtained with an analysis using final states with two same-sign or three leptons and jets
[arXiv:1706.03731](https://arxiv.org/abs/1706.03731)



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 α
- 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/α and SM matter \propto fermion mass via Yukawa coupling ⇒ top

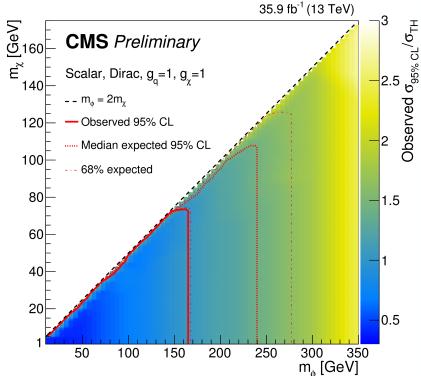
Parameters:

- $m(\phi/\alpha)$, $m(\chi)$, 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

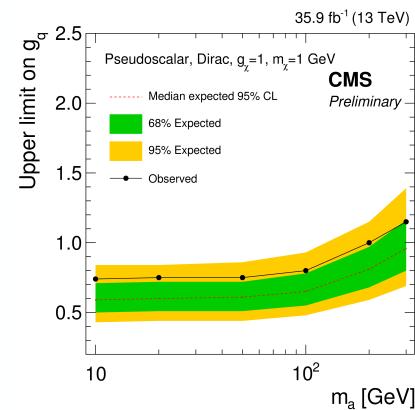
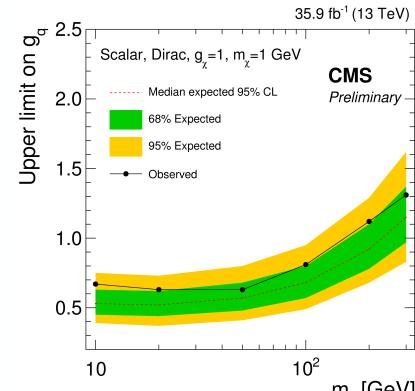
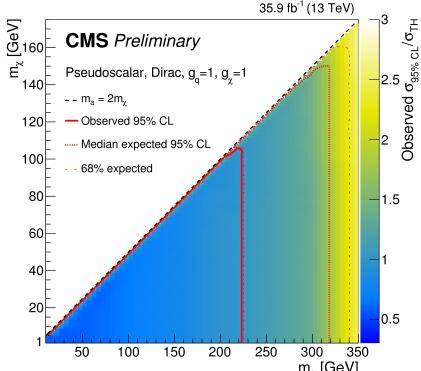
Simplified model: top pair + DM - CMS

→ CMS 0,1,2 L combination [CMS-PAS-EXO-16-049](#)

scalar



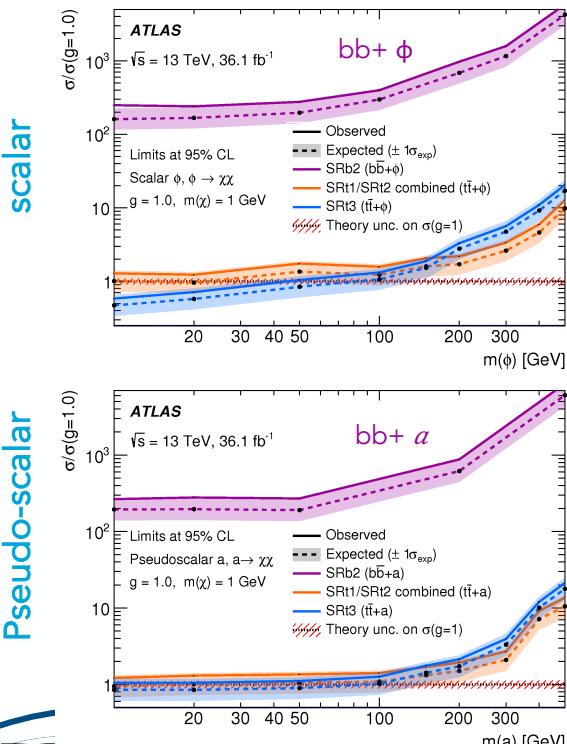
Limits on coupling



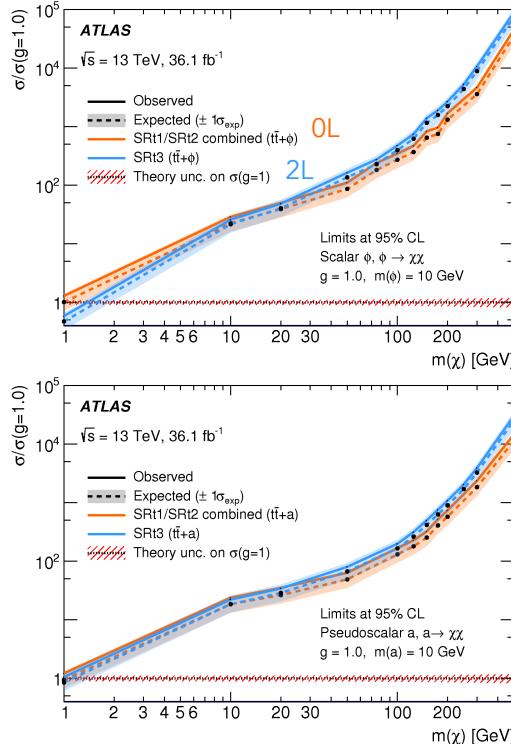
Simplified model: top pair + DM - ATLAS

→ ATLAS 2L 0L [arXiv:1710.11412](https://arxiv.org/abs/1710.11412) + ATLAS 1L (susy) [arXiv: 1711.11520](https://arxiv.org/abs/1711.11520)

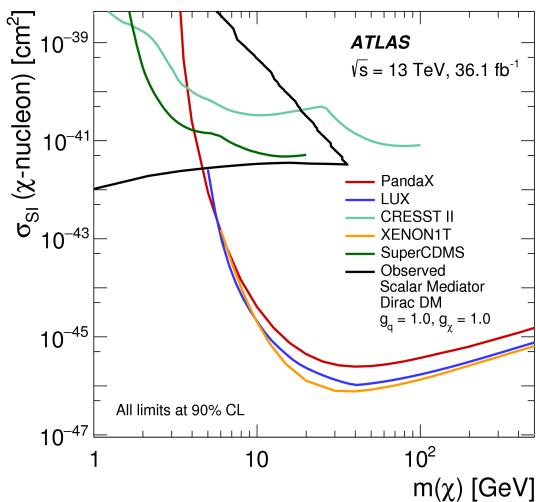
Vs mediator mass



Vs DM mass



→ Comparison (2L) with direct detection spin independent

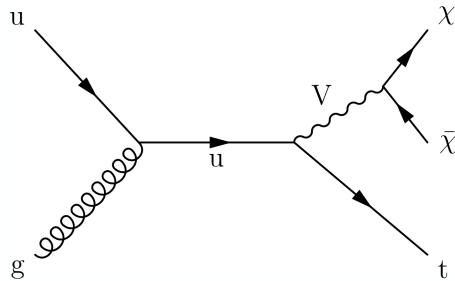


→ Direct detection not competitive for pseudo-scalar mediator

Single top + DM

Models

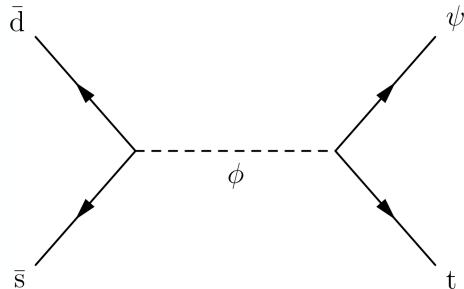
- “Non resonant”: FCNC producing a top quark + a vector boson that decays to DM



Couplings:

- g_χ^V and g_χ^A $V = \text{vector}, A = \text{axial-vector}$
- $g_u^V, g_u^A, g_d^V, g_d^A$, 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

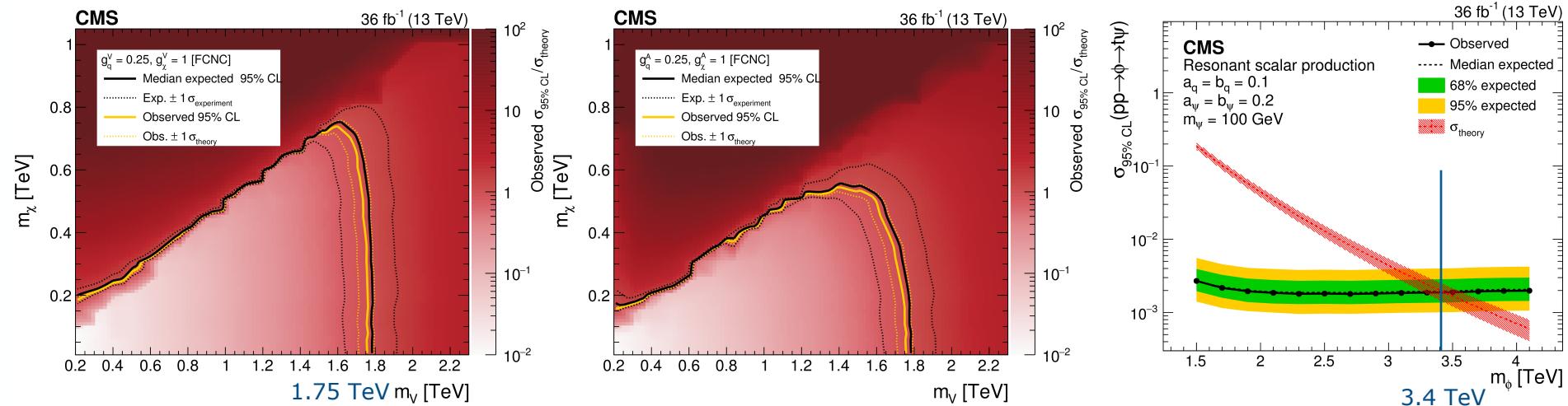
Analysis

- CMS, hadronic top decay [arXiv:1801.08427](https://arxiv.org/abs/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

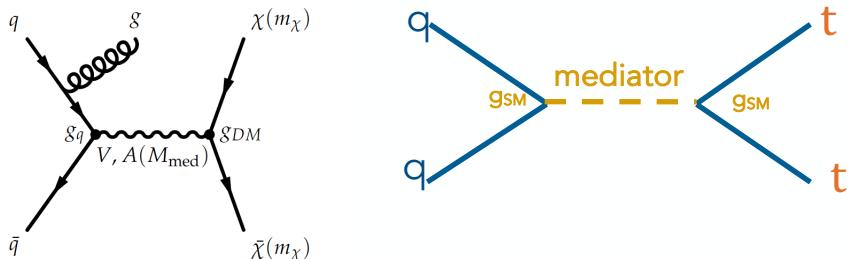
Resonant



- Limits also given for couplings vs m(V)

Simplified model: (axial-)vector mediator

Model:



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

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

Scenarios:

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

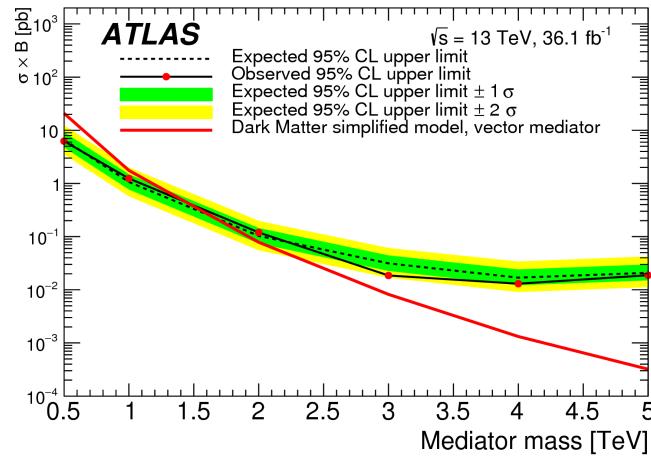
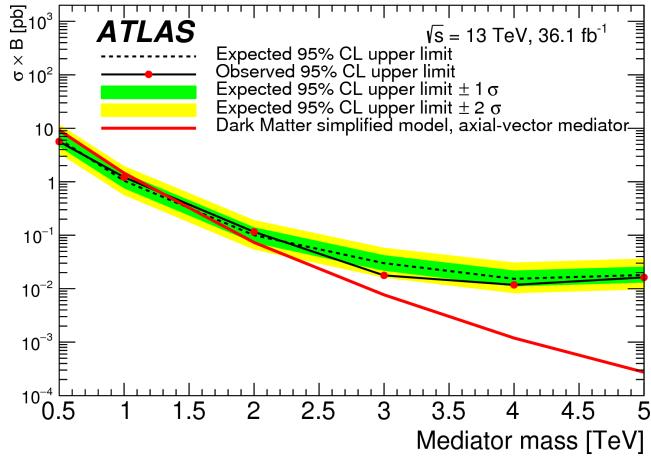
- Free parameters: $m(\chi)$, $m(\text{med})$, g_{DM} and g_q , g_t
- Minimal width computed according to couplings and considered particles mass
 - mediator decays considered = ones strictly necessary to maintain model self-consistency

Scenarios	g_q	g_{DM}	g_t
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](https://arxiv.org/abs/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

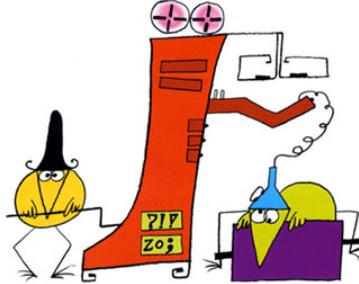
- Allow to show complementarity between collider search and direct detection experiments
- Allow to take advantage of the wide analyses sensitivities at LHC to constrain models using the analyses without DM particle in the final state
- Common benchmark model defined at DM forum help to focus in interested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

Top quark is an interesting tool in that frame

- Already a lot of results and more to come

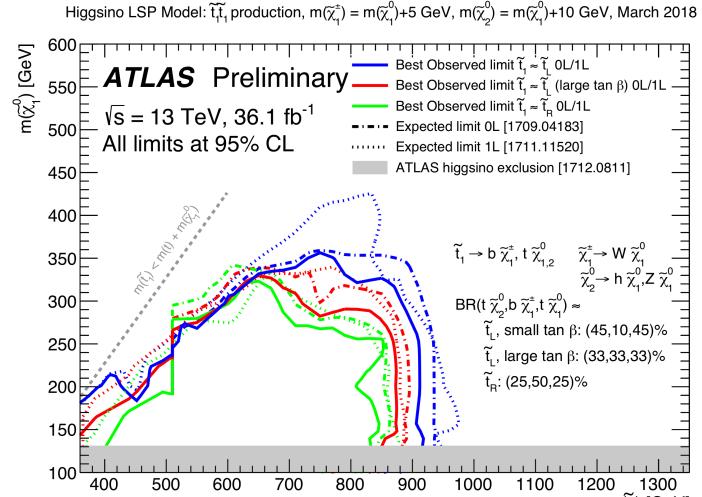
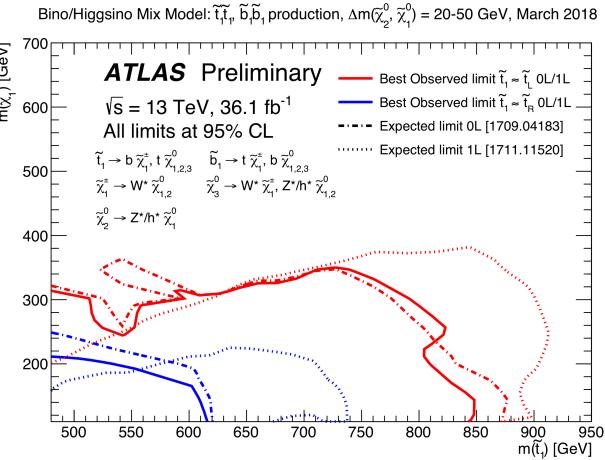
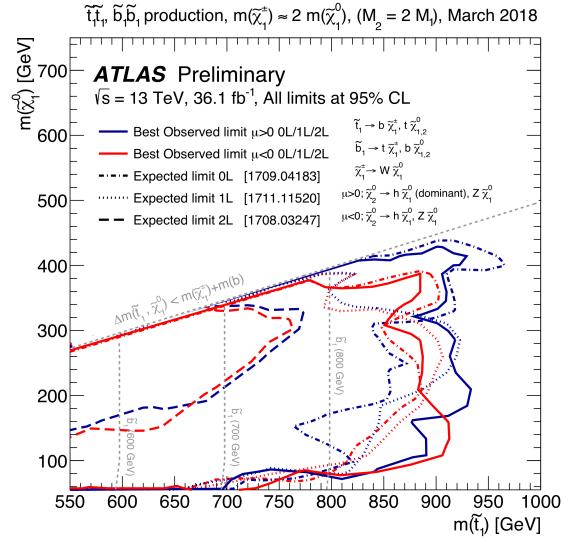


TO GO FURTHER...



Susy Stop pair search: summary

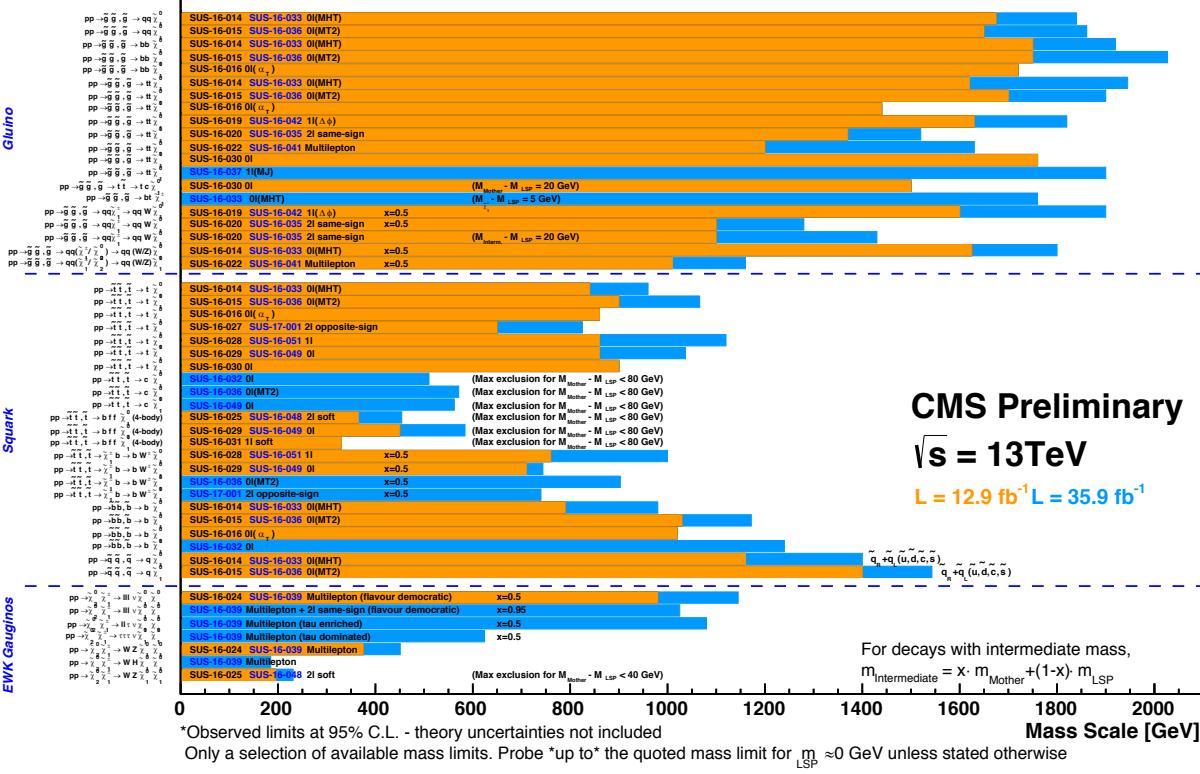
Other scenarii



Susy CMS summary

Selected CMS SUSY Results* - SMS Interpretation

ICHEP '16 - Moriond '17



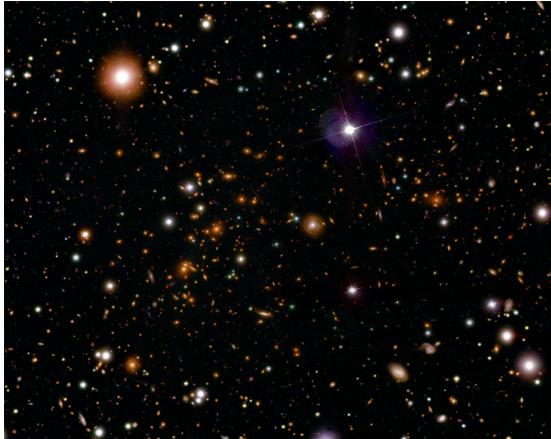
Susy ATLAS summary

ATLAS SUSY Searches* - 95% CL Lower Limits
December 2017

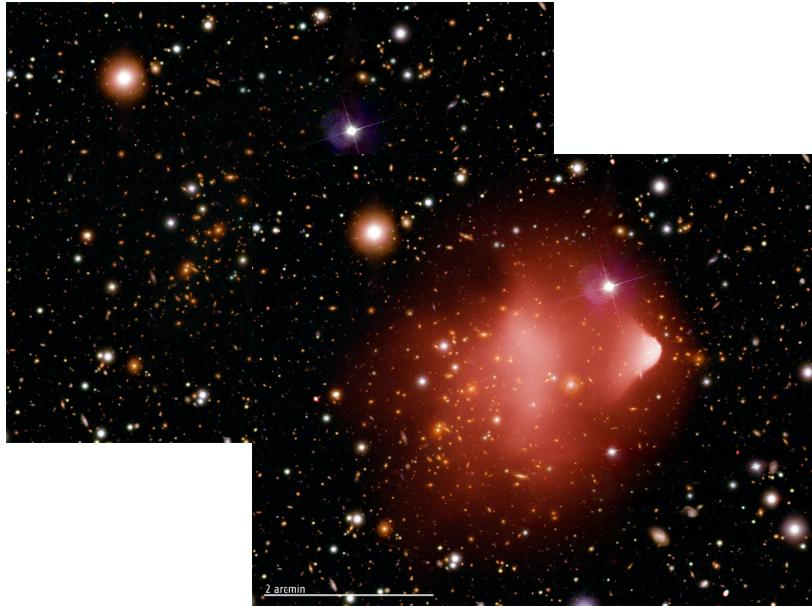
Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int L dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8, 13 \text{ TeV}$		Reference	
						$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$		
Inclusive Searches									
$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{q}^{(0)}$	-	-	-	2.6	Yes	36.1	\tilde{q}	1712.02332	
$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{q}^{(0)}$ (compressed)	-	1-3 jets	-	36.1	Yes	36.1	\tilde{q}	1711.0301	
$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{q}^{(0)}$	0	2-6 jets	-	36.1	Yes	36.1	\tilde{q}	1712.02332	
$\tilde{g}\tilde{g}, \tilde{g}\rightarrow g\tilde{g}^{(0)}$	0	2-6 jets	-	36.1	Yes	36.1	\tilde{q}	1712.02332	
$\tilde{g}\tilde{g}, \tilde{g}\rightarrow g\tilde{g}^{(0)}$	0	2-6 jets	-	36.1	Yes	36.1	\tilde{q}	1611.05791	
$\tilde{g}\tilde{g}, \tilde{g}\rightarrow g\tilde{g}^{(0)}$	ee, $\mu\mu$	2 jets	-	14.7	Yes	36.1	\tilde{q}	1706.03731	
$\tilde{g}\tilde{g}, \tilde{g}\rightarrow g\tilde{g}^{(0)}$	ee, $\mu\mu$	4 jets	-	36.1	Yes	36.1	\tilde{q}	1708.02794	
GMSB (bino NLSP)	0	7-11 jets	-	36.1	Yes	36.1	\tilde{q}	1607.05979	
GGM (bino NLSP)	2 γ	-	-	36.1	Yes	36.1	\tilde{q}	ATLAS-CONF-2017-080	
GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	Yes	36.1	\tilde{q}	ATLAS-CONF-2017-080	
Gravitino LSP	0	mono-jet	Yes	20.3	-	-	$m(\tilde{q}) < 1.8 \times 10^4 \text{ eV}$, $m(\tilde{q}) = m(\tilde{g}) = 1.5 \text{ TeV}$	1502.01518	
$\tilde{q}^{(0)} \tilde{q}^{(0)}$ med	-	-	-	-	-	865 GeV	-	-	
$\tilde{q}\tilde{q}, \tilde{q}\rightarrow b\tilde{b}^{(0)}$	0	3 b	Yes	36.1	Yes	36.1	\tilde{q}	1711.01901	
$\tilde{q}\tilde{q}, \tilde{q}\rightarrow b\tilde{b}^{(0)}$	0-1 e, μ	3 b	Yes	36.1	Yes	36.1	\tilde{q}	1711.01901	
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{q}^{(0)}$	0	2 b	Yes	36.1	Yes	36.1	\tilde{b}_1	1708.09266	
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{q}^{(0)}$	2 e, μ (SS)	1 b	Yes	36.1	Yes	36.1	\tilde{b}_1	1708.09271	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow t\tilde{q}^{(0)}$	0-2 e, μ	1-2 b	Yes	36.1	Yes	36.1	\tilde{t}_1	1209.2102, ATLAS-CONF-2016-077	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow W\tilde{b}^{(0)}$ or $\tilde{b}_1^{(0)}$	0-2 e, μ	0-2 jets+1-2 b	Yes	20.3/6.6	Yes	36.1	\tilde{t}_1	1506.08616, 1708.04183, 1711.11520	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow t\tilde{q}^{(0)}$	0	mono-jet	-	36.1	Yes	36.1	\tilde{t}_1	1711.03301	
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	Yes	36.1	\tilde{t}_1	1405.5222	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow t\tilde{q}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	Yes	36.1	\tilde{t}_1	1706.03986	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow t\tilde{q}_1 + h$	1-2 e, μ	4 b	Yes	36.1	Yes	36.1	\tilde{t}_1	1706.03986	
EW direct	-	-	-	-	-	-	-	-	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow e\tilde{e}^{(0)}$	2 e, μ	0	Yes	36.1	Yes	36.1	\tilde{e}	ATLAS-CONF-2017-039	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow e\tilde{e}^{(0)}$	2 e, μ	0	Yes	36.1	Yes	36.1	\tilde{e}	ATLAS-CONF-2017-039	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow e\tilde{e}^{(0)}$	2 τ	-	Yes	36.1	Yes	36.1	\tilde{e}	1708.07875	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow e\tilde{e}^{(0)}$	3 e, μ	0	Yes	36.1	Yes	36.1	\tilde{e}	ATLAS-CONF-2017-039	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow e\tilde{e}^{(0)}$	2-3 e, μ	0-2 jets	Yes	36.1	Yes	36.1	\tilde{e}	1501.07110	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow W\tilde{e}^{(0)}$	2 e, τ	-	Yes	20.3	Yes	36.1	\tilde{e}_1	1501.07110	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow W\tilde{e}^{(0)}$	2 e, τ	2-3 b	Yes	36.1	Yes	36.1	\tilde{e}_1	1405.50986	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow W\tilde{e}^{(0)}$	4 e, τ	0	Yes	20.3	Yes	36.1	\tilde{e}_1	1507.05493	
GGM (wino NLSP) weak prod.	$\tilde{e}^0 \rightarrow \nu$	1 $e,\mu + \gamma$	-	Yes	20.3	Yes	\tilde{W}	ATLAS-CONF-2017-080	
GGM (bino NLSP) weak prod.	$\tilde{t}_1 \rightarrow \ell\bar{\nu}$	2 γ	-	Yes	36.1	Yes	\tilde{W}	-	
Long-lived particles	-	-	-	-	-	-	-	-	
Direct $\tilde{t}_1\tilde{t}_1$ prod.	Disapp. trk	1 jet	Yes	36.1	\tilde{t}_1	460 GeV	\tilde{t}_1	1715.02118	
Direct $\tilde{t}_1\tilde{t}_1$ prod.	long-lived $\tilde{t}_1\tilde{t}_1$	disapp. trk	Yes	19.4	\tilde{t}_1	495 GeV	\tilde{t}_1	1508.05332	
Stable stopped 3 τ -hadron	trk	1-5 jets	Yes	27.9	\tilde{t}_1	850 GeV	\tilde{t}_1	1319.65884	
Metastable 3 τ -hadron	disapp. trk	-	-	3.2	\tilde{t}_1	-	\tilde{t}_1	1606.05129	
Metastable 3 τ -hadron, $\tilde{t}_1 \rightarrow (\tilde{t}, \tilde{\tau})(\tilde{e}, \tilde{\mu})\tau(\ell, \mu)$	disapp. vtx	-	-	32.8	\tilde{t}_1	-	\tilde{t}_1	1604.04620	
GMSB stable 3 τ , $\tilde{t}_1 \rightarrow (\tilde{t}, \tilde{\tau})(\tilde{e}, \tilde{\mu})\tau(\ell, \mu)$	1-2 μ	-	-	19.1	\tilde{t}_1	537 GeV	\tilde{t}_1	1710.04901	
GMSB $\tilde{t}_1 \rightarrow \tau\gamma$, long-lived \tilde{t}_1	2 γ	-	Yes	20.3	\tilde{t}_1	440 GeV	\tilde{t}_1	1411.6795	
$\tilde{t}_1\tilde{t}_1$, $\tilde{e}\nu\rightarrow \ell\nu/\mu\nu/\tau\nu$	disapp. ee/ $e\mu/\mu\tau$	-	-	20.3	\tilde{t}_1	1.0 TeV	\tilde{t}_1	1405.5542	
RV	-	-	-	-	-	-	-	-	
LFB, $p_T \rightarrow \tilde{\nu}_e + X \rightarrow \tau \rightarrow \nu\tau/\ell\tau/\mu\tau$	$e\mu/\ell\mu/\tau\mu$	-	-	3.2	$\tilde{\nu}_e$	-	$\tilde{\nu}_e$	1607.09079	
Billinear RV GMSB	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{\nu}_e$	-	$\tilde{\nu}_e$	1404.5290	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow W\tilde{e}^{(0)}$	4 e, μ	-	Yes	36.3	\tilde{e}	1.14 TeV	\tilde{e}	ATLAS-CONF-2016-075	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow W\tilde{e}^{(0)}$	3 e, μ	1-3 b	Yes	20.3	\tilde{e}	450 GeV	\tilde{e}	1409.50986	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow W\tilde{e}^{(0)}$	4-5 large- R jets	-	-	36.1	\tilde{e}	-	\tilde{e}	SUSY 2016-32	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow W\tilde{e}^{(0)}$	1-2 e, μ	8-10 jets+0-4 b	-	36.1	\tilde{e}	1.875 TeV	\tilde{e}	1704.08493	
$\tilde{e}\tilde{e}, \tilde{e}\rightarrow W\tilde{e}^{(0)}$	1-2 e, μ	8-10 jets+0-4 b	-	36.1	\tilde{e}	2.1 TeV	\tilde{e}	1704.08493	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow h\tilde{s}$	0	2 jets+2 b	-	36.1	\tilde{t}_1	1.65 TeV	\tilde{t}_1	1710.07171	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow h\tilde{b}$	2 e, μ	2 b	-	36.1	\tilde{t}_1	0.4-1.45 TeV	\tilde{t}_1	1710.05544	
Other	Scalar charm, $\tilde{e}\rightarrow e\tilde{e}^{(0)}$	0	2 c	Yes	20.3	\tilde{e}	510 GeV	$m(\tilde{e}) < 200 \text{ GeV}$	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Bullet cluster

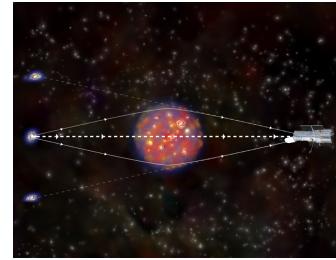
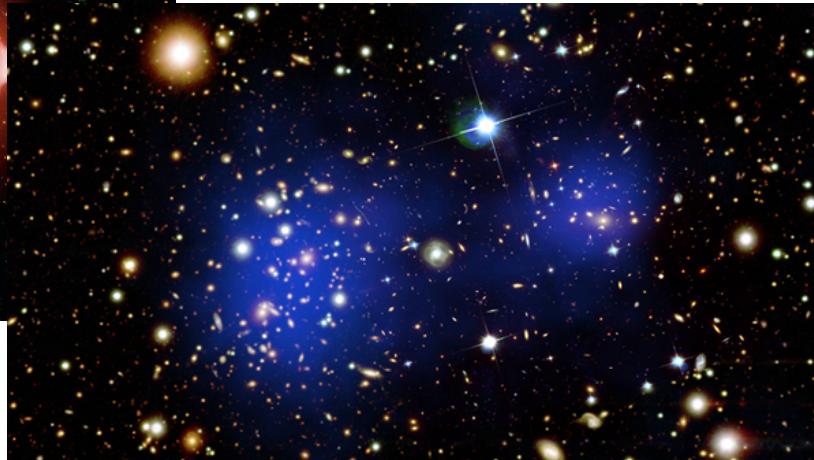


Bullet cluster



Hot gaz (X-ray)

Bullet cluster



Mass (gravitational lensing)

Bullet cluster

