Searches for Dark Matter and Long Lived Particles at the LHC

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On behalf of the ATLAS, CMS and LHCb collaborations

La Thuile 2019 - Les Rencontres de Physique de la Vallée d'Aoste

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Introduction

While the Standard Model is in excellent agreement with the LHC measurements, many questions still unanswered:

- The origin of Dark Matter remains a mystery
- The solution to the hierarchy problem

These questions lead to searches for physics beyond the Standard Model

This talk will focus on searches based on:

- Direct searches for Dark Matter (DM) production in the LHC
- Searches for novel long lived particles (LLPs)

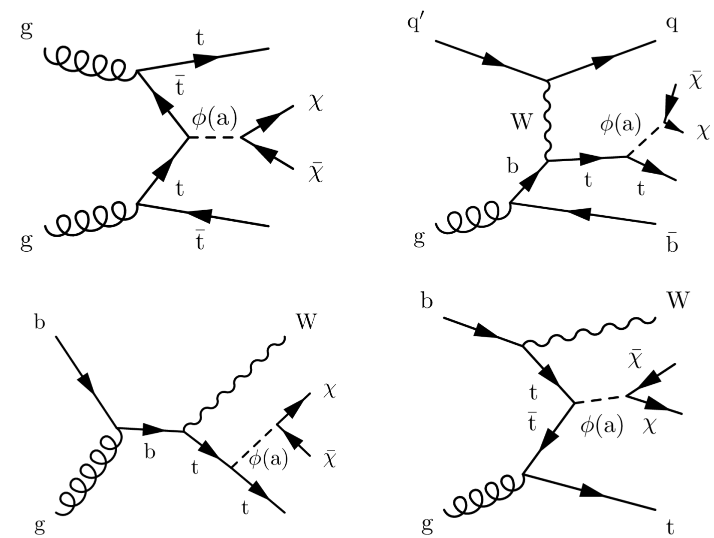
Dark matter candidates also arise in SUSY models, see SUSY overview talk by Tommaso Lari

Results shown from the ATLAS, CMS and LHCb collaborations at the LHC, utilising (a part of) the 13 TeV run-2 dataset

CMS: Single top or a top pair + dark matter

arXiv:1901.01553
ATLAS: arXiv:1812.09743, arXiv:1711.11520

Looking at models with a scalar or a pseudoscalar mediator particle and the mass of the mediator and DM particles are free parameters



Trigger: High MET or a high p_T lepton

Selection:

- Split based on number b-tagged jets (1, 2, or more) and number of forward jets

- Regions split based on number of leptons (*all hadronic* or *single-lepton)*

	Single-lepton SRs			All-hadronic SRs		
	1ℓ, 1 b-tag, 0 FJ	1ℓ, 1 b-tag, 1FJ	1ℓ, 2 b-tag	0ℓ, 1 b-tag, 0 FJ	0ℓ,1 b-tag, 1 FJ	0ℓ, 2 b-tag
Forward jets	=0	≥1	—	= 0	≥1	—
n_b	=1	=1	≥2	= 1	=1	≥2
n_{lep}	=1	=1	=1	= 0	=0	=0
$p_T(j_1)/H_T$		—		—		<0.5
n_{jet}		≥2			≥3	
p_T^{miss}		>160 GeV			>250 GeV	
m_T		>160 GeV			—	
m_{T2}^W		>200 GeV			—	
$\min\Delta\phi(j_{1,2}, \vec{p}_T^{miss})$		>1.2 rad.			>1.0 rad.	
m_T^b		>180 GeV			>180 GeV	

CMS: Single top or a top pair + dark matter

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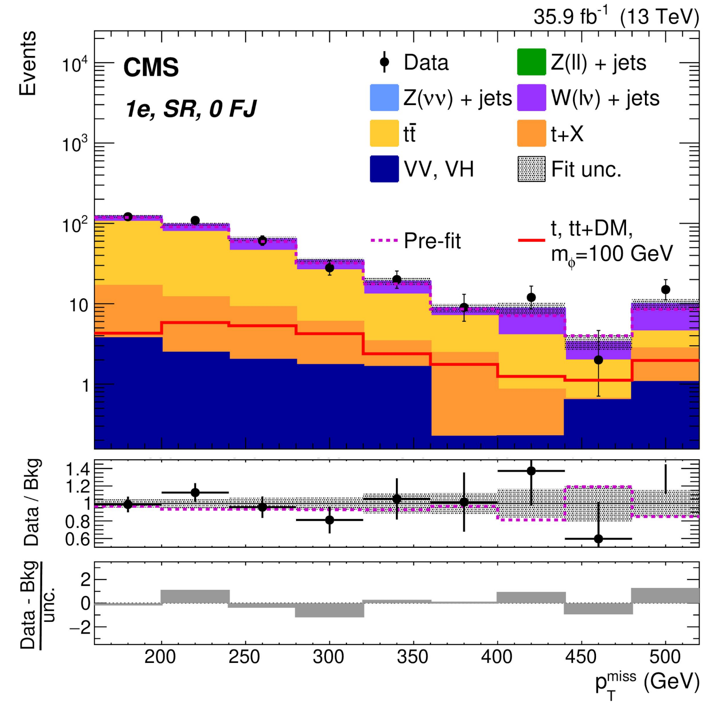
The normalisation of the main backgrounds is established in specific control regions

- These include the tt, W and Z backgrounds
- Fit between data/MC performed in these enriched regions
- Normalisation determined as a function of p_T^{miss}



	Single-lepton CRs		All-hadronic CRs		
	CR $t\bar{t}(2\ell)$	CR $W(\ell\nu)$	CR $t\bar{t}(1\ell)$	CR $W(\ell\nu)$	CR $Z(\ell\ell)$
n_b	≥ 1	$=0$	≥ 1	$=0$	$=0$
n_{lep}	$=2$	$=1$	$=1$	$=1$	$=2$
n_{jet}	≥ 2	≥ 2	≥ 3	≥ 3	≥ 3
p_T^{miss}	>160 GeV	>160 GeV	>250 GeV	>250 GeV	>250 GeV
m_T	—	>160 GeV	<160 GeV	<160 GeV	—
$\min\Delta\phi(j_{1,2}, \vec{p}_T^{miss})$	—	—	>1.0 rad.	—	—
$m_{\ell\ell}$	—	—	—	—	$[60, 120]$ GeV

CMS: Single top or a top pair + dark matter

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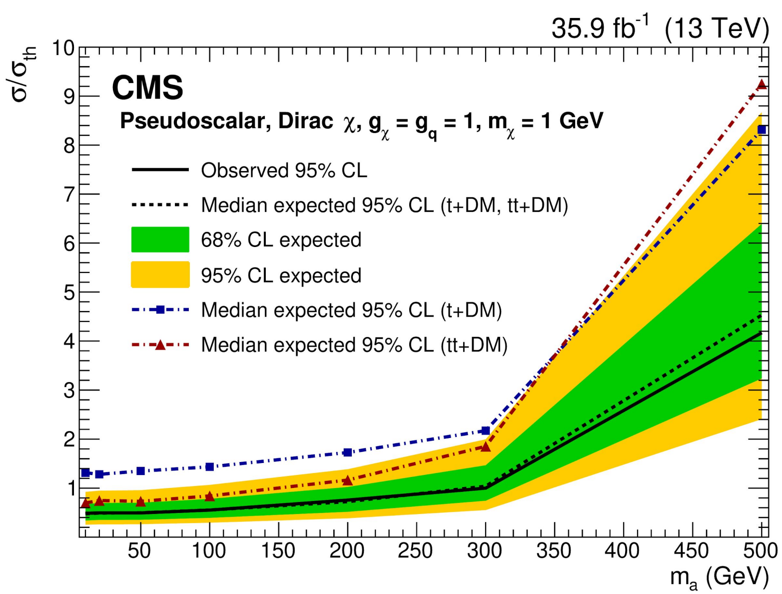
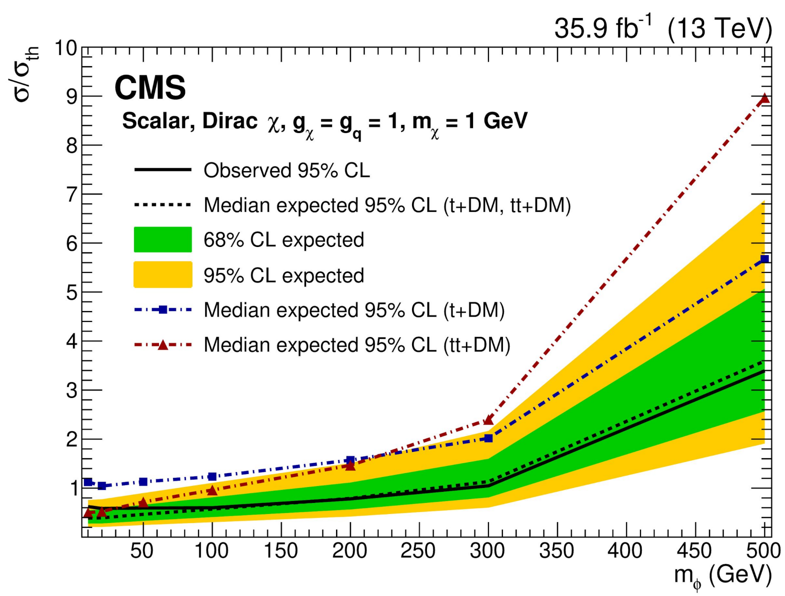
No excess above expected background observed

Exclusion of scalar and pseudoscalar at 95% confidence level for masses below 290 and 300 GeV respectively





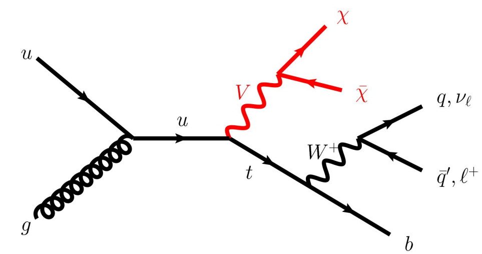
ATLAS: Single top + dark matter

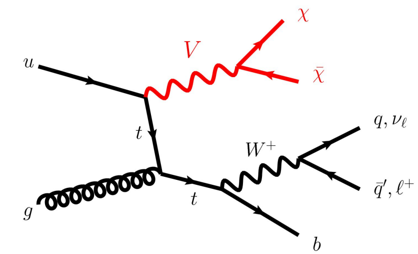
arXiv:1812.09743

Analysis using a similar strategy, targeting models:

1. Massive vector boson V decaying to two DM particles χ
2. Resonant production of a colored, charge ⅔ scalar ϕ decaying into a spin ½ DM particle χ and a top quark

Similar strategy to previous analysis, relying additionally on large radius jets and top tagging using substructure information.





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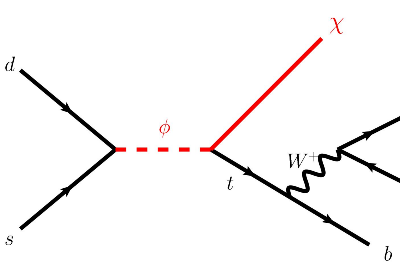
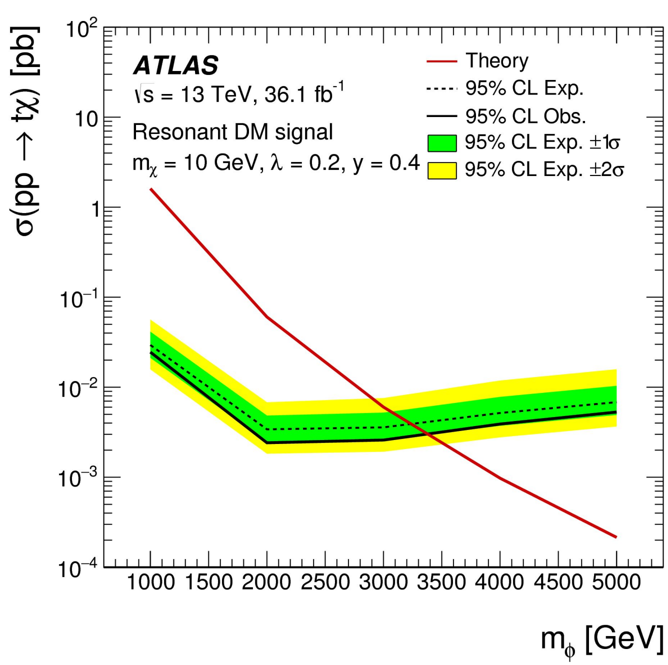
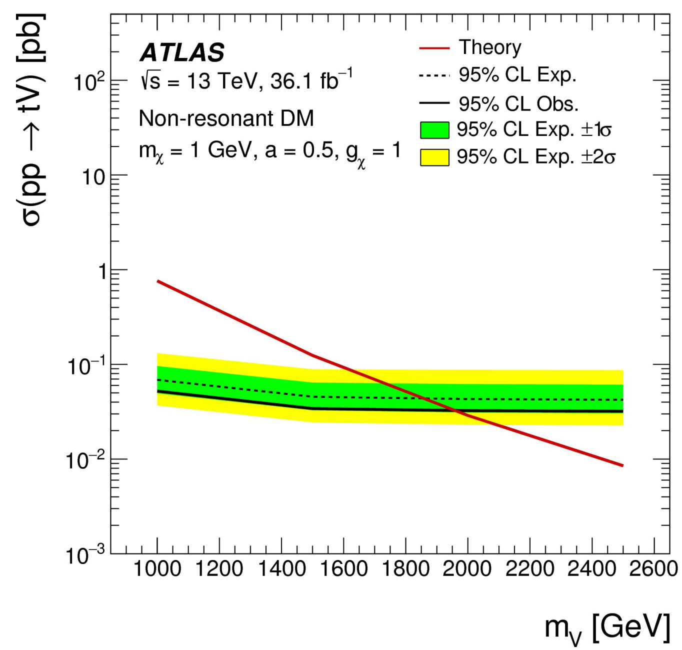






ATLAS: Dark matter summary paper

[arXiv:1903.01400](https://arxiv.org/abs/1903.01400)

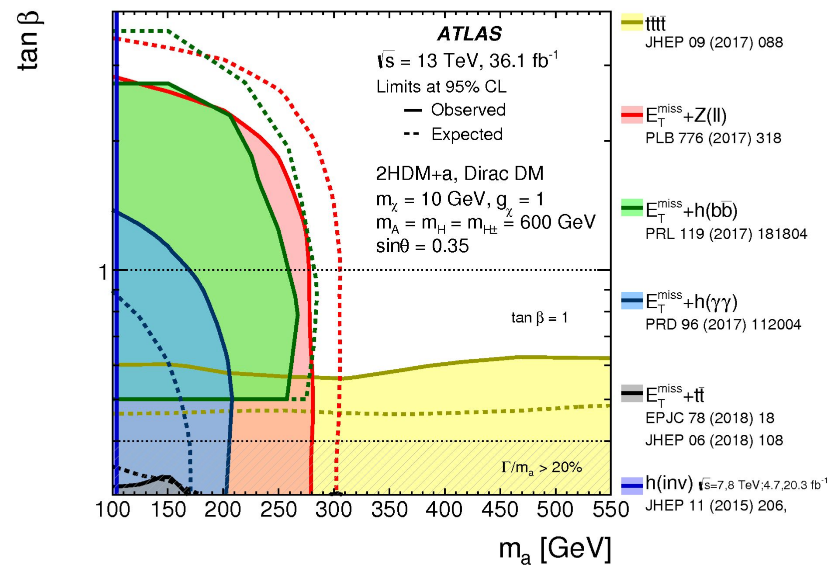
CMS: [arXiv:1811.06562](https://arxiv.org/abs/1811.06562)

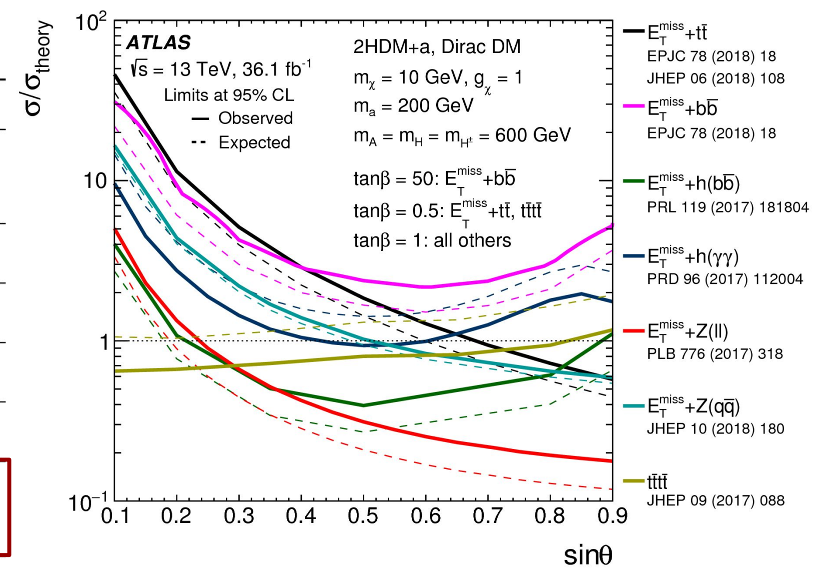
2HDM + pseudo-scalar mediator model

A paper summarising the ATLAS limits on mediator-based Dark Matter models

- Considering Dirac fermions as WIMP DM particles (χ)
- Assumed to be pair produced in LHC collisions
- In certain models can decay back to SM particles

DM/SM interactions through mediator particle





Short description	Acronym	Symbol	JCP	Charge	Signatures
Vector/axial-vector mediator	V/AV	Z'_V/Z'_A	$1^{\pm}$	-	jet/$\gamma/W/Z$+E_T^{miss}, di-fermion resonance
Vector baryon-charged mediator	VBC	Z'_B	1^{+}	baryon-number	$h+E_T^{miss}$
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$_{q/b}$	$\eta_{q/b}$	0^{+}	colour, 2/3 electric-charge	jet+E_T^{miss}, $b+E_T^{miss}$
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), $t\bar{t}t\bar{t}$

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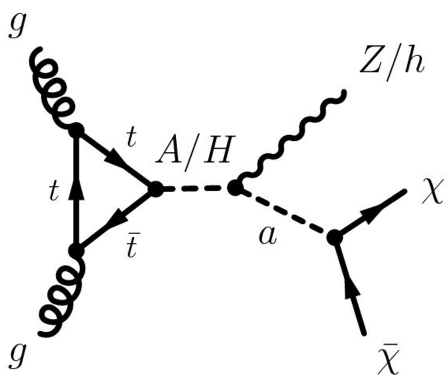

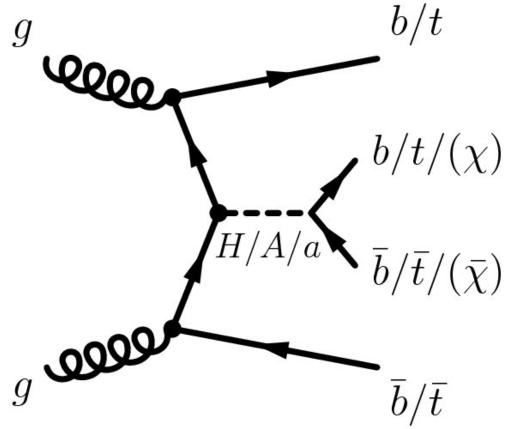

See also talk by Veronica Fabiani on Tuesday

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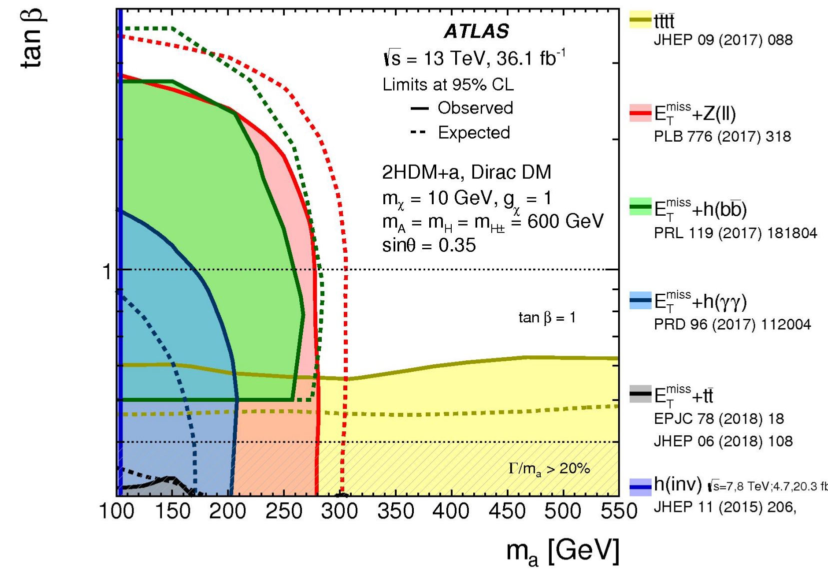
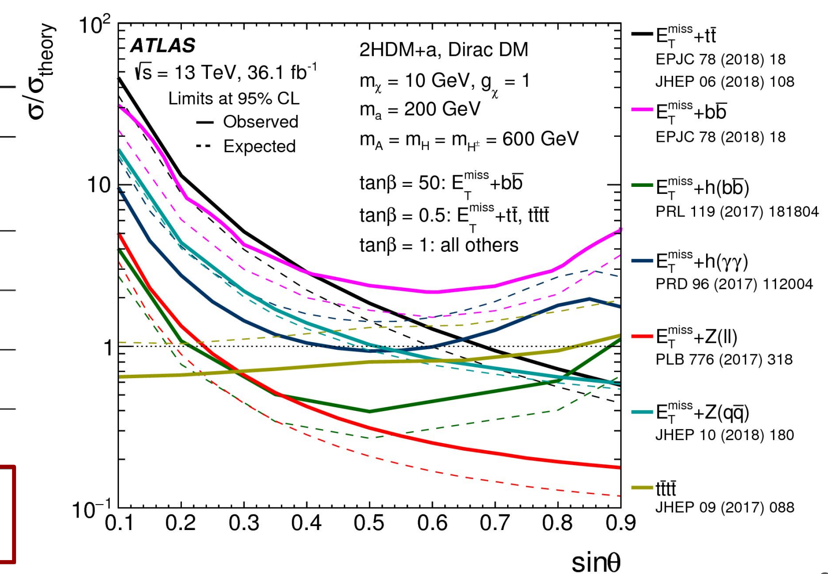


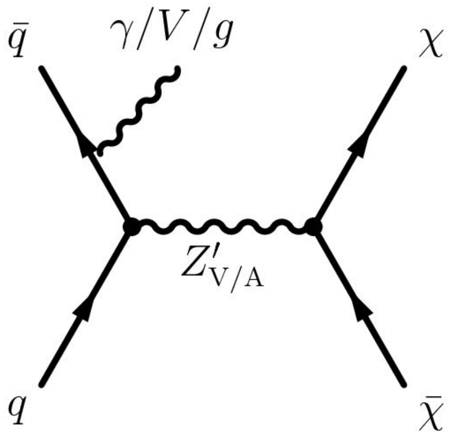


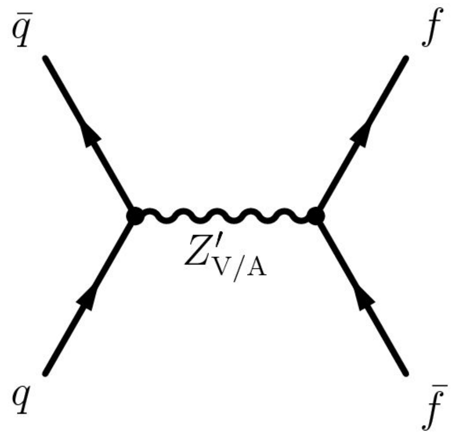
ATLAS: Dark matter summary paper

(Axial-)vector mediator model

arXiv:1903.01400

CMS: arXiv:1811.06562





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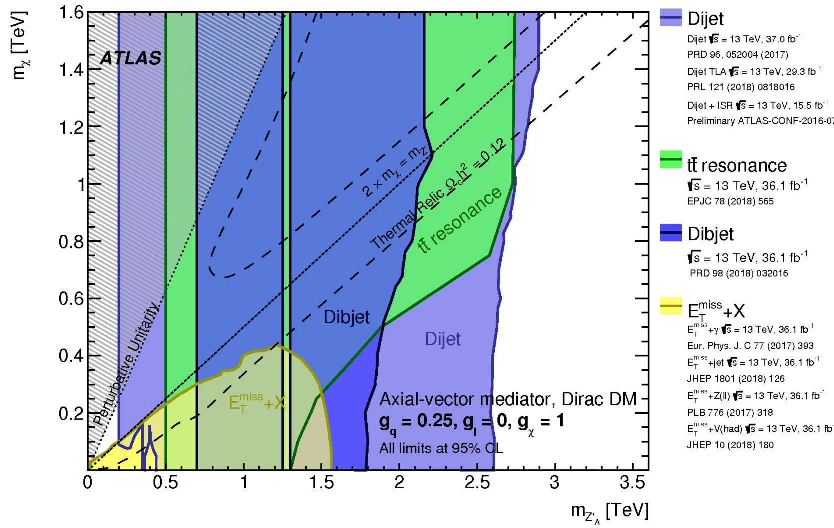
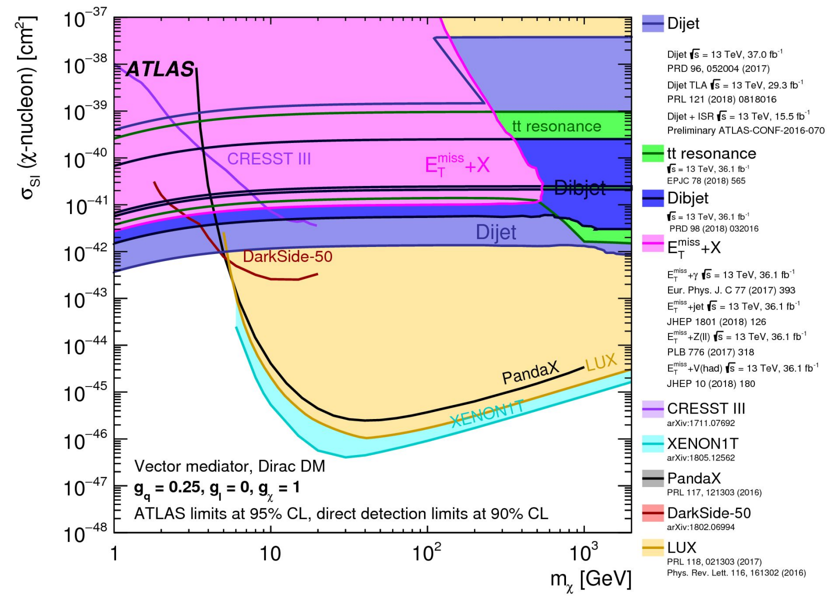




ATLAS: DM in invisible Higgs decays

ATLAS-CONF-2018-054
CMS: arXiv:1809.05937

Combination of limits from multiple previous results:

VBF: VBF production (See talk by Andrey Popov)

VH: Higgstrahlung with vector boson (Z/W) decay into quarks

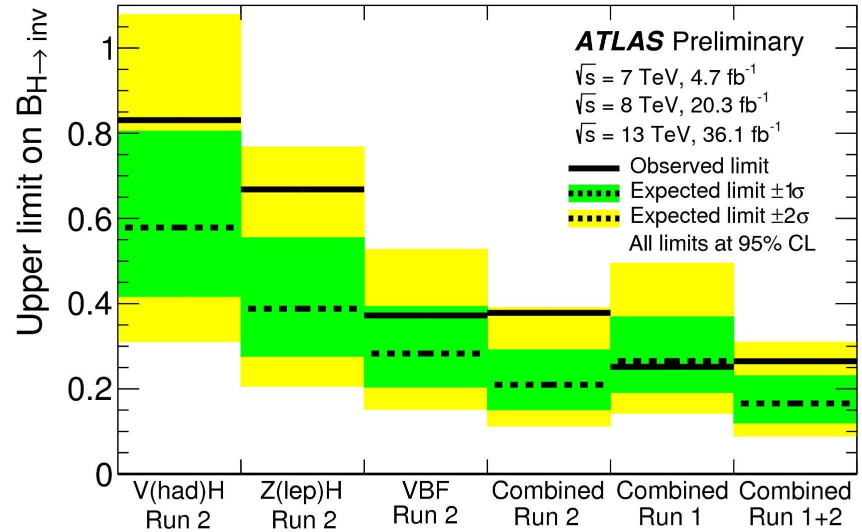
ZH: Higgstrahlung with Z decay to e^+e^- or $\mu^+\mu^-$

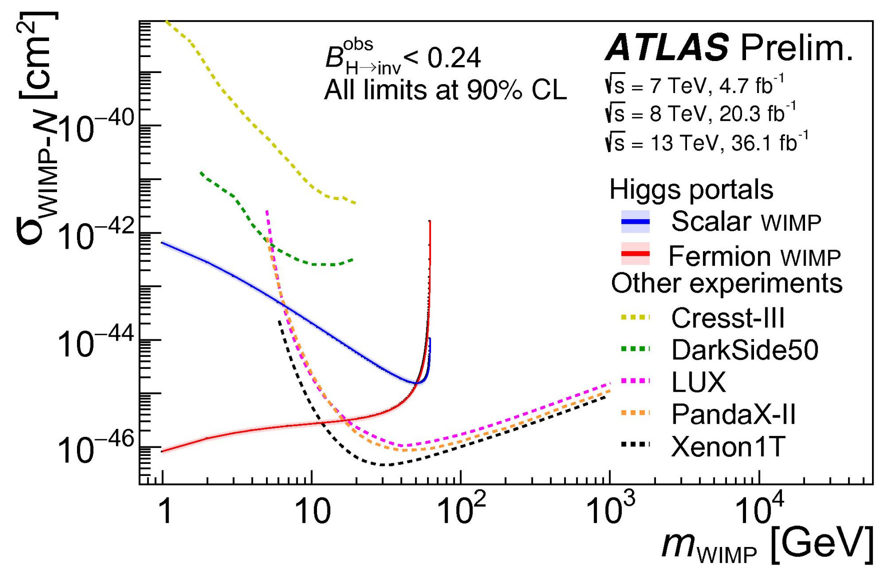
Additionally combined with the run-1 result (see arXiv:1903.01400)

Input analyses orthogonal to each other and correlation between systematics considered.

Combination performed by maximising the binned likelihood ratio

The result is an upper limit on $B_{H\to\,inv} < 0.26$





LHCb: Dark Photons

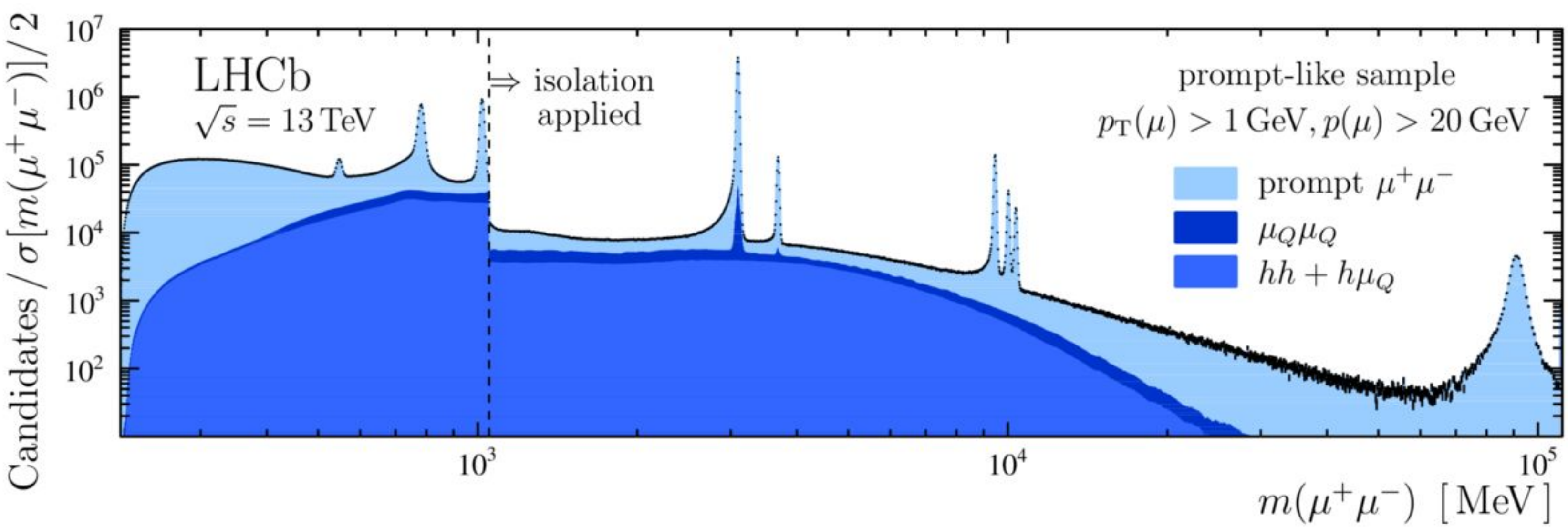
arXiv:1710.02867

Search for dark photons of mass m(A') with SM couplings suppressed by a factor ε.

Considering the A' → $\mu^+ \mu^-$ decays, both promptly decaying and long-lived

Analysis performed via fit on m($\mu^+ \mu^-$) spectrum

- Prompt-lepton background estimated from data
- Mis-identified muon backgrounds estimated using same sign muons



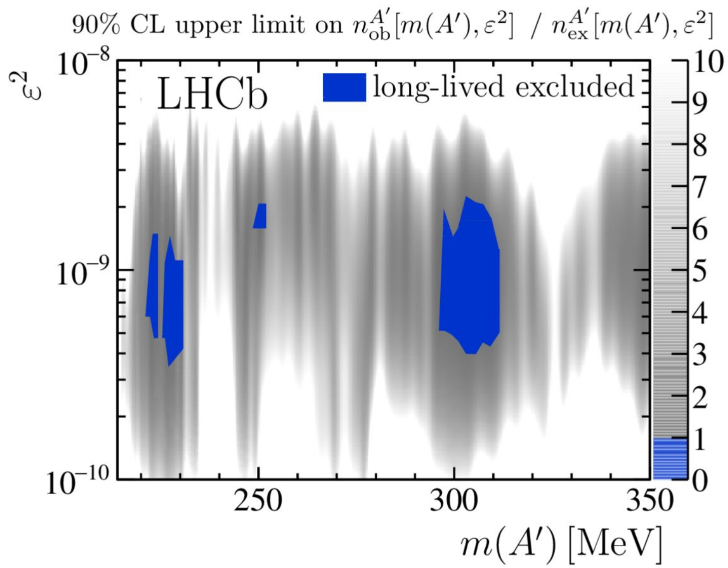
LHCb: Dark Photons

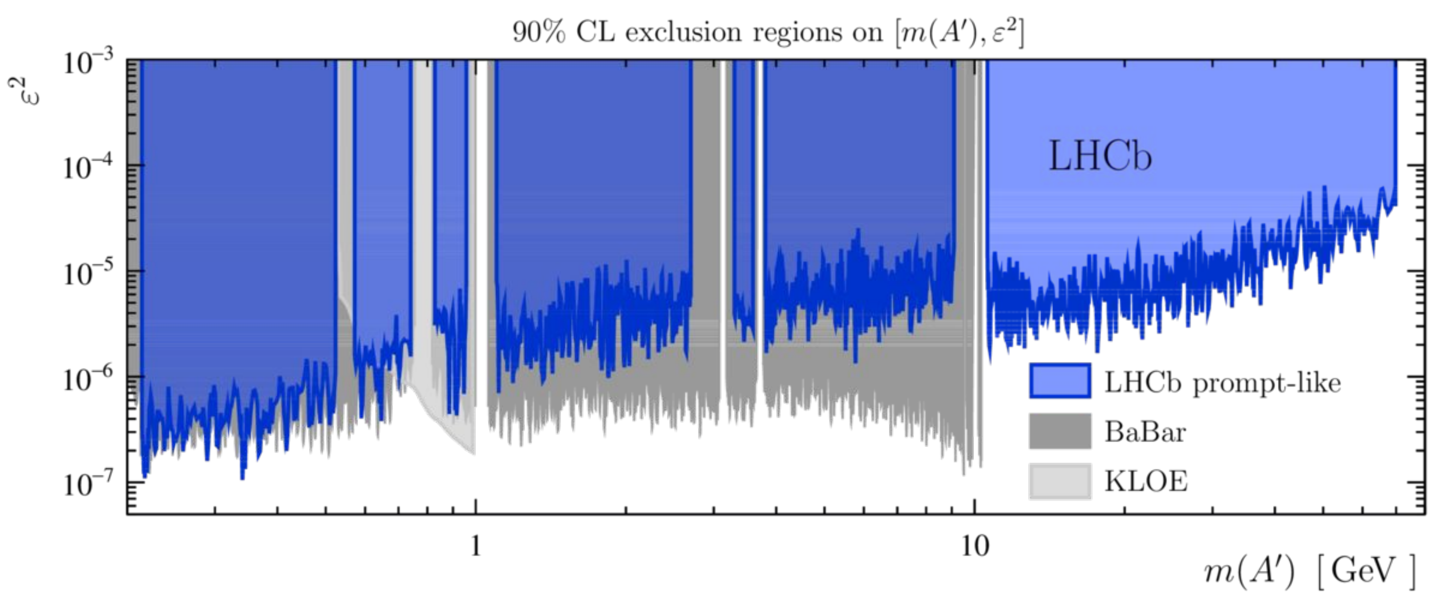
arXiv:1710.02867

No excess above background observed and limits set.

Results for promptly decaying dark photons (below) most stringent above 10 GeV, competitive with current best limits elsewhere!

For long-lived dark photons (right) limits are set for the first time!



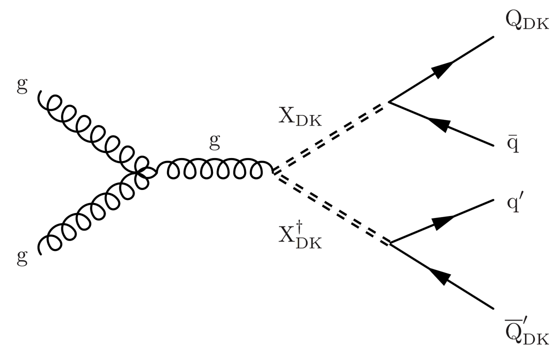


CMS: Jets and emerging jets

arXiv:1810.10069

Investigating a model where a new heavy particle (X_{DK}) with QCD dark-QCD couplings decays to a dark quark (Q_{DK})

- The dark quark will hadronise to a jet of dark pions
- Dark pions have long lifetime and decay to quarks
- Result in displaced vertices in an “emerging” jet
- For longer lifetimes can result in p_T^{miss}.

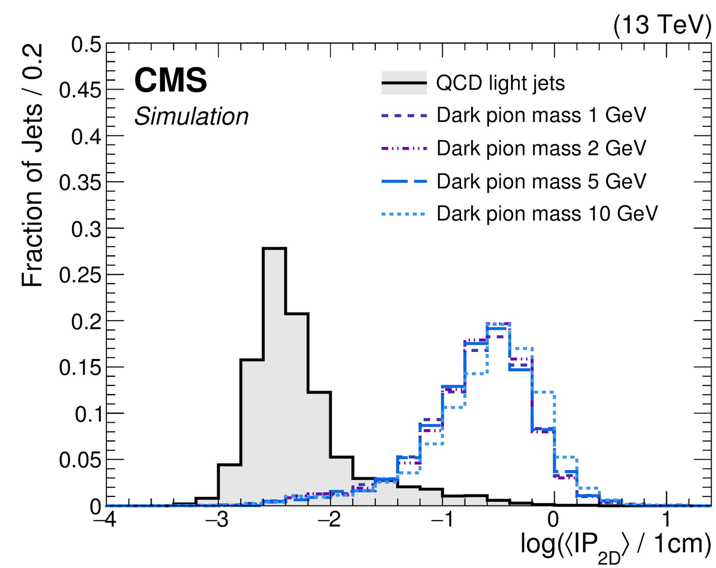


Models constructed in terms of mass of X_{DK} , lifetime and mass of the dark pions

Trigger: Selecting high-p_T jets

Selection: Selecting jets within |eta| < 2 where impact parameter resolution is best.

At least four jets are required, with two emerging jets, or one emerging jet and large p_T^{miss}.



CMS: Jets and emerging jets

arXiv:1810.10069

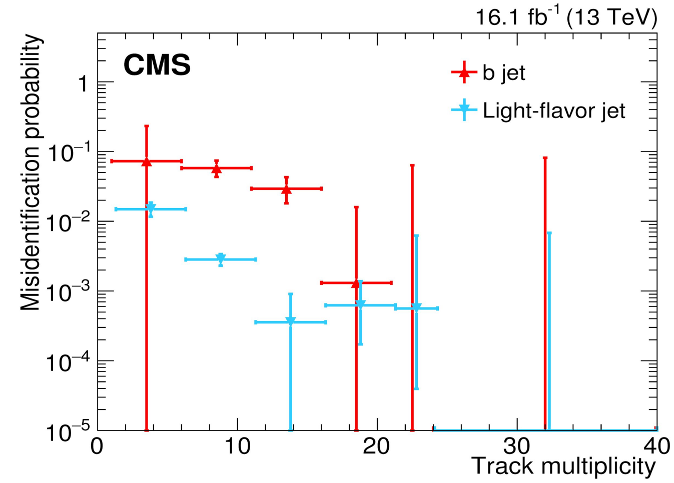
Backgrounds are estimated in a data-driven way starting from a sample of events with four jets but no identified emergent jets

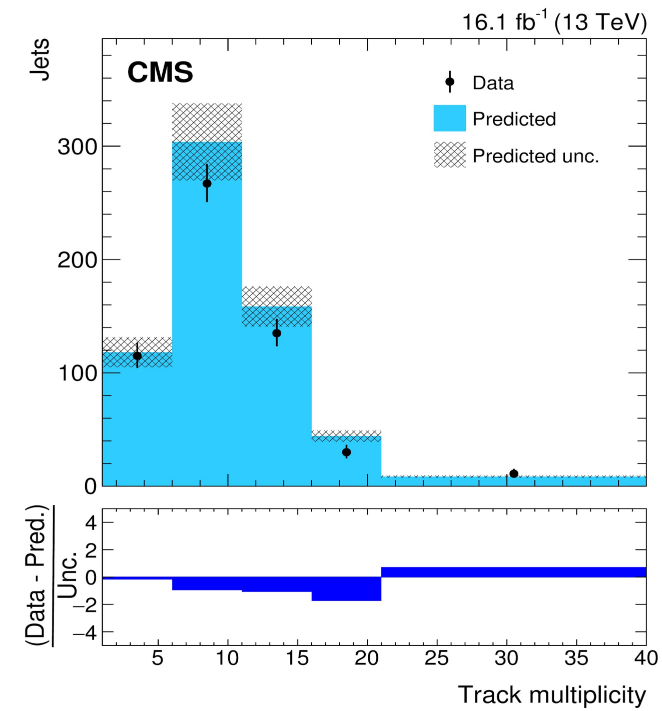
- The probability of a jet being misidentified as an emergent jet is modeled
- Depends on the flavour of the initiating parton and track multiplicity

Misidentification probability estimated using independent control sample (single photon trigger)

- Flavour composition determined using a template fit to the b-tagging discriminator variable

The results are evaluated in dedicated analysis regions





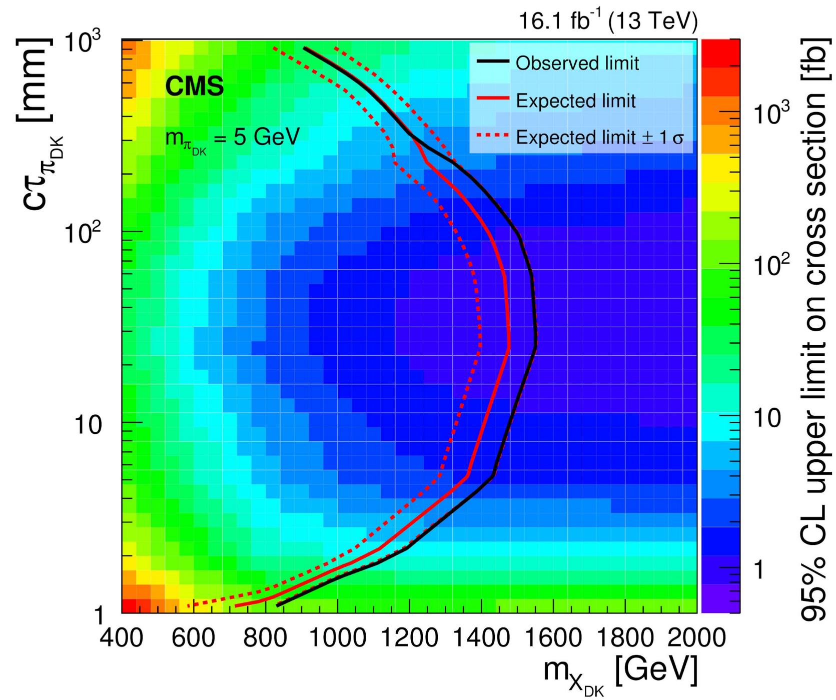
arXiv:1810.10069

CMS: Jets and emerging jets

No significant excess above the SM expectation observed.
Limits are placed on the considered models

Models with dark pion masses between 400 and 1250 GeV are excluded for decay lengths 5-225 mm

A larger range is excluded at low masses but with higher mass dependence



Set number	Expected	Observed	Signal	Model parameters $m_{X_{DK}}$ [GeV]	$m_{\pi_{DK}}$ [GeV]	$c\tau_{\pi_{DK}}$ [mm]
1	$168 \pm 15 \pm 5$	131	36.7 ± 4.0	600	5	1
2	$31.8 \pm 5.0 \pm 1.4$	47	$(14.6 \pm 2.6) \times 10^2$	400	1	60
3	$19.4 \pm 7.0 \pm 5.5$	20	15.6 ± 1.6	1250	1	150
4	$22.5 \pm 2.5 \pm 1.5$	16	15.1 ± 2.0	1000	1	2
5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0	1000	2	150
6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5	1000	10	300
7	$4.40 \pm 0.84 \pm 0.28$	2	5.61 ± 0.64	1250	5	225

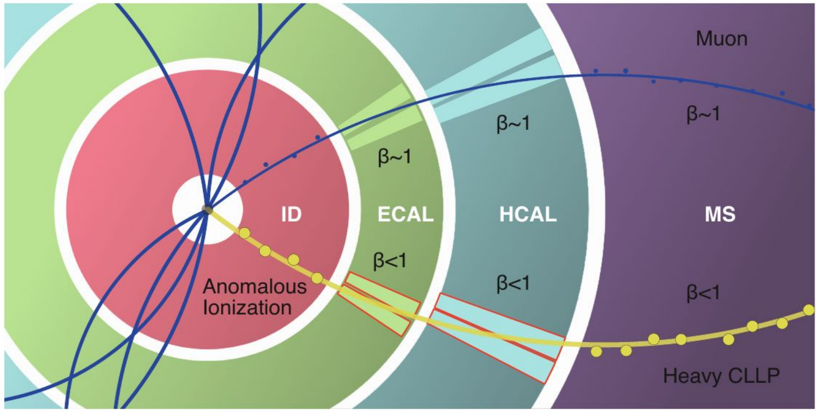
ATLAS: Heavy charged long-lived particles

arXiv:1902.01636
CMS: arXiv:1609.08382

Looking for heavy charged particles produced in LHC in a SUSY context

- Gluinos/squarks (R-hadrons), staus or charginos
- Heavy with low velocity → highly ionising

From arXiv:1810.12602



Primary observables:

- dE/dx measurement from charge in the Pixel detector
- TOF measurement in Tile, RPC and MDT detectors

Trigger: High-MET or isolated high-p_T muons

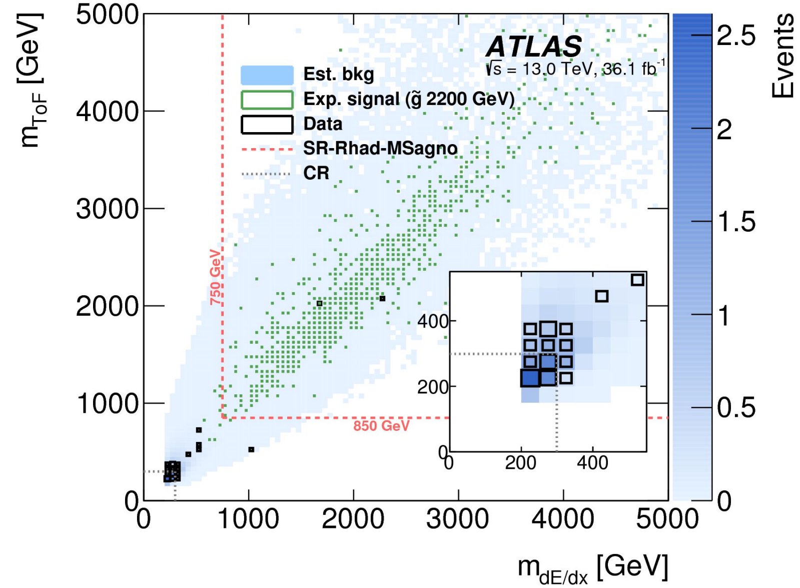
Selection: One or two candidate tracks with associated mass measurement

Split based on whether muon spectrometer is used and number of candidate tracks

Signal region	Trigger	Candidate selection	Candidates per event	Final requirements $\lvert\eta\rvert$	p [GeV]	β_{ToF}	$(\beta\gamma)_{dE/dx}$	Mass
SR-Rhad-MSagno	E_T^{miss}	ID+CALO	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.0	ToF & dE/dx
SR-Rhad-FullDet	E_T^{miss}/μ	LOOSE	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.3	ToF & dE/dx
SR-Rhad-FullDet	E_T^{miss}/μ	ID+CALO	≥ 1	≤ 1.65	≥ 200	≤ 0.75	≤ 1.0	ToF & dE/dx
SR-2Cand-FullDet	E_T^{miss}/μ	LOOSE	$= 2$	≤ 2.00	≥ 100	≤ 0.95	-	ToF
SR-1Cand-FullDet	E_T^{miss}/μ	TIGHT	$= 1$	≤ 1.65	≥ 200	≤ 0.80	-	ToF

ATLAS: Heavy charged long-lived particles

arXiv:1902.01636
CMS: arXiv:1609.08382

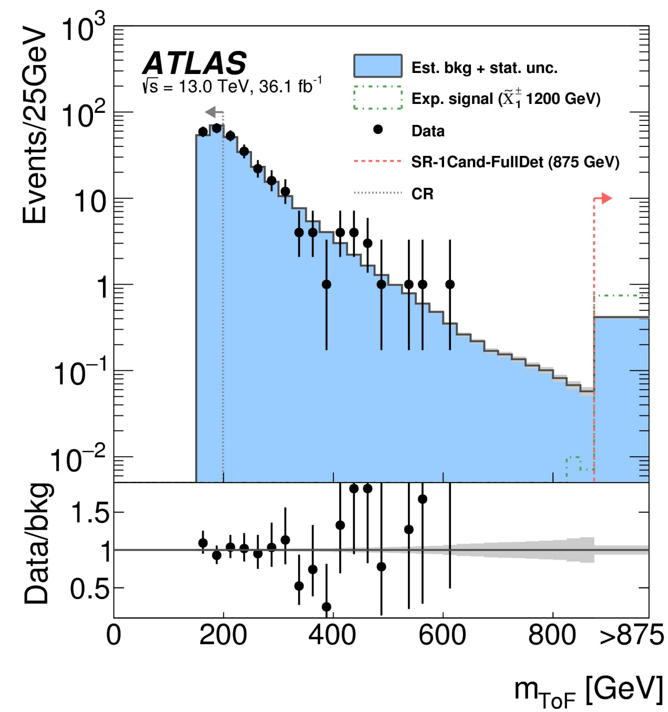


Background PDFs fully data-driven manner

- Invert the momentum requirements and obtain the PDFs for β_{TOF} , $(\beta\gamma)_{dE/dx}$. Vice-versa for the momentum PDF.
- Randomly sampling from these construct the m_{TOF} and $m_{dE/dx}$

PDFs normalised in control regions

- Control regions are defined based on side-bands to the SR requirements
- Normalisation derived from data and backgrounds scaled

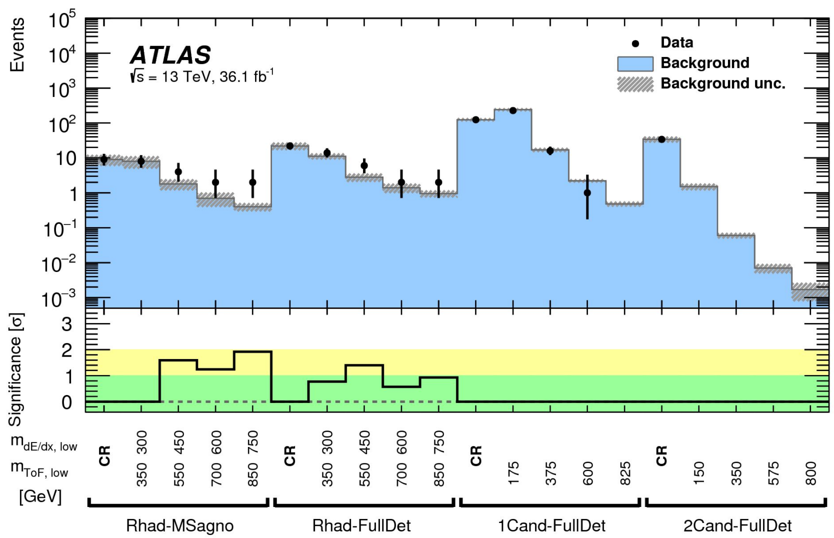


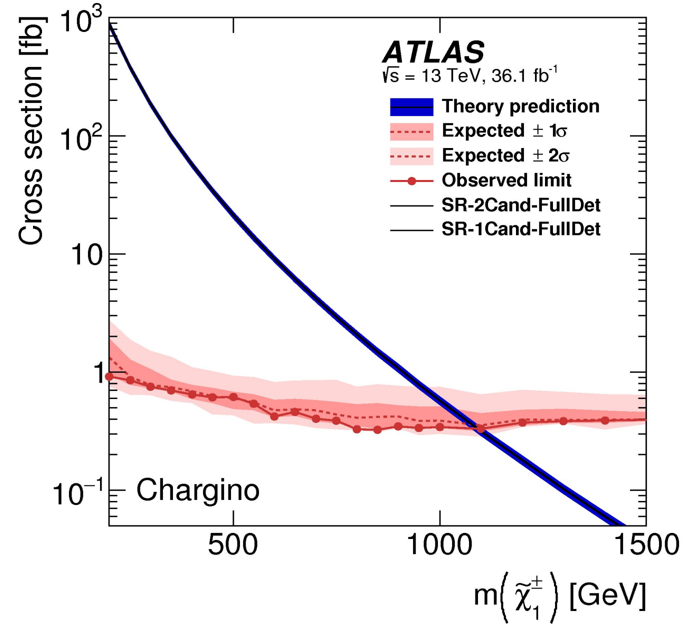
ATLAS: Heavy charged long-lived particles

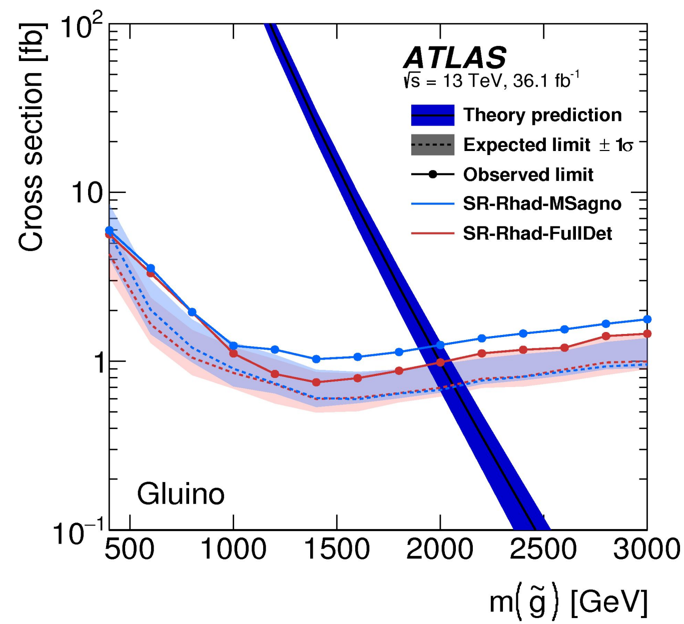
No significant excess above the expected background observed

Limits set on multiple different long-lived particles

- **Gluinos:** < 2000 GeV
- **Sbottom:** < 1250 GeV
- **Stop:** < 1340 GeV
- **Staus:** < 430 GeV
- **Charginos:** < 1090 GeV







ATLAS: Neutral Long-Lived Particles

arXiv:1902.03094
CMS: arXiv:1811.07991

Searching for production of a heavy neutral scalar particle decaying into two long-lived scalars.

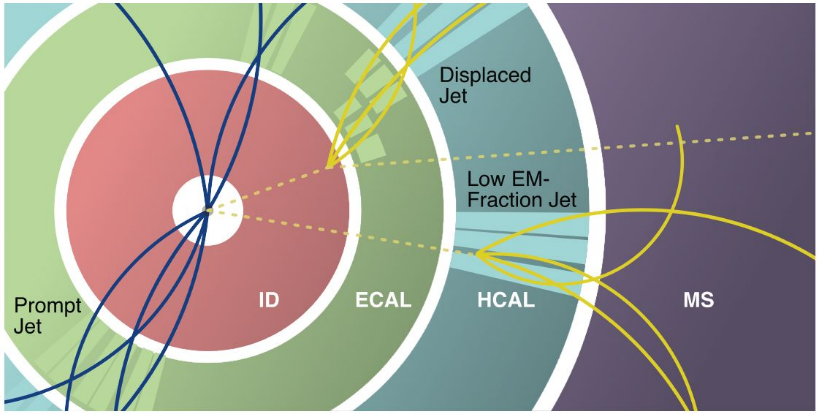
Signature: Scalars decay into fermions in the calorimeter, but after EM calorimeter (Higgs-like couplings assumed)

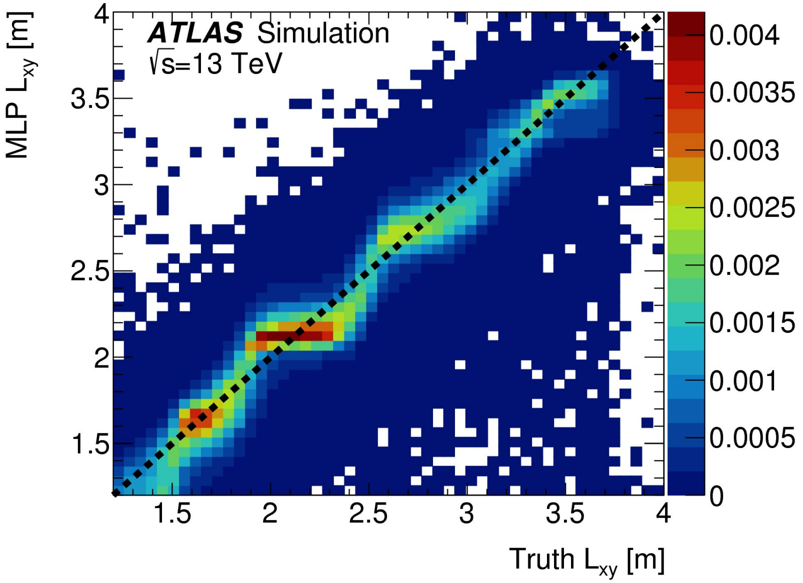
Trigger: Jets with high ratio of energy in the hadronic calorimeter, low-E_T and high-E_T triggers

Selection: At least two jets with no associated tracks (jet formed after tracker)

Jet origin estimated with a neural network and a further BDT classifies jets as signal-like, multijet-like and beam background-like

From **arXiv:1810.12602**





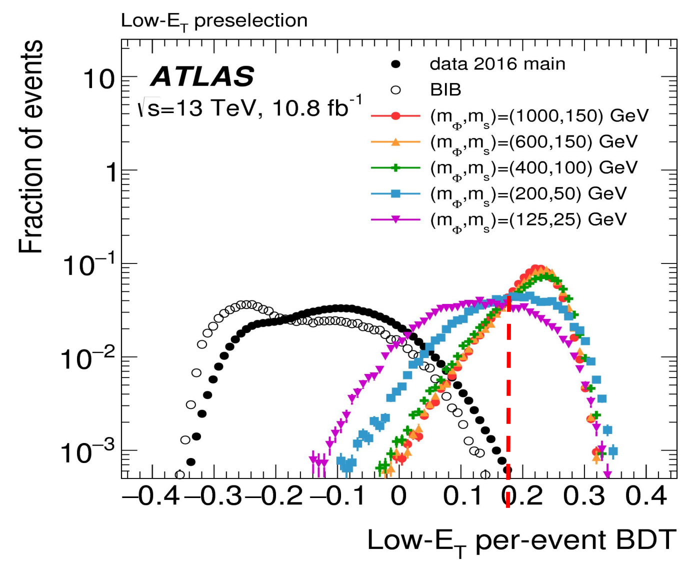
ATLAS: Neutral Long-Lived Particles

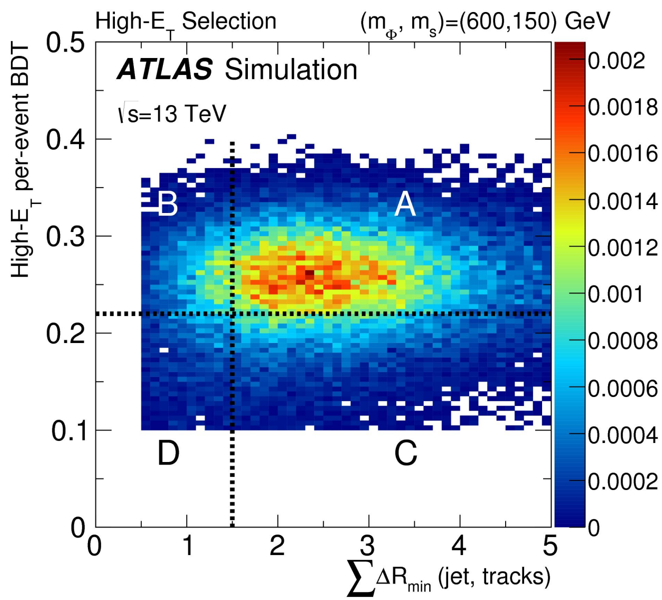
arXiv:1902.03094
CMS: arXiv:1811.07991

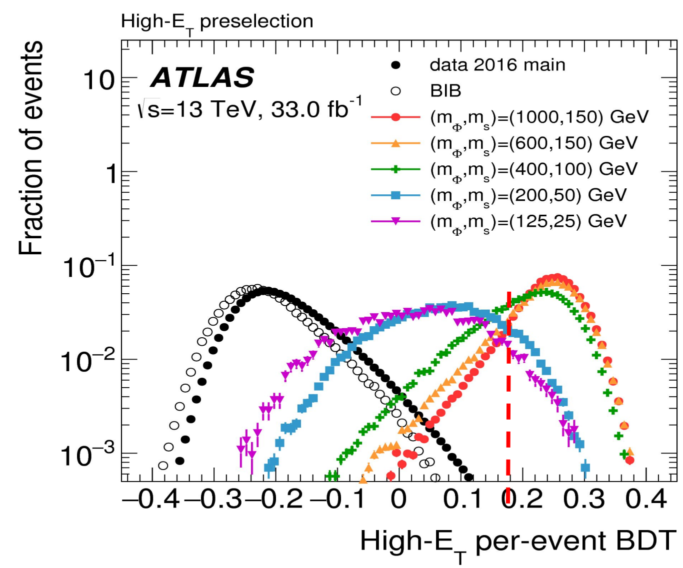
Signal regions defined in terms of a event-level BDT as well as E_H/E_{ecal}, jet p_T and H_T^{miss} / H_T.
The selection is split into high- and low-E_T.

Multijets is primary background following the selection.

The background is estimated in a data-driven manner using an ABCD method, splitting based on the BDT output and track-jet separation.







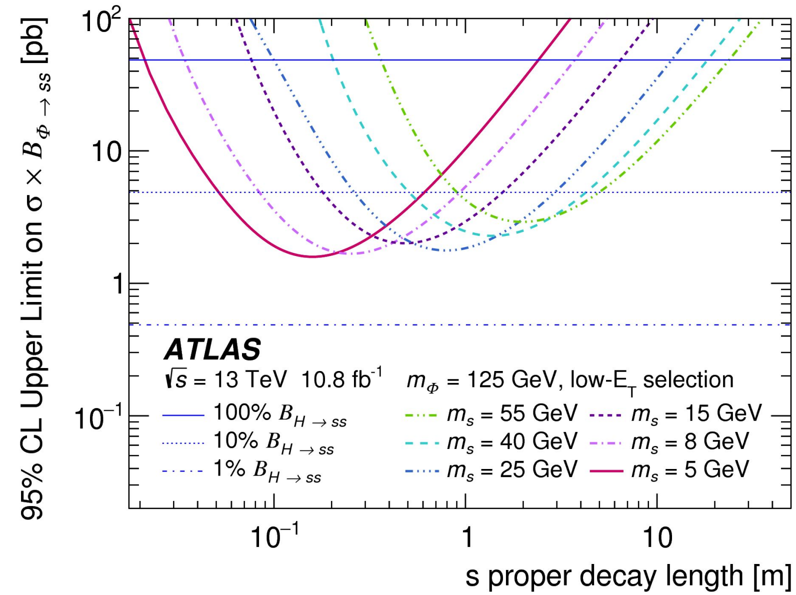
ATLAS: Neutral Long-Lived Particles

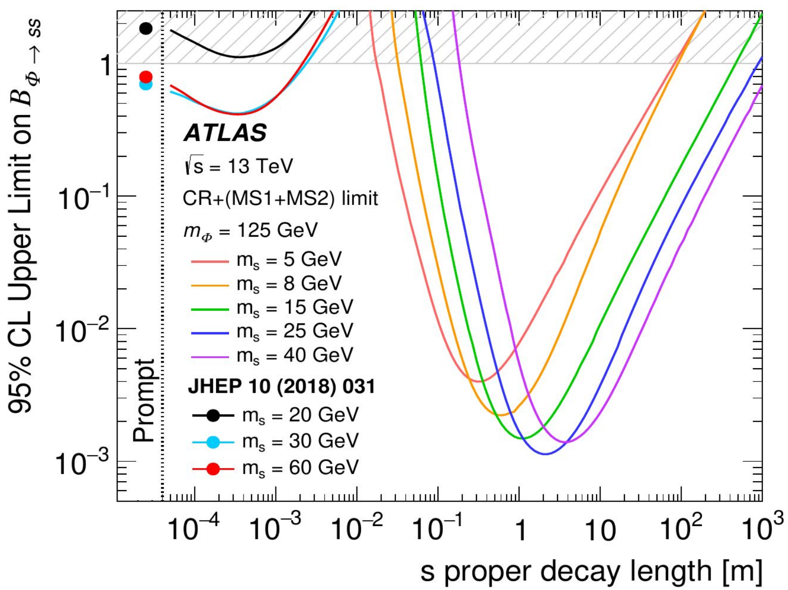
arXiv:1902.03094
CMS: arXiv:1811.07991

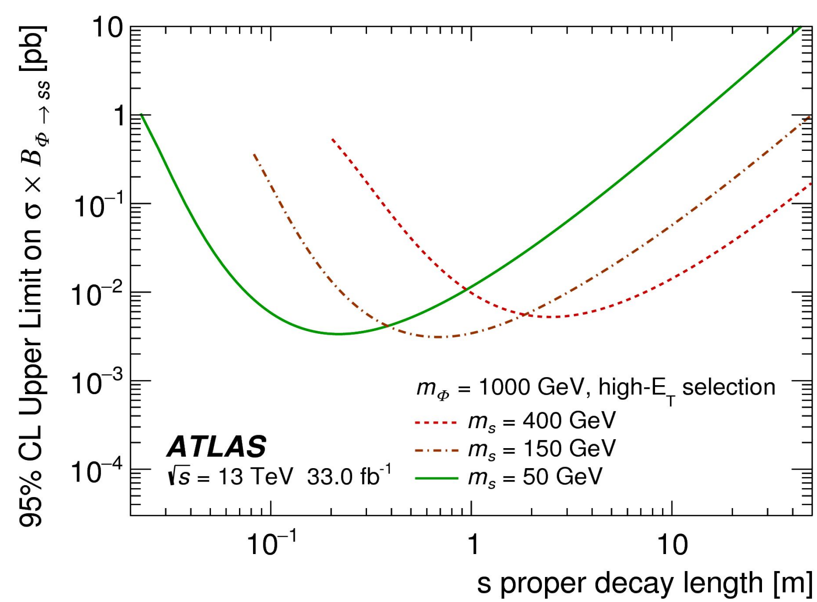
No excess above expected background observed and limits are set.

For mediator scalar compatible with Higgs boson limits on scalar masses between 5 - 55 GeV for proper decay lengths 5 cm - 5 m.

Results combined with search for displaced jets in the muon spectrometer (see arXiv:1811.07370) and H → aa → bbbb (see arXiv:1806.07355).







CMS: Displaced vertices in multijet events

arXiv:1808.03078
ATLAS: arXiv:1710.04901

Looking for signals with multiple jets and two displaced vertices in a SUSY context

Trigger: Using H_T (sum of jet p_T) trigger

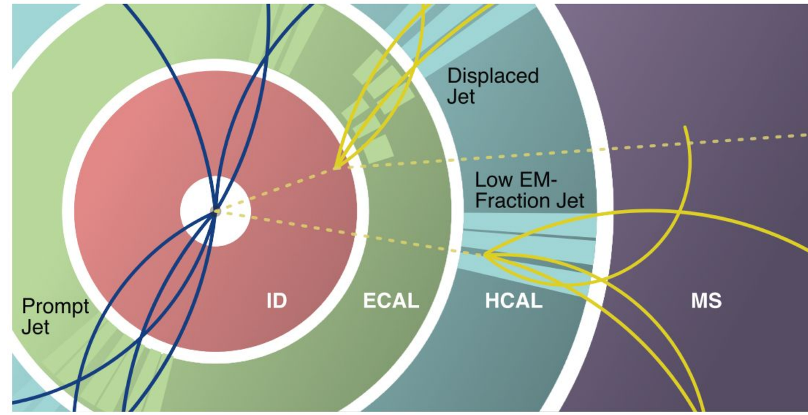
Selection: At least four jets and two significantly displaced vertices, H_T > 1000 GeV

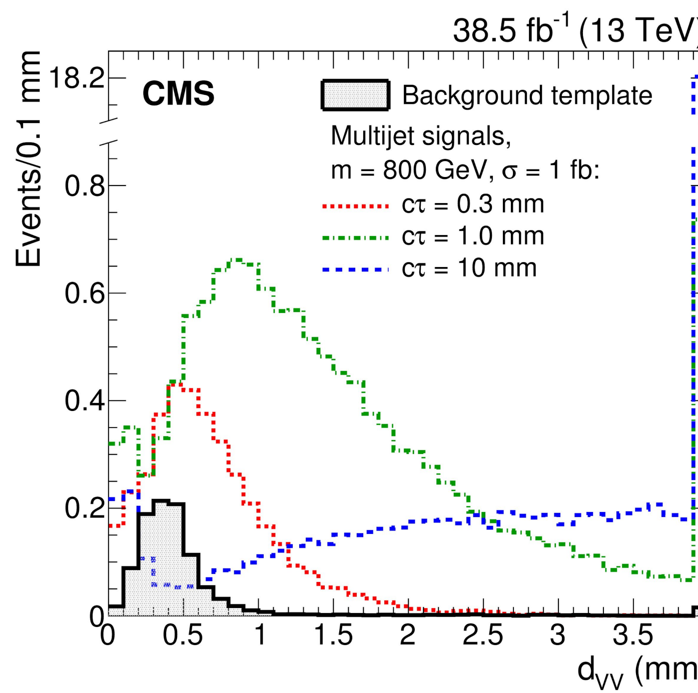
The signal vertices are required to have at least five tracks

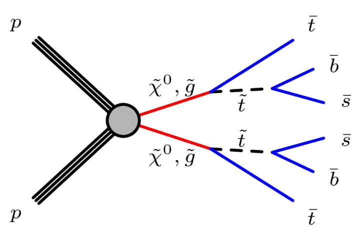
- Vertices with 3-4 tracks or only one signal vertex used to constrain backgrounds

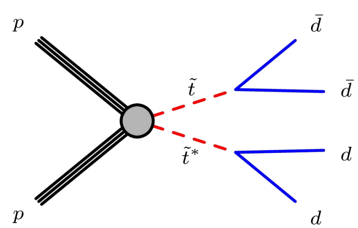
Main discriminating variable is d_{VV}, the distance between the jets in the x-y plane.

From **arXiv:1810.12602**









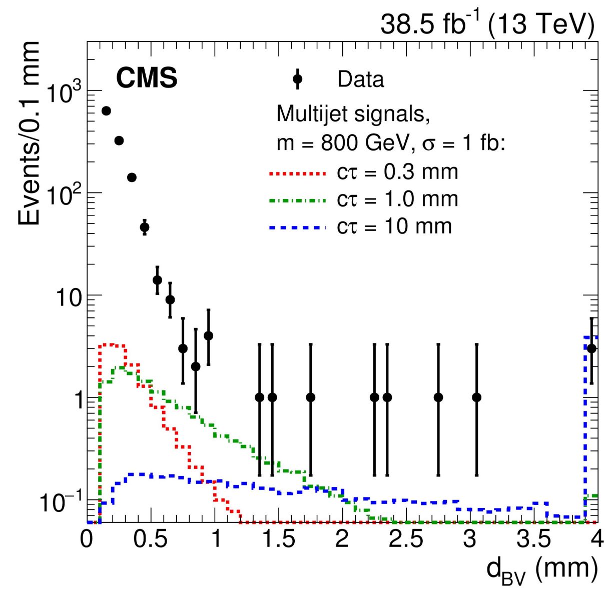
CMS: Displaced vertices in multijet events

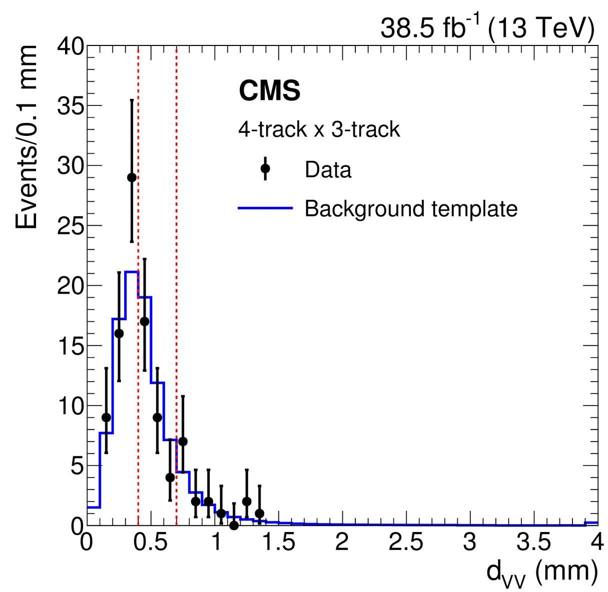
arXiv:1808.03078
ATLAS: arXiv:1710.04901

The background in this measurement arises from mis-reconstructed tracks overlapping with other tracks to form a vertex

- The input to the background estimation is sampled from the distribution of distance from the beamline (d_{BV}) for the single vertex with ≥ 5 tracks sample
- The angular distribution of the vertices is approximated based on a dijet opening angle in the 3-track single vertex sample
- Corrections are applied for merging of vertices as well as angular correlations arising from b-quark production

The procedure is validated in the 3 and 4 track vertex samples





CMS: Displaced vertices in multijet events

arXiv:1808.03078
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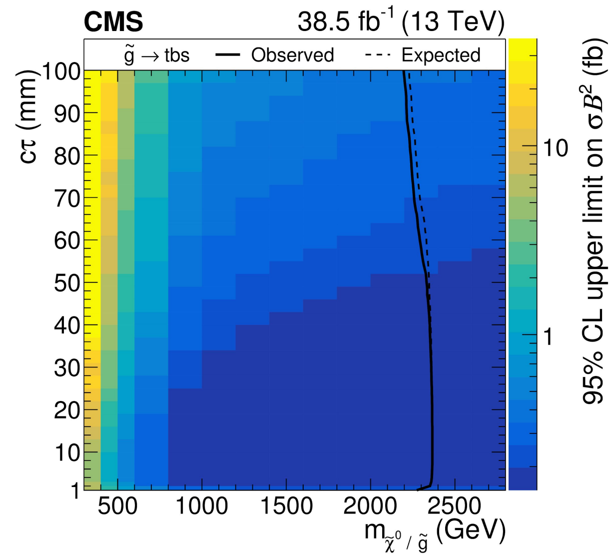
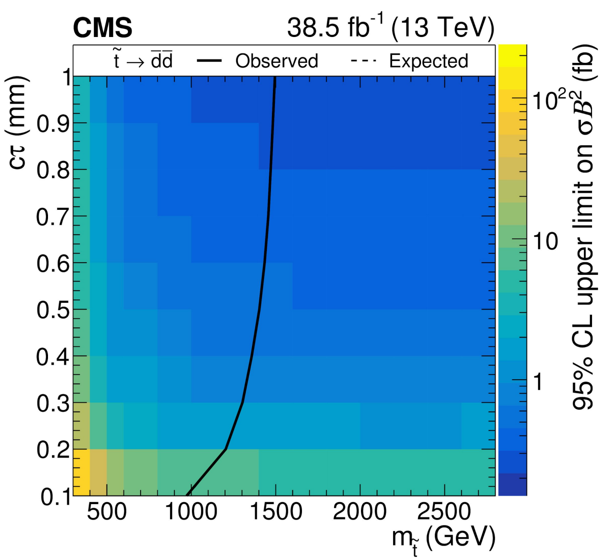
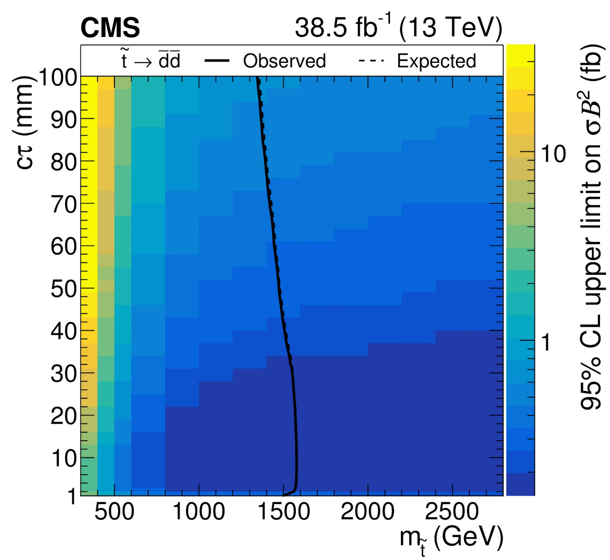


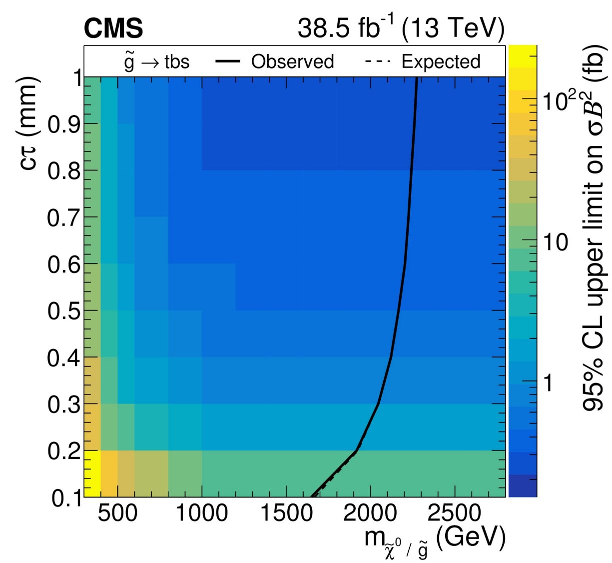
No significant excess above the expected background is observed.

Limits are set on the lifetime and mass of neutralinos/gluinos/squarks assuming a 100% branching ratio

Additionally limits are set on the branching ratio for a fixed lifetime or a fixed mass







Summary

Showed a selection of recent results from ATLAS, CMS and LHCb

- Cover many different models and final states
- Still only a fraction of the Run-2 data analysed, stay tuned!

These are analyses with novel final states

- Many different signatures to cover
- Diverse final states mean a lot of creativity goes into these analyses

For many of the analyses shown an extensive set of data is published for re-interpretations (HepData) in different models!

For a glimpse into the future see the talk by *Maximilian Emanuel Goblirsch-Kolb* tomorrow on prospects at the HL-LHC!

BACKUP SLIDES

Event display of events with emerging jets