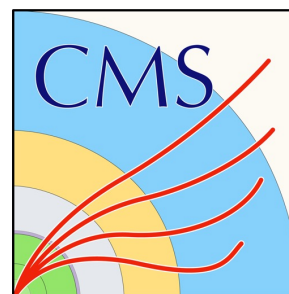


# Probes of the Dark Sector from the ATLAS and CMS experiments

Long Wang (Univ. of Maryland)

On behalf of the ATLAS and CMS collaborations

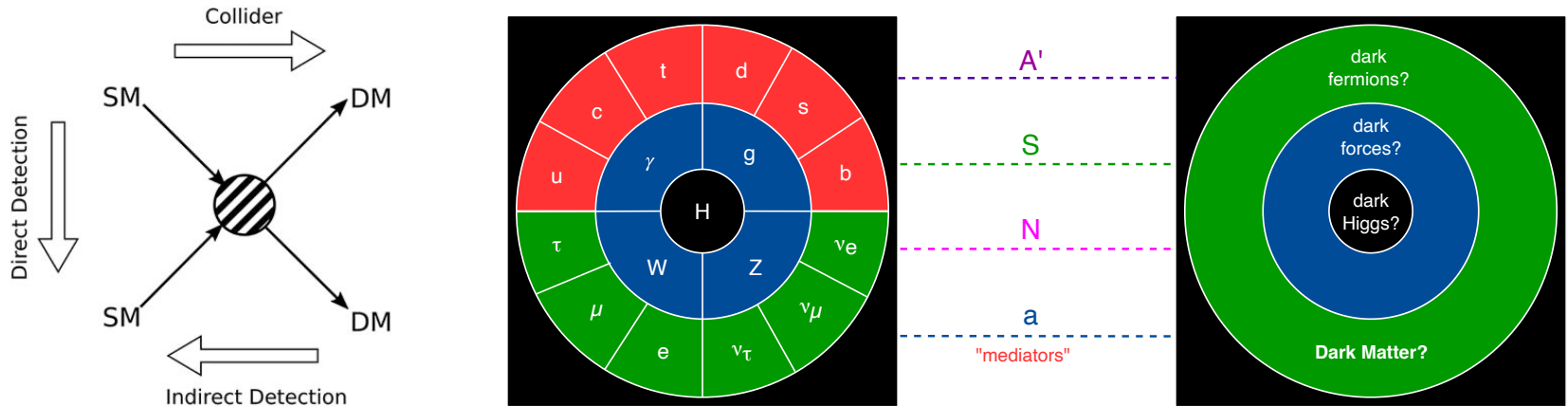


Blois 2022: 33rd Rencontres de Blois on "Exploring the Dark Universe"

# Outline

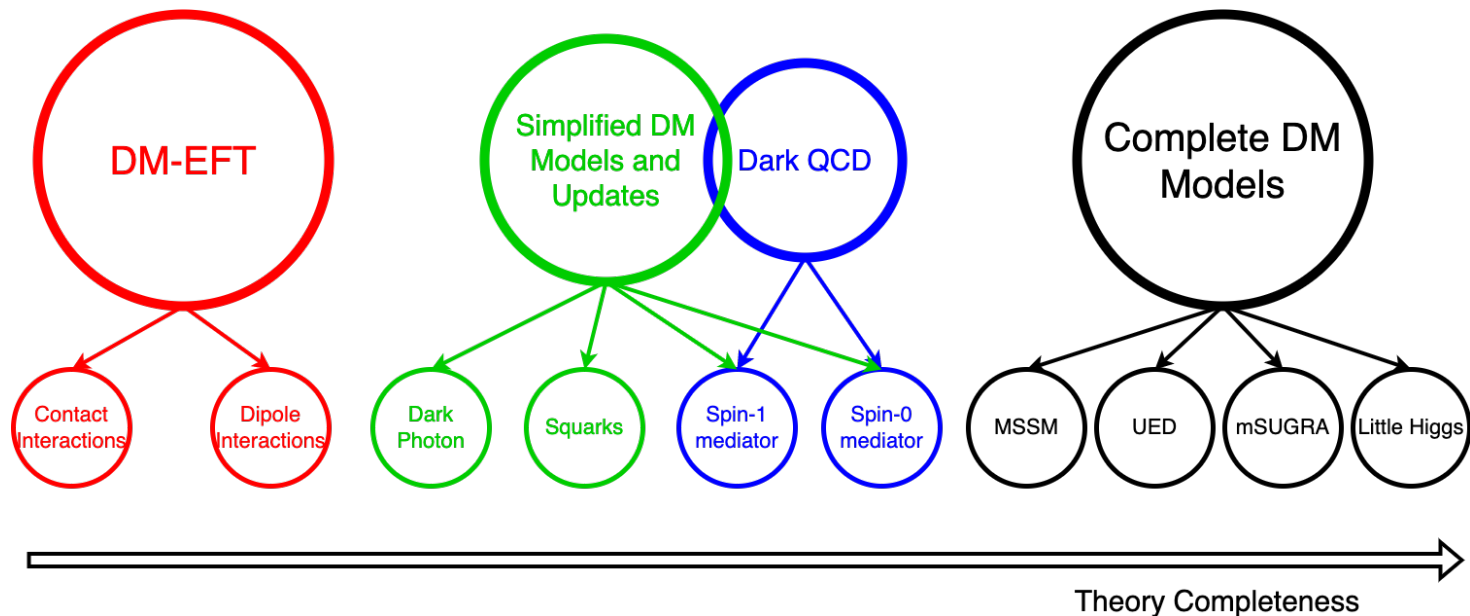
- ❖ Physical motivation
- ❖ LHC DM theory space and probes
- ❖ New results from ATLAS and CMS
- ❖ Experimental challenges
- ❖ Prospects and summary

# Motivation for a Dark Sector



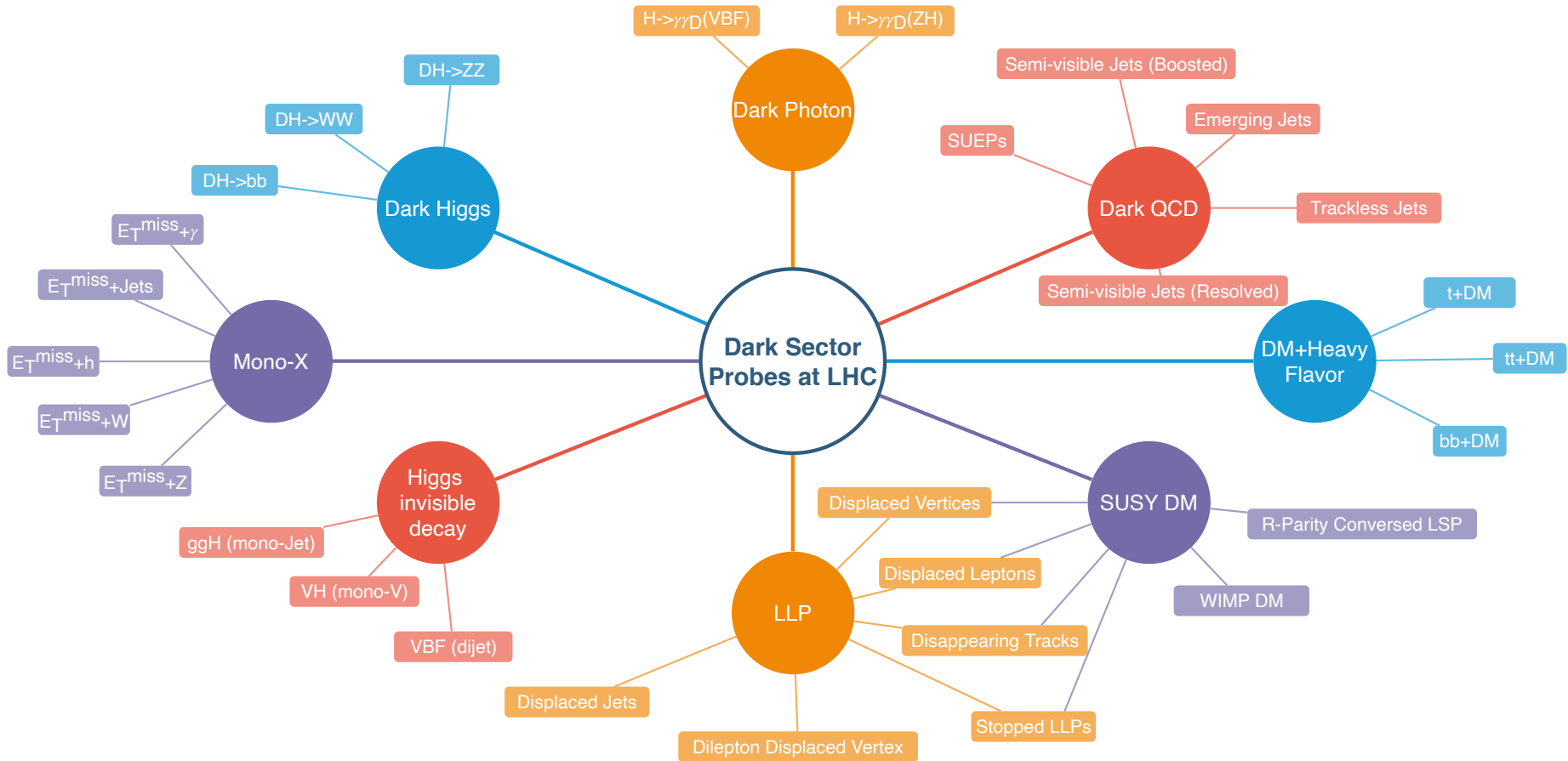
- A Dark Sector (DS) can explain the Dark Matter (DM) mystery and help address some open problems in the SM, e.g., strong CP problem, gauge hierarchy, etc.
- As a ground assumption for collider DM search, we assume non-gravitational interactions exist between SM particles and DM particles

# Theory space covered at LHC



- Experimental searches for DM can generally be kept model independent. However, theoretical models are needed to characterize a possible discovery and for comparison with non-collider results.
- A rich collection of collider DM theories were developed during early LHC Run2 and updated during Run2
  - Simplified models capture the essential DM signatures through a minimal set of parameters, focusing on mediator characterization;
    - Recent updates include t-channel models
  - Dark QCD models improve simplified models with simplified DM self interactions;
  - Full DM models in SUSY cover missing features.

# Signature driven DM portals



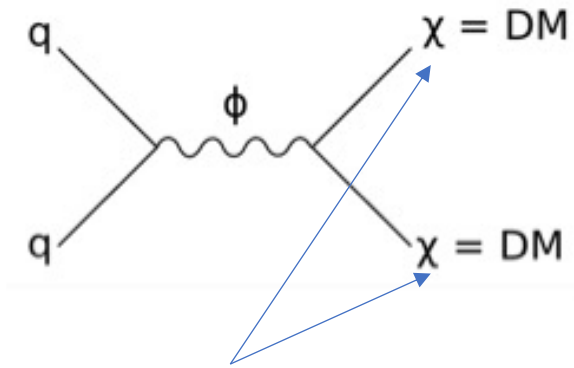
- DM searches at ATLAS and CMS are mostly signature-based;
  - Analysis are designed around specific final states, feasible to probe multiple models.
- Simplified DM sectors utilize the signature of invisible final states recoiling against an SM object;
- Rich DM sectors are probed by mixed visible-invisible final states - a test of dark sector structure.

# Exotica, Beyond-2-Generations, and Higgs-and-Diboson Searches

- ATLAS Exotic public results:  
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>
- ATLAS HDBS public results:  
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HDBSPublicResults>
- CMS Exotica public results:
  - Publications: <http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html>
  - Preliminary results: <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html>
- CMS B2G public results:
  - Publications: <http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html>
  - Preliminary results: <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html>

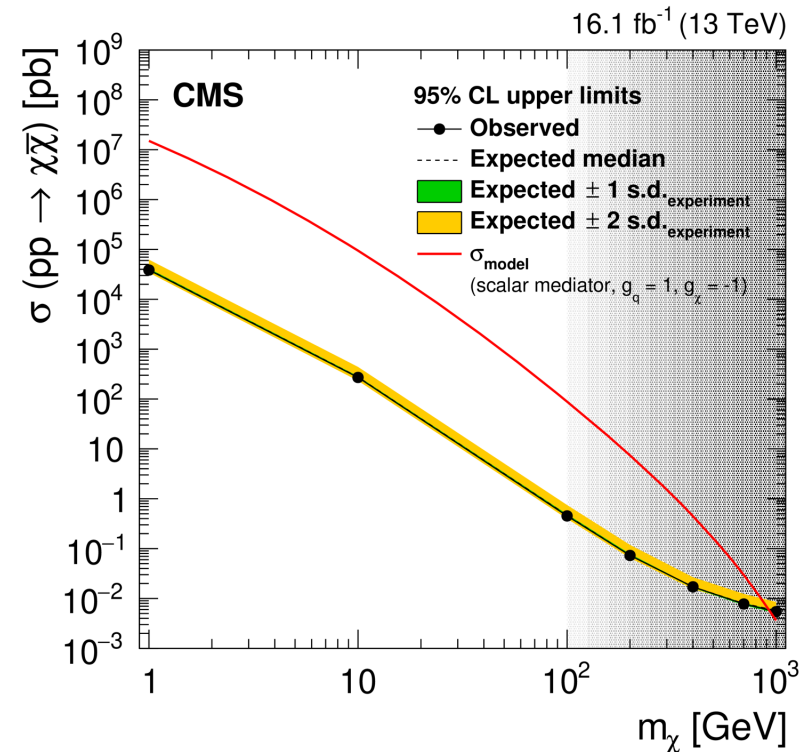
# SIMP with trackless jets

*Eur. Phys. J. C 82 (2022) 213*



SIMPs only interact in calorimeter

- A search for strongly interacting massive particles (SIMP);
  - CMS 2016 Data is used;
- Signature: Trackless di-jet events with signals only in calorimeter;
- Model-independent upper limit on visible cross section at 0.18 fb;
- Excludes SIMP dark matter candidates up to 100 GeV with couplings  $g_\chi = -1$  and  $g_q = 1$  ;
- Further sensitivity is explored towards higher masses above 100 GeV (shaded area, where the modelling becomes more speculative thus limits increasingly uncertain).

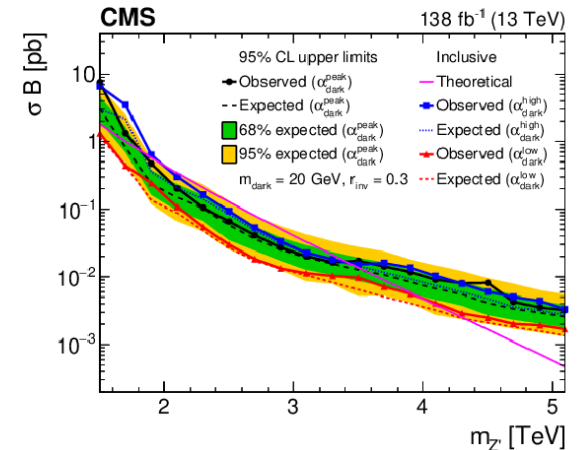
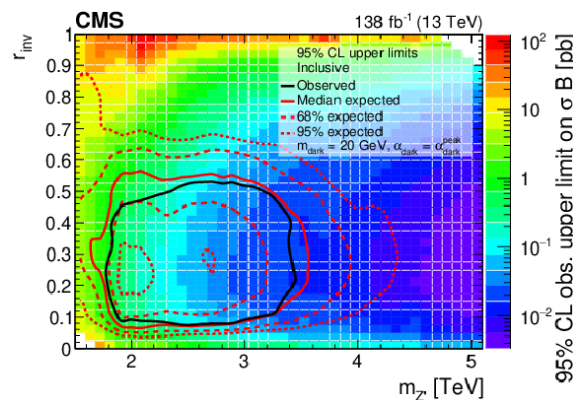
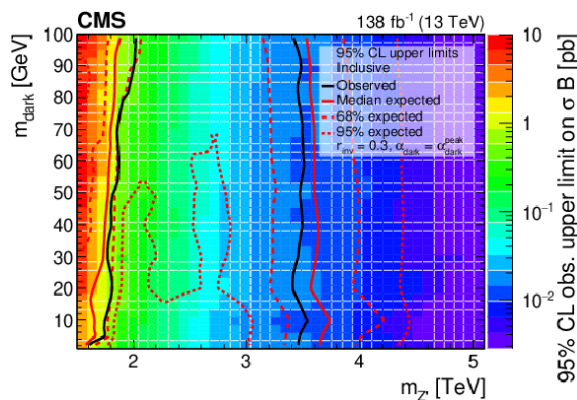
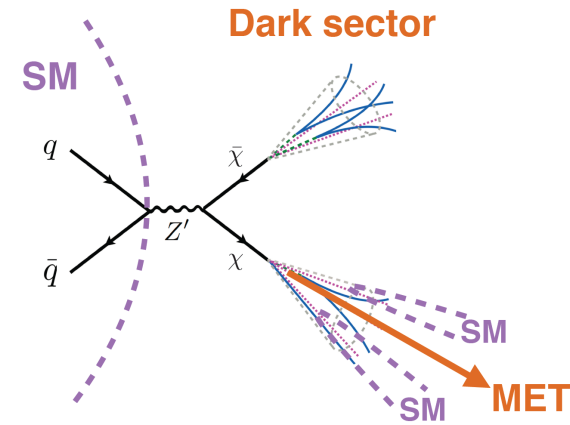


[\*] ATLAS's similar search: [Eur. Phys. J. C 79 \(2019\) 481](#)

# Semi-visible Jets

[CMS-EXO-19-020](#); Submitted to *J. High Energy Phys.*

- Search details in [Thomas' parallel talk](#).
- Strongly coupled dark matter model.
- Signature: two jets that each contain partially SM content, partially invisible DM content,  $E_T^{miss}$  is aligned with a jet
- Parameters:  $m_{med}$ ,  $m_{DM}$ ,  $r_{inv}$  (invisible content fraction)



□ Results from inclusive search method at 95% CL:

1. Exclusion range on  $r_{inv}$  from 0.08 to 0.53
2. Exclusion range on  $m_{med}$  from 1.5 to 3.9 TeV

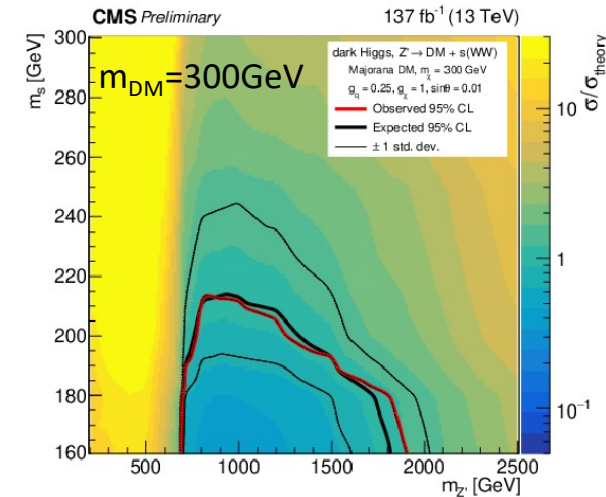
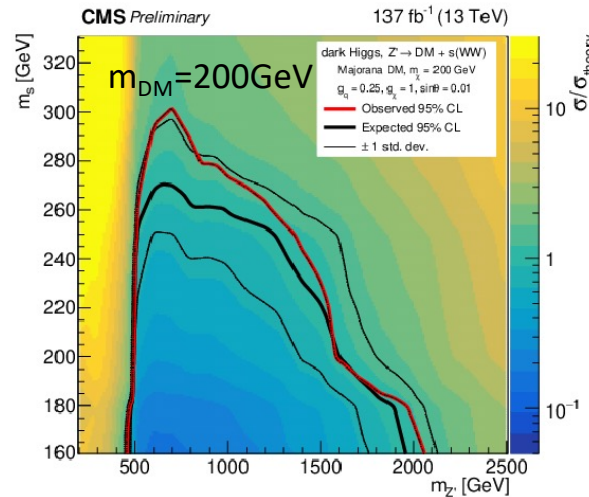
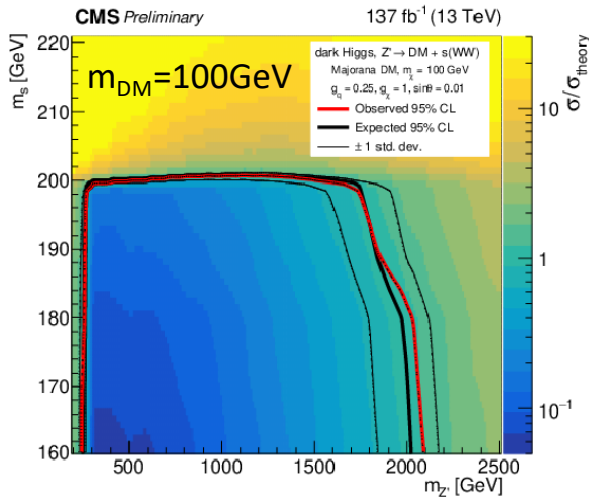
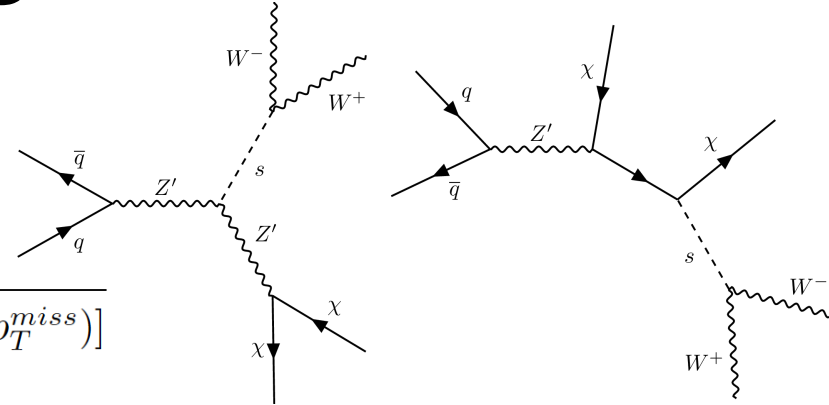


# Dark Higgs decaying to $W^+W^-$

[CMS-PAS-EXO-20-013](#)

- Probe through the dileptonic decay of the  $W^+W^-$  boson pair
- Test observable

$$m_T^{l \min, p_T^{miss}} = \sqrt{2p_T^{l \min} p_T^{miss} [1 - \cos \Delta \phi(p_T^{l \min}, p_T^{miss})]}$$

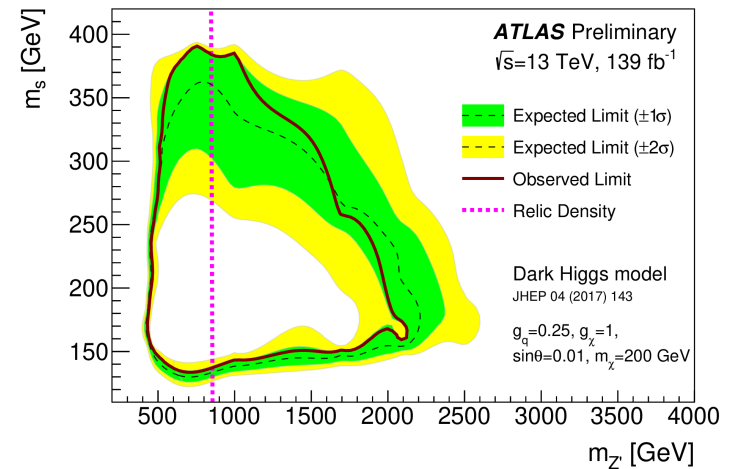
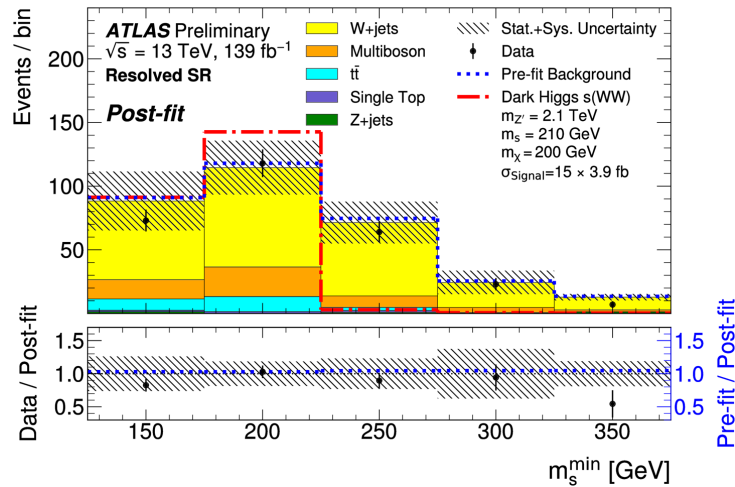
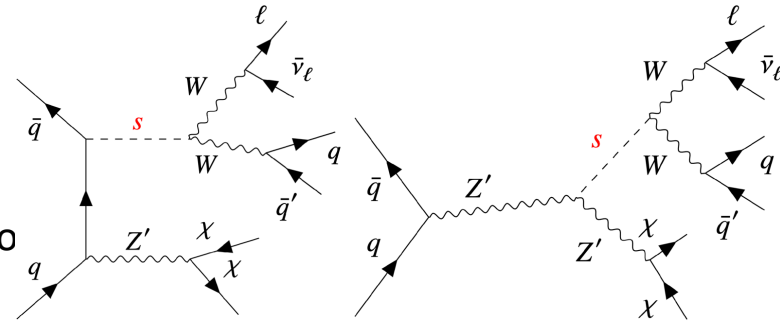


- Exclusion region at 95% CL shown for the dark Higgs model in the  $(m_s, m_{Z'})$  plane for  $m_{DM}$  of 100, 200, and 300 GeV;
- Excludes  $m_s$  masses up to  $\approx 300 \text{ GeV}$  for a mass range  $\approx 480 < m_{Z'} < 1200 \text{ GeV}$ , and up to  $m_{Z'} \approx 2000 \text{ GeV}$  for a  $m_s = 160 \text{ GeV}$ .

# Dark Higgs decaying to $W^+W^-$

[ATLAS-CONF-2022-029](#)

- Probe through the semi-leptonic decay of the  $W^+W^-$  boson pair
- A track-assisted reclustering algorithm is employed to reconstruct  $W^\pm \rightarrow q\bar{q}'$  decay
- A minimal possible dark Higgs mass is reconstructed as discriminant of signal and background



- Excludes  $m_s$  mass up to 390 GeV; excludes  $m_{Z'}$  mass up to  $\sim 2$  TeV.

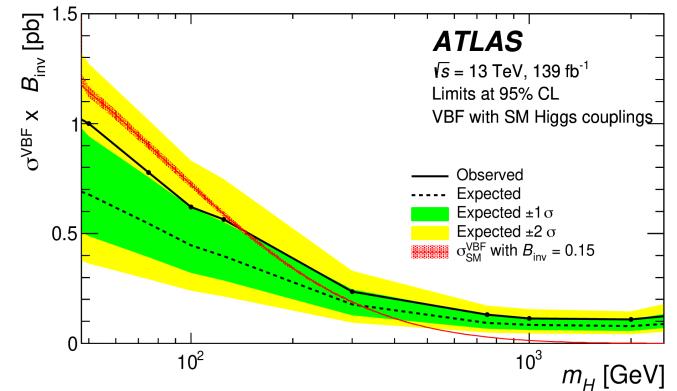
[\*] Dark Higgs to  $W^+W^-$  full hadronic final state search: [Phys. Rev. Lett. 126, 121802 \(2021\)](#)

[\*\*] Dark Higgs to  $bb$  search: [ATL-PHYS-PUB-2019-032](#)

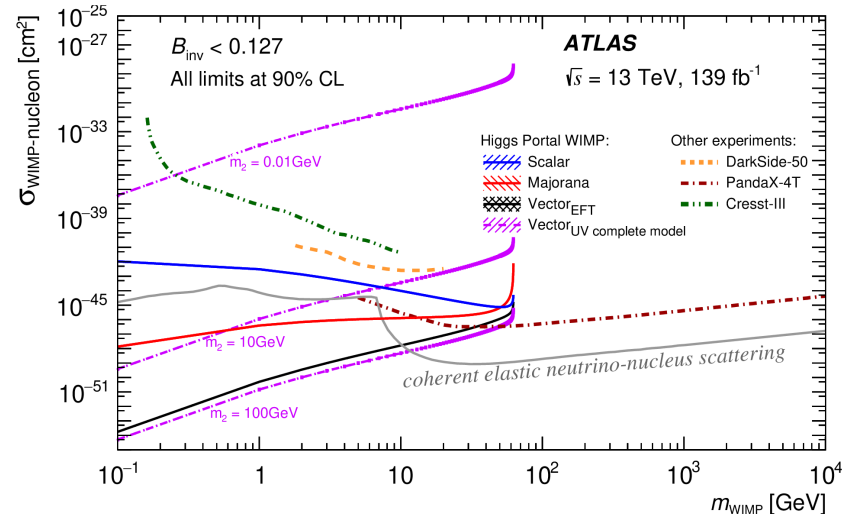
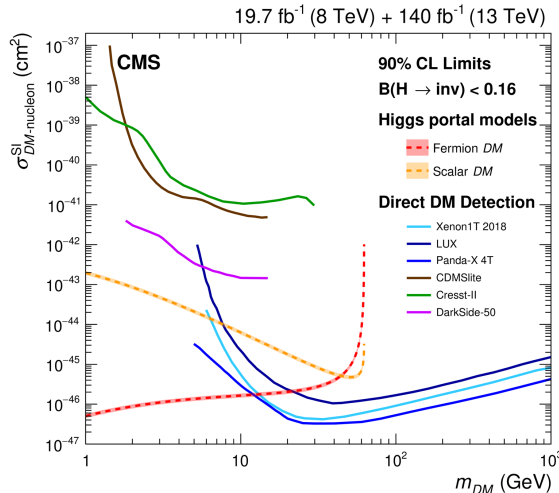
# H → invisible

CMS: [arXiv:2201.11585](https://arxiv.org/abs/2201.11585); ATLAS: [arXiv:2202.07953](https://arxiv.org/abs/2202.07953)

- Probe through VBF Higgs production;
  - Large value of pseudorapidity separation and dijet invariant mass, small value of azimuthal separation;
  - Reduced hadronic activity within the rapidity gap of the leading jets due to absence of color connection;
  - Details of ATLAS search in [Claudia's parallel talk](#).
- Observed upper limit of 0.145 from ATLAS and 0.18 from CMS at the 95% CL on  $\mathcal{B}(H \rightarrow inv)$ .



- Upper limits on  $\sigma^{VBF} \times \mathcal{B}_{inv}$  for invisible decays of heavy scalar particles acting as mediators to dark matter.

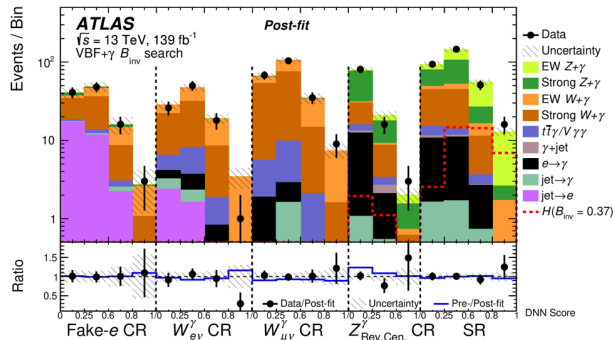
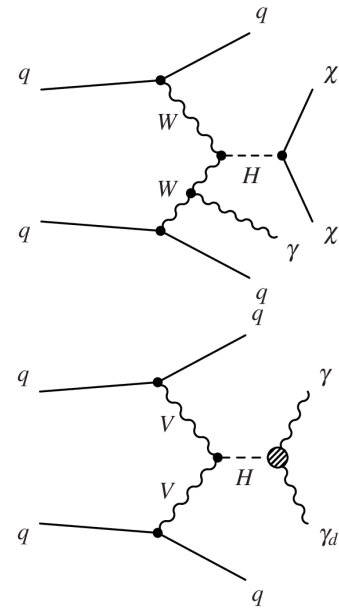


- Upper limits from ATLAS (right) and CMS (left) on the spin-independent DM-nucleon cross section for various  $m_{DM}$ .
  - The observed 90% CL upper limit on  $\mathcal{B}(H \rightarrow inv)$  is used to enable comparison with the 90% CL direct detection limit.

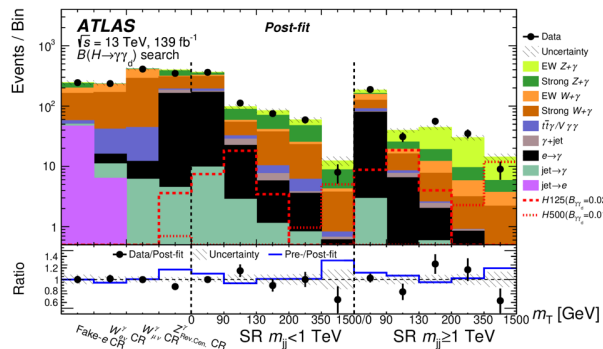
# H → invisible + γ and H → γγ<sub>D</sub>

*Eur. Phys. J. C 82 (2022) 105*

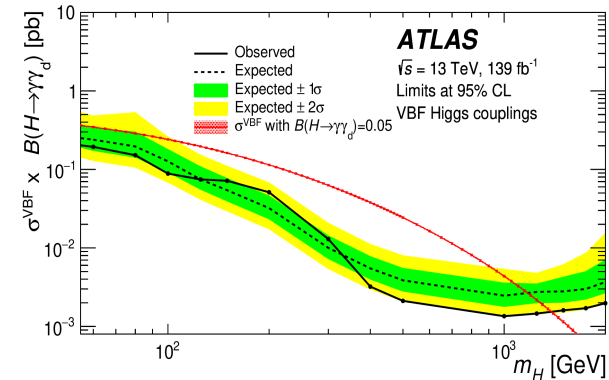
- Signature: large  $E_T^{miss}$  and a photon, in addition to a pair of forward jets.
  - Dominant background from V γ+jets
- For H → inv. search, a DNN based on kinematic feature was used, and result was extracted from likelihood fit on DNN output bins.
- H → γγ<sub>D</sub> search result was extracted from maximum likelihood fit to the photon-  $E_T^{miss}$  transverse mass and di-jet invariant mass distribution



- Observed (expected) upper limit of 0.37 (0.34) at 95% CL on  $\mathcal{B}(H \rightarrow inv)$



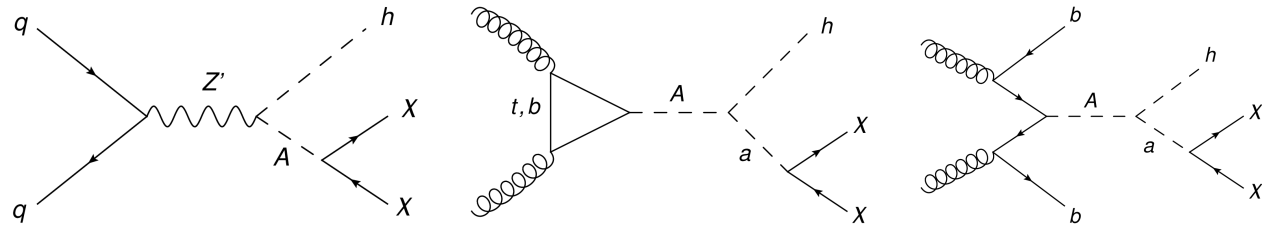
- Observed (expected) upper limit of 0.018 (0.017) at 95% CL on  $\mathcal{B}(H \rightarrow \gamma\gamma_D)$



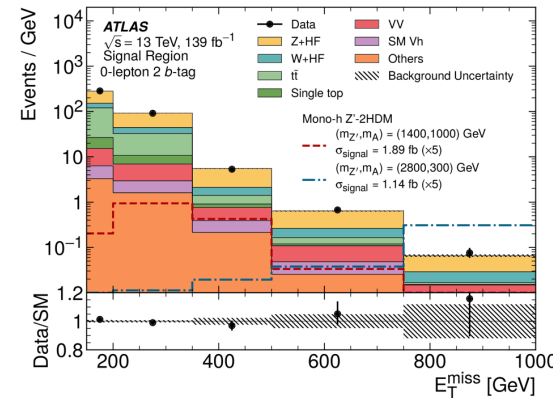
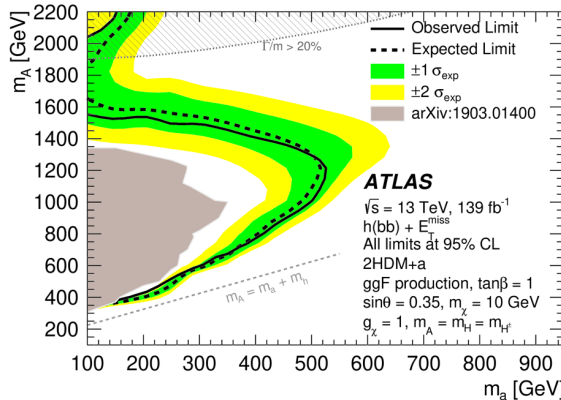
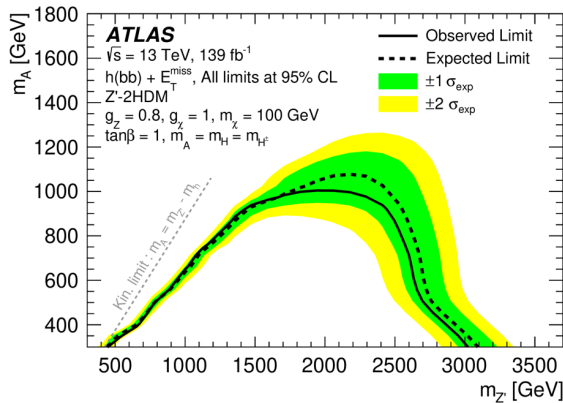
- Upper limits on  $\sigma^{VBF} \times \mathcal{B}_{\gamma\gamma_D}$  for a VBF-produced Higgs with different mass hypotheses in the narrow width approximation.

# Mono-H

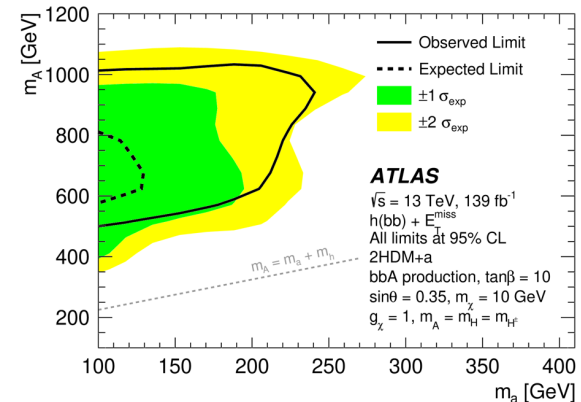
*JHEP 11 (2021) 209*



- Signature: events with  $E_T^{miss}$  and  $b$ -tagged jets consistent with a Higgs boson decay;
- A profile likelihood function is used to fit the event categorization bins and extract upper limits at 95% confidence level;
- No significant deviation from SM expectations is observed;
- Result interpreted in  $Z'$ +2HDM model and 2HDM+a model.



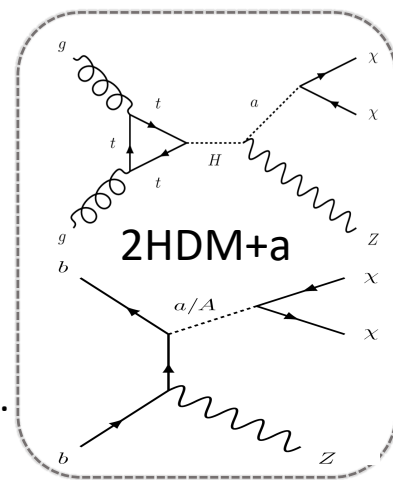
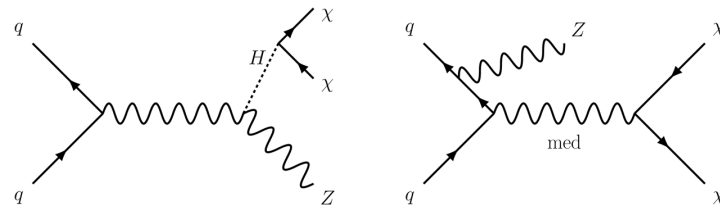
- Excludes the  $Z'$  mass up to 3 TeV in the  $Z'$ -2HDM model;
- Excludes the pseudoscalar masses up to 520 GeV and 240 GeV for  $\tan\beta=1$  and  $\tan\beta=10$  respectively in the 2HDM+a model.



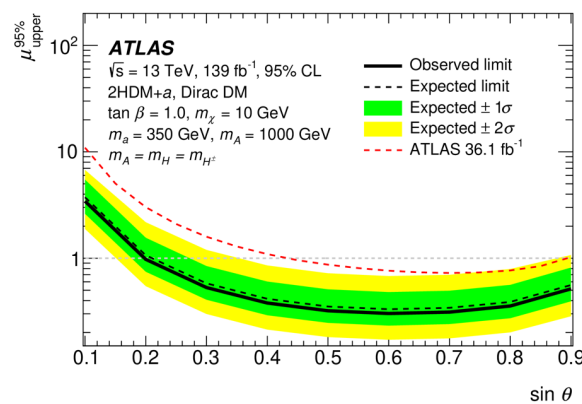
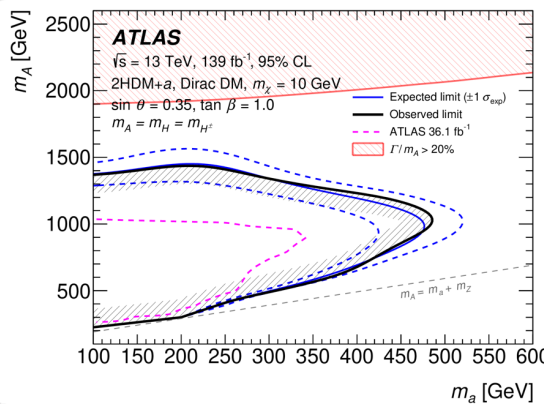
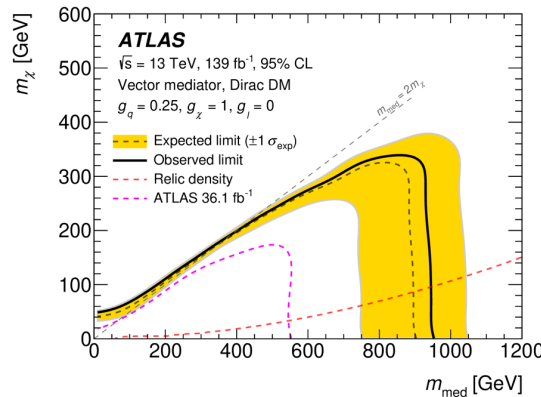
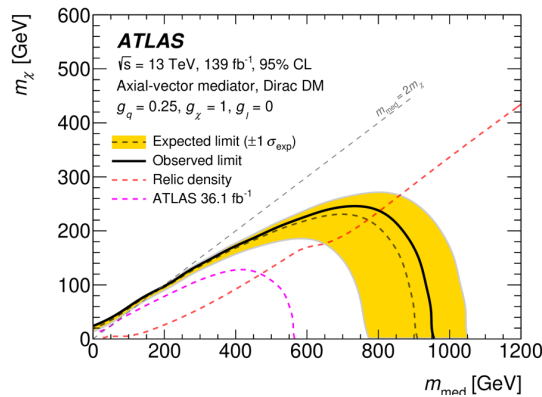
# Mono-Z

[Phys. Lett. B 829 \(2022\) 137066](#)

- Target signature: two oppositely charged electrons or muons consistent with originating from a Z boson decay, recoiling against a significant  $E_T^{miss}$ ;
- Sensitive to Higgs invisible decay, simplified DM models, and 2HDM+a models.
- Observed upper limit of 19% at 95% CL on  $\mathcal{B}(H \rightarrow inv)$ .
- Combination of mono-Z and mono-H : [ATLAS-CONF-2021-036](#)



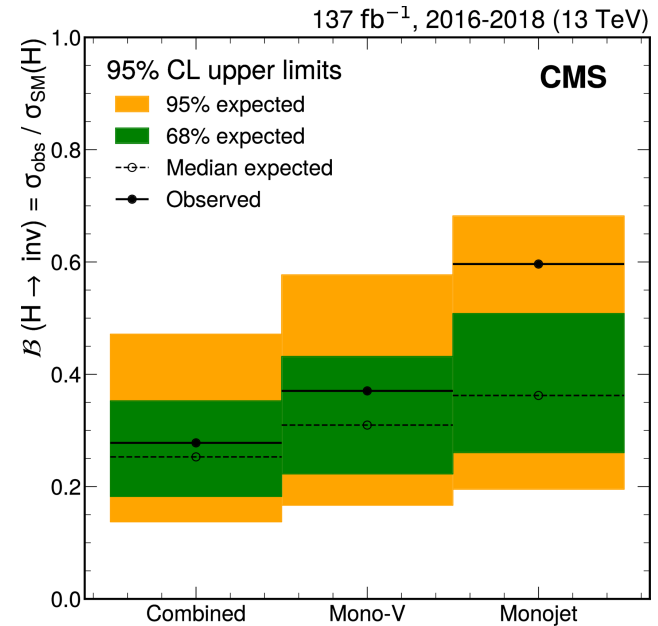
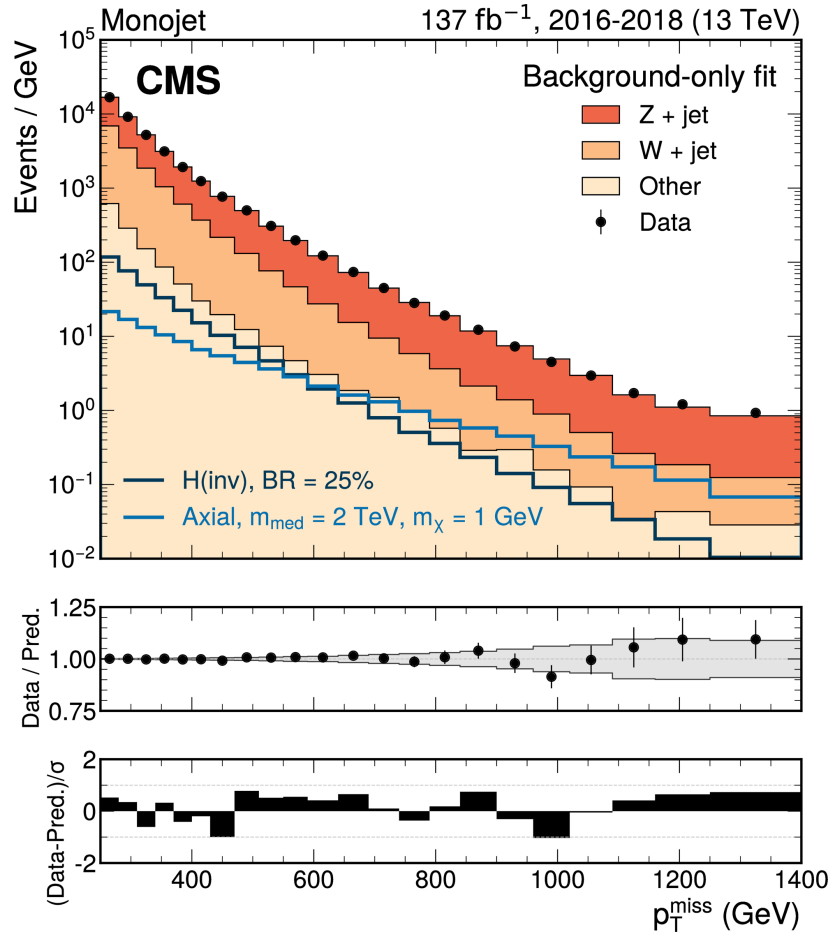
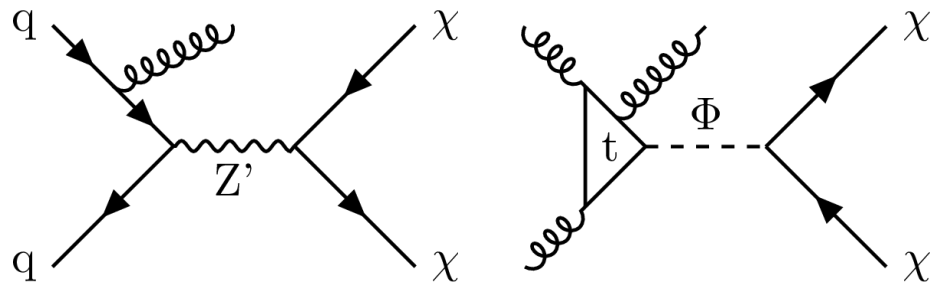
Exclusion limits for  $m_\chi$  and  $m_{med}$  in simplified DM models assuming an axial-vector mediator (left) or a vector mediator vector (right)



Exclusion limits for several model parameters with others chosen at fixed values in 2HDM+a model

# $E_T^{miss} + \text{Jet}$

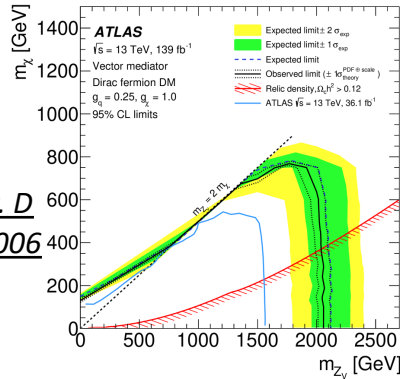
[JHEP 11 \(2021\) 153](#)



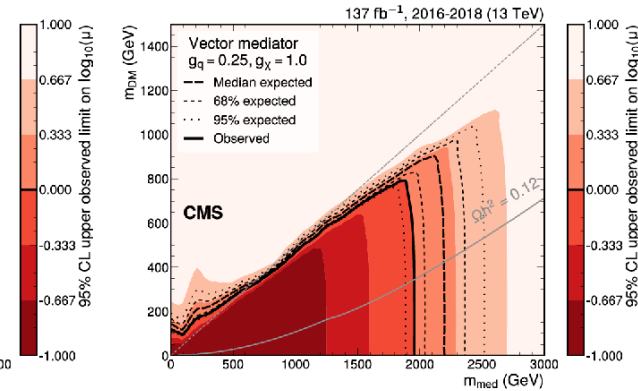
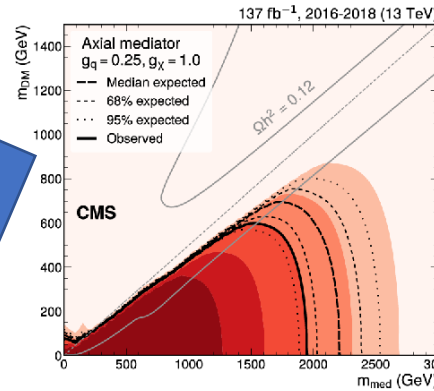
- Search for events with energetic jets and large  $E_T^{miss}$ .
- Monojet and mono-V(had) combined using full CMS Run2 data
- Upper limit at 95% CL on  $\mathcal{B}(H \rightarrow inv)$  is 27.8% (comparable with 34% from ATLAS similar search: [Phys. Rev. D 103, 112006](#))

# $E_T^{miss} + \text{Jet}$

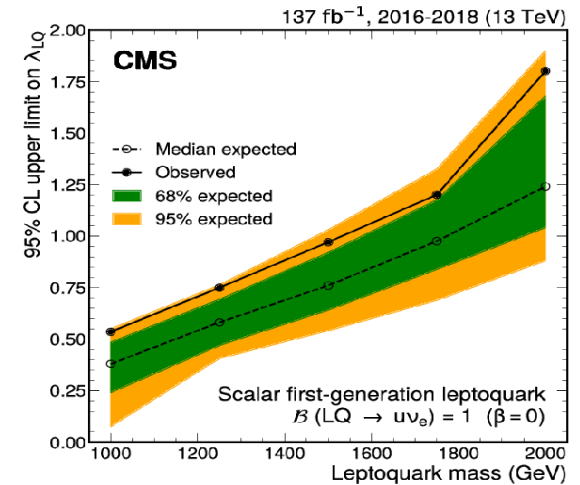
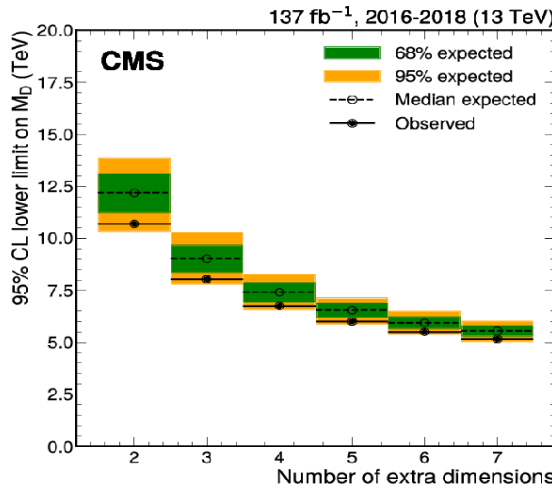
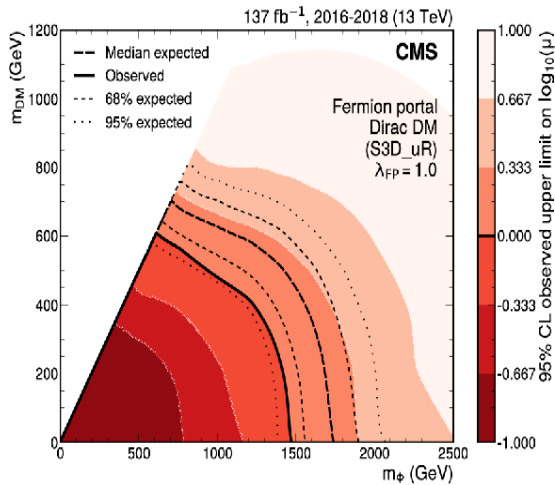
JHEP 11 (2021) 153



comparison  
 ATLAS:CMS



- Exclusion on mass of s-channel spin-1 mediator in simplified model
  - up to 1.95 TeV from CMS search;
  - up to 2.05 TeV from ATLAS search.
- Comparable results from the two experiments.



- Exclusion on mass of t-channel mediator in simplified model up to 1.5 TeV

- Stringent exclusion limits on dark matter mass in extra dimension model for different Dim. values.

- Upper limits at 95% CL on  $\lambda_{LQ}$  as a function of leptoquark mass in leptoquark model.

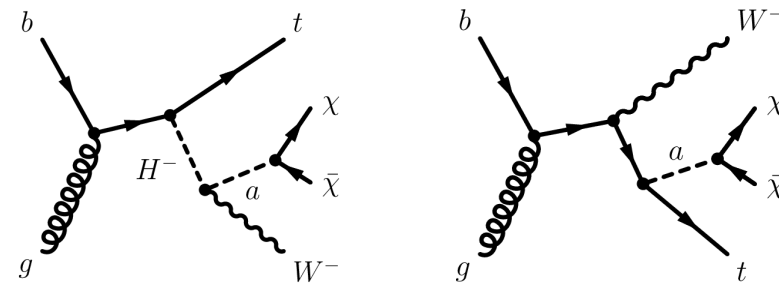
5/25/22

Long Wang (UMD)

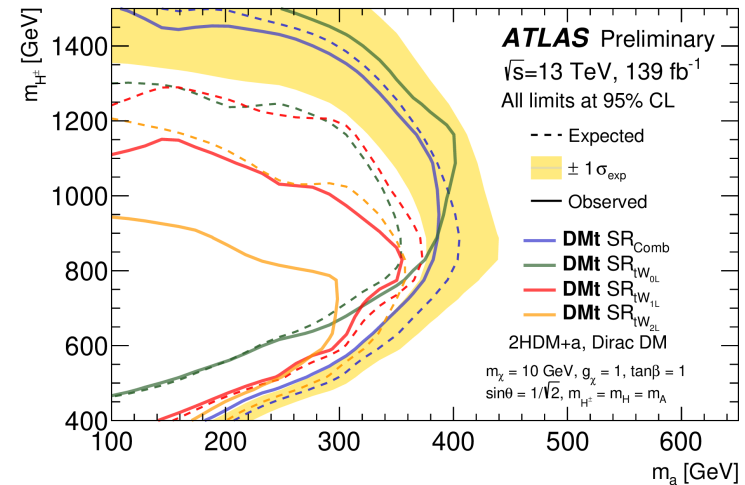
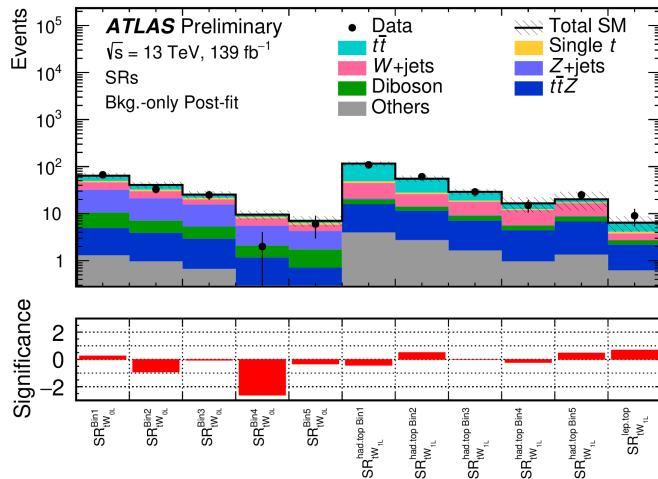


# tW + DM

[ATLAS-CONF-2022-012](#)



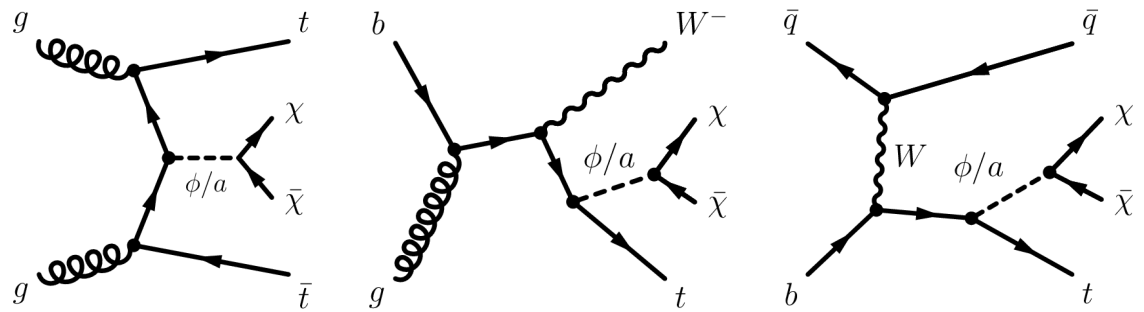
- Search for dark matter produced in association with a single top quark and an energetic W boson
  - Targets final states with zero or one charged lepton, at least one b-jet and large  $E_T^{miss}$
  - Combined with two charged lepton final states from tW + DM production
- Theoretical scenario: 2HDM+a
- The search is particularly sensitive to on-shell production of the charged Higgs boson state,  $H^\pm$



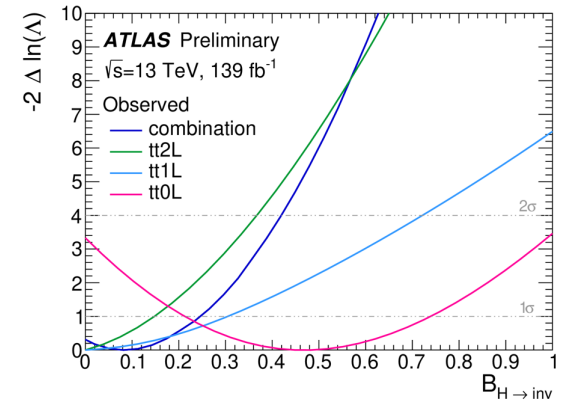
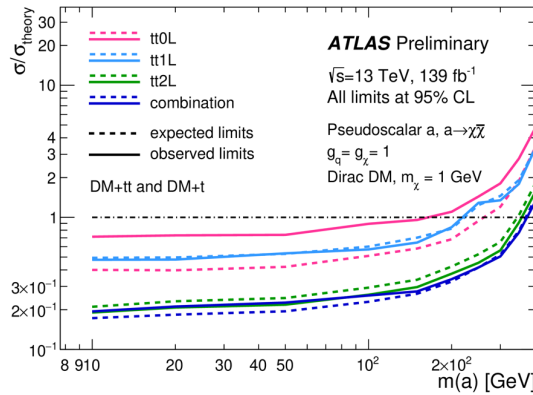
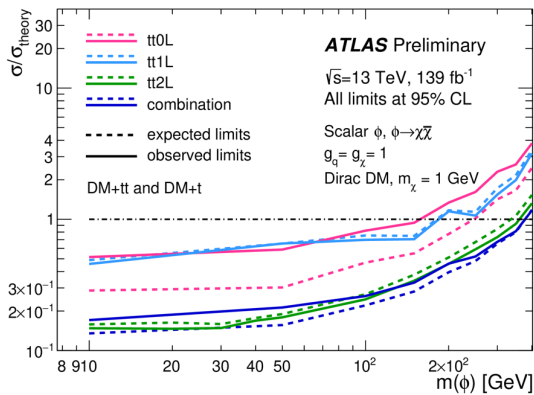
- Comparison of fit of the background-only template, extrapolated to all SRs, with the observed data.
- Excludes  $H^\pm$  mass up to 1.5 TeV and mediator mass up to 350 GeV assuming  $\tan\beta=1$ .

# $t\bar{t} + \text{DM}$

[ATLAS-CONF-2022-007](#)

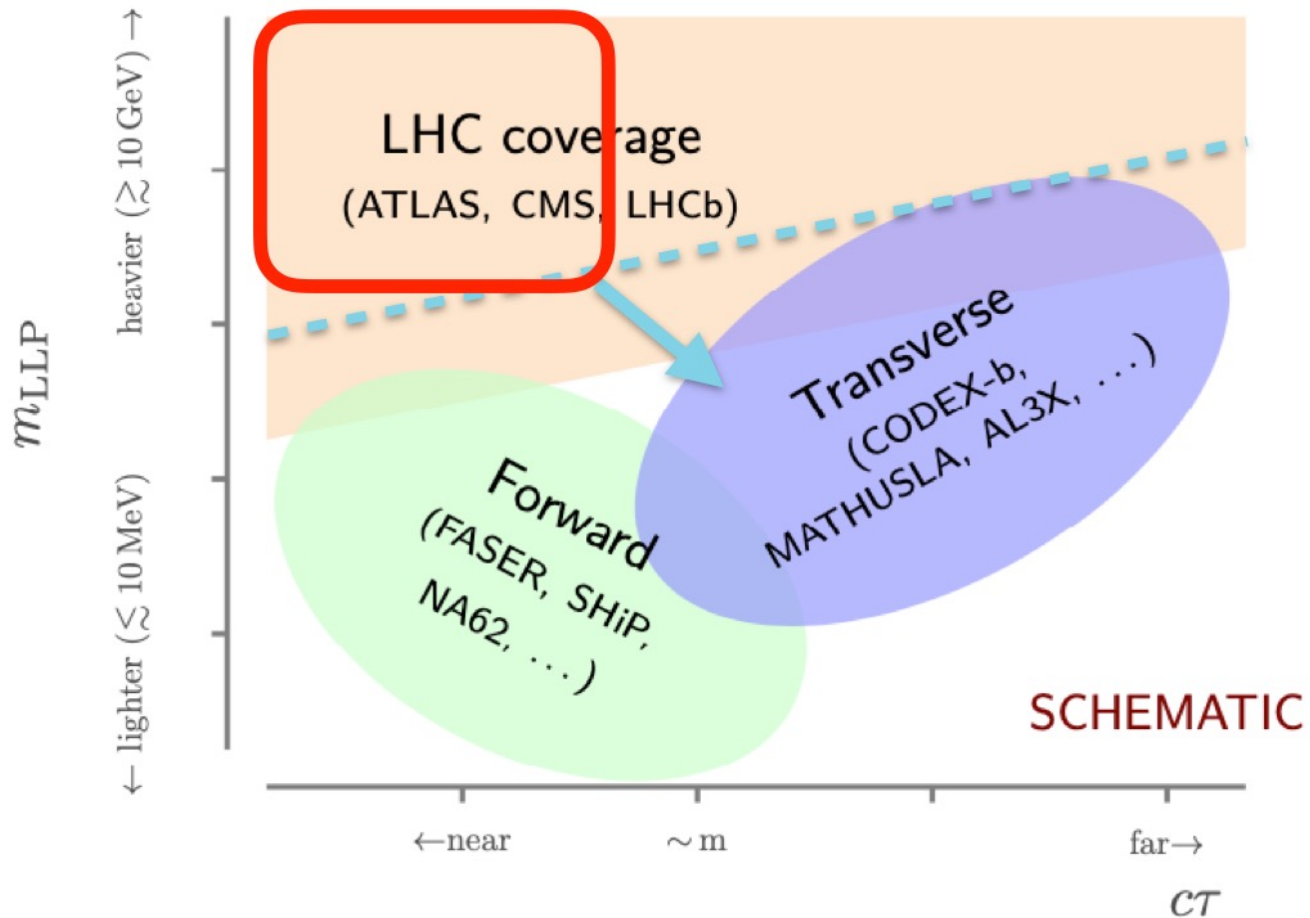


- Targets final states with two top quarks and invisible particles;
- Statistical combination in 0-lepton low  $E_T^{miss}$ , 0-lepton high  $E_T^{miss}$ , 1-lepton, 2-lepton categories;
  - Associated production of DM with single top quarks also included in combination.
- Upper limits presented in two ways: on the mass of a scalar in a simplified DM model and as upper limits on  $\mathcal{B}(H \rightarrow inv)$ .



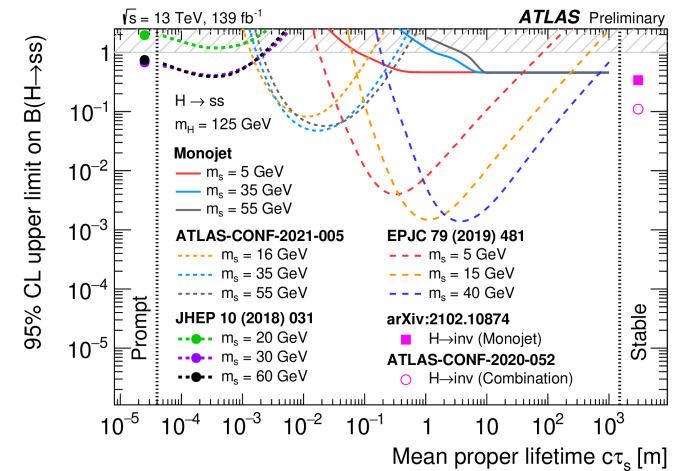
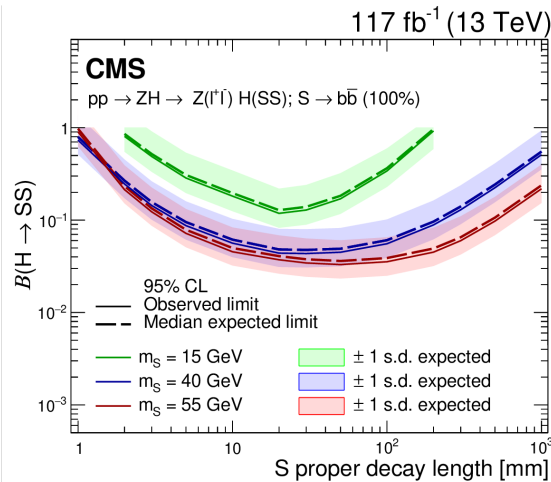
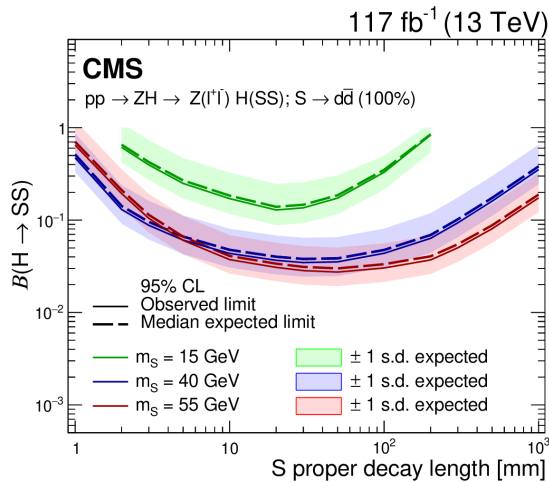
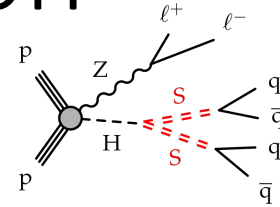
- Excludes scalar (pseudoscalar) mediator masses up to 370 GeV in the simplified model;
- Observed upper limit of 0.40 at 95% CL on  $\mathcal{B}(H \rightarrow inv)$ .

# DS from Long-lived particle (LLP) searches



# LLP in association with a Z boson

CMS: [JHEP 03 \(2022\) 160](#); ATLAS: [JHEP 11 \(2021\) 229](#)

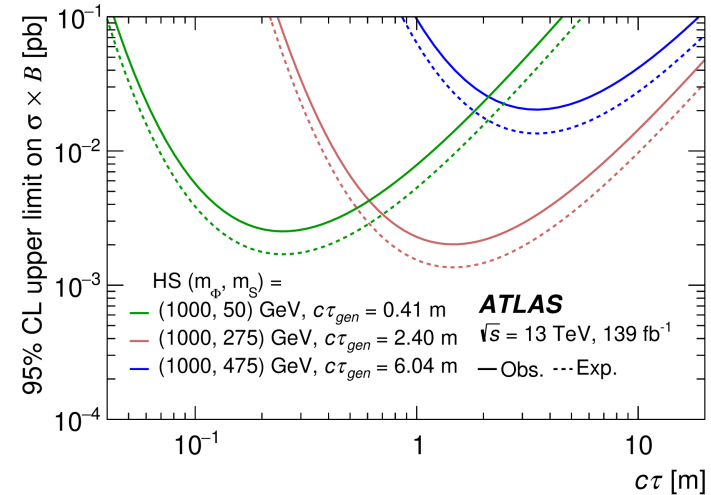
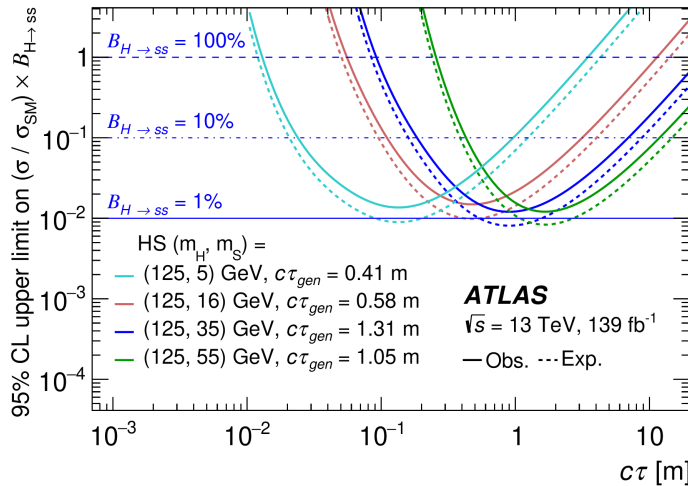
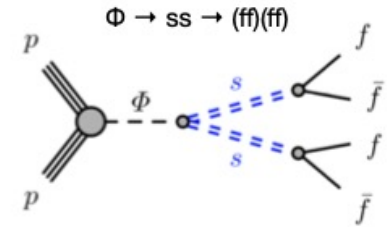


- Two comparable searches from CMS (left two plots) and ATLAS (right plot);
- LLPs decay into the tracker systems;
- Signature: Multiple displaced jets with a pair of leptons consistent with originating from a Z boson;
- Upper limits set on  $\mathcal{B}(H \rightarrow SS)$  as functions of LLP lifetime, for several selected S mass hypotheses;
- ATLAS result includes the comparison to the prompt decay search ([JHEP 10 \(2018\) 031](#)) and LLP interpretation of mono-Jet search ([ATL-PHYS-PUB-2021-020](#)).

# LLP search in ATLAS calorimeter

[arXiv:2203.01009](https://arxiv.org/abs/2203.01009)

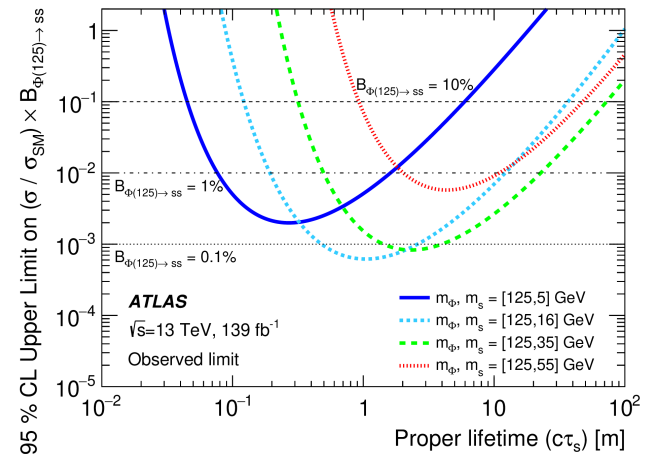
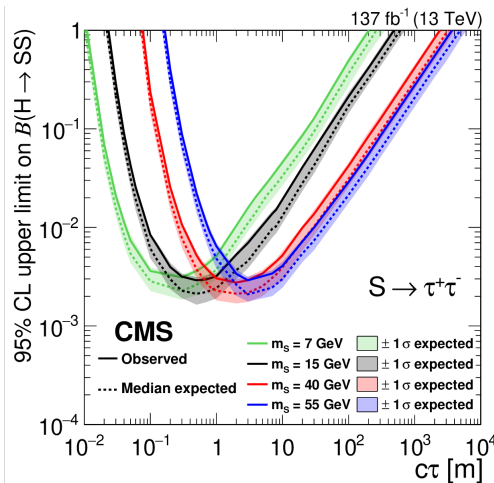
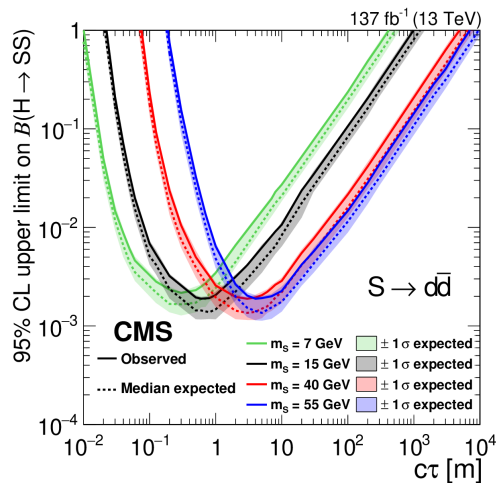
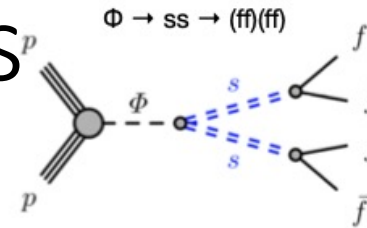
- Search for pair-produced LLPs decaying hadronically in the ATLAS calorimeter
- A neural network is trained on a per-jet basis to discriminate displaced signal jets from non-displaced jets and beam-induced background jets
- Dominant background is estimated from a data-driven ABDC method.



- Upper limits set on the BR of a SM Higgs boson mediator decaying to two LLPs (left) and a scalar mediator decaying to two LLPs (left) from the hidden sector (HS) models (right).

# LLP search in Muon Detectors

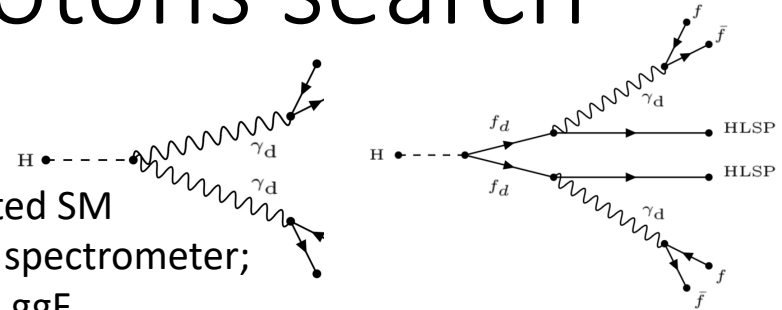
CMS: [Phy. Rev. Lett. 127 \(2021\) 261804](#); ATLAS: [arXiv:2203.00587](#)



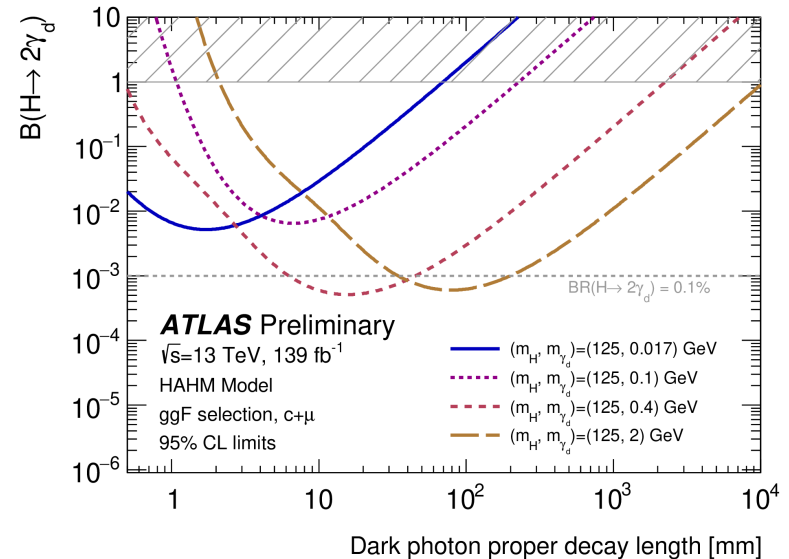
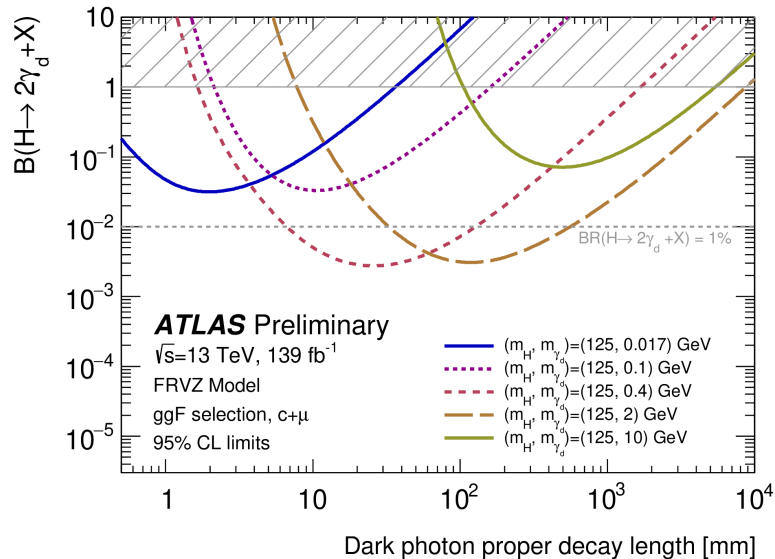
- Two searches from CMS (left two plots) and ATLAS (right plot);
- LLPs decay into the muon systems;
  - Large geometric acceptance;
  - Sensitive to large lifetime ;
- Signature:
  - CMS: large cluster of hits in muon system whilst without tracks nor jets.
  - ATLAS: two displaced vertices from LLP pairs decaying into jets in the muon spectrometer
- Upper limits set on  $\mathcal{B}(H \rightarrow SS)$  as functions of S lifetime in two S decay modes, for several selected S mass hypotheses.

# Long-lived dark photons search

[ATLAS-CONF-2022-001](#)



- Probes final states containing displaced collimated SM fermions reconstructed in calorimeter or muon spectrometer;
- Two mutually exclusive search categories: Higgs ggF production mode and WH associated production mode;
- Two models: [FRVZ model](#) and [Hidden Abelian Higgs Model](#)

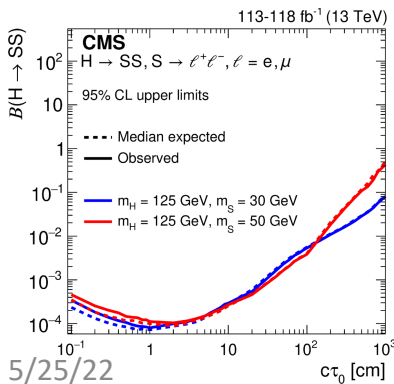
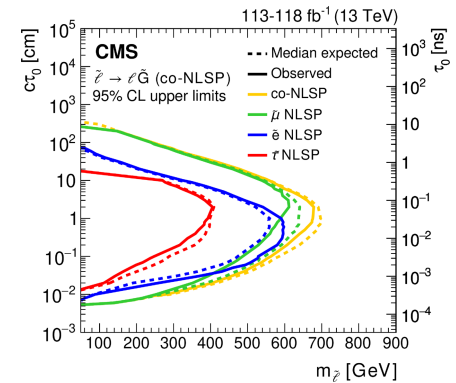
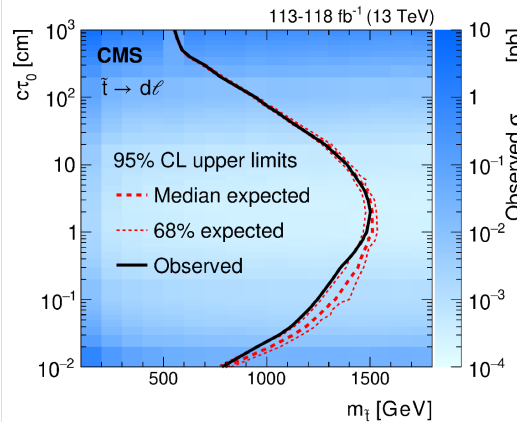
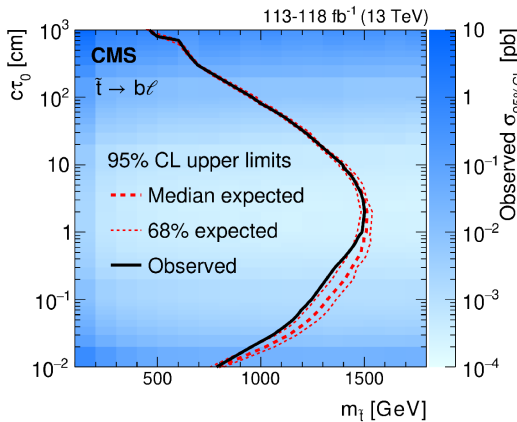
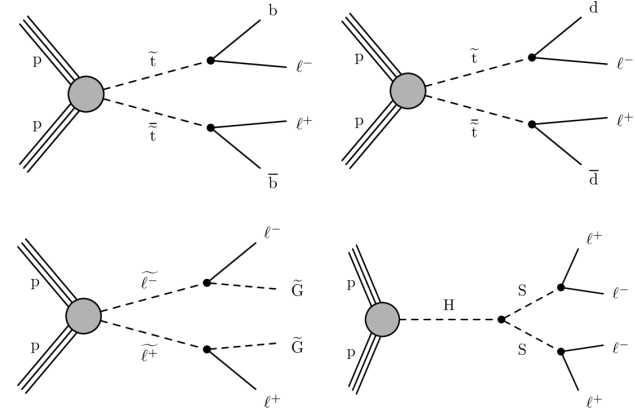


- Observed exclusion limits set for different dark photon masses at 95% CL on  $\mathcal{B}(H \rightarrow 2\gamma_d + X)$  for FRVZ model (left) and HAHM model (right), assuming a SM Higgs boson.

# LLP decaying to leptons

[EPJC 82 \(2022\) 153](#)

- Signature: LLPs decay into two displaced leptons with large transverse impact parameter;
- The search is designed to be sensitive to a wide range of models with displaced di-muon final states.
- Result is used to constrain stop, slepton, and  $\mathcal{B}(H \rightarrow SS)$



- Excludes stop quark mass up to 1500 GeV at 95% CL;
- Excludes slepton mass up to 700 GeV at 95% CL;
- Upper limits set on  $\mathcal{B}(H \rightarrow SS)$  as functions of S lifetime, for several selected S mass hypotheses.

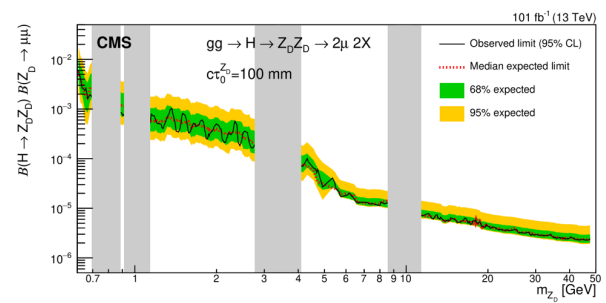
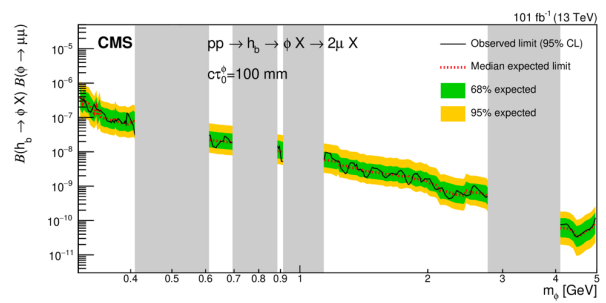
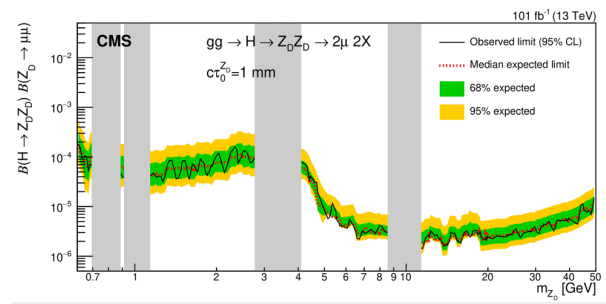
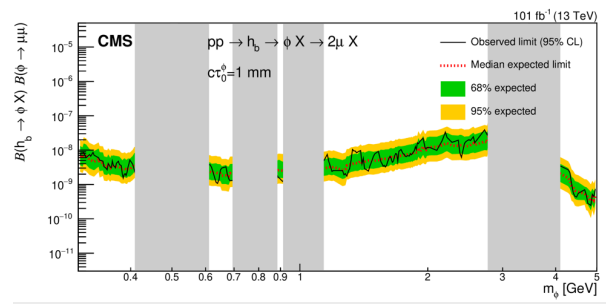
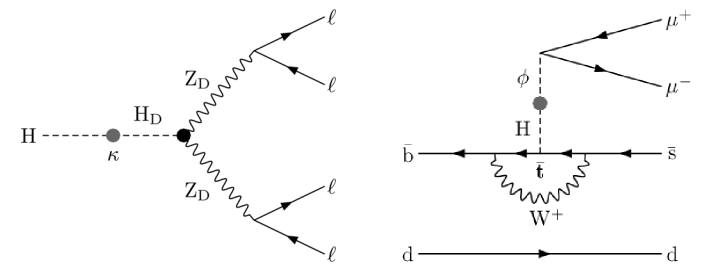
[\*] Similar search from the ATLAS collaboration can be found at [Phys. Rev. Lett. 127, 051802](#)



# LLP decaying to low mass dimuon resonance

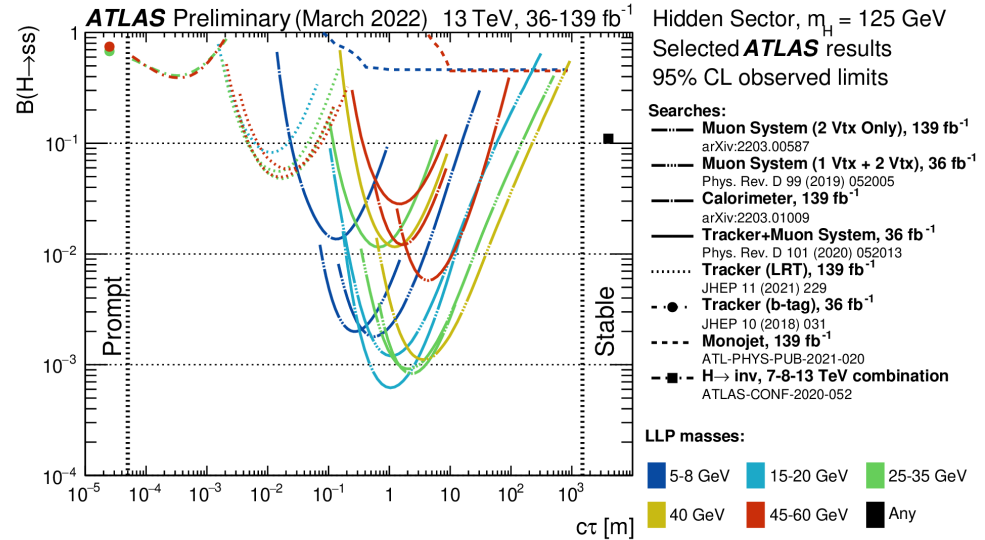
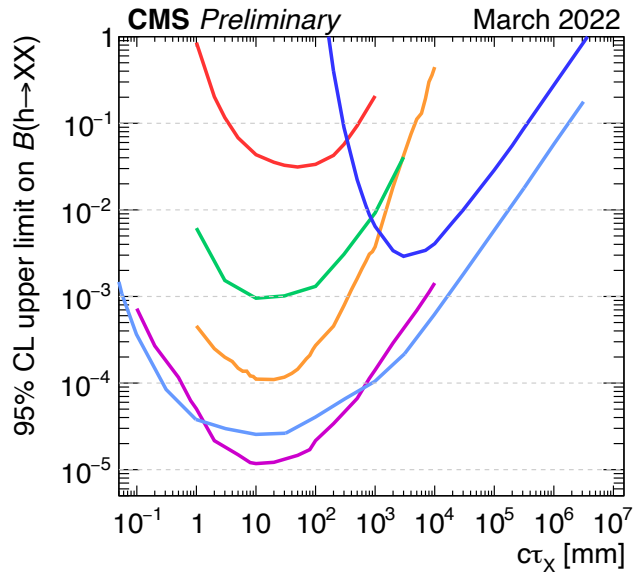
[JHEP 04 \(2022\) 062](#)

- Signature: at least 2 displaced muons and an associated displaced vertex.
- Novel exploration phase space at low dimuon mass



- Search result interpreted as production branching ratio upper limit constraints on dark sector mediators  $Z_D$  and  $\phi$  from two models as functions of their masses for two different lifetime hypotheses.

# LLP summary for HS models



- Exclusion limit on  $\mathcal{B}(H \rightarrow XX)$  from previous analyses for ATLAS (right) and CMS (left).
  - Note: There are differences on the LLP decay  $\mathcal{B}r$  assumption

- More CMS summary on LLP DS searches:

[https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Higgs\\_decays\\_to\\_long\\_lived\\_parti](https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Higgs_decays_to_long_lived_parti)

- More ATLAS summary on LLP DS searches:

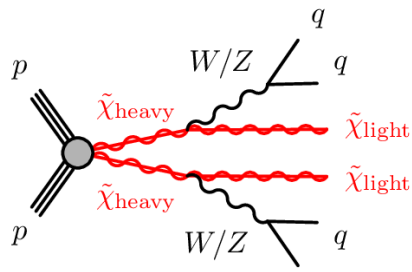
<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-007/>

# DS Probes from SUSY

- ATLAS SUSY public results:  
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults>
- CMS SUSY public results:
  - Publications: <http://cms-results.web.cern.ch/cms-results/public-results/publications/SUS/index.html>
  - Preliminary results: <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html>

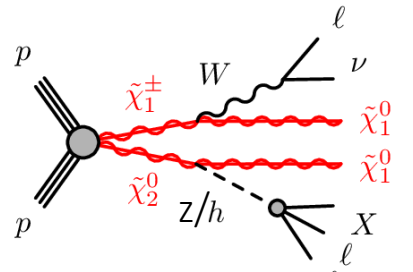
# Chargino-neutralino search in ATLAS

1



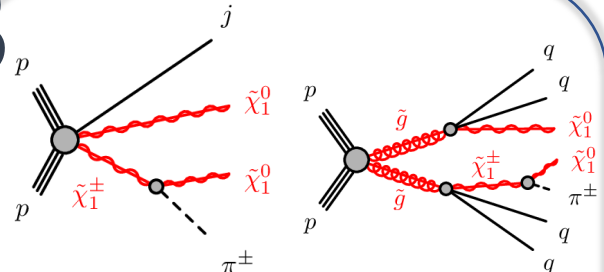
- [Phys. Rev. D 104 \(2021\) 112010](#);
- Search in final states with two boosted hadronically decaying bosons and  $E_T^{miss}$

2



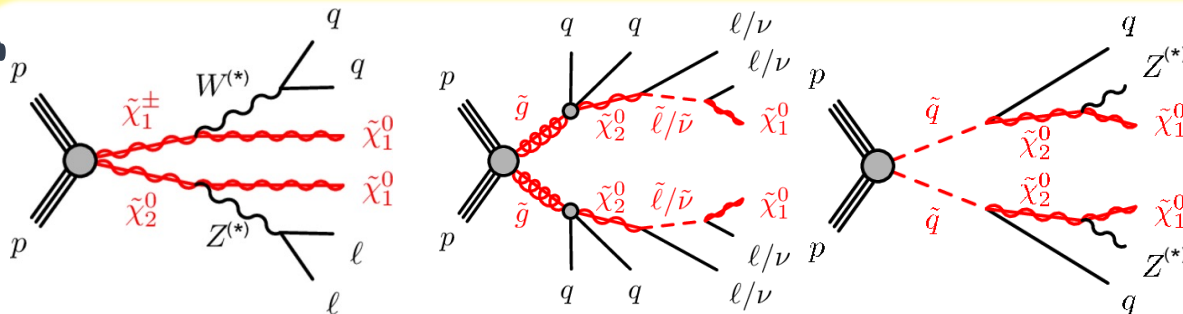
- [Eur. Phys. J. C 81 \(2021\) 1118](#);
- Search in final states with three leptons and  $E_T^{miss}$

3



- [EPJC arXiv:2201.02472](#);
- Search for long-lived charginos based on a disappearing-track signature

4

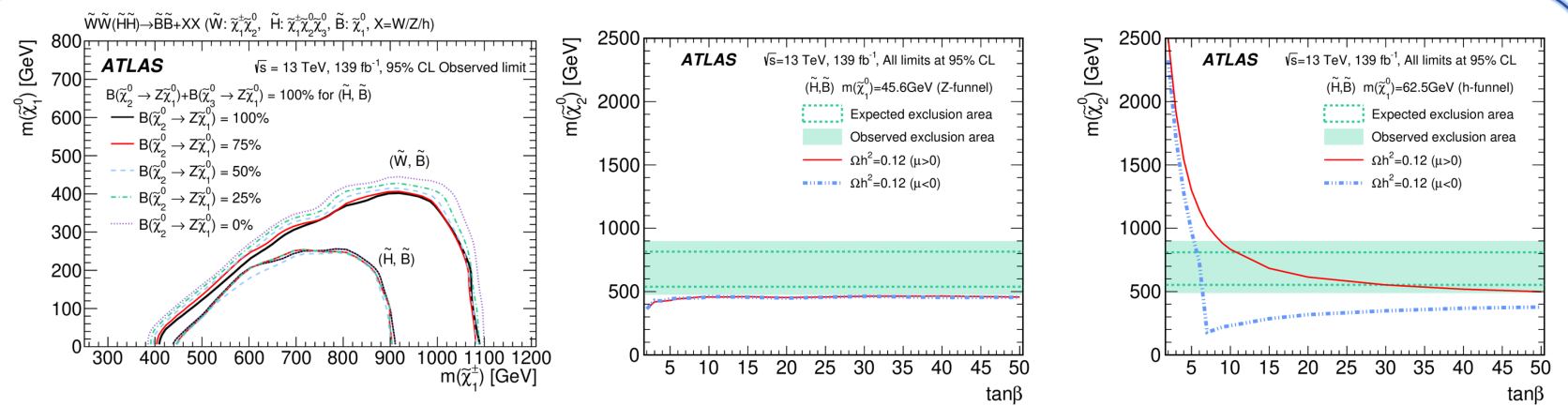


- [EPJC arXiv:2204.13072](#);
- Search in final states containing an  $e^+e^-$  or  $\mu^+\mu^-$  pair, jets, and  $E_T^{miss}$ ;
- squark search included

- Four new searches from ATLAS on chargino-neutralino in different final states;
- Results are shown in the following two slides;
- [R-Parity Converted lightest neutralino serves as a natural DM candidate.](#)

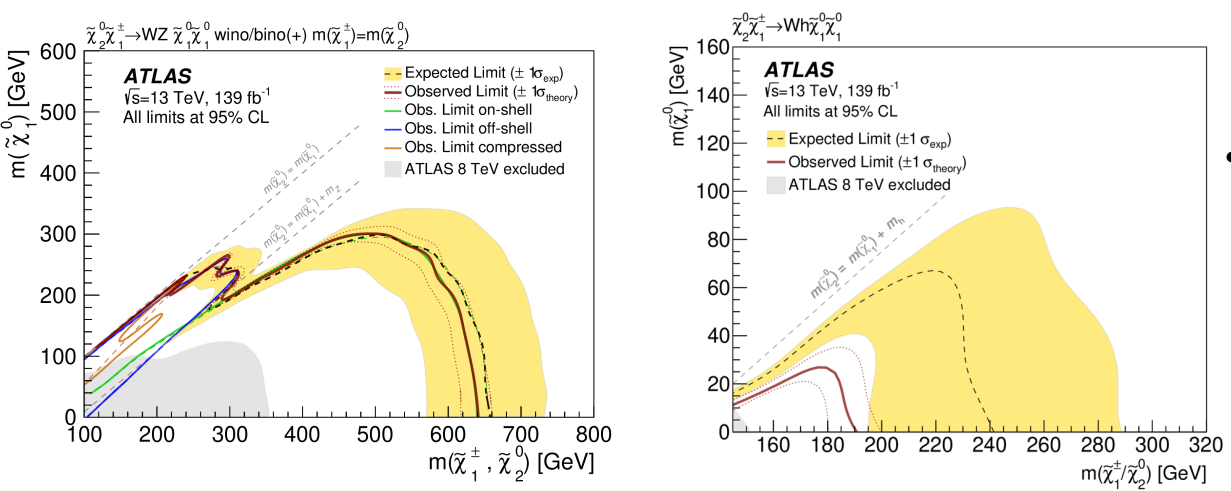
# Chargino-neutralino search in ATLAS

1



- Excludes wino (higgsino) mass up to 1060 (900) GeV.
- Exclusion limits on the Z/h-funnel dark matter model for bino-like LSP half of z/h mass.

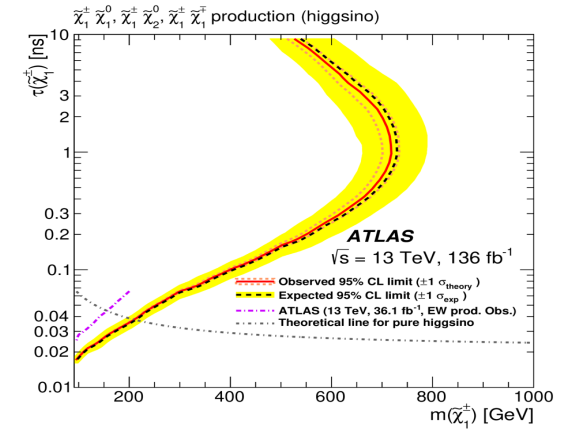
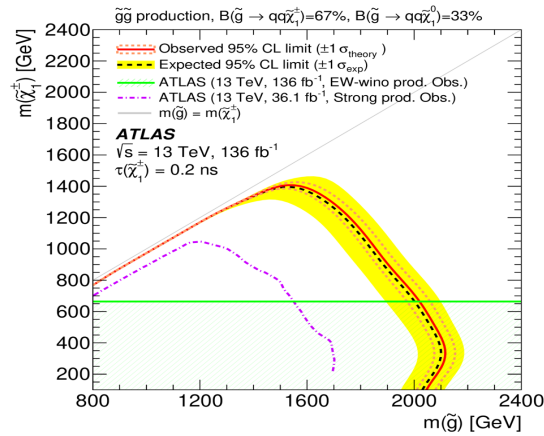
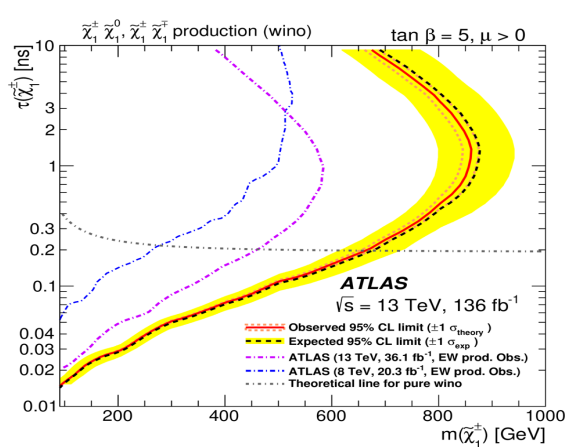
2



- Excludes  $\tilde{\chi}_2^0$  masses up to 210 (640) GeV for For Wh (WZ) mediated model;

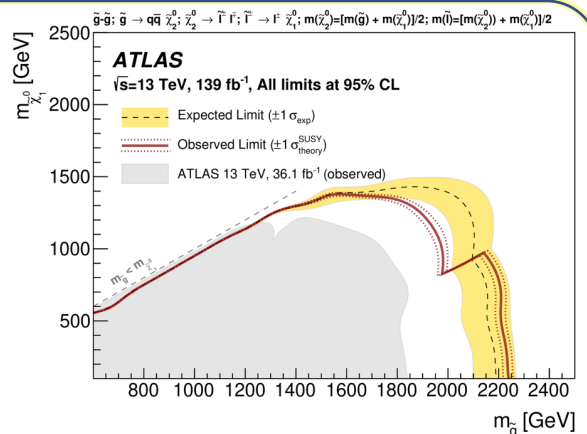
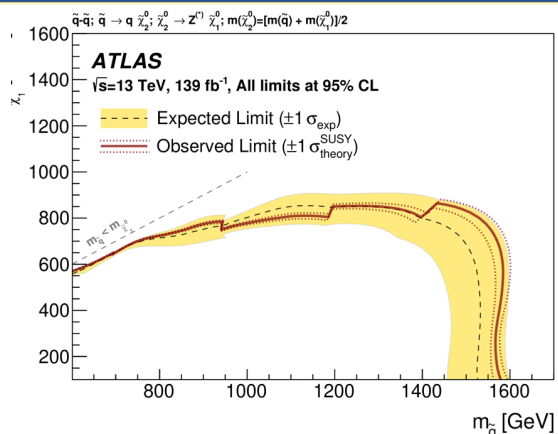
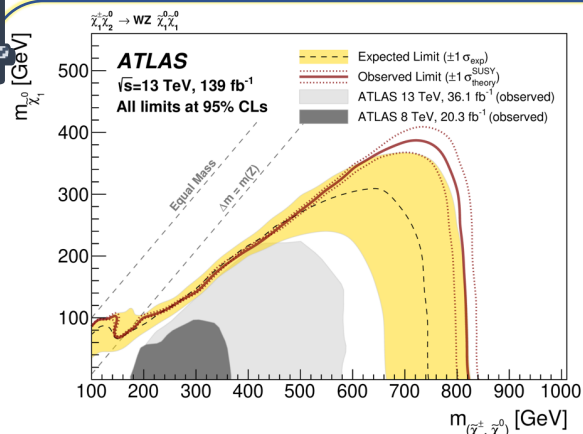
# Chargino-neutralino search in ATLAS

3



- Excludes wino (higgsino) masses up to 660 (210) GeV
- Excludes gluinos masses up to 2.1 TeV

4

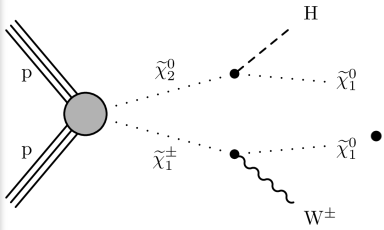


- Excludes masses up to 900 GeV for electroweakinos, 1550 GeV for squarks, and 2250 GeV for gluinos.

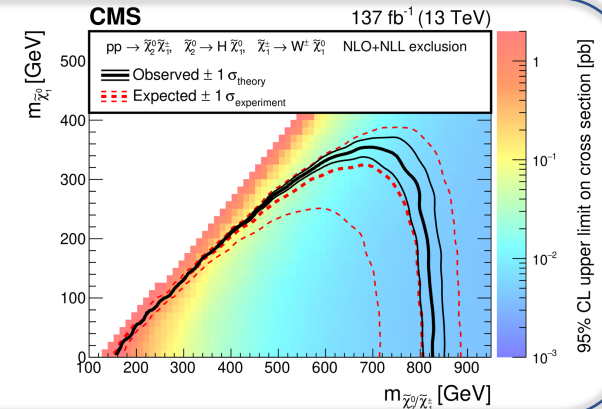
# Chargino-neutralino search in CMS

## Electroweak production

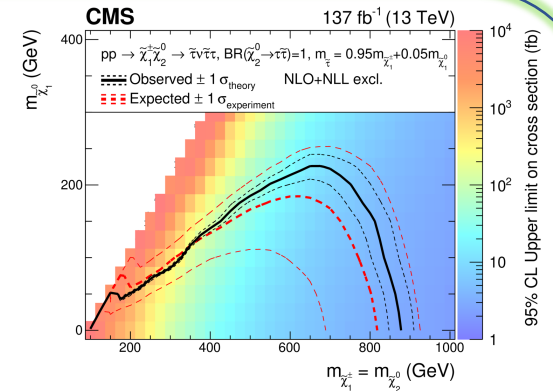
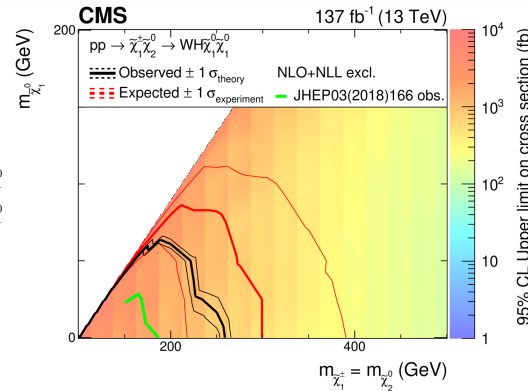
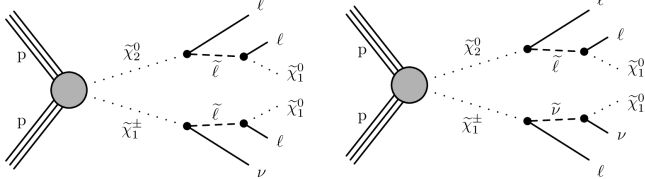
### 1-lepton



- JHEP 10 (2021) 045: CMS search in events with a Higgs and a W boson, with the W decaying semi-leptonically, and the Higgs boson decaying to a pair of bottom quarks
- Exclusion limits on charginos and neutralinos (LSP) masses up to 820 (350) GeV



### multi-lepton

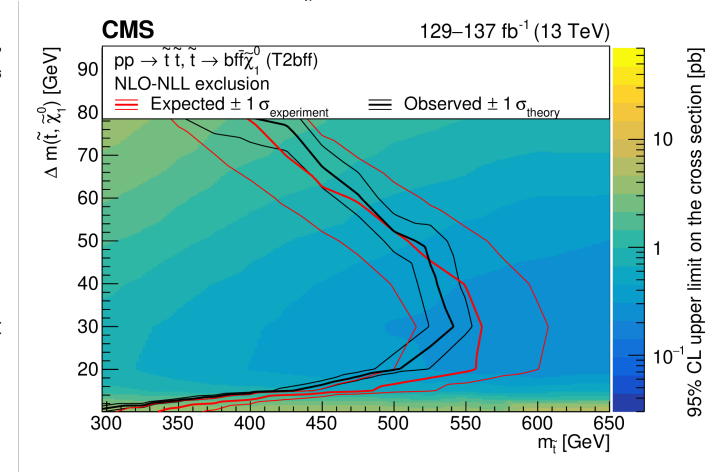
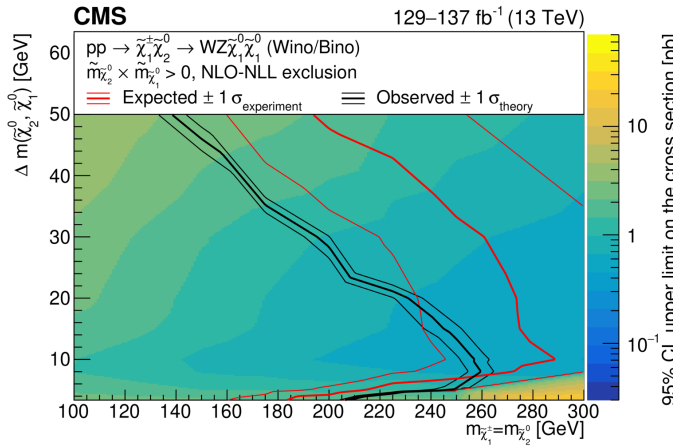
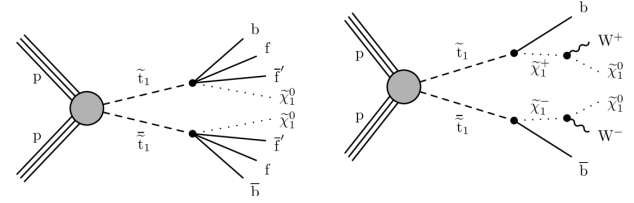
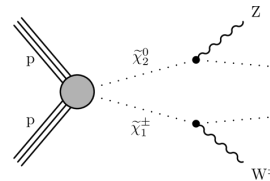


- JHEP 04 (2022) 147: CMS search in final states with three or four leptons, with up to two hadronically decaying  $\tau$  leptons, or two same-sign light leptons
- Exclusion limits are set separately for flavor-democratic slepton-mediated,  $\tau$ -enriched slepton-mediated,  $\tau$ -dominated slepton-mediated, WZ-mediated, WH-mediated and ZZ-mediated decays
- Exclusion range for charginos and neutralinos up to 1450 GeV

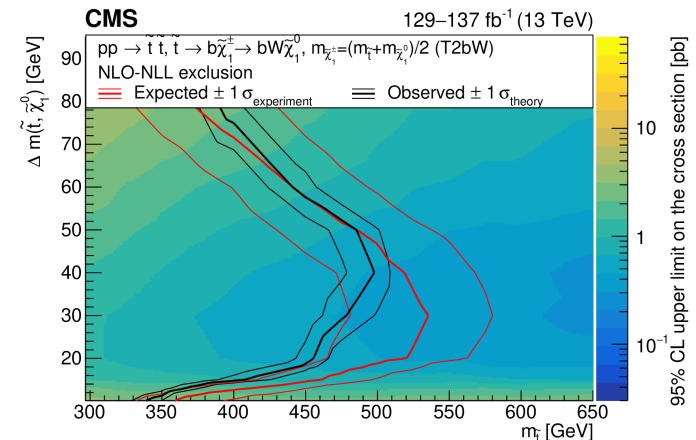
# Chargino-neutralino and stop search

[JHEP 04 \(2022\) 091](#)

## multi-soft-lepton



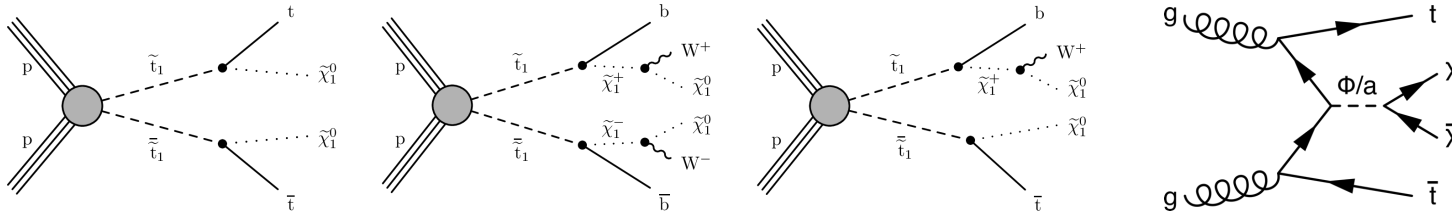
- Search in final states with 2 or 3 soft leptons and  $E_T^{miss}$ ;
- Result is also interpreted in terms of top squark pair production;
- Exclusion limits on chargino and neutralino masses up to 275 GeV for a mass difference of 10 GeV in the wino-bino model;
- Exclusion limits on top squark masses up to 480 GeV for chargino-mediated decays.



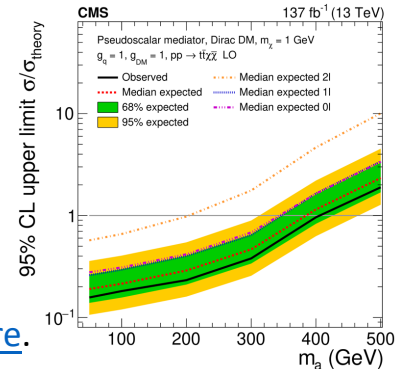
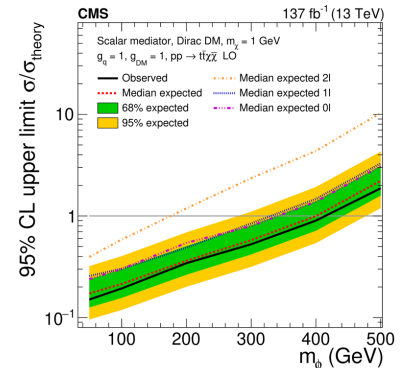
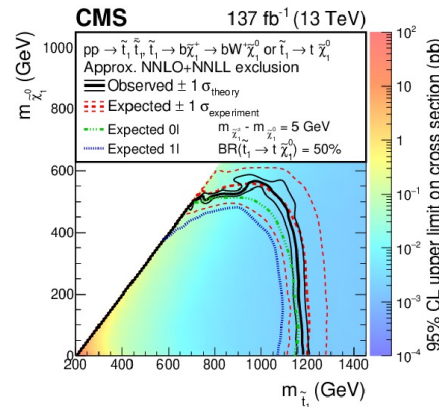
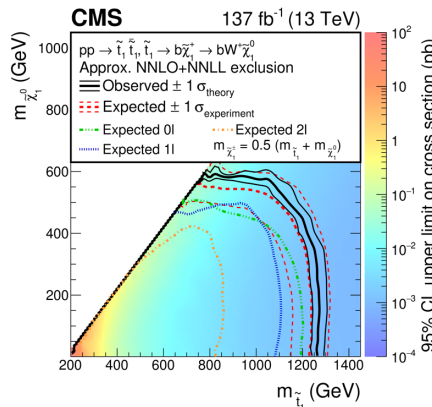
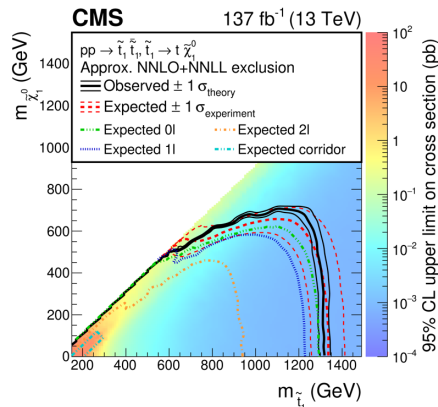


# DM from stop search

*Eur. Phys. J. C 81 (2021) 970*



- Combination of CMS top squark search with 0, 1, and 2 leptons in the final state
- Excludes neutralino mass up to 700 GeV;
- Also interpreted in a simplified  $tt$ +DM production model;
- Excludes the simplified model scalar (pseudoscalar) mediator mass up to 420 GeV.

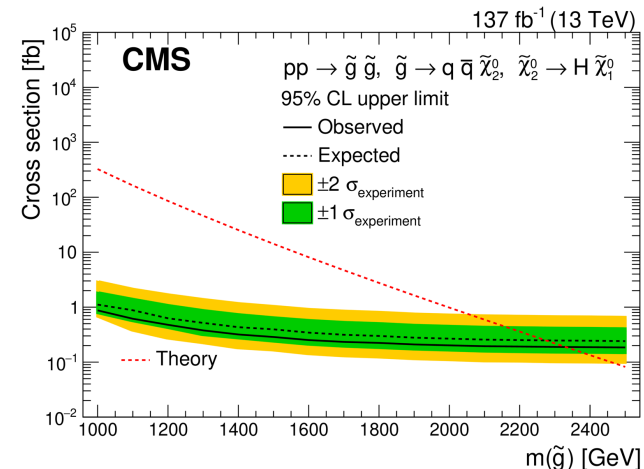
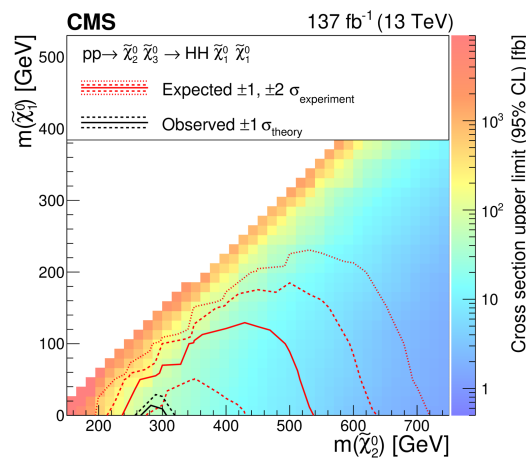
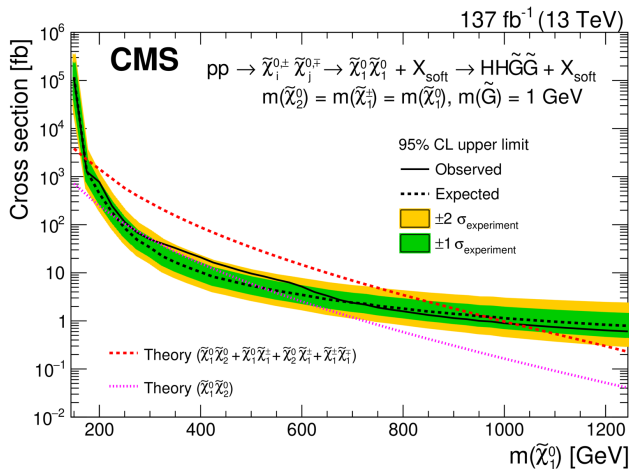
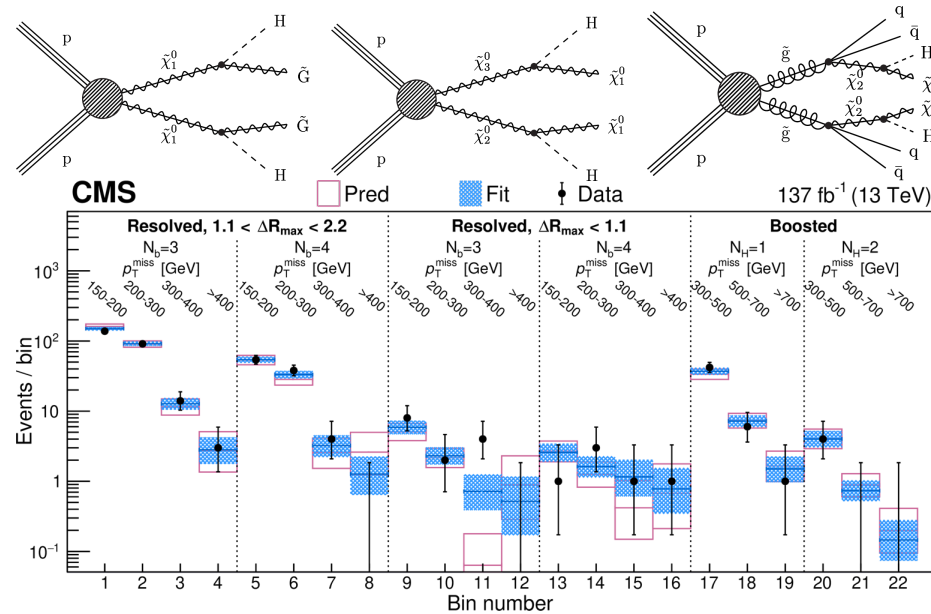


[\*] Similar search for stop in 2-lepton final state from ATLAS: [JHEP 04 \(2021\) 165](#) with result [here](#).

# DM from higgsinos search

*J. High Energy Phys;* [arXiv:2201.04206](https://arxiv.org/abs/2201.04206)

- Search in channels with two Higgs bosons, each decaying via  $H \rightarrow bb$  and large  $E_T^{miss}$
- Excludes neutralino mass from [175,1025] GeV for the electroweak production of nearly mass-degenerate higgsinos, each of whose decay chains yields a neutralino that in turn decays to a massless goldstino and a Higgs boson;
- No observed exclusion for neutral-neutral Higgsino model
- Excludes gluino mass up to 2330 GeV



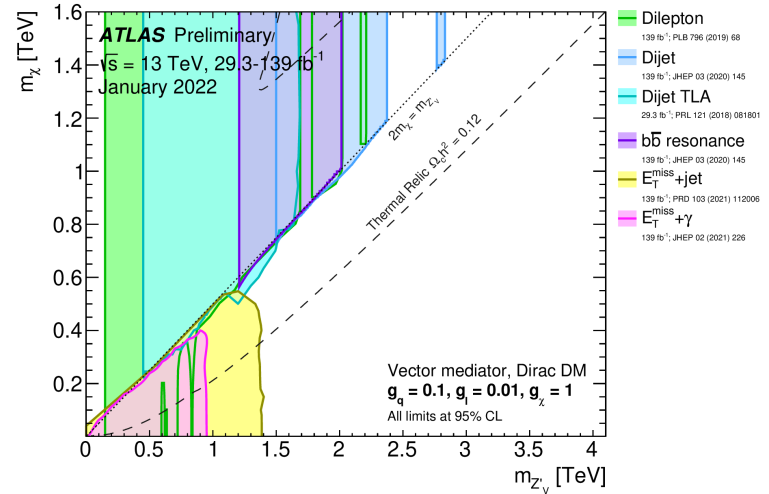
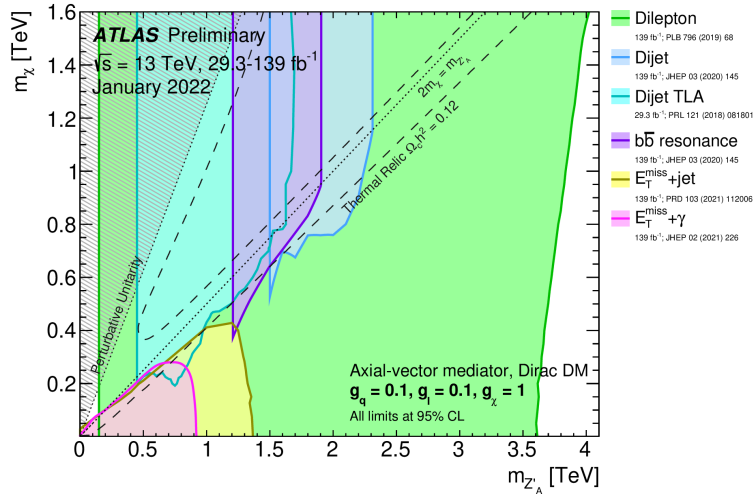
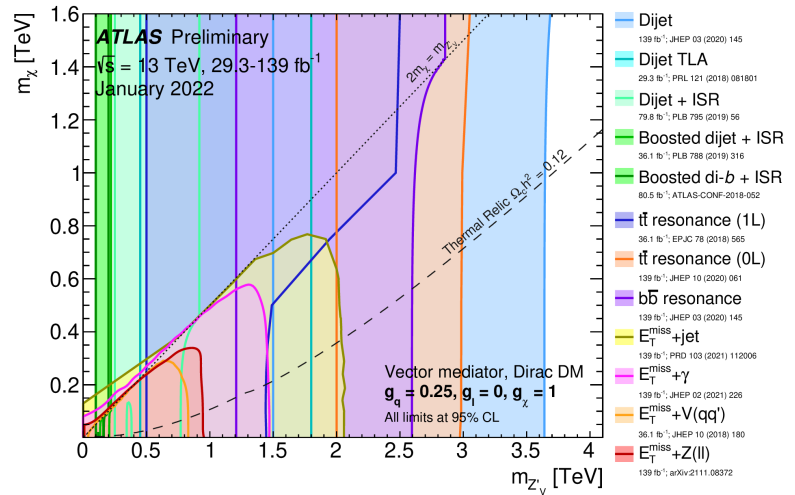
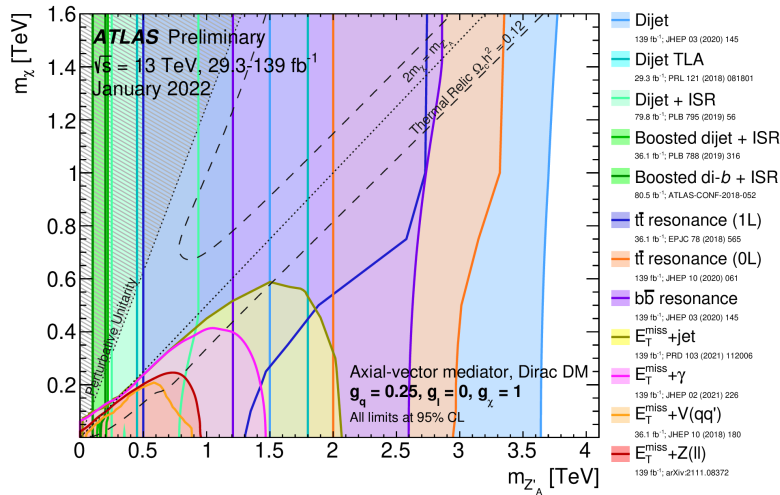
# Prospects and Summary

- ✓ No discrepancy is found between ATLAS/CMS data and expectations from standard model processes;
- ✓ A wide range of DM model parameters have been excluded;
- ✓ More DM analyses with full LHC Run2 data are coming out;
  
- ❖ Many experimental challenges for collider DM search;
  - ❖ Lots of rooms for triggers to be optimized to increase the selection efficiency of potential DM signal events across various kinematic phase space;
  - ❖ Potential DM signal events might be confused with detector malfunction not pass data certification;
  - ❖ Challenge in  $E_T^{miss}$  measurement to exclude pileup contribution and other background noise;
  - ❖ Rare and unusual signals buried in large backgrounds.
  
- Into the future:
  - More ideas from DM theory community to cover collider search blind spots;
  - Experiments upgrades from LS2 provide new capabilities for more valuable data;
    - better tracking -> better object identification, pileup removing
    - timing detectors -> improvement for LLP search
  - 150/fb data to be delivered in Run3; 3000/fb in total expected at HL-LHC;
  - Analysis techniques will be better revised for searches in Run3.

# Backup Slides

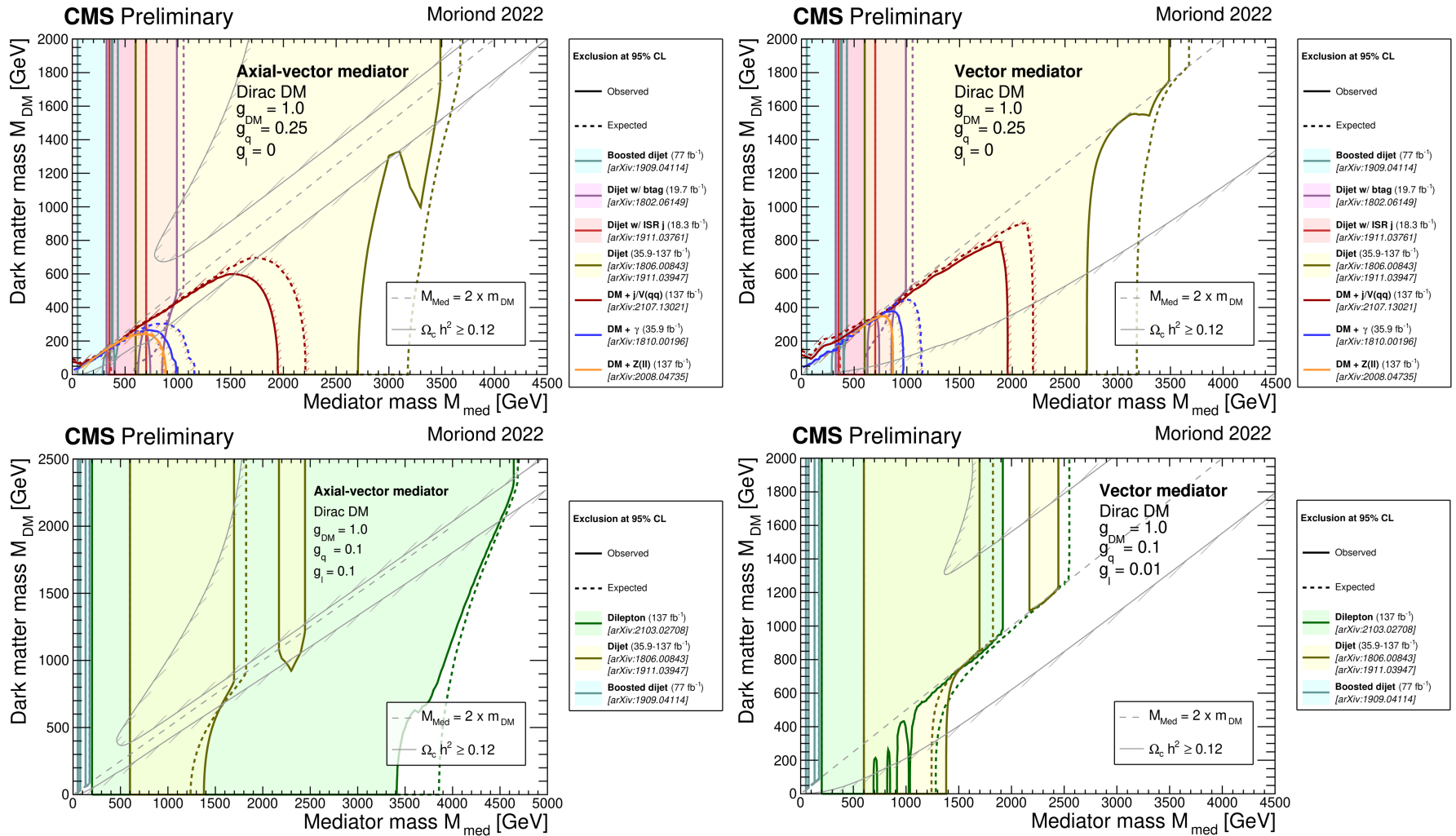
(More up-to-date summary plots and ATLAS/CMS DM search status)

# DM search summary from ATLAS Run2



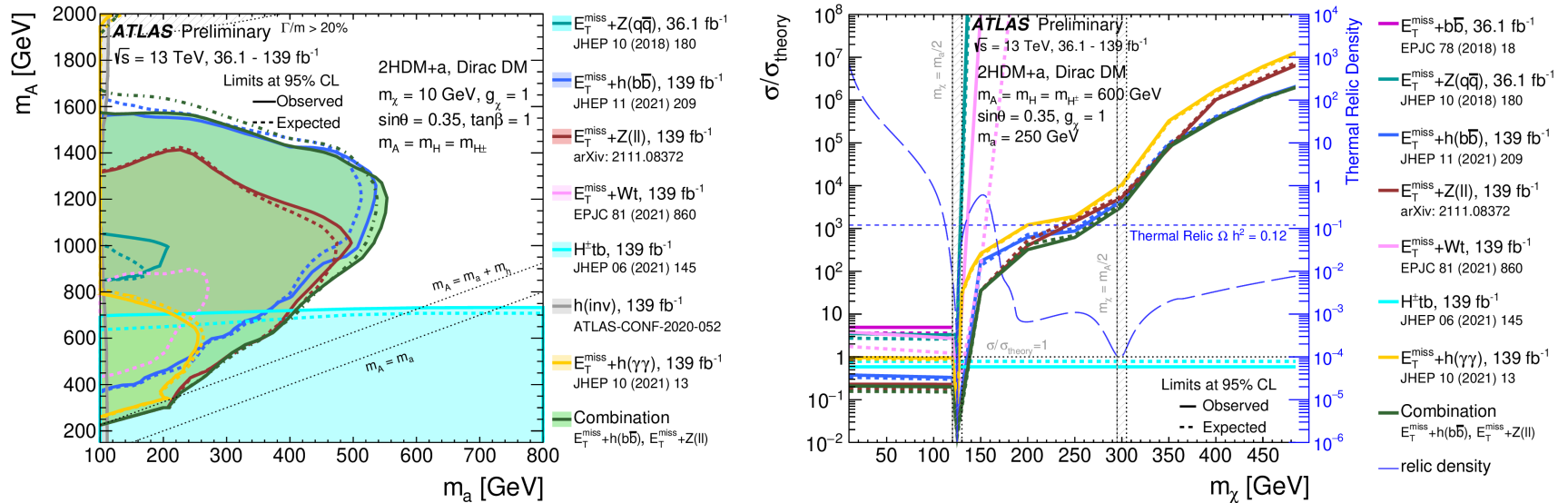
- Exclusion regions of  $m_{\text{Med}}$  and  $m_{\text{DM}}$  for simplified s-channel DM models in leptophobic and leptophilic mediator cases

# DM search summary from CMS Run2



- Exclusion regions of  $m_{Med}$  and  $m_{DM}$  for simplified s-channel DM models in leptophobic and leptophilic mediator cases

# DM 2HDM+a summary from ATLAS Run2



- Exclusion regions for  $m_a$  and  $m_A$  combined from public search channels
  - Most sensitive channels from mono-H and mono-Z
  - Results depend on missing angles ( $\sin\theta, \tan\beta$ )
- Excludes pseudoscalar mass up to  $\sim 550$  GeV;
- Excludes Higgs double mass up to  $\sim 1550$  GeV.

# ATLAS Run2 DM search status

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$

$\sqrt{s} = 8, 13 \text{ TeV}$

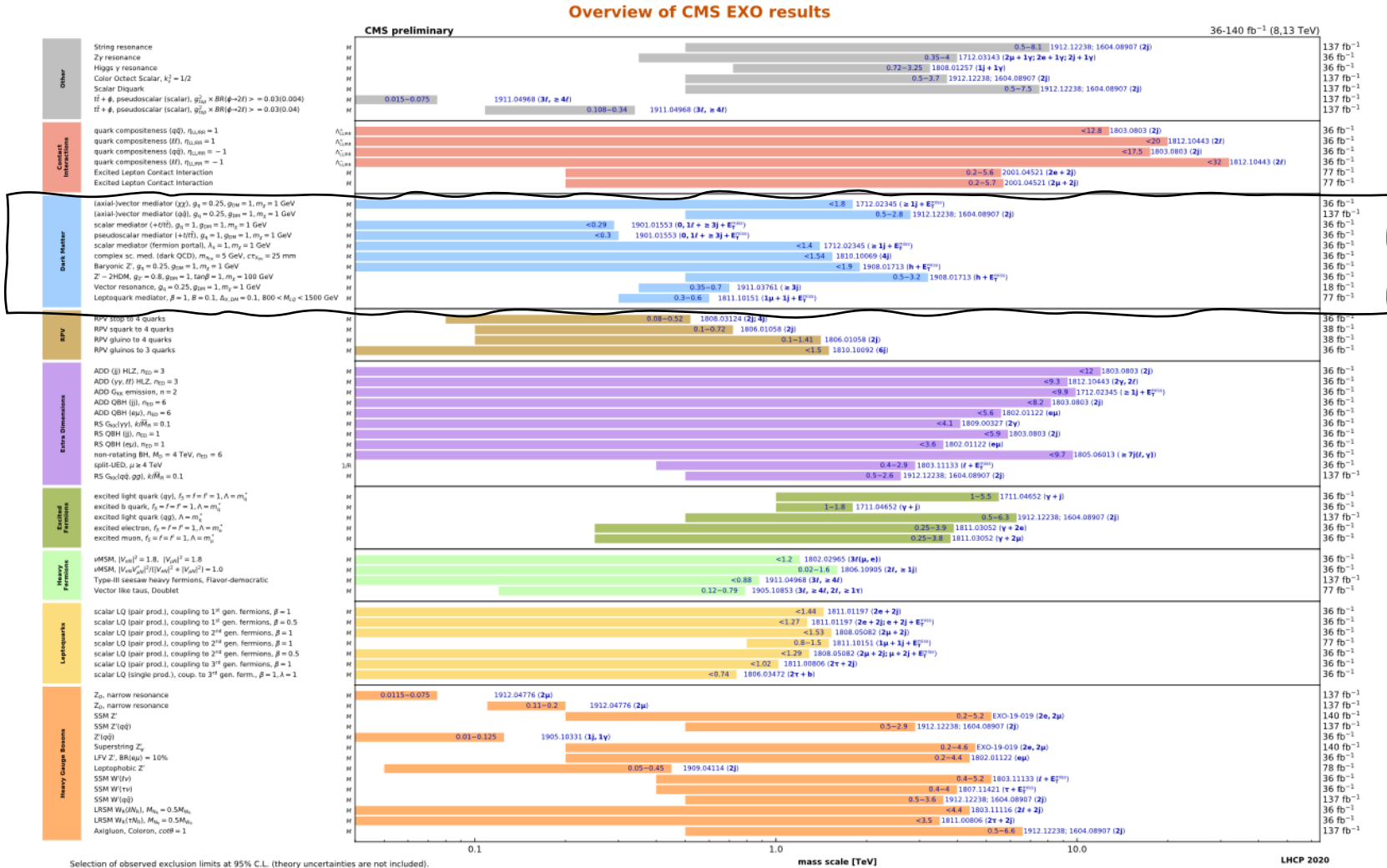
Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu$	$1 - 4 j$	Yes	36.1	$M_D$ 7.7 TeV	$n = 2$
	ADD non-resonant $\gamma\gamma$	$2 \gamma$	-	-	36.7	$M_S$ 8.6 TeV	$n = 3$ HLZ NLO
	ADD QBH	-	$2 j$	-	37.0	$M_{\text{th}}$ 8.9 TeV	$n = 6$
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	$M_{\text{th}}$ 8.2 TeV	$n = 6, M_D = 3 \text{ TeV}$ , rot BH
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{th}}$ 9.55 TeV	$n = 6, M_D = 3 \text{ TeV}$ , rot BH
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	36.7	$G_{KK}$ mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK}$ mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	$1 e, \mu$	$2 j / 1 J$	Yes	139	$G_{KK}$ mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$g_{KK}$ mass 3.8 TeV	$\Gamma/m = 15\%$
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	$Z'$ mass 5.1 TeV	
	SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	-	36.1	$Z'$ mass 2.42 TeV	
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	36.1	$Z'$ mass 2.1 TeV	
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$Z'$ mass 4.1 TeV	$\Gamma/m = 1.2\%$
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	-	139	$W'$ mass 6.0 TeV	
	SSM $W' \rightarrow \tau\nu$	$1 \tau$	-	-	36.1	$W'$ mass 3.7 TeV	
	HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	$W'$ mass 4.3 TeV	$g_V = 3$
	HVT $V' \rightarrow WV \rightarrow qq qq$ model B	$0 e, \mu$	$2 J$	-	139	$V'$ mass 3.8 TeV	$g_V = 3$
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	$V'$ mass 2.93 TeV	$g_V = 3$
	HVT $W' \rightarrow WH$ model B	$0 e, \mu$	$\geq 1 b, \geq 2 J$	-	139	$W'$ mass 3.2 TeV	$g_V = 3$
LRSM $W_R \rightarrow tb$	multi-channel	-	-	36.1	$W_R$ mass 3.25 TeV	CERN-EP-2020-073	
LRSM $W_R \rightarrow \mu N_R$	$2 \mu$	$1 J$	-	80	$W_R$ mass 5.0 TeV	$m(N_R) = 0.5 \text{ TeV}, g_L = g_R$	
CI	CI $qqqq$	-	$2 j$	-	37.0	$\Lambda$ 21.8 TeV	$\eta_{LL}$
	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	$\Lambda$ 35.8 TeV	$\eta_{LL}$
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\Lambda$ 2.57 TeV	$ C_{41}  = 4\pi$
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$1 - 4 j$	Yes	36.1	$m_{\text{med}}$ 1.55 TeV	$g_a = 0.25, g_s = 1.0, m(\chi) = 1 \text{ GeV}$
	Colored scalar mediator (Dirac DM)	$0 e, \mu$	$1 - 4 j$	Yes	36.1	$m_{\text{med}}$ 1.67 TeV	$g = 1.0, m(\chi) = 1 \text{ GeV}$
	$VV\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	3.2	$M_*$ 700 GeV	$m(\chi) < 150 \text{ GeV}$
	Scalar reson. $\phi \rightarrow \tau\nu$ (Dirac DM)	$0-1 e, \mu$	$1 b, 0-1 j$	Yes	36.1	$m_\phi$ 3.4 TeV	$y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$
LQ	Scalar LQ 1 <sup>st</sup> gen	$1, 2 e$	$\geq 2 j$	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$
	Scalar LQ 2 <sup>nd</sup> gen	$1, 2 \mu$	$\geq 2 j$	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$2 \tau$	$2 b$	-	36.1	LQ <sub>3</sub> mass 1.03 TeV	$\mathcal{B}(LQ_3^u \rightarrow br) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$0-1 e, \mu$	$2 b$	Yes	36.1	LQ <sub>3</sub> mass 970 GeV	$\mathcal{B}(LQ_3^d \rightarrow rr) = 0$
	Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV
VLQ $BB \rightarrow Wt/Zb + X$		multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet
VLQ $T_{5/3} T_{5/3}   T_{5/3}   Wt + X$		$2(SS) \geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	
VLQ $Y \rightarrow Wb + X$		$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$
VLQ $B \rightarrow Hb + X$		$0 e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$
VLQ $QQ \rightarrow WqWq$		$1 e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV	ATLAS-CONF-2018-024
Excited fermions	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	$q^*$ mass 6.7 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 j$	-	36.7	$q^*$ mass 5.3 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	36.1	$b^*$ mass 2.6 TeV	
	Excited lepton $\ell^*$	$3 e, \mu$	-	-	20.3	$\ell^*$ mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$
	Excited lepton $\nu^*$	$3 e, \mu, \tau$	-	-	20.3	$\nu^*$ mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$
	Other	Type III Seesaw	$1 e, \mu$	$\geq 2 j$	Yes	79.8	$N^0$ mass 560 GeV
LRSM Majorana $\nu$		$2 \mu$	$2 j$	-	36.1	$N_R$ mass 3.2 TeV	$m(W_R) = 4.1 \text{ TeV}, g_L = g_R$
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$		$2, 3, 4 e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$		$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$
Multi-charged particles		-	-	-	36.1	multi-charged particle mass 1.22 TeV	DY production, $ q  = 5e$
Magnetic monopoles		-	-	-	34.4	monopole mass 2.37 TeV	DY production, $ g  = 1g_D, \text{spin } 1/2$

\*Only a selection of the available mass limits on new states or phenomena is shown.

<sup>†</sup>Small-radius (large-radius) jets are denoted by the letter j (J).



# CMS Run2 DM search status



# ATLAS LS2 upgrade

## ATLAS DETECTOR LS2 UPGRADES

### MUON NEW SMALL WHEELS (NSW)

Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.



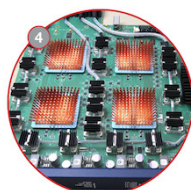
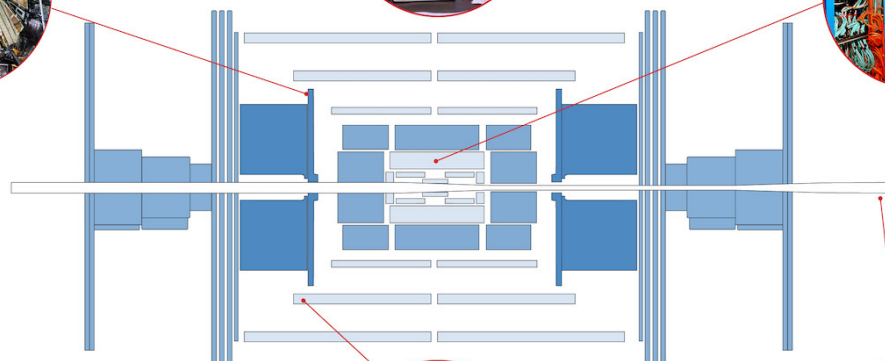
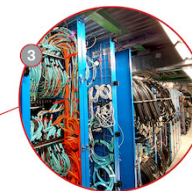
### NEW READOUT SYSTEM FOR THE NSWs

The NSW system includes two million micromega readout channels and 350 000 small strip thin-gap chambers (sTGC) electronic readout channels.



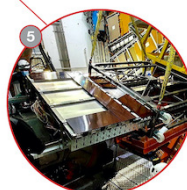
### LIQUID ARGON CALORIMETER

New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.



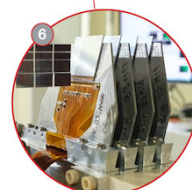
### TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)

Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.



### NEW MUON CHAMBERS IN THE CENTRE OF ATLAS

Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.



### ATLAS FORWARD PROTON (AFP)

Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new "out-of-vacuum" solution.

# CMS LS2 upgrade

## CMS DETECTOR LS2 UPGRADES

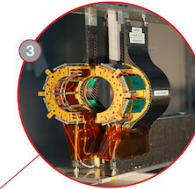
### BEAM PIPE

Replaced with an entirely new one compatible with the future tracker upgrade for HL-LHC, improving the vacuum and reducing activation.



### PIXEL TRACKER

All-new innermost barrel pixel layer, in addition to maintenance and repair work and other upgrades.



### BRIL

New generation of detectors for monitoring LHC beam conditions and luminosity.

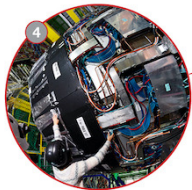


### CATHODE STRIP CHAMBERS (CSC)

Read-out electronics upgraded on all the 180 CSC muon chambers allowing performance to be maintained in HL-LHC conditions.

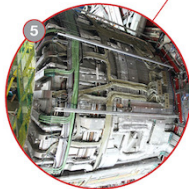
### HADRON CALORIMETER

New on-detector electronics installed to reduce noise and improve energy measurement in the calorimeter.



### SOLENOID MAGNET

New powering system to prevent full power cycles in the event of powering problems, saving valuable time for physics during collisions and extending the magnet lifetime.



### GAS ELECTRON MULTIPLIER (GEM) DETECTORS

An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.

