Probes of the Dark Sector from the ATLAS and CMS experiments

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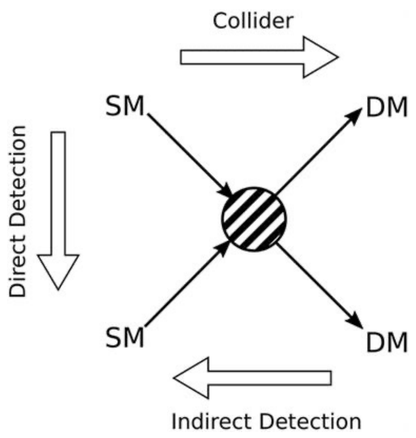
On behalf of the ATLAS and CMS collaborations

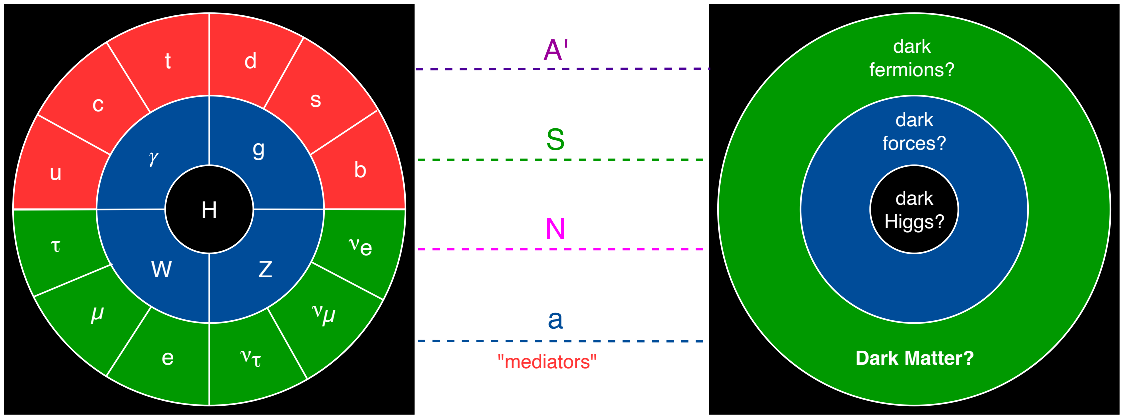
Blois 2022: 33rd Rencontres de Blois on "Exploring the Dark Universe"

Outline

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

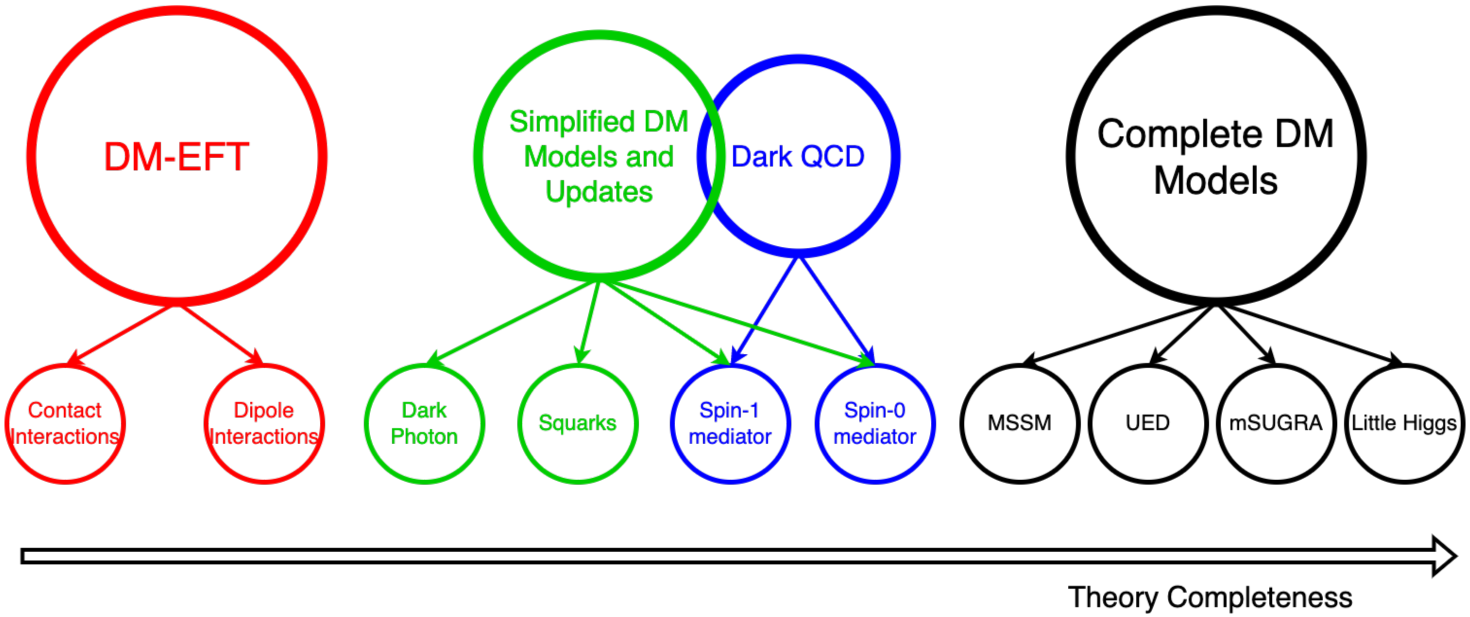
Motivation for a Dark Sector





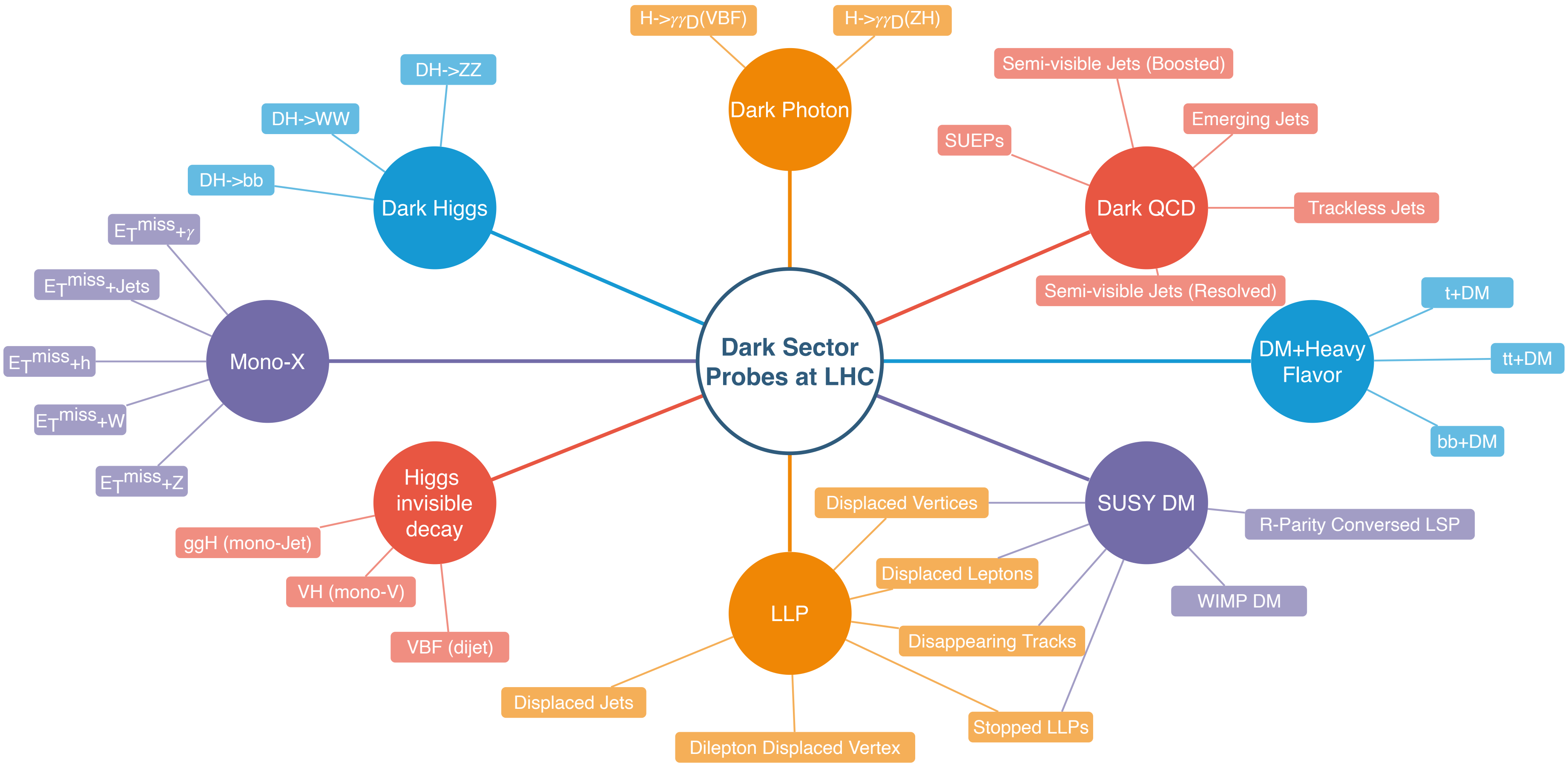
- A Dark Sector (DS) can explain the Dark Matter (DM) mystery and help address some open problems in the SM, e.g., strong CP problem, gauge hierarchy, etc.
- As a ground assumption for collider DM search, we assume non-gravitational interactions exist between SM particles and DM particles

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



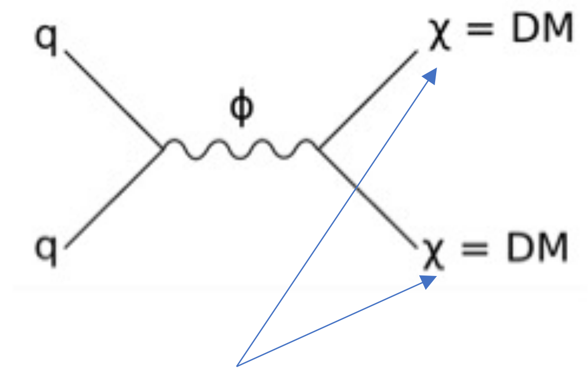
- DM searches at ATLAS and CMS are mostly signature-based;
  - Analysis are designed around specific final states, feasible to probe multiple models.
- Simplified DM sectors utilize the signature of invisible final states recoiling against an SM object;
- Rich DM sectors are probed by mixed visible-invisible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

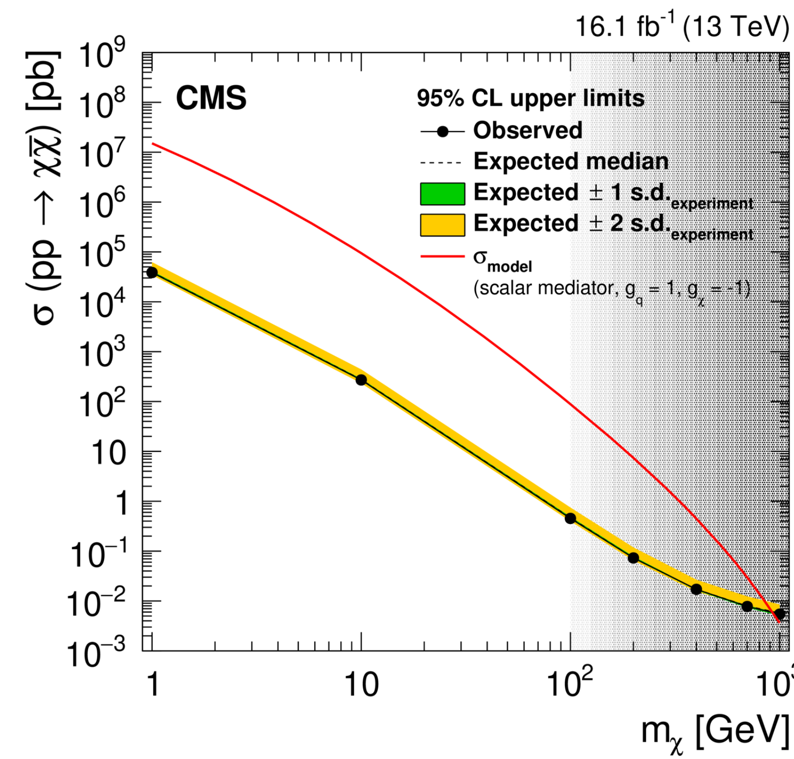
SIMP with trackless jets

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).

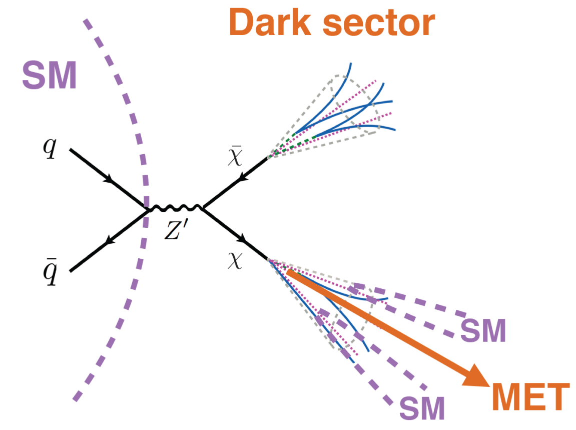


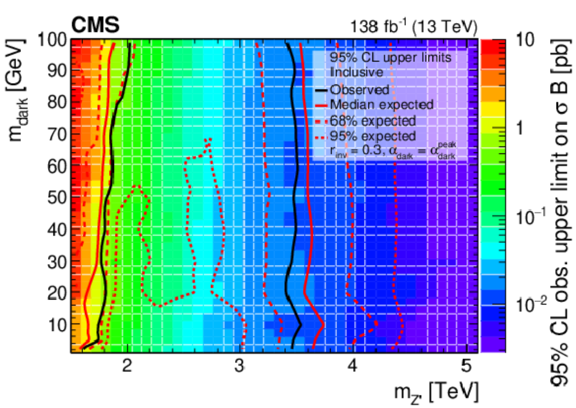
*[*] ATLAS's similar search: Eur. Phys. J. C **79** (2019) 481*

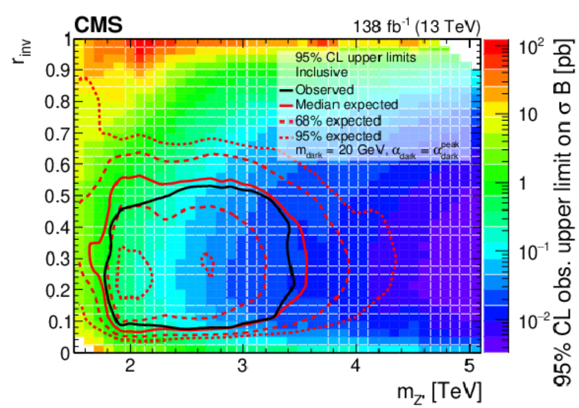
Semi-visible Jets

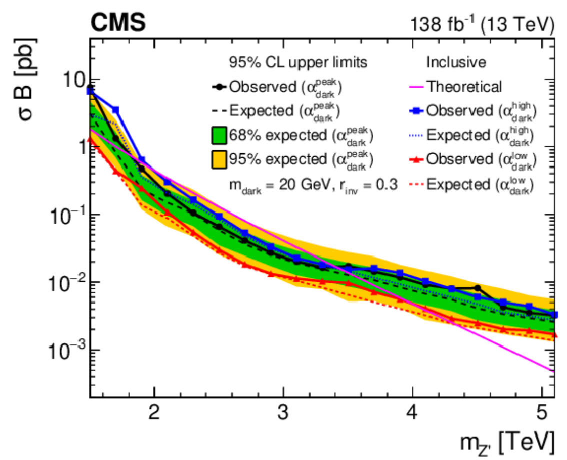
[CMS-EXO-19-020](); Submitted to J. High Energy Phys.

- 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)









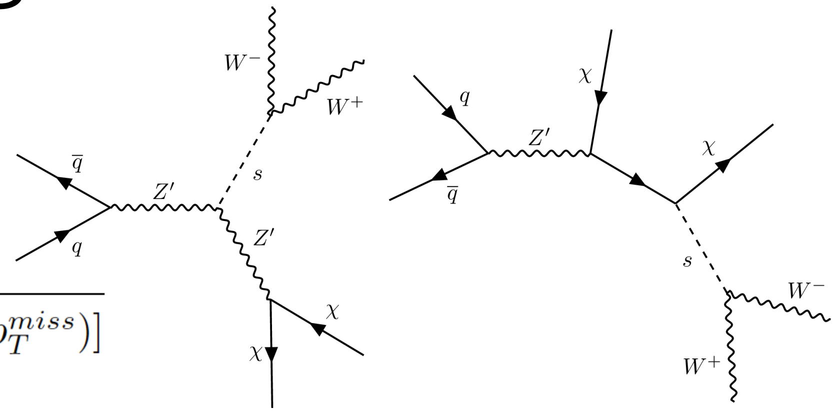
- Results from inclusive search method at 95% CL:
  1. Exclusion range on r_{inv} from 0.08 to 0.53
  2. Exclusion range on m_{med} from 1.5 to 3.9 TeV

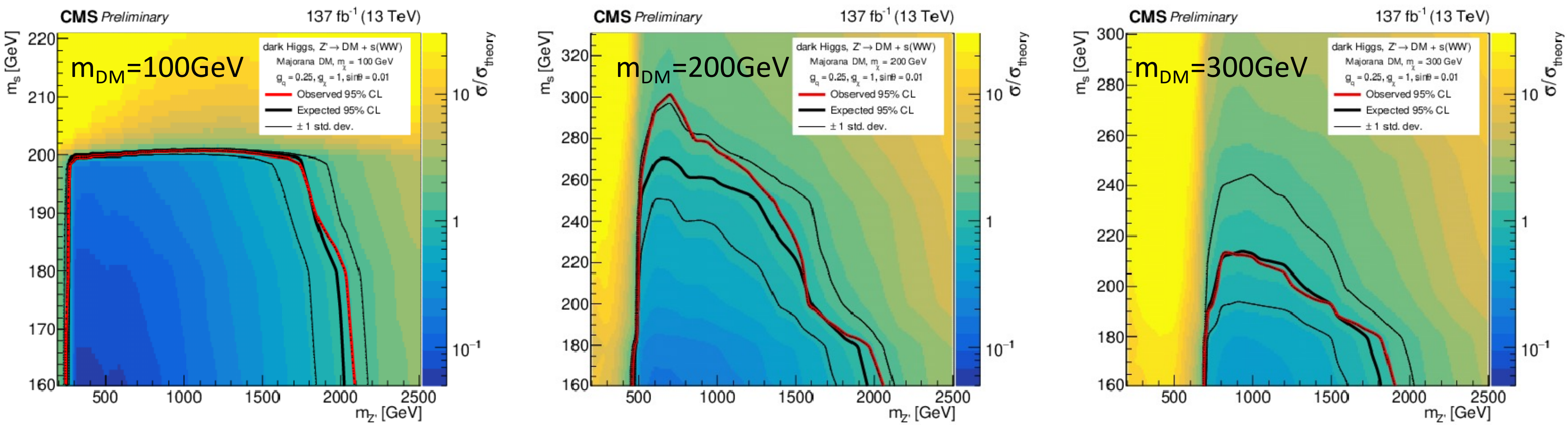
Dark Higgs decaying to W^+W^-

[CMS-PAS-EXO-20-013]

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

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

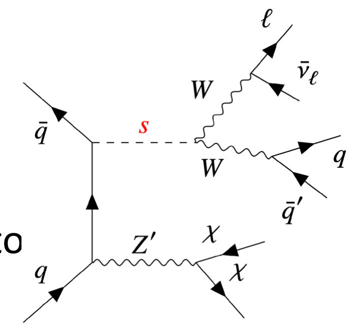


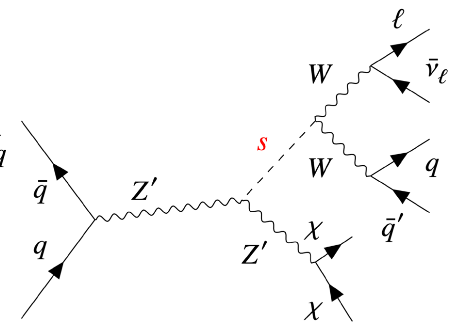


- Exclusion region at 95% CL shown for the dark Higgs model in the (m_s, $m_{Z'}$) plane for m_{DM} of 100, 200, and 300 GeV;
- Excludes m_s masses up to ≈300 GeV for a mass range ≈480 <$m_{Z'}$<1200 GeV, and up to $m_{Z'}$ ≈ 2000 GeV for a m_s= 160 GeV.

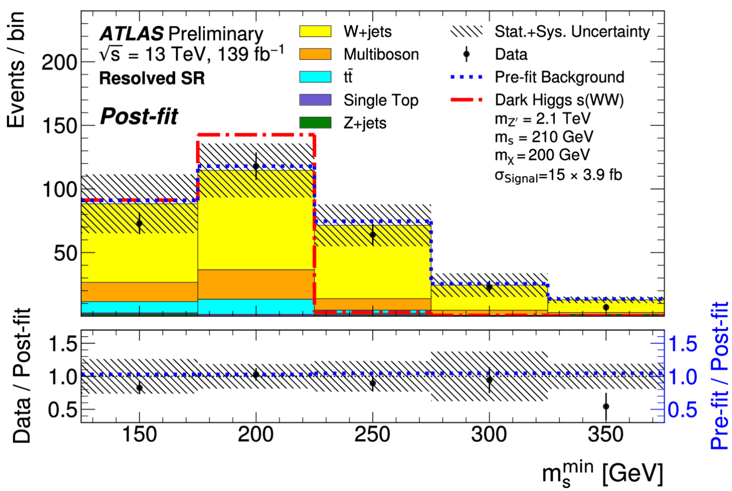
Dark Higgs decaying to W^+W^-

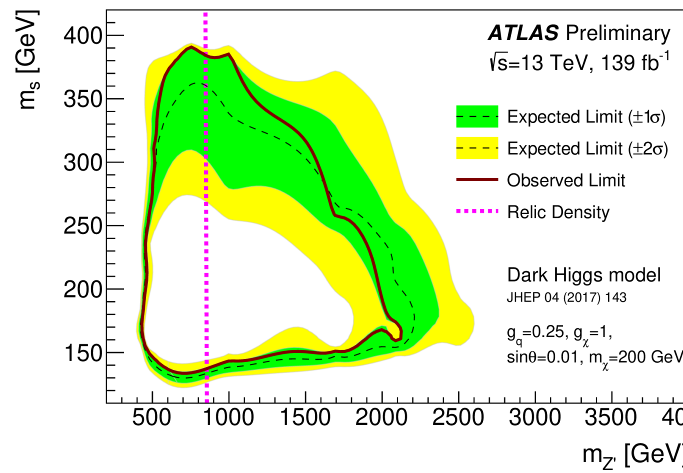
ATLAS-CONF-2022-029





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





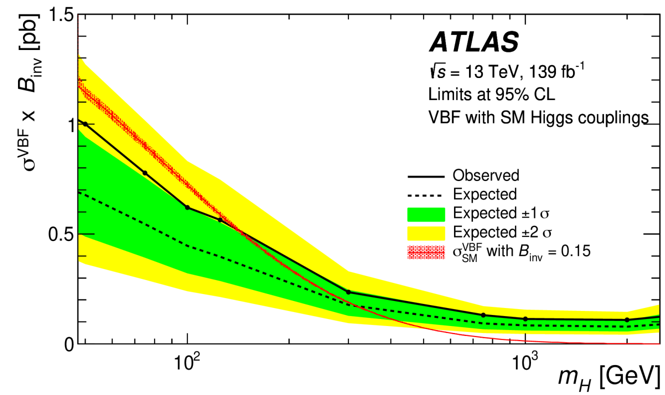
- Excludes m_s mass up to 390 GeV; excludes $m_{Z'}$ mass up to ~2 TeV.

[*] 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

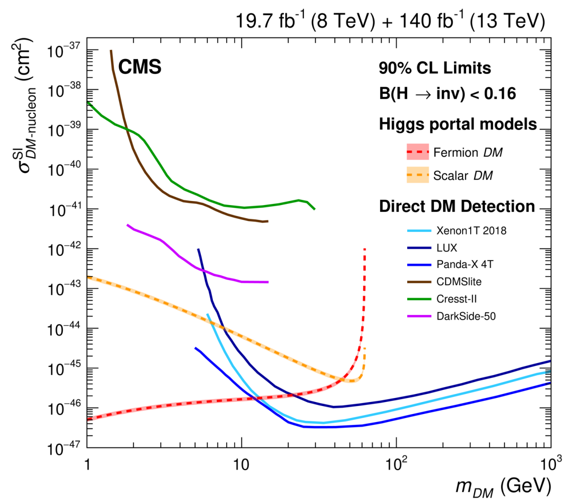
H→invisible

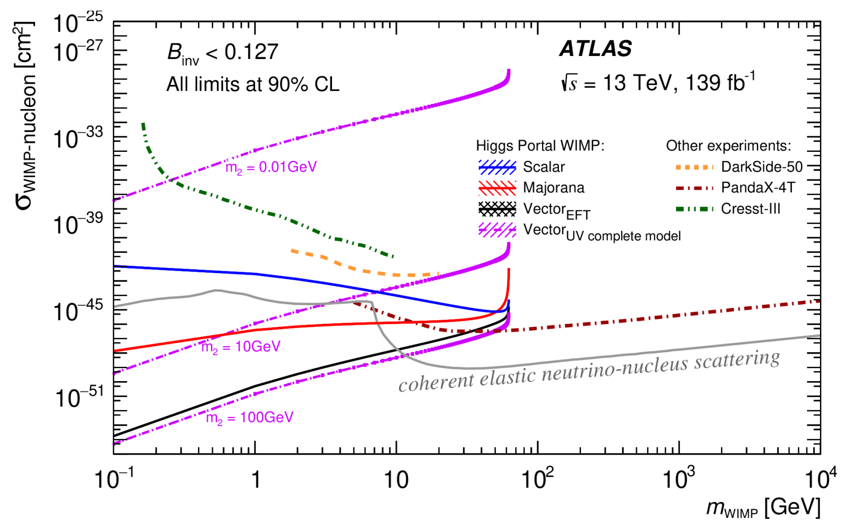
CMS: [arXiv:2201.11585](); ATLAS: [arXiv:2202.07953]()

- 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 $\mathfrak{B}(H \rightarrow inv)$.



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

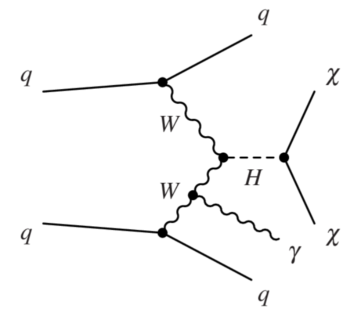


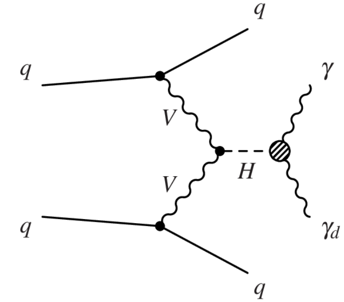


- Upper limits from ATLAS (right) and CMS (left) on the spin-independent DM-nucleon cross section for various m_{DM}.
  - The observed 90% CL upper limit on $\mathfrak{B}(H \rightarrow inv)$ is used to enable comparison with the 90% CL direct detection limit.

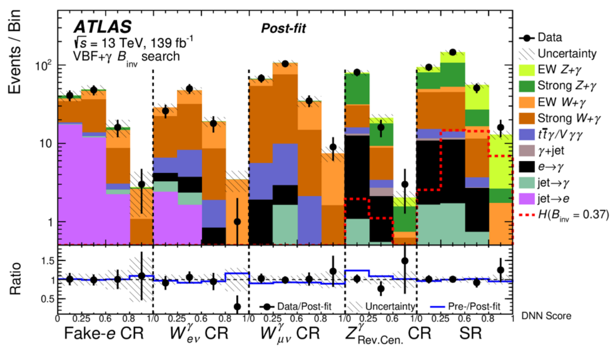
H→ invisible + γ and H→$\gamma\gamma_D$

[Eur. Phys. J. C 82 (2022) 105]

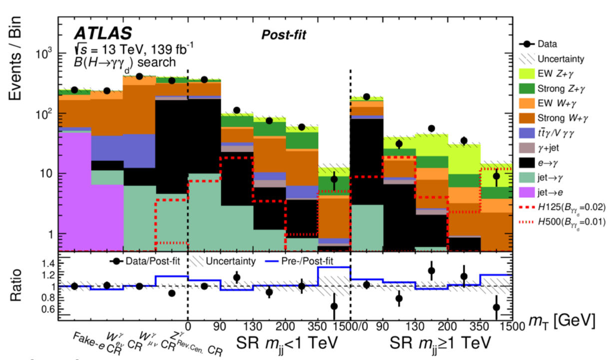




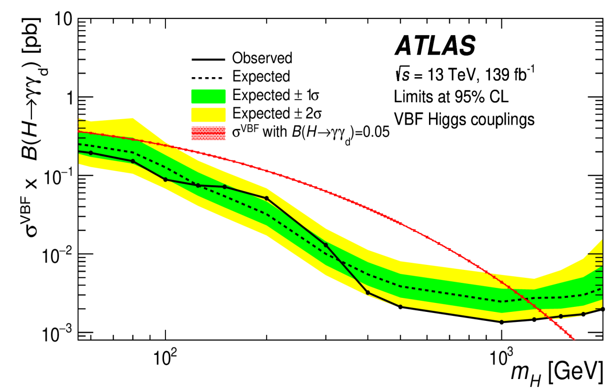
- Signature: large E_T^{miss} and a photon, in addition to a pair of forward jets.
  - Dominant background from V γ+jets
- For H → inv. search, a DNN based on kinematic feature was used, and result was extracted from likelihood fit on DNN output bins.
- H → $\gamma\gamma_D$ search result was extracted 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 $\mathfrak{B}(H \rightarrow inv)$



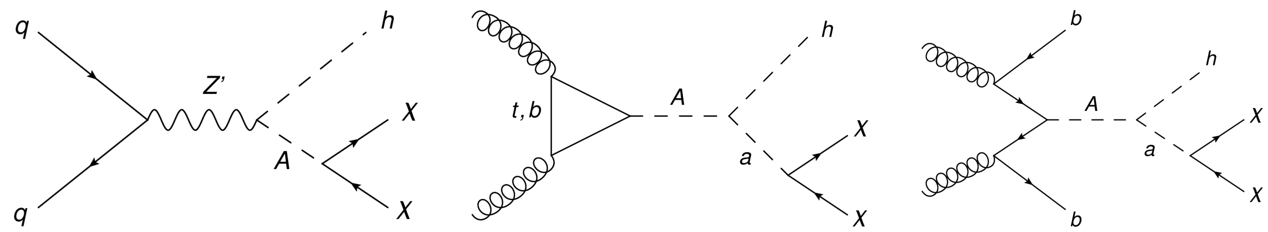
- Observed (expected) upper limit of 0.018 (0.017) at 95% CL on $\mathfrak{B}(H \rightarrow \gamma\gamma_D)$



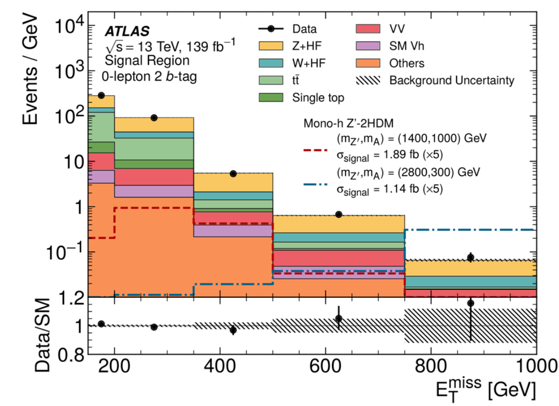
- Upper limits on $\sigma^{VBF} \times \mathfrak{B}_{\gamma\gamma_D}$ for a VBF-produced Higgs with different mass hypotheses in the narrow width approximation.

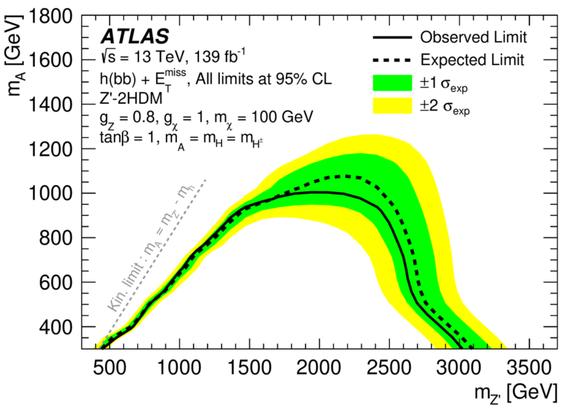
Mono-H

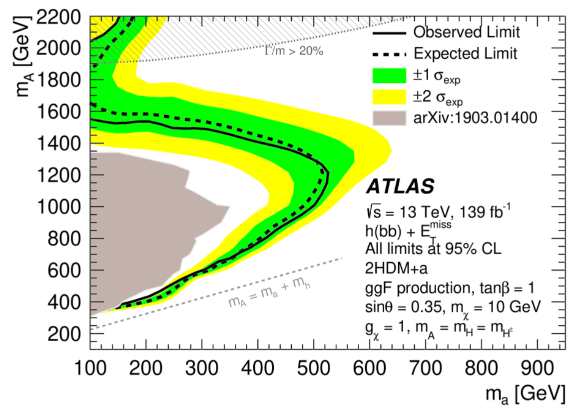
[*JHEP 11 (2021) 209*](#)

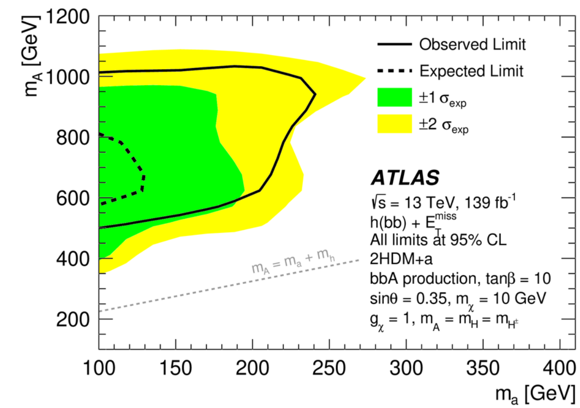


- Signature: events with E_T^{miss} and b-tagged jets consistent with a Higgs boson decay;
- A profile likelihood function is used to fit the event categorization bins and extract upper limits at 95% confidence level;
- No significant deviation from SM expectations is observed;
- Result interpreted in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





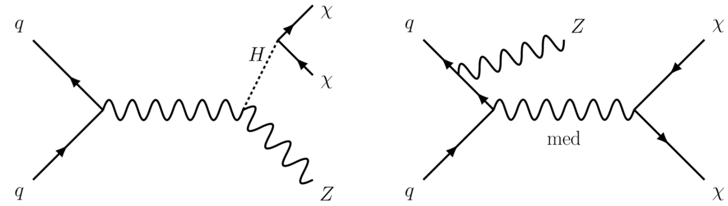


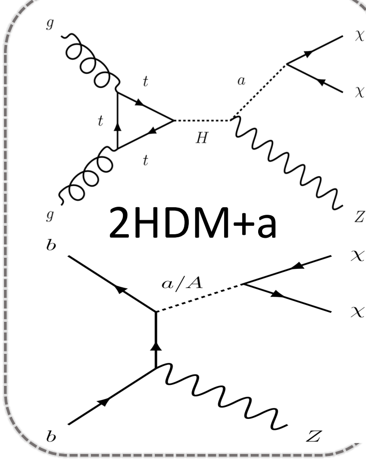


- Excludes the Z' mass up to 3 TeV in the Z'-2HDM model;
- Excludes the pseudoscalar masses up to 520 GeV and 240 GeV for tanβ=1 and tanβ=10 respectively in the 2HDM+a model .

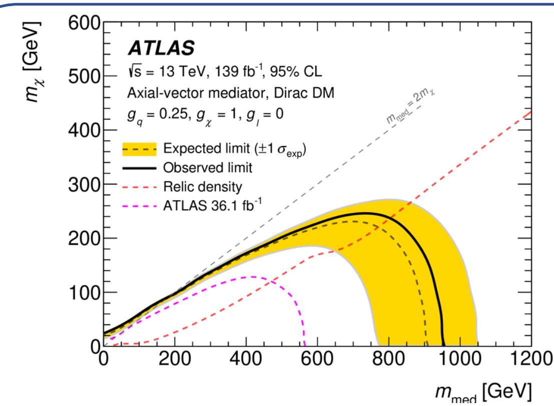
Mono-Z

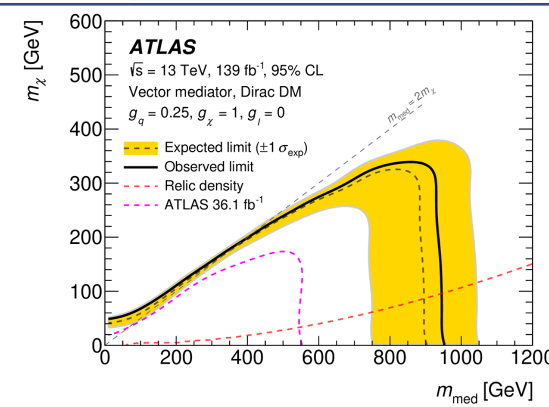
[Phys. Lett. B 829 (2022) 137066](https://doi.org/)



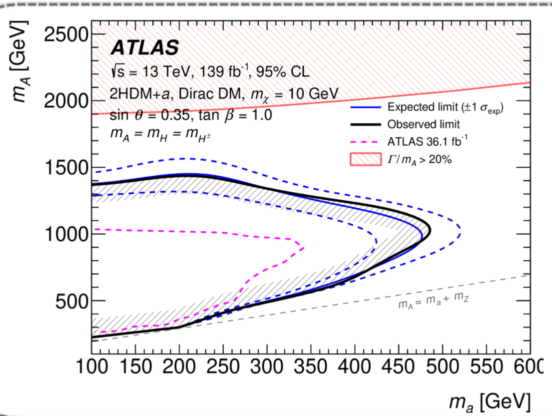


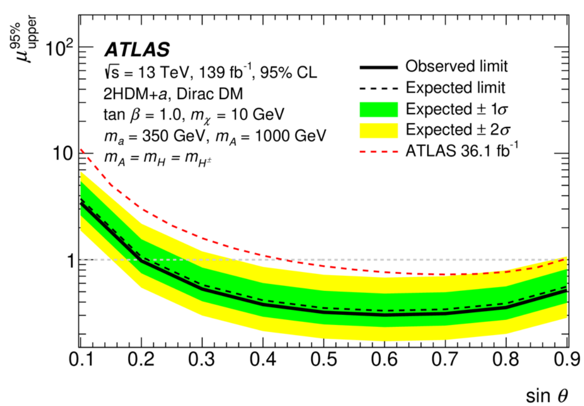
- Target signature: two oppositely charged electrons or muons consistent with originating from a Z boson decay, recoiling against a significant E_T^{miss};
- Sensitive to Higgs invisible decay, simplified DM models, and 2HDM+a models.
- Observed upper limit of 19% at 95% CL on $\mathfrak{B}(H \to inv)$.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





Exclusion limits for $m_χ$ 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} + Jet

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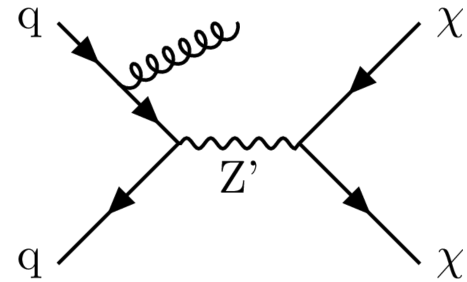
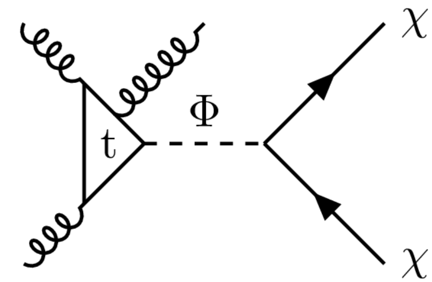
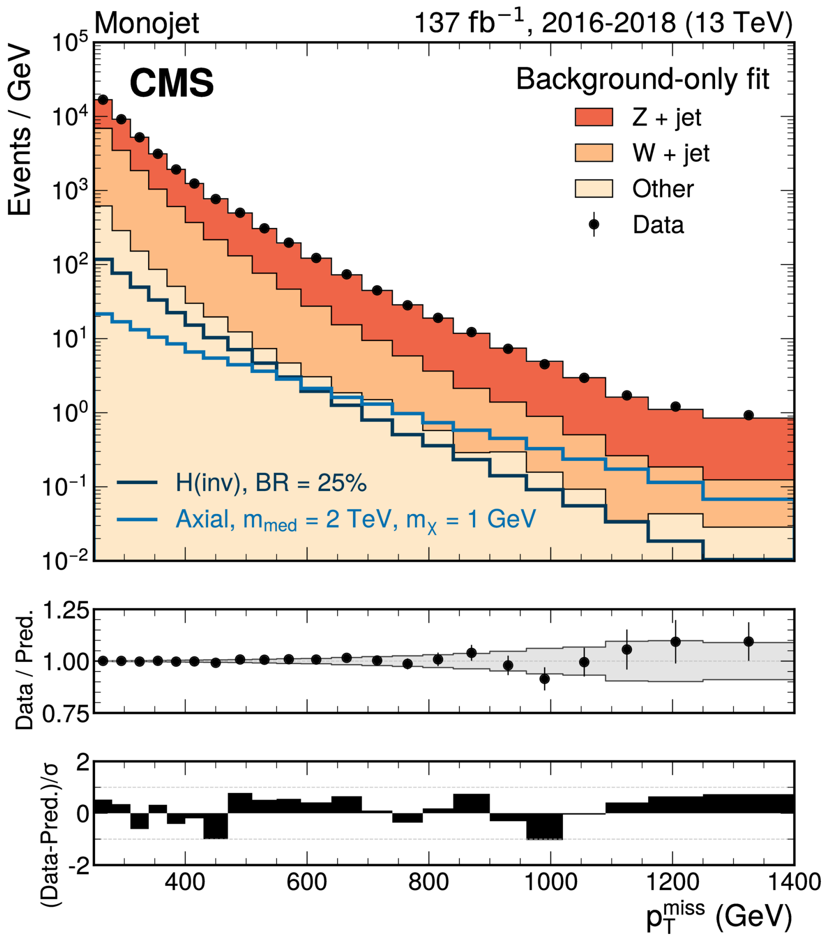
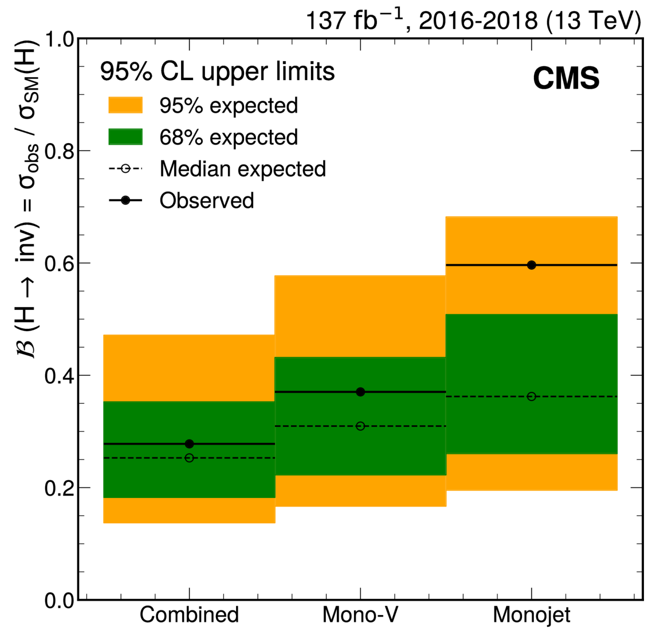






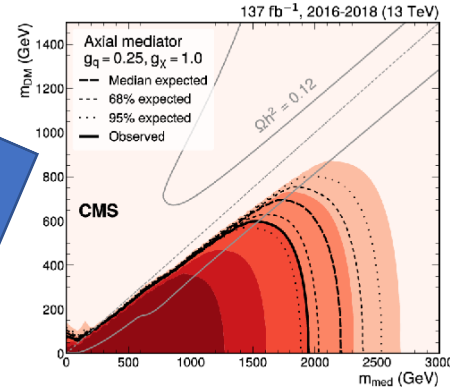


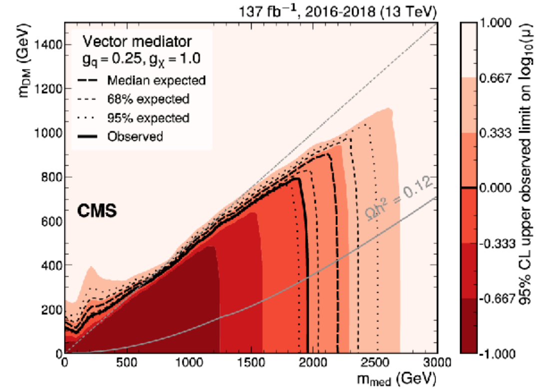
- Search for events with energetic jets and large E_T^{miss}.
- Monojet and mono-V(had) combined using full CMS Run2 data
- Upper limit at 95% CL on $\mathfrak{B}(H \to inv)$ is 27.8% (comparable with 34% from ATLAS similar search: *Phys. Rev. D 103, 112006*)

E_T^{miss} + Jet

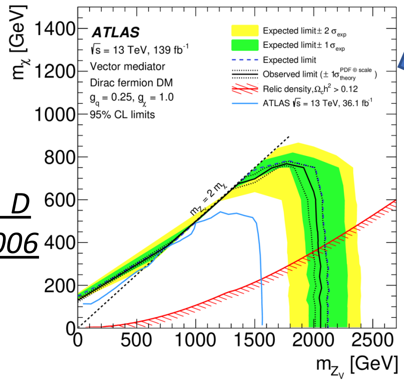
[*JHEP 11 (2021) 153*](#)

comparison
ATLAS:CMS

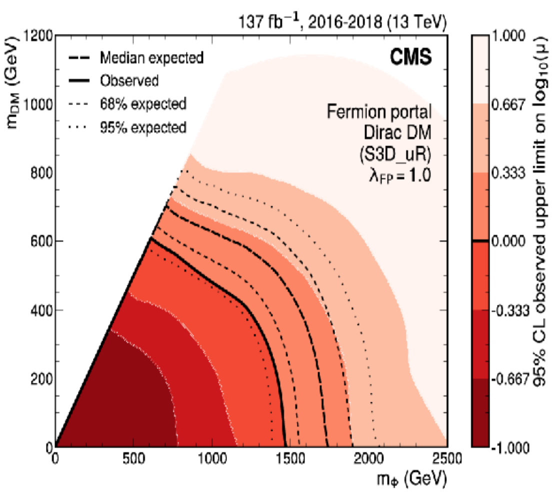


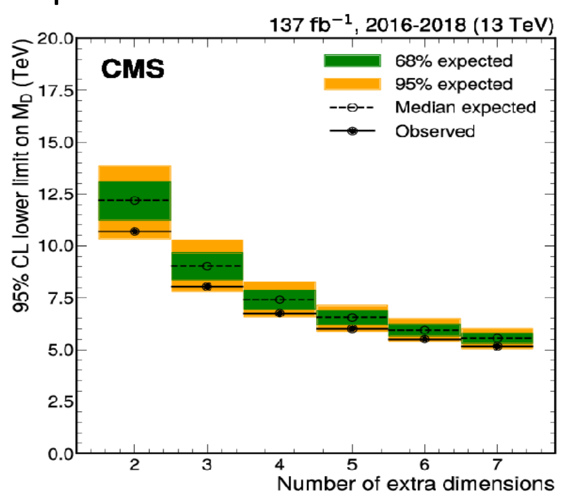


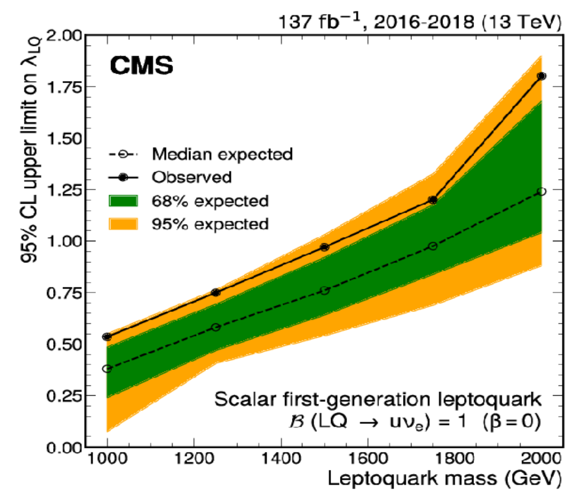
Phys. Rev. D ***103**, 112006*



- 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.



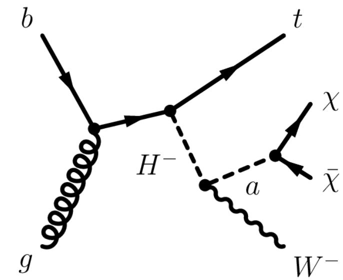


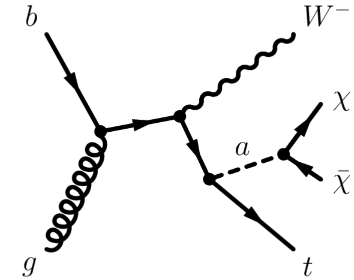


- Exclusion on mass of t-channel mediator in simplified model up to 1.5 TeV
- Stringent exclusion limits on dark matter mass in extra dimension model for different Dim. values.
- Upper limits at 95% CL on λ_{LQ} as a function of leptoquark mass in leptoquark model.

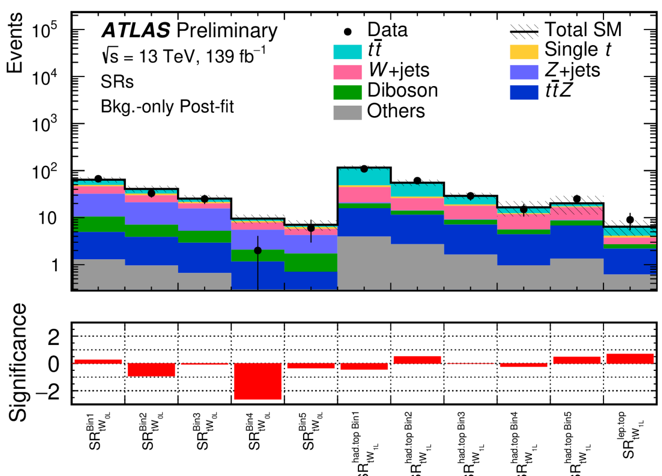
tW + DM

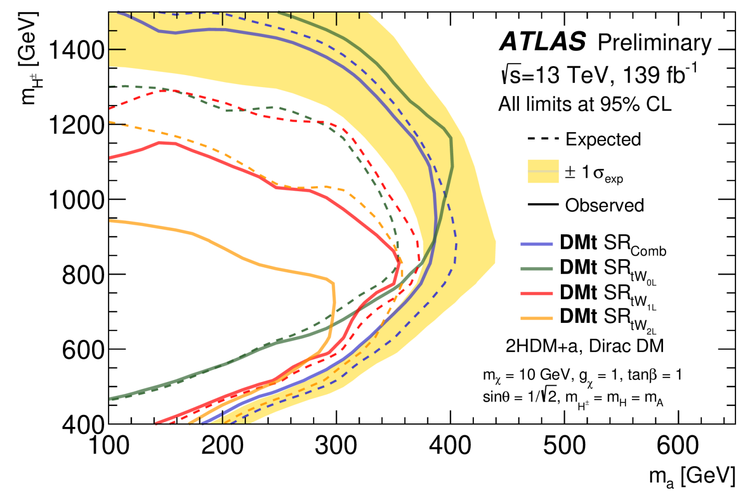
ATLAS-CONF-2022-012





- 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, $H^{\pm}$

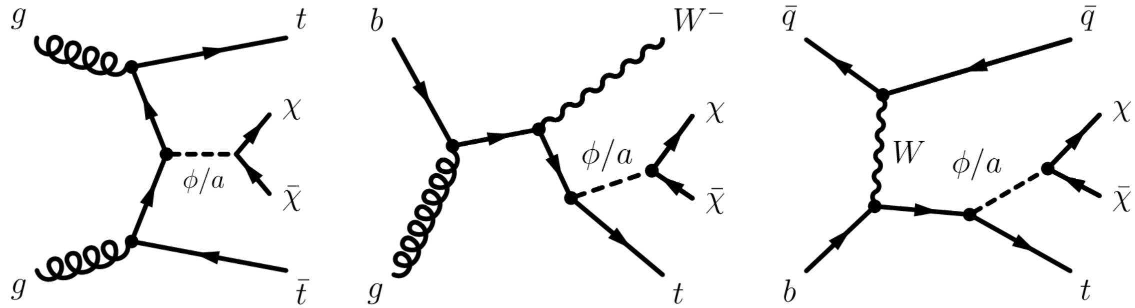




- Comparison of fit of the background-only template, extrapolated to all SRs, with the observed data.
- Excludes $H^{\pm}$ mass up to 1.5 TeV and mediator mass up to 350 GeV assuming tanβ=1.

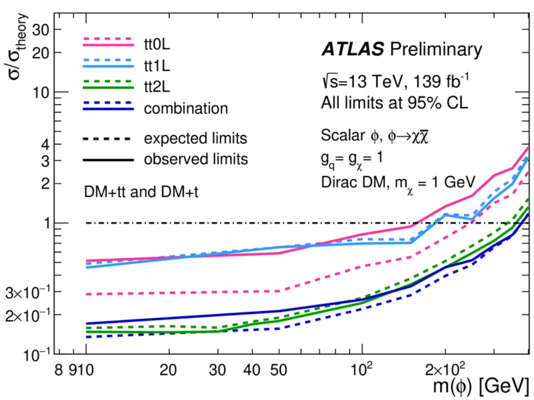
$t\bar{t}$ + DM

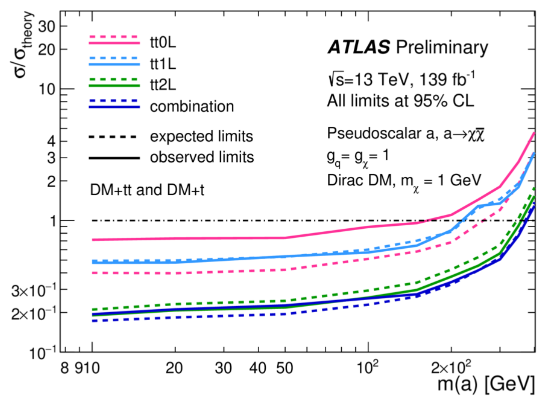
[ATLAS-CONF-2022-007](#)

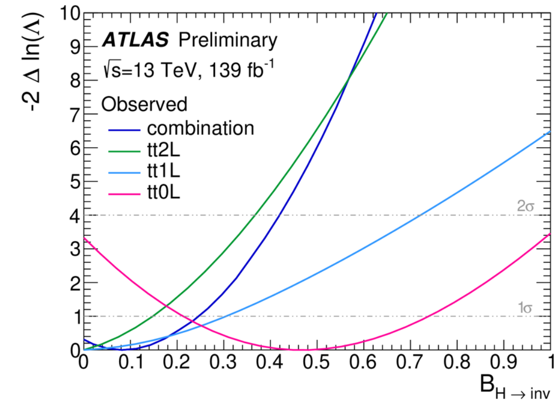


- Targets final states with two top quarks and invisible particles;
- Statistical combination in 0-lepton low E_T^{miss}, 0-lepton high E_T^{miss}, 1-lepton, 2-lepton categories;
  - Associated production of DM with single top quarks also included in combination.

- Upper limits presented in two ways: on the mass of a scalar in a simplified DM model and as upper limits on $\mathfrak{B}(H \to inv)$.

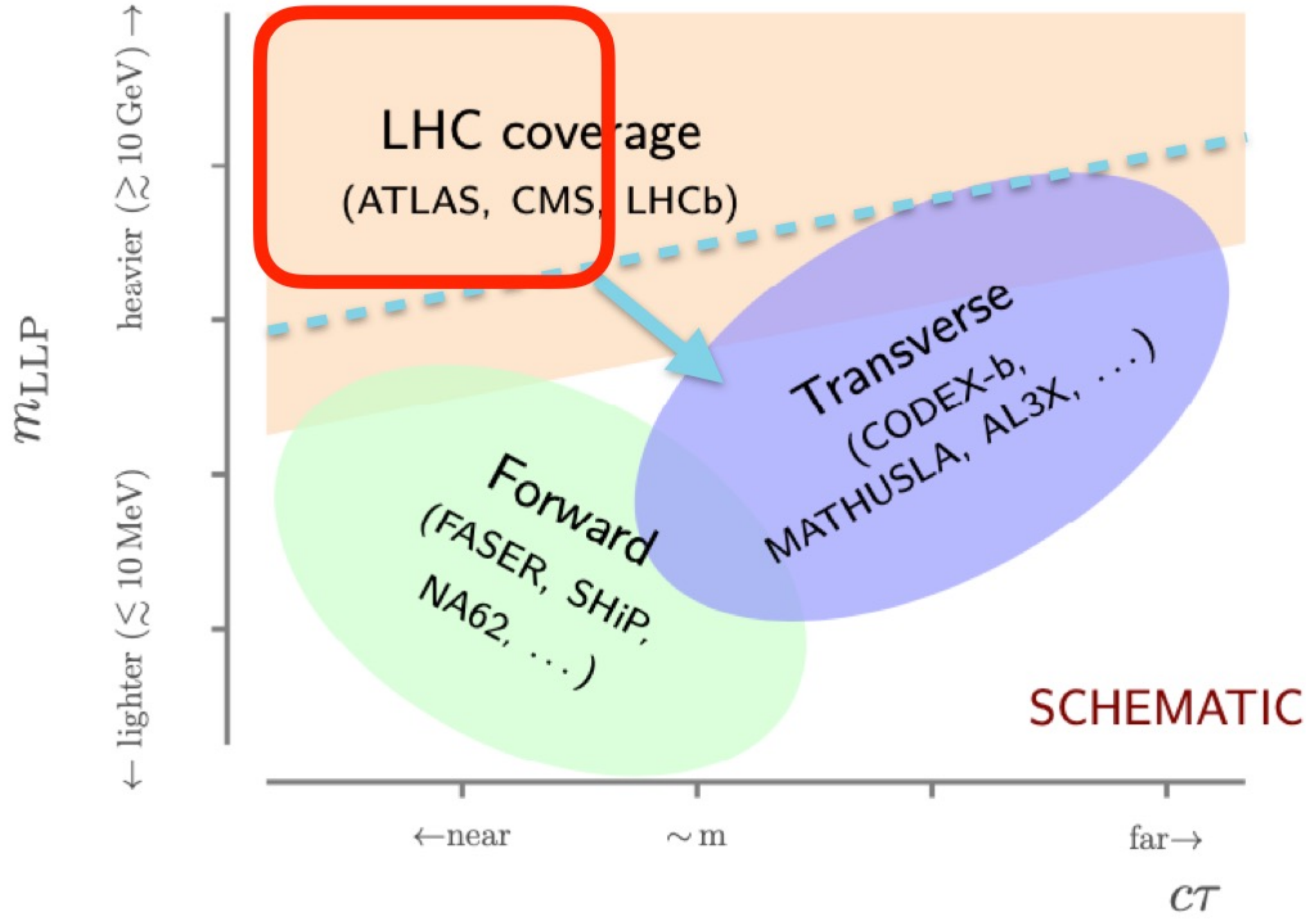






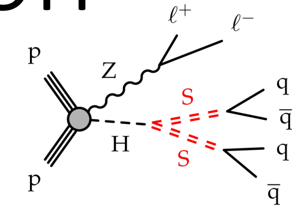
- Excludes scalar (pseudoscalar) mediator masses up to 370 GeV in the simplified model;
- Observed upper limit of 0.40 at 95% CL on $\mathfrak{B}(H \to inv)$.

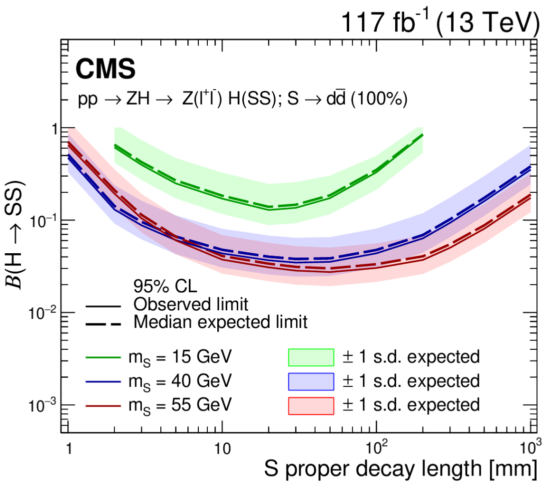
DS from Long-lived particle (LLP) searches

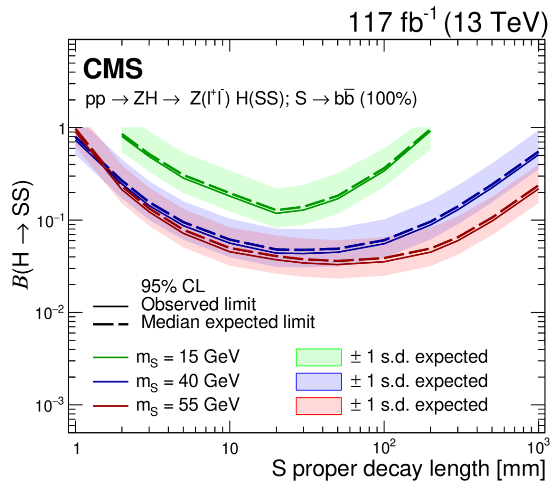


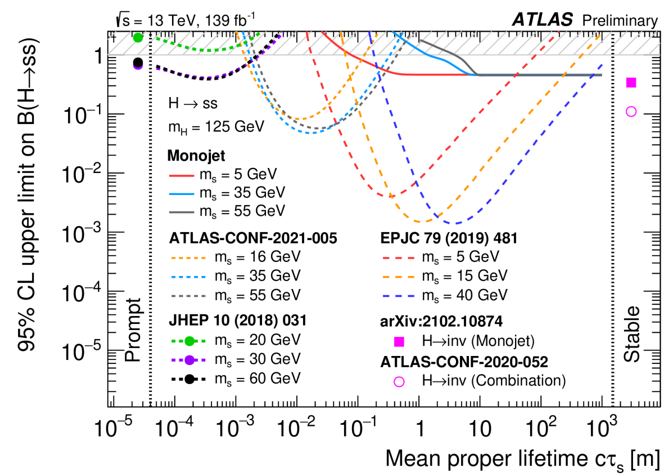
LLP in association with a Z boson

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







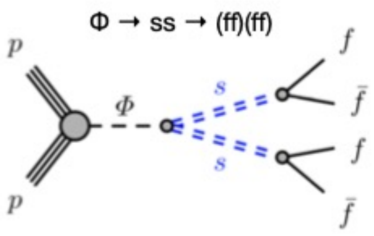


- Two comparable searches from CMS (left two plots) and ATLAS (right plot);
- LLPs decay into the tracker systems;
- Signature: Multiple displaced jets with a pair of leptons consistent with originating from a Z boson;

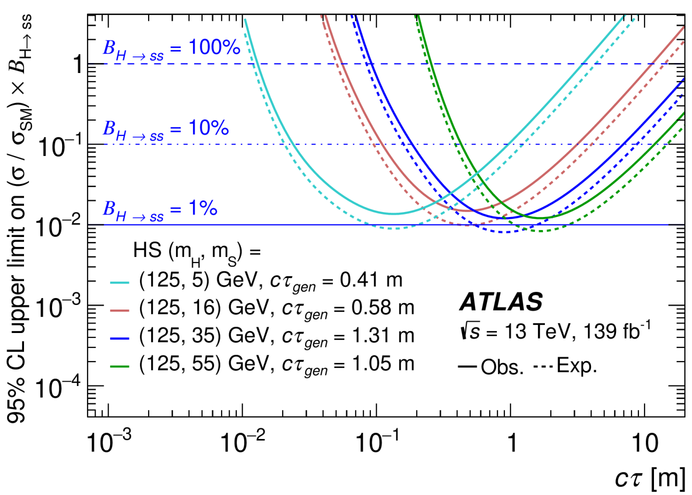
- Upper limits set on $\mathfrak{B}(H \to SS)$ as functions of LLP lifetime, for several selected S mass hypotheses;
- ATLAS result includes the comparison to the prompt decay search ([JHEP 10 (2018) 031]()) and LLP interpretation of mono-Jet search ([ATL-PHYS-PUB-2021-020]()).

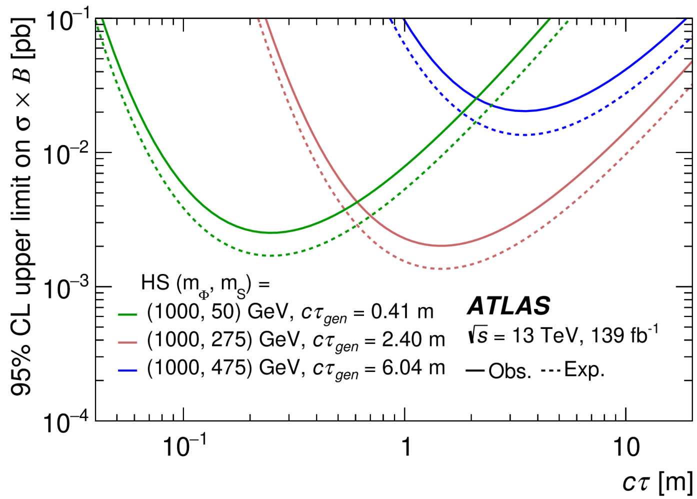
LLP search in ATLAS calorimeter

arXiv:2203.01009



- 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.

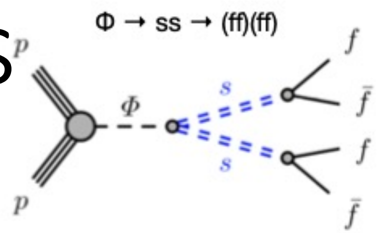


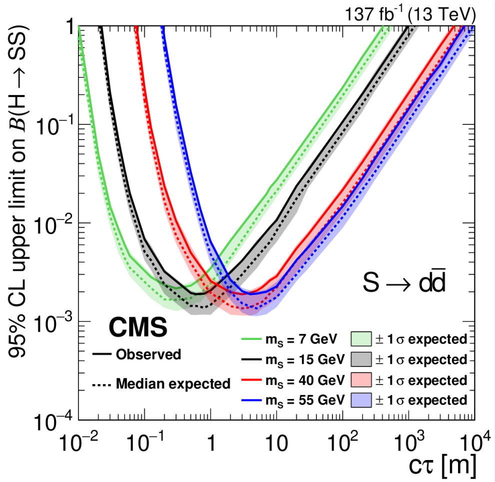


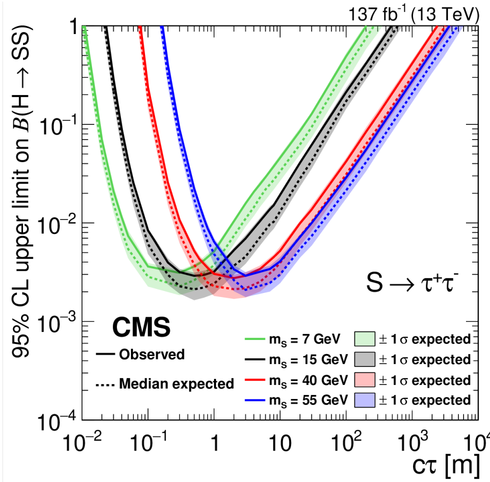
- Upper limits set on the BR of a SM Higgs boson mediator decaying to two LLPs (left) and a scalar mediator decaying to two LLPs (left) from the hidden sector (HS) models (right).

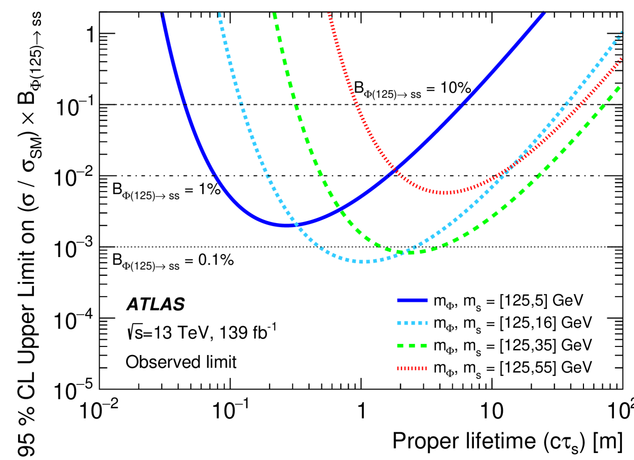
LLP search in Muon Detectors

CMS: *Phy. Rev. Lett. 127 (2021) 261804*; ATLAS: *arXiv:2203.00587*







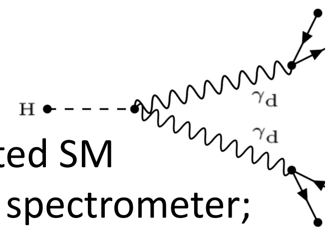


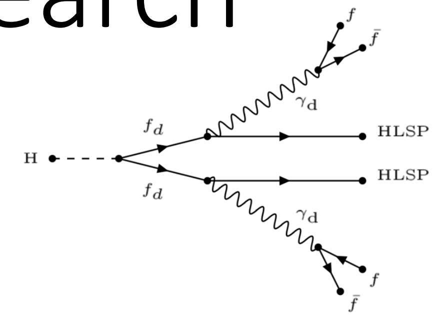
- Two searches from CMS (left two plots) and ATLAS (right plot);
- LLPs decay into the muon systems;
  - Large geometric acceptance;
  - Sensitive to large lifetime ;
- Signature:
  - CMS: large cluster of hits in muon system whilst without tracks nor jets.
  - ATLAS: two displaced vertices from LLP pairs decaying into jets in the muon spectrometer

- Upper limits set on $\mathfrak{B}(H \rightarrow SS)$ as functions of S lifetime in two S decay modes, for several selected S mass hypotheses.

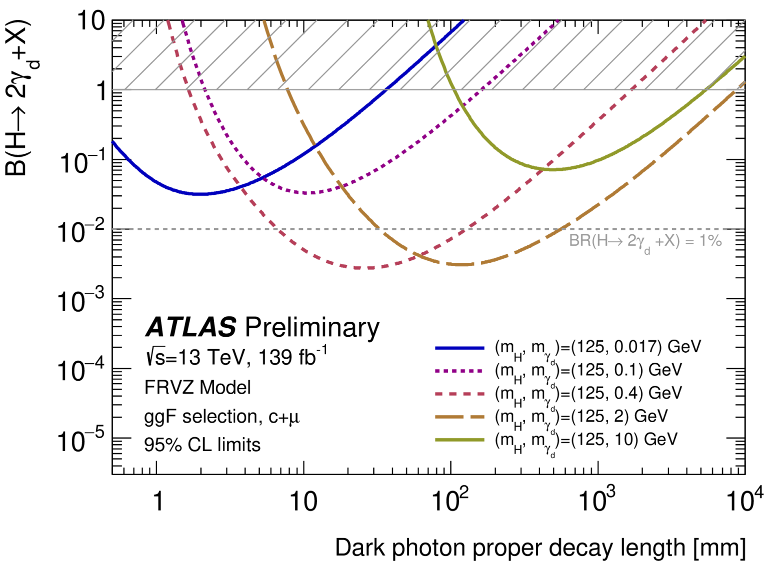
Long-lived dark photons search

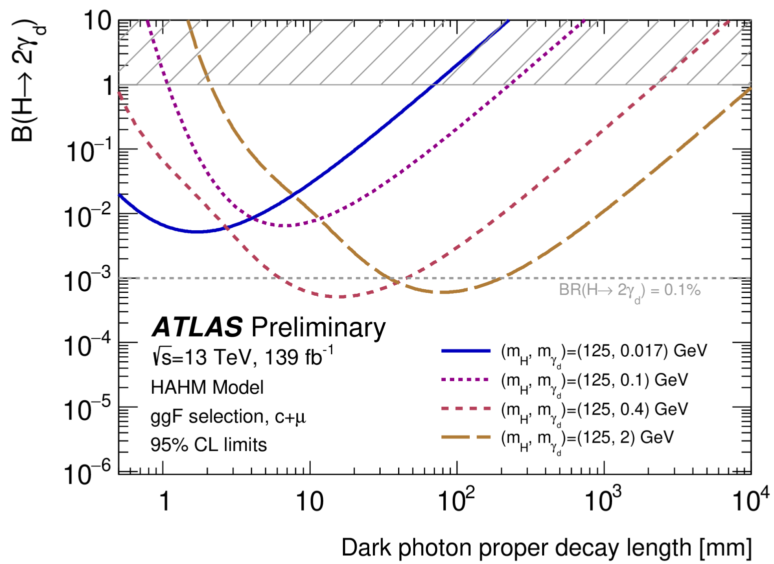
ATLAS-CONF-2022-001





- 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



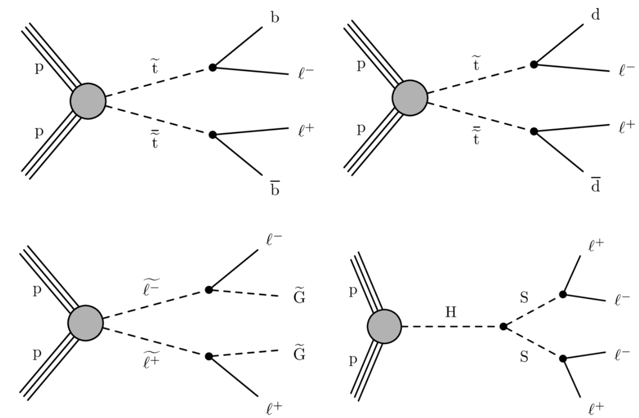


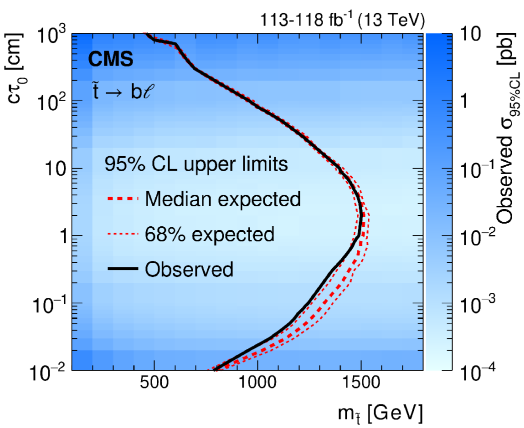
- Observed exclusion limits set for different dark photon masses at 95% CL on $\mathfrak{B}(H \rightarrow 2\gamma_d + X)$ for FRVZ model (left) and HAHM model (right), assuming a SM Higgs boson.

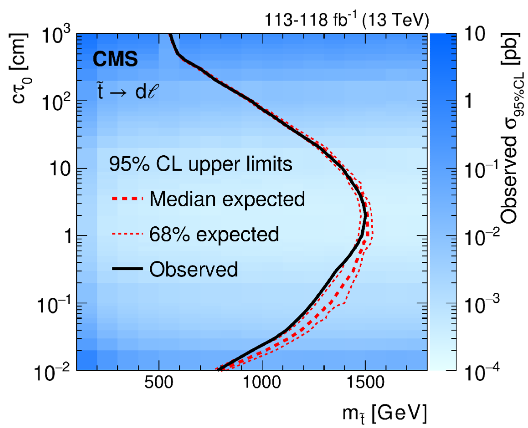
LLP decaying to leptons

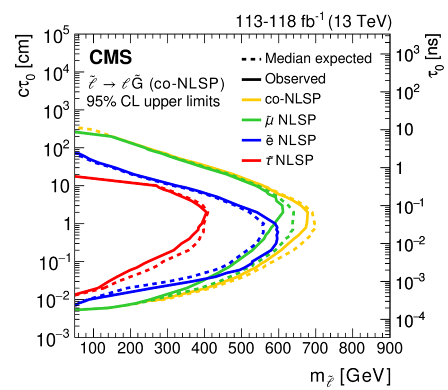
[EPJC 82 (2022) 153](#)

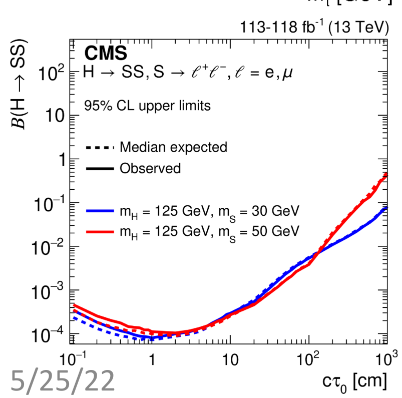
- Signature: LLPs decay into two displaced leptons with large transverse impact parameter;
- The search is designed to be sensitive to a wide range of models with displaced di-muon final states.
- Result is used to constrain stop, slepton, and $\mathfrak{B}(H \to SS)$







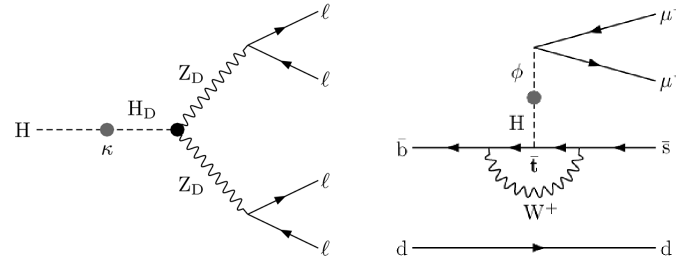




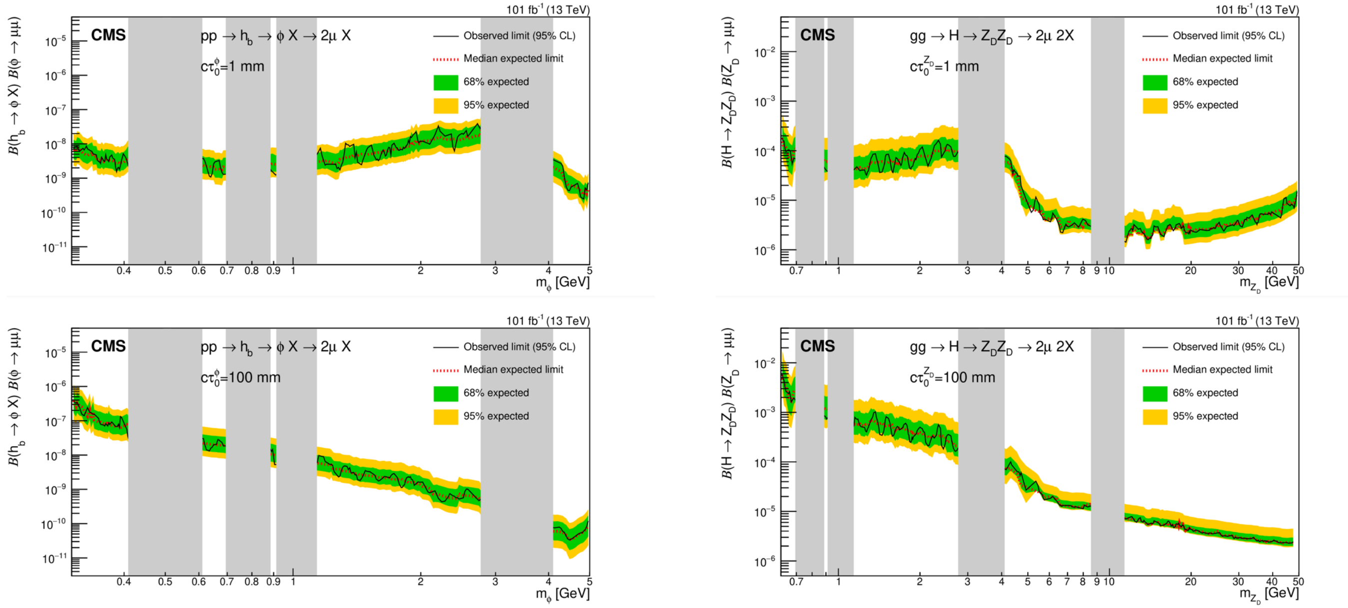
- Excludes stop quark mass up to 1500 GeV at 95% CL;
- Excludes slepton mass up to 700 GeV at 95% CL;
- Upper limits set on $\mathfrak{B}(H \to SS)$ as functions of S lifetime, for several selected S mass hypotheses.

[*] 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]

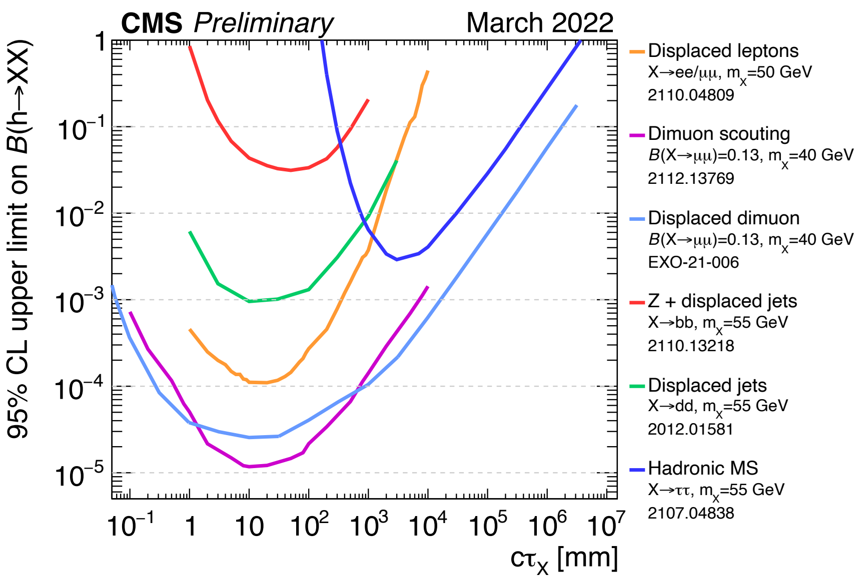


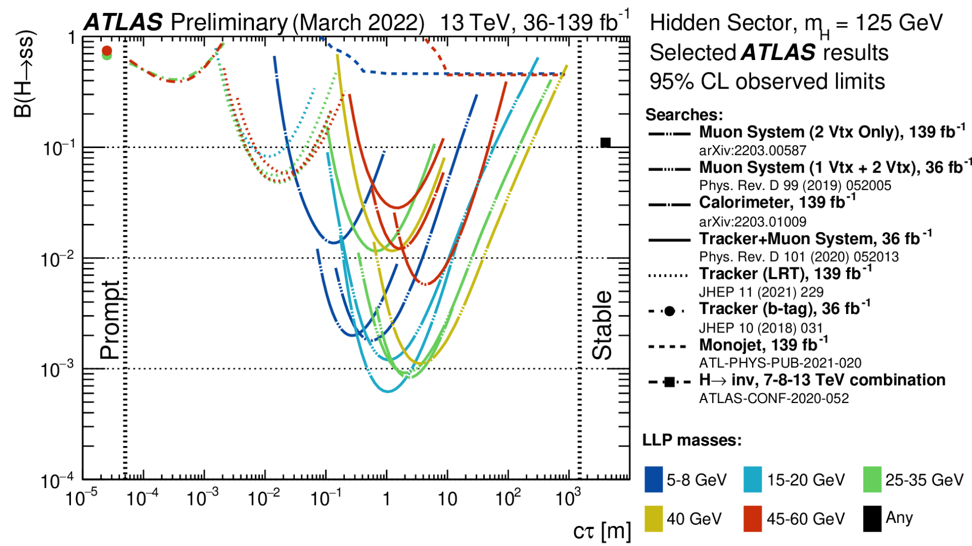
- Signature: at least 2 displaced muons and an associated displaced vertex.
- Novel exploration phase space at low dimuon mass



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

LLP summary for HS models





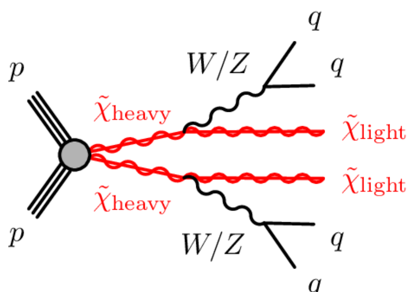
- Exclusion limit on $\mathfrak{B}(H \to XX)$ from previous analyses for ATLAS (right) and CMS (left).
  - Note: There are differences on the LLP decay $\mathfrak{B}r$ assumption
- More CMS summary on LLP DS searches: https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Higgs_decays_to_long_lived_parti
- 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

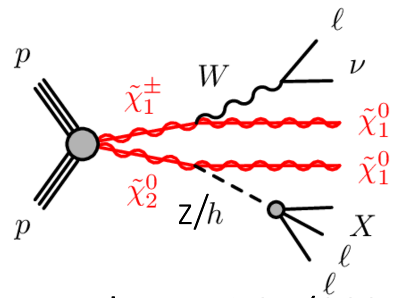
Chargino-neutralino search in ATLAS

1



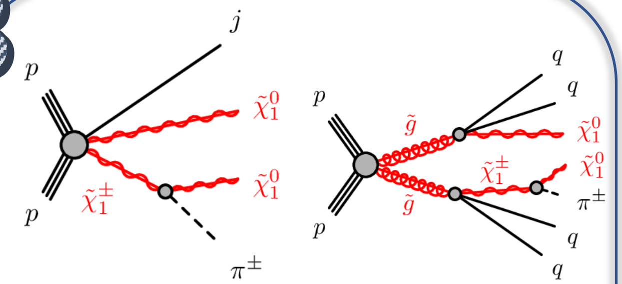
- Phys. Rev. D 104 (2021) 112010;
- Search in final states with two boosted hadronically decaying bosons and E_T^{miss}

2



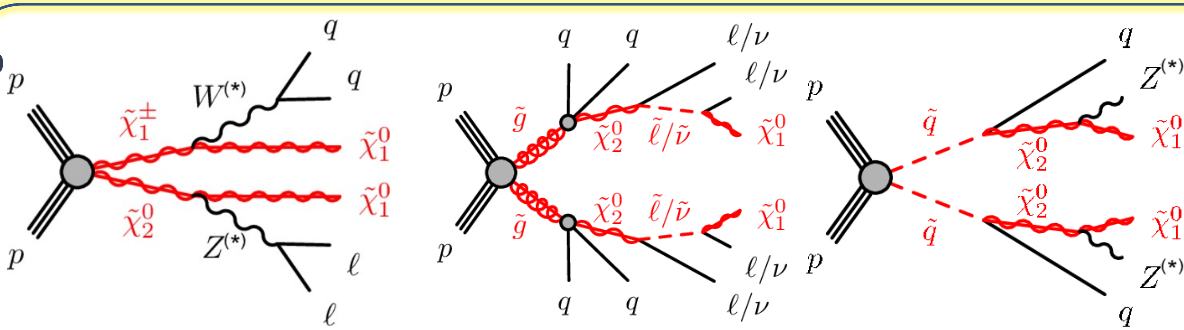
- Eur. Phys. J. C 81 (2021) 1118;
- Search in final states with three leptons and E_T^{miss}

3



- EPJC arXiv:2201.02472;
- Search for long-lived charginos based on a disappearing-track signature

4

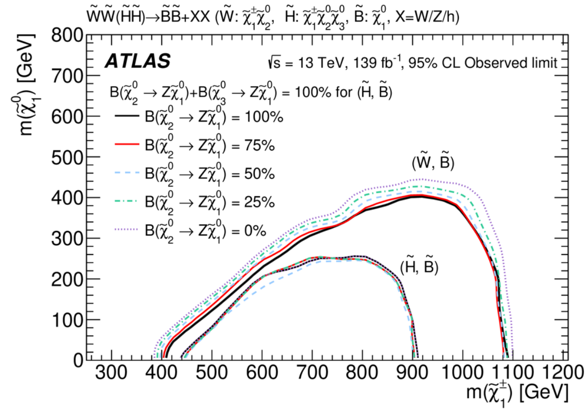


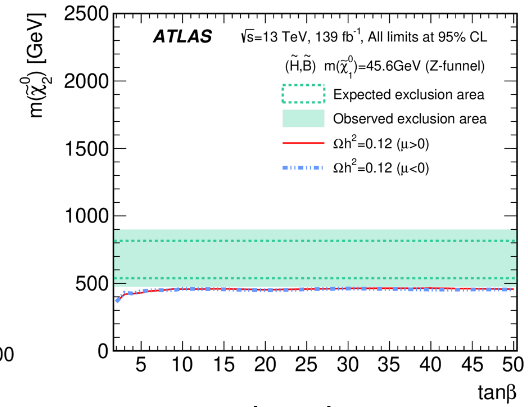
- EPJC arXiv:2204.13072;
- Search in final states containing an e^+e^- or $\mu^+\mu^-$ pair, jets, and E_T^{miss};
- squark search included

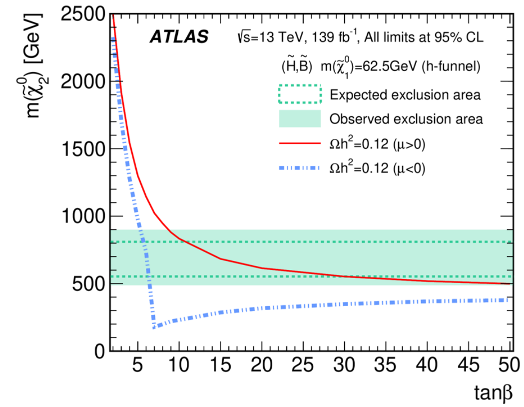
- Four new searches from ATLAS on chargino-neutralino in different final states;
- Results are shown in the following two slides;
- R-Parity Conversed lightest neutralino serves as a natural DM candidate.

Chargino-neutralino search in ATLAS

1

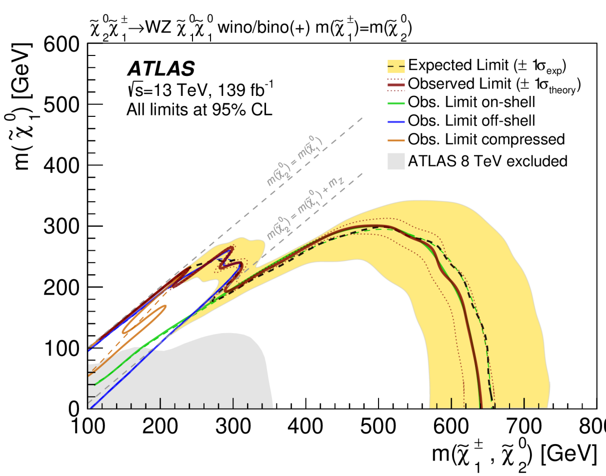


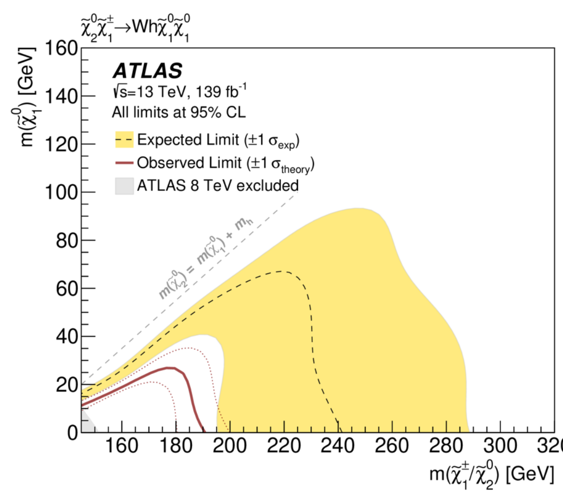




- Excludes wino (higgsino) mass up to 1060 (900) GeV.
- Exclusion limits on the Z/h-funnel dark matter model for bino-like LSP half of z/h mass.

2

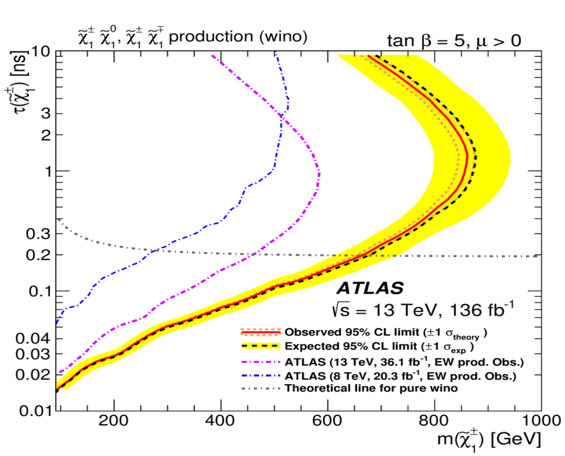


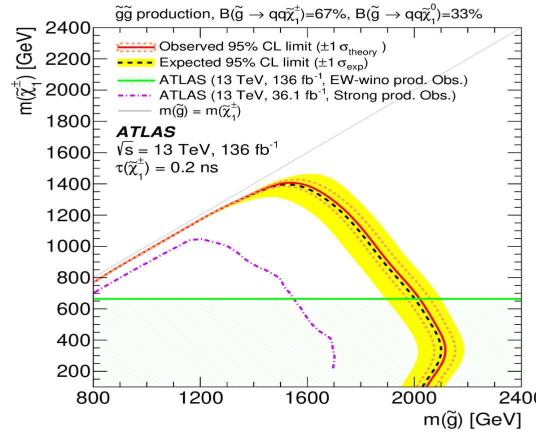


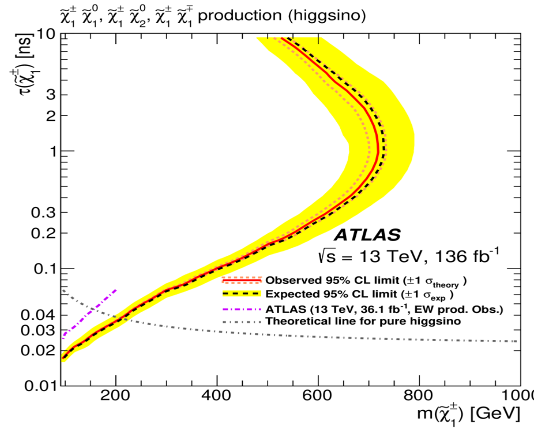
- Excludes $\tilde{\chi}_2^0$ masses up to 210 (640) GeV for For Wh (WZ) mediated model;

Chargino-neutralino search in ATLAS

3

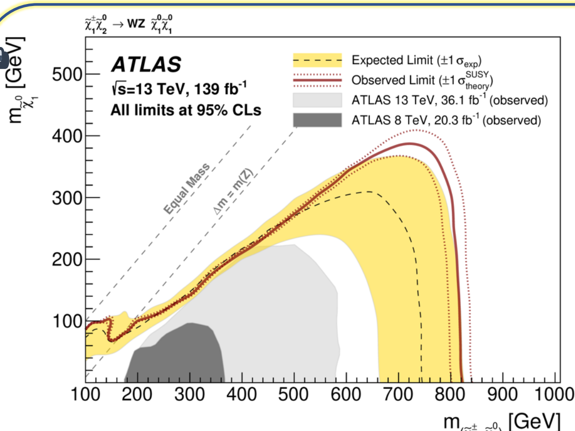


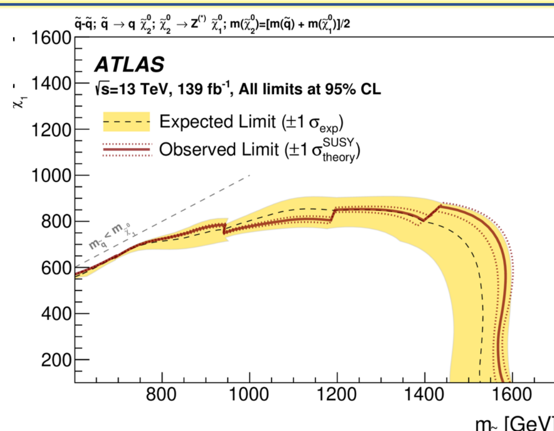


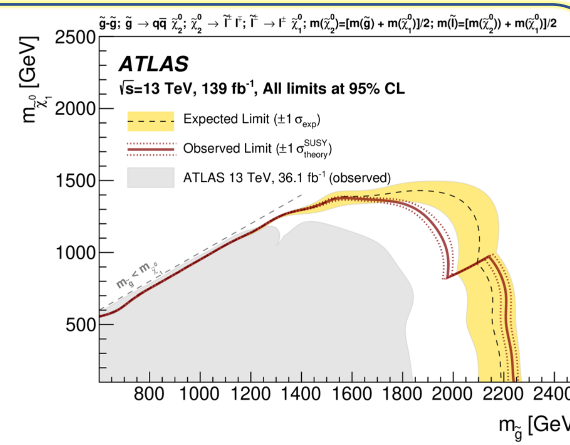


- Excludes wino (higgsino) masses up to 660 (210) GeV
- Excludes gluinos masses up to 2.1 TeV

4





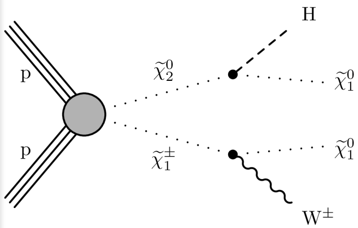


- Excludes masses up to 900 GeV for electroweakinos, 1550 GeV for squarks, and 2250 GeV for gluinos.

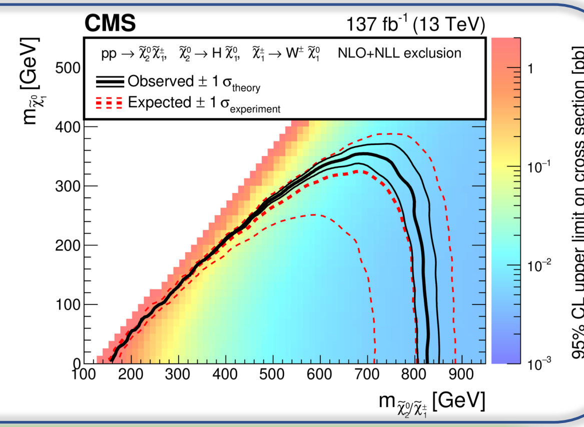
Chargino-neutralino search in CMS

Electroweak production

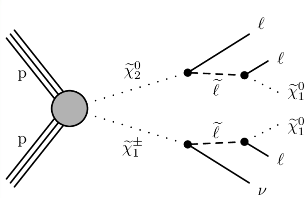
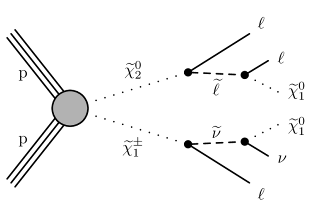
1-lepton

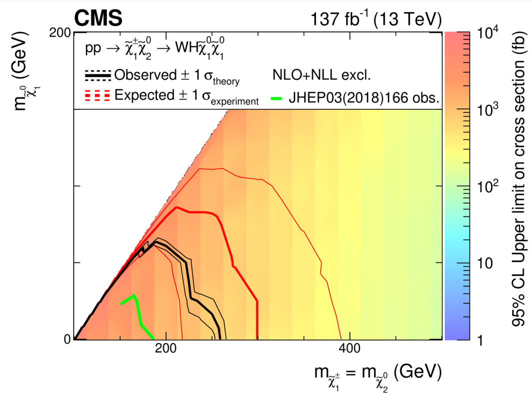


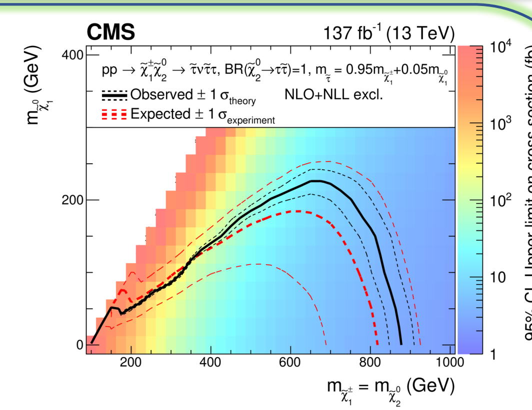
- JHEP 10 (2021) 045: CMS search in events with a Higgs and a W boson, with the W decaying semi-leptonically, and the Higgs boson decaying to a pair of bottom quarks
- Exclusion limits on charginos and neutralinos (LSP) masses up to 820 (350) GeV



multi-lepton

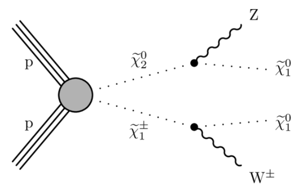


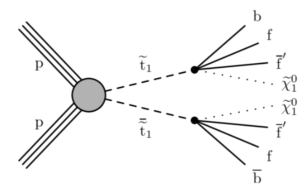


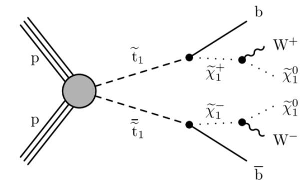
- JHEP 04 (2022) 147: CMS search in final states with three or four leptons, with up to two hadronically decaying τ leptons, or two same-sign light leptons
- Exclusion limits are set separately for flavor-democratic slepton-mediated, τ-enriched slepton-mediated, τ-dominated slepton-mediated, WZ-mediated,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

Chargino-neutralino and stop search

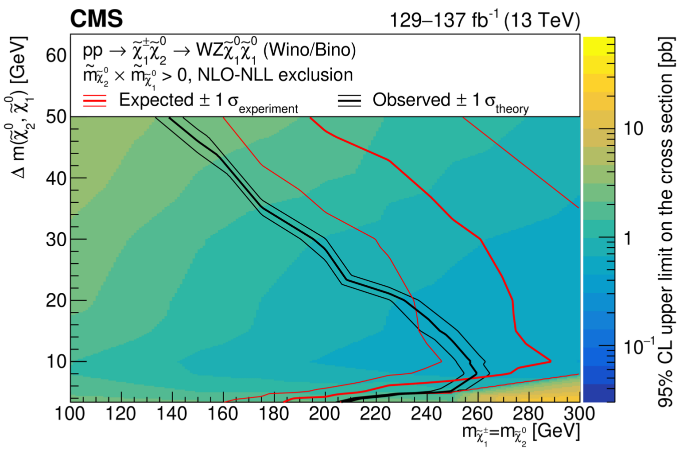
JHEP 04 (2022) 091

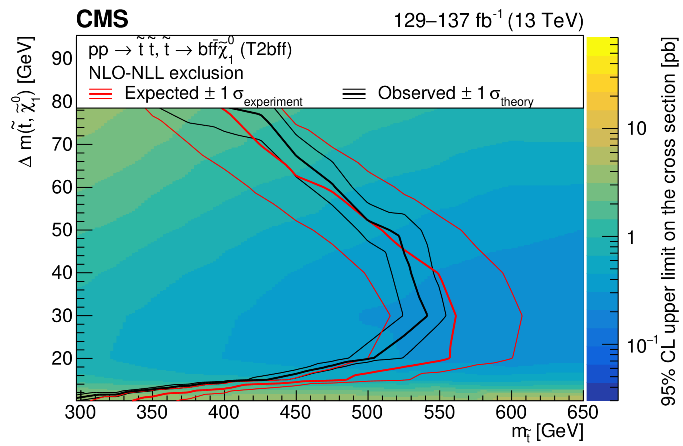




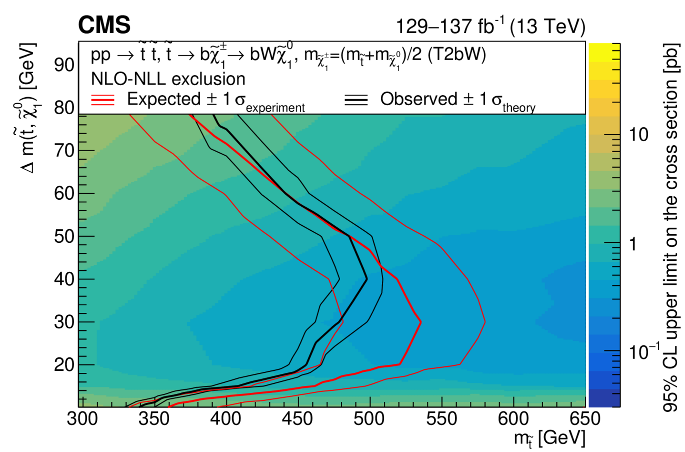


multi-soft-lepton



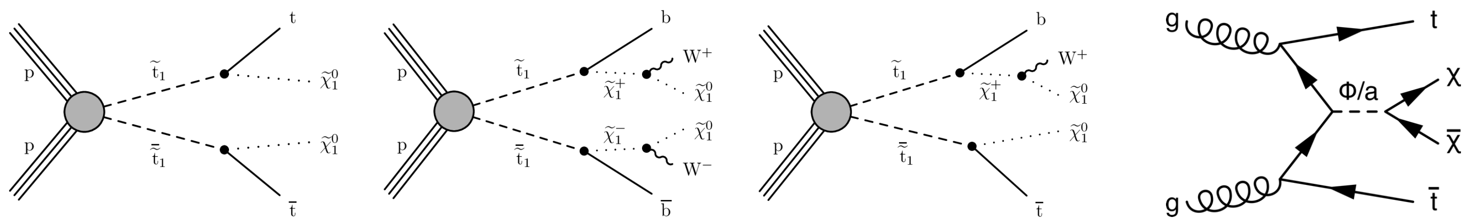


- Search in final states with 2 or 3 soft leptons and E_T^{miss};
- Result is also interpreted in terms of top squark pair production;
- Exclusion limits on chargino and neutralino masses up to 275 GeV for a mass difference of 10 GeV in the wino-bino model;
- Exclusion limits on top squark masses up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

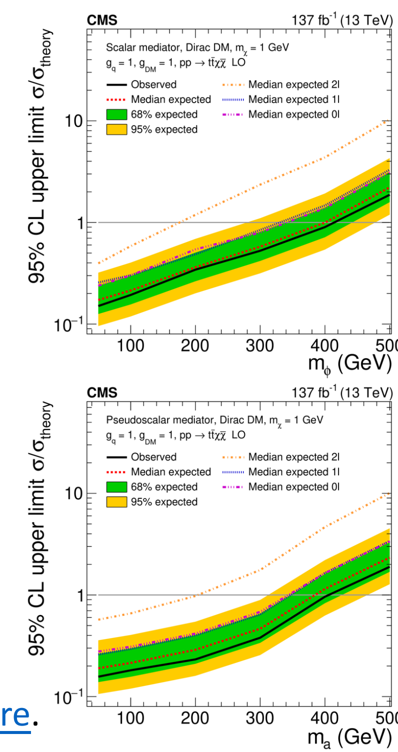


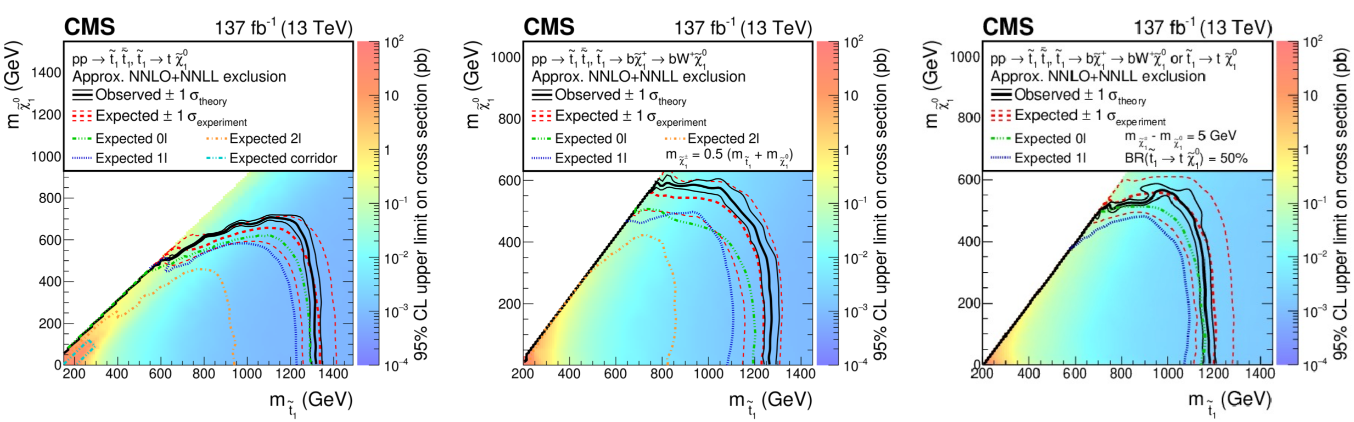
DM from stop search

[*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.



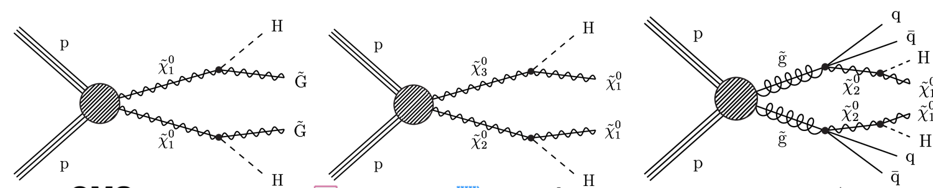


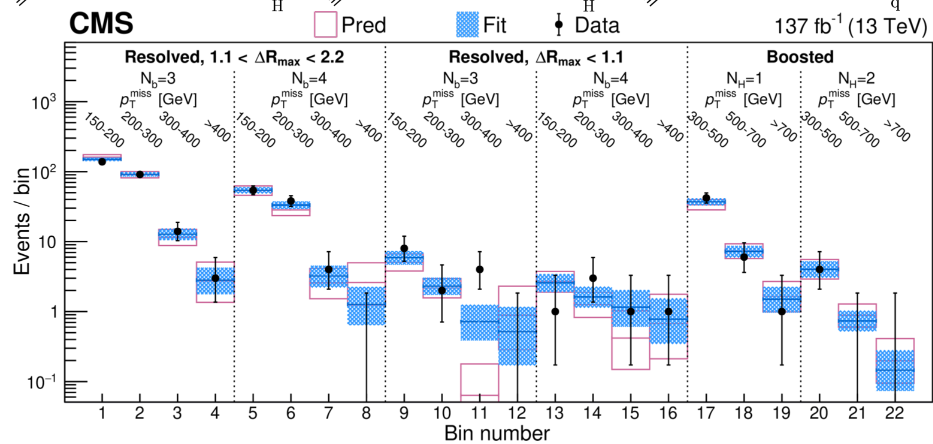
[*] Similar search for stop in 2-lepton final state from ATLAS: [*JHEP 04 (2021) 165*] with result [here].

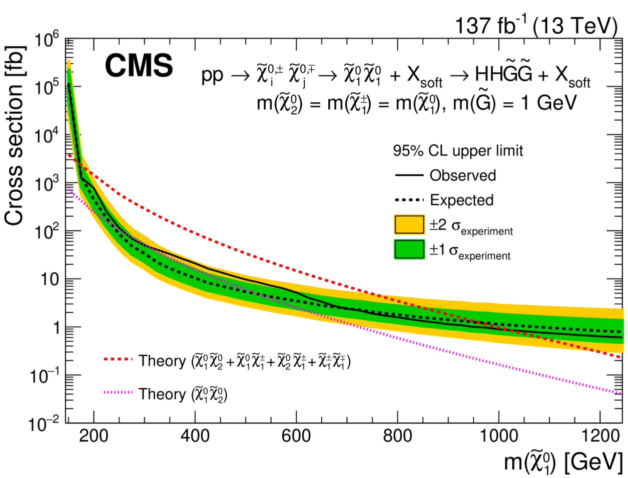
DM from higgsinos search

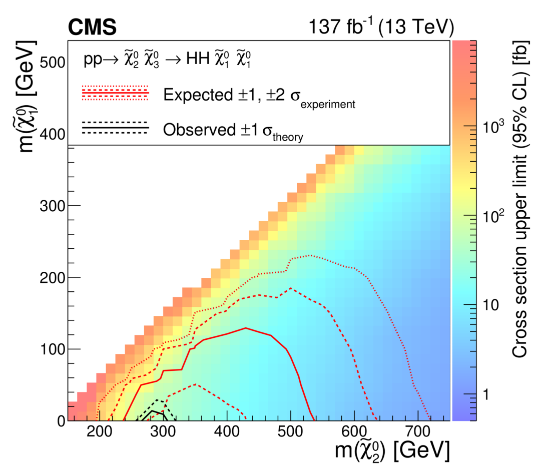
J. High Energy Phys; arXiv:2201.04206

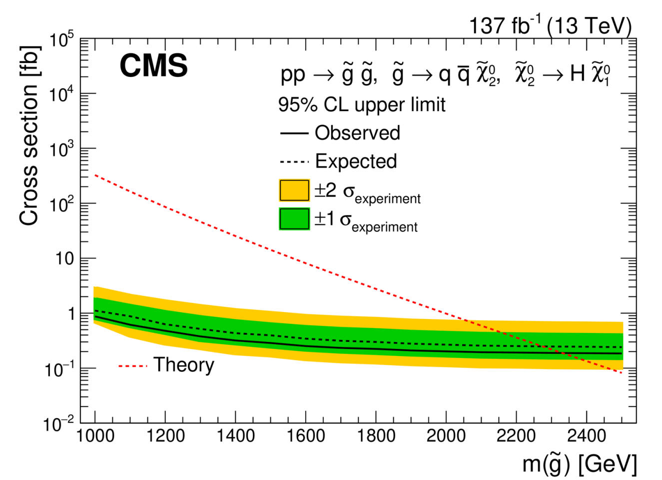
- Search in channels with two Higgs bosons, each decaying via H $\rightarrow$bb and large E_T^{miss}
- Excludes neutralino mass from [175,1025] GeV for the electroweak production of nearly mass-degenerate higgsinos, each of whose decay chains yields a neutralino that in turn decays to a massless goldstino 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;

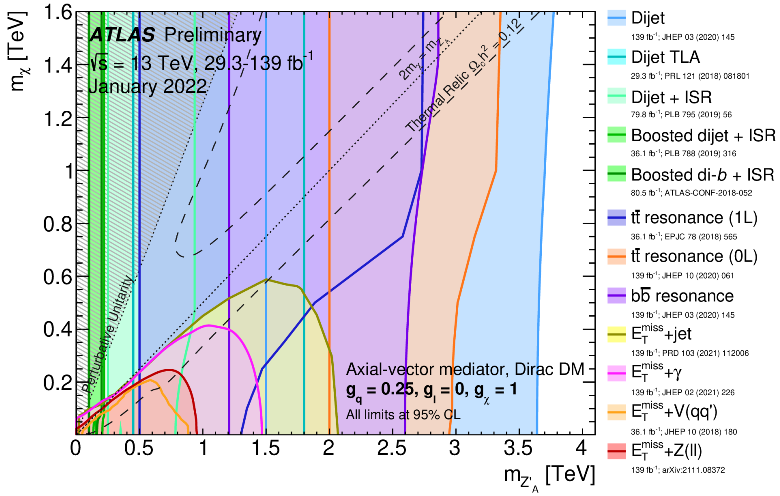
- ❖ Many experimental challenges for collider DM search;
  - ❖ Lots of rooms for triggers to be optimized to increase the selection efficiency of potential DM signal events across various kinematic phase space;
  - ❖ Potential DM signal events might be confused with detector malfunction not pass data certification;
  - ❖ Challenge in E_T^{miss} measurement to exclude pileup contribution and other background noise;
  - ❖ Rare and unusual signals buried in large backgrounds.

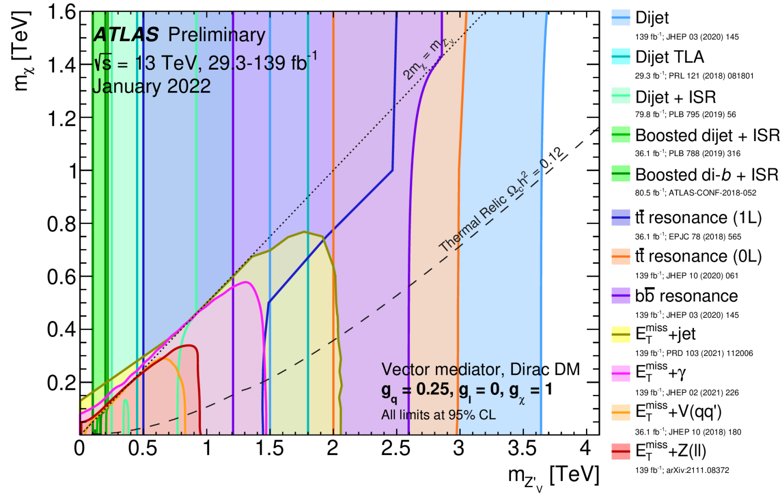
- ➢ Into the future:
  - ➢ More ideas from DM theory community to cover collider search blind spots;
  - ➢ Experiments upgrades from LS2 provide new capabilities for more valuable data;
    - ➢ better tracking -> better object identification, pileup removing
    - ➢ timing detectors -> improvement for 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.

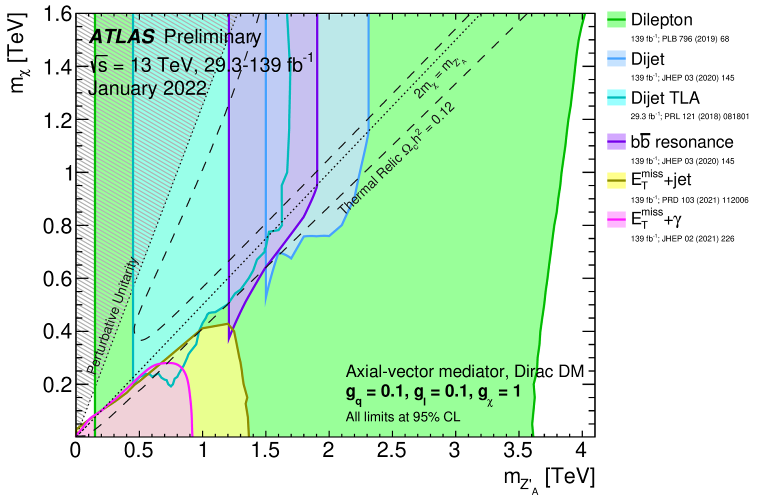
Backup Slides

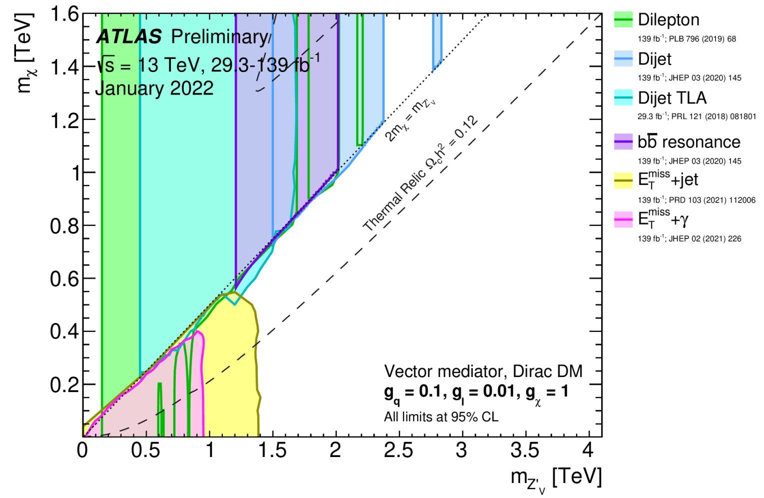
(More up-to-date summary plots and ATLAS/CMS DM search status)

DM search summary from ATLAS Run2



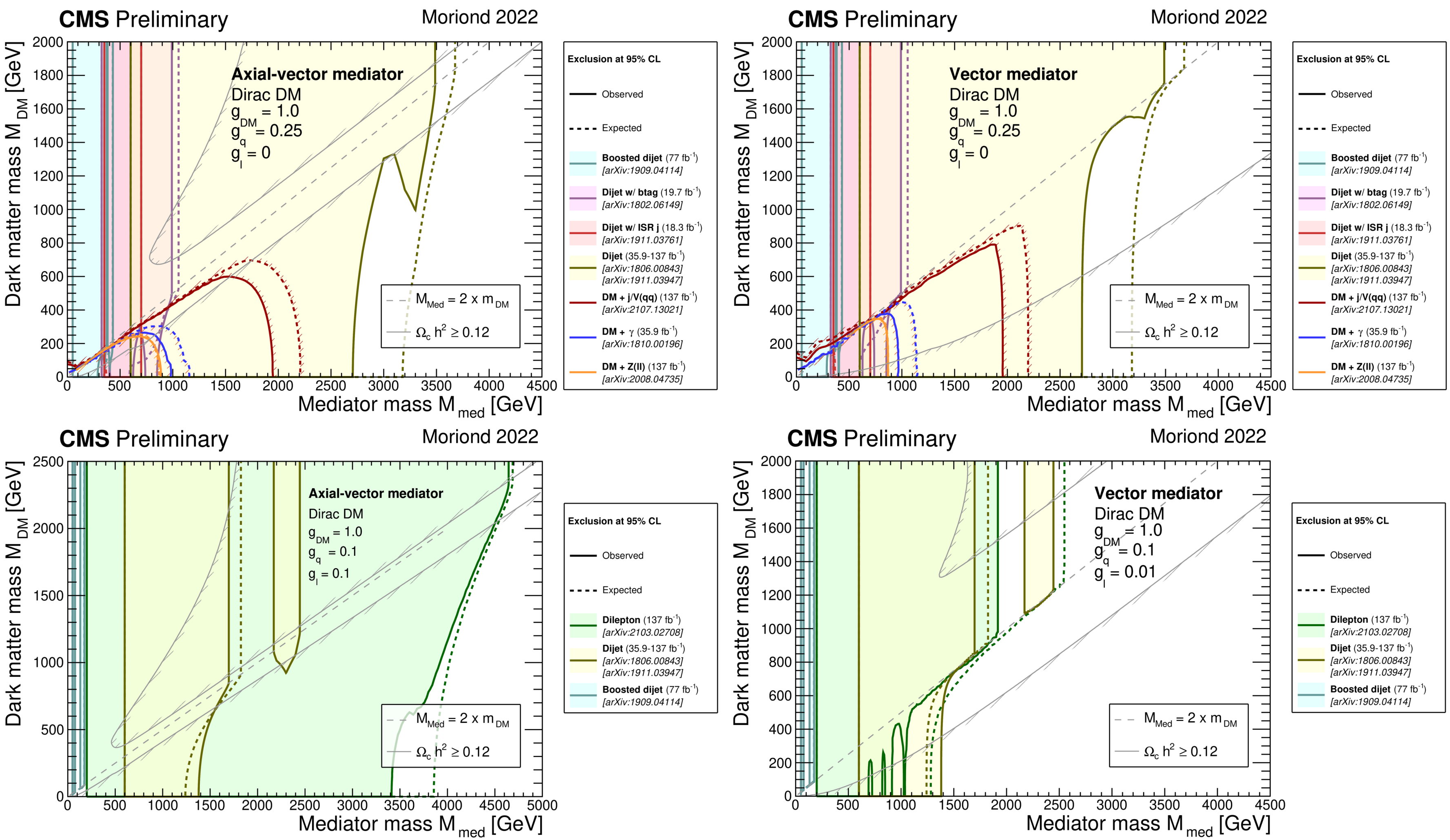






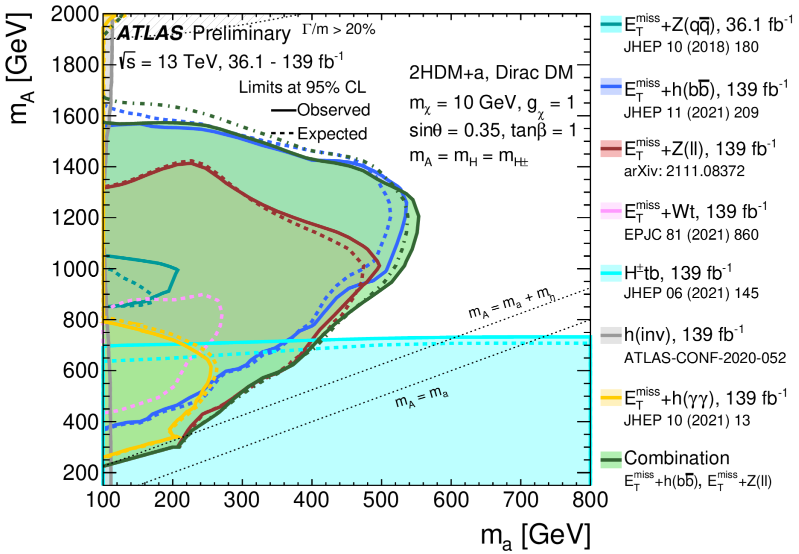
- Exclusion regions of m_{Med} and m_{DM} for simplified s-channel DM models in leptophobic and leptophilic mediator cases

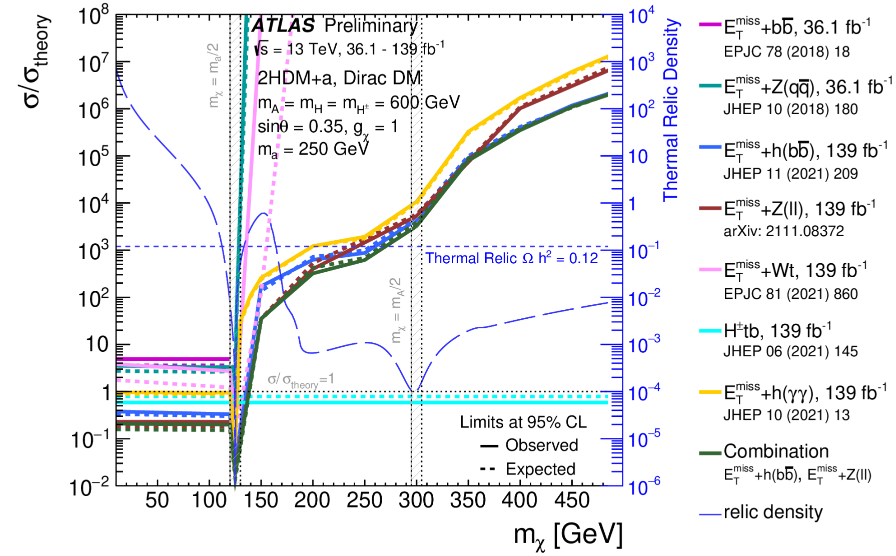
DM search summary from CMS Run2



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

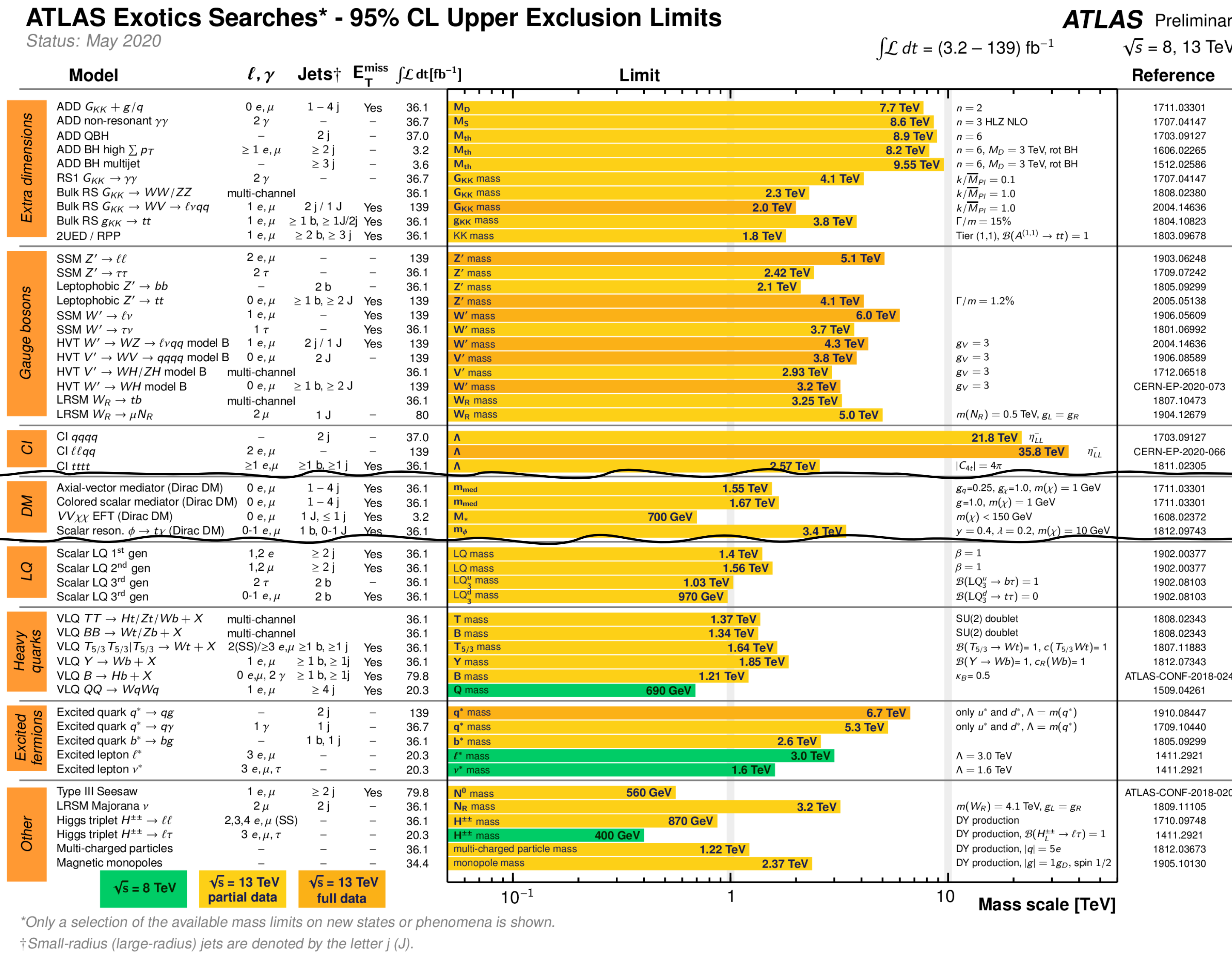
DM 2HDM+a summary from ATLAS Run2



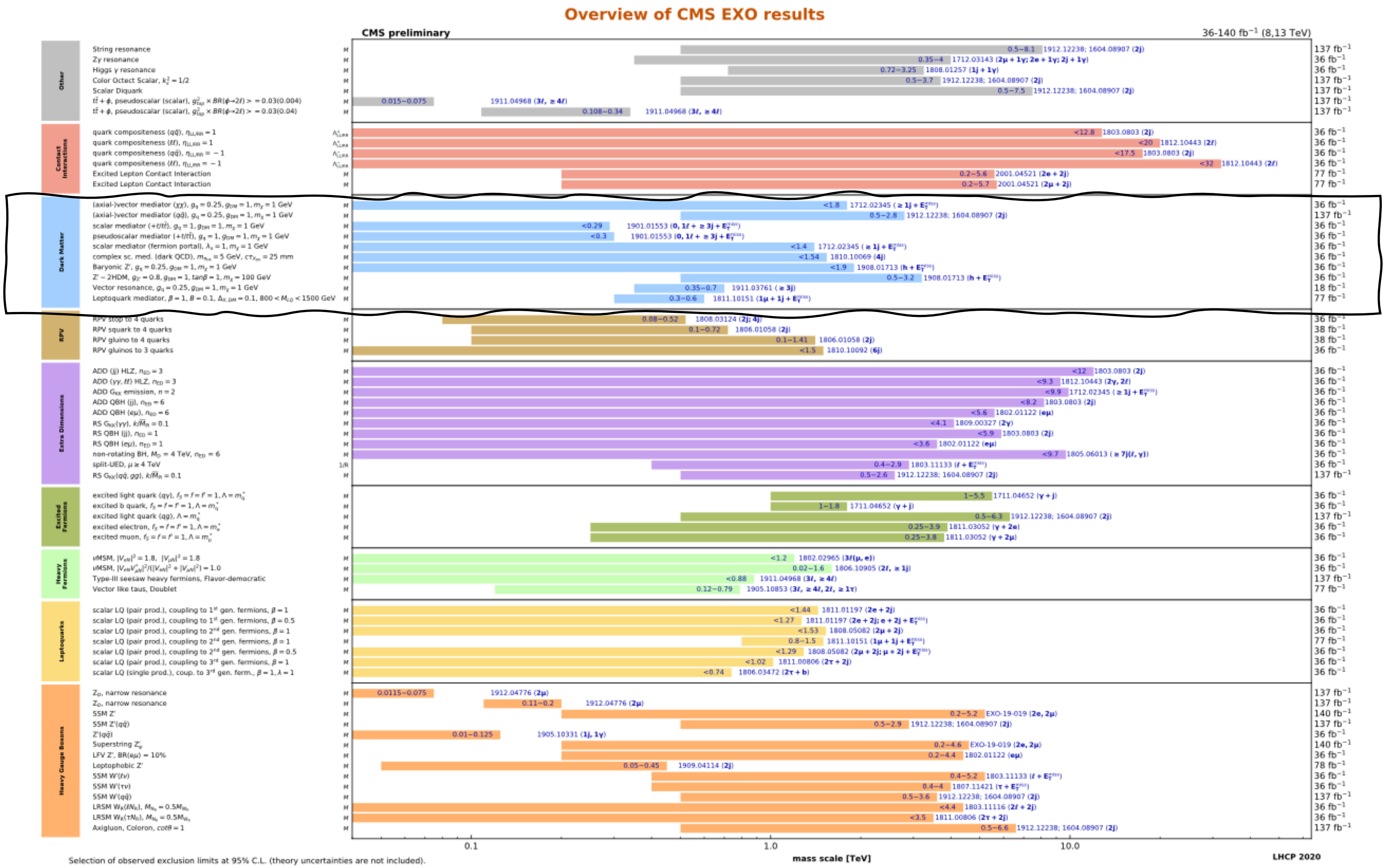


- Exclusion regions for m_a and m_A combined from public search channels
  - Most sensitive channels from mono-H and mono-Z
  - Results depend on missing angles (sinθ,tanβ)
- Excludes pseudoscalar mass up to ~550 GeV;
- Excludes Higgs double mass up to ~1550 GeV.

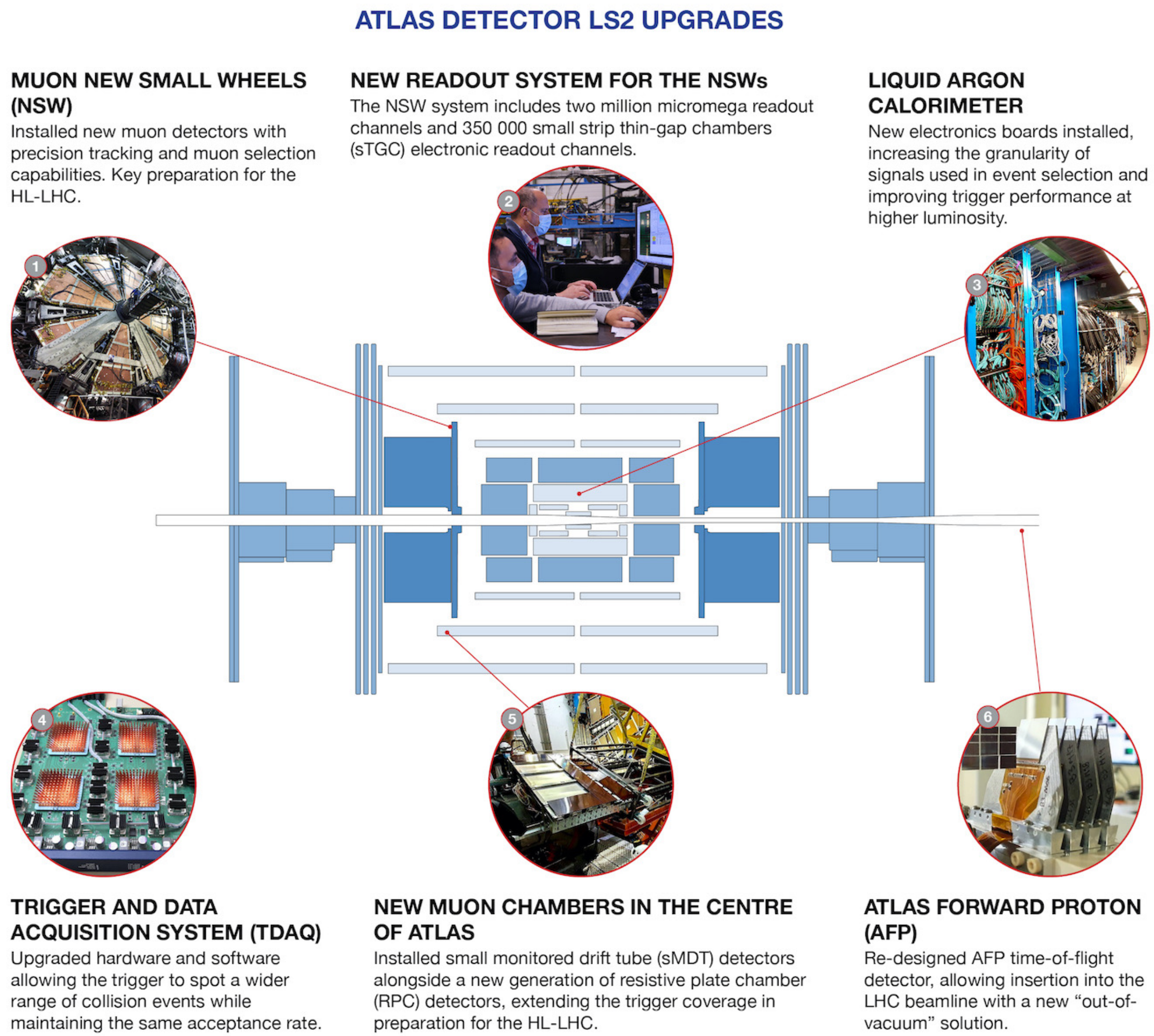
ATLAS Run2 DM search status



CMS Run2 DM search status



ATLAS LS2 upgrade



CMS LS2 upgrade