Searches for dark matter with the ATLAS detector

DIS 2022

May 3, 2022

Danika MacDonell, on behalf of the ATLAS Collaboration

Summary of Talk

Introduction to dark matter detection

Searches for invisible Higgs decays

Constraints on new spin-0 dark matter mediators

Constraints on 2HDM+a model from X+E_T^{miss} searches

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Introduction to dark matter detection

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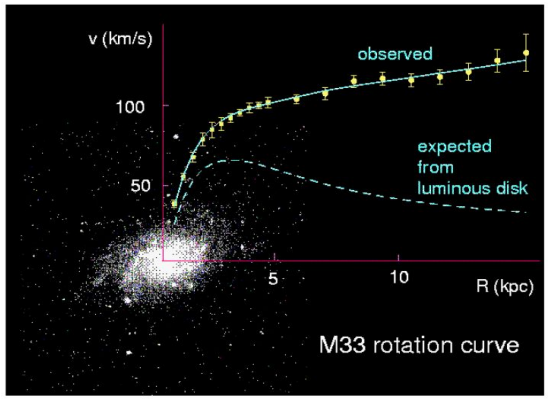
Constraints on 2HDM+a model from X+E_T^{miss} searches

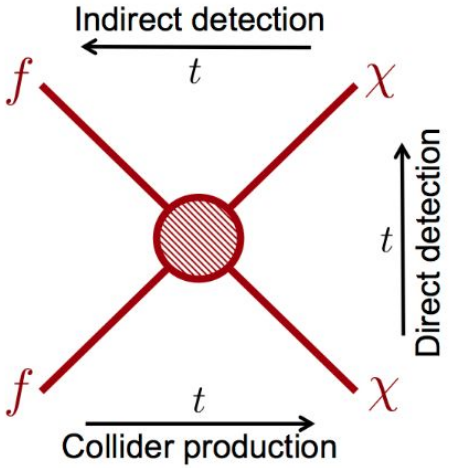
DM generically represented as χ

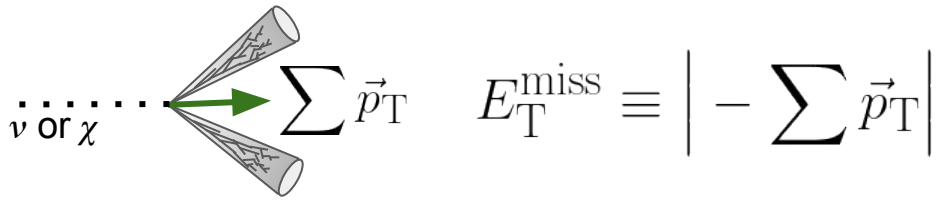
Dark Matter Detection

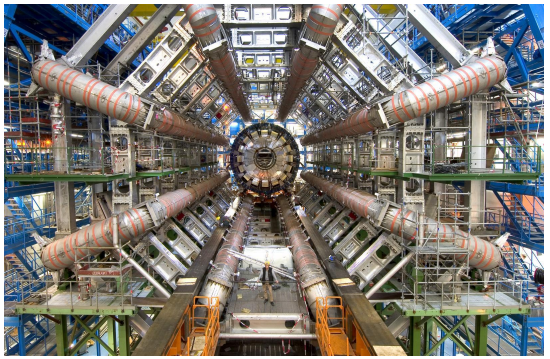


Rept.Prog.Phys.63:793,2000

- Longstanding evidence for dark matter (DM) from observations of its gravitational interactions.
- Many complementary methods aim to detect DM via non-gravitational interactions.
- DM production probed at the energy frontier at the Large Hadron Collider (LHC).
  - Assume DM is a WIMP, which passes invisibly through the detector ⇒ detectable as E_T^{miss} due to $\mathbf{p}_T$ conservation.
  - Search for signature of X+E_T^{miss}, where "X" represents visible SM particle(s).





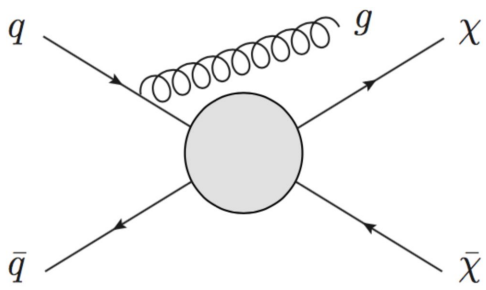


- Focus on recent DM search results using the ATLAS detector at the LHC.

Models of DM Production

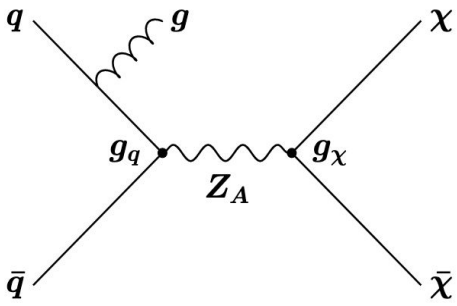
Effective Field Theories (EFT)

Dark matter production mechanism unspecified.



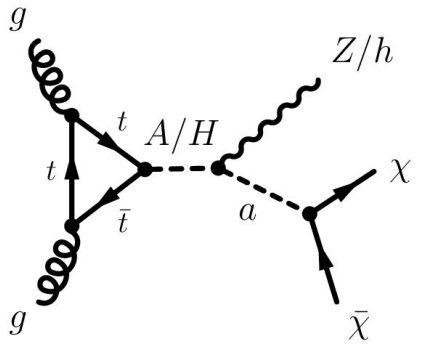
Simplified Models

- Signature-driven first-order description of new physics.
- Bridge gap between EFT and complete models.



Complete Models

- Dark matter predicted as part of a complete theory.
- Eg. 2HDM+a



Models of DM Production

EFTs were focus of Run-1 searches (2009-2013 LHC data).
⇒ limited range of signatures.

Effective Field Theories (EFT)

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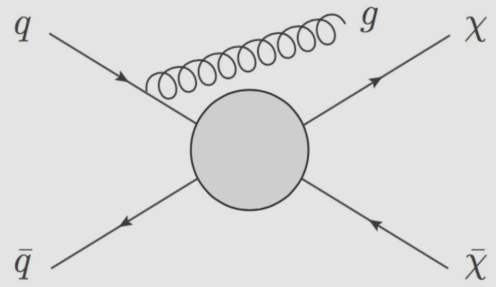

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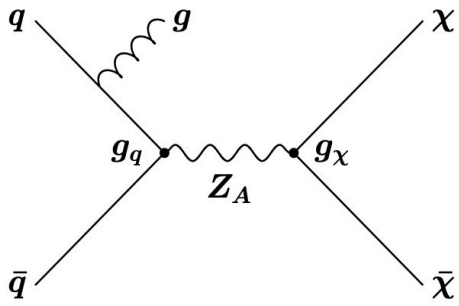

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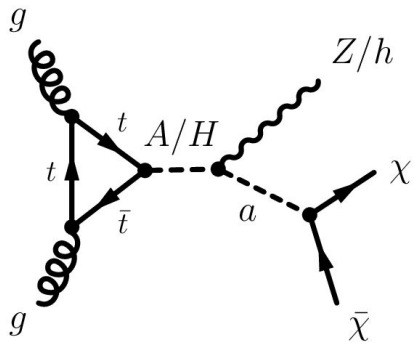

Talk covers interpretations using simplified models, and complete 2HDM+a model.

⇒ Primary focus of *Run-2* searches (2015-2018 LHC data).

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Simplified Models

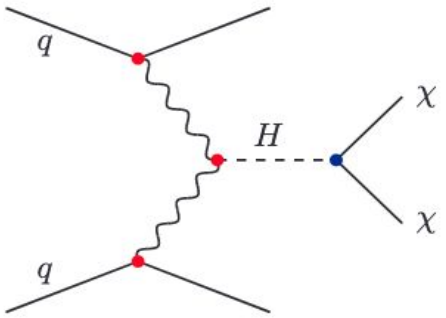
Hypothesize one or more *mediators* of interactions between DM and Standard Model (SM) particles.

⇒ Probed by E_T^{miss}+X searches, and direct resonance searches for the mediators.

Higgs portal

Free parameters:

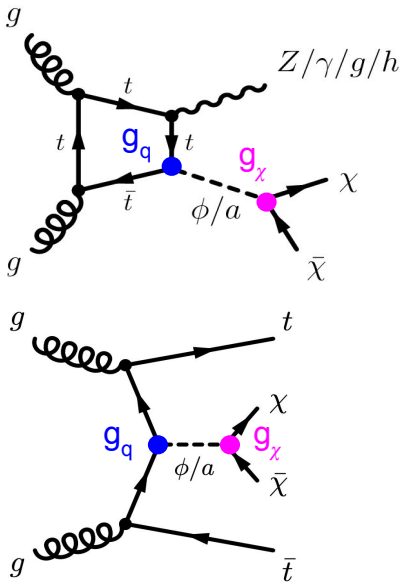
- m_χ
- χ spin



New spin-0 mediator

Free parameters:

- m_χ
- $m_{\phi/a}$
- g_q
- g_χ



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Simplified Models

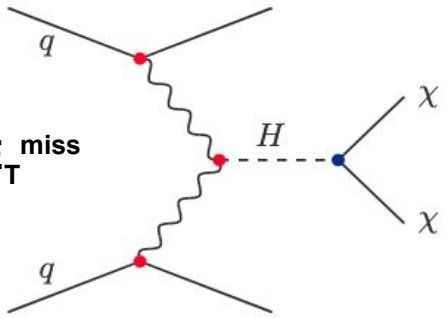
Can be probed with a rich range of final-state signatures.

- Higgs portal constrained by searches for Higgs→invisible decays.
- Spin-0 mediator model probed in $X+E_T^{miss}$ and $tt+E_T^{miss}$ final states.

Higgs portal

Most sensitive signature:

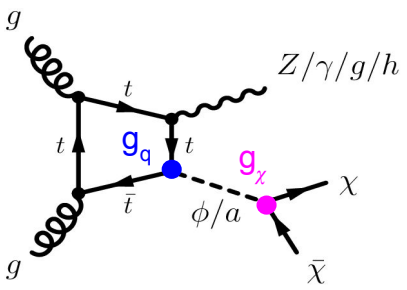
VBF+E_T^{miss}



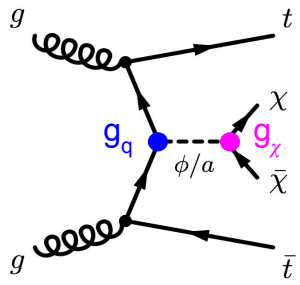
New spin-0 mediator

Signatures:

X+E_T^{miss}



tt+E_T^{miss}



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Constraints on 2HDM+a model from $X+E_T^{miss}$ searches

arXiv:2202.07953

VBF+E_T^{miss}

Higgs Portal: If the SM Higgs mediates SM-DM interactions, BF (B_{inv}) for h→inv decays could be much higher than ~0.1% predicted by SM.

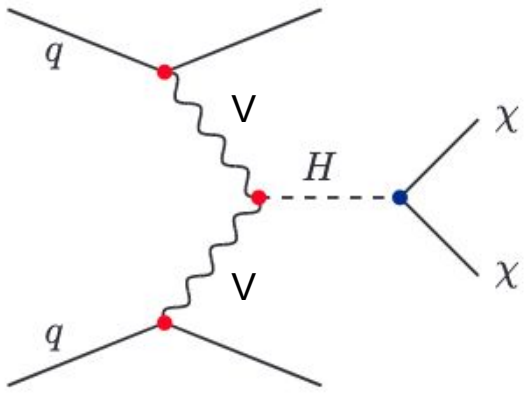
VBF+E_T^{miss} signature: Highest expected global sensitivity to B_{inv}.

- VBF+E_T^{miss}+γ (EPJC 82, 105 (2022)) and Z($\ell\ell$)+E_T^{miss} (Phys. Lett. B 829 (2022)) final states also set limits on B_{inv}.

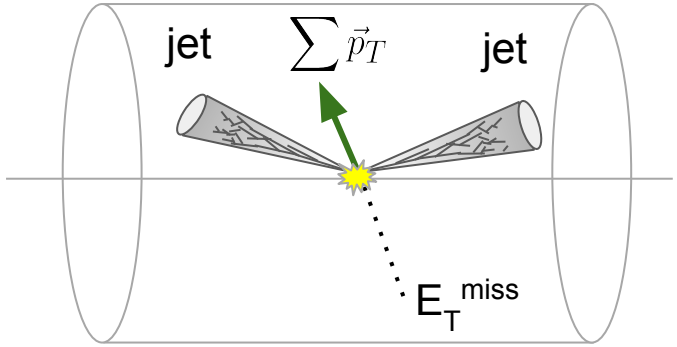
Event selection: Select for expected signal topology in signal region (SR):

- Two energetic jets in opposite hemispheres: large m_{jj} and $\Delta\eta_{jj}$.
- High E_T^{miss} to select for $\chi\chi$ in final state.
- Up to 4 final-state jets (allows for ISR/FSR).
- No leptons: n_ℓ=0.

VBF+E_T^{miss} signature



Signal Topology in Detector



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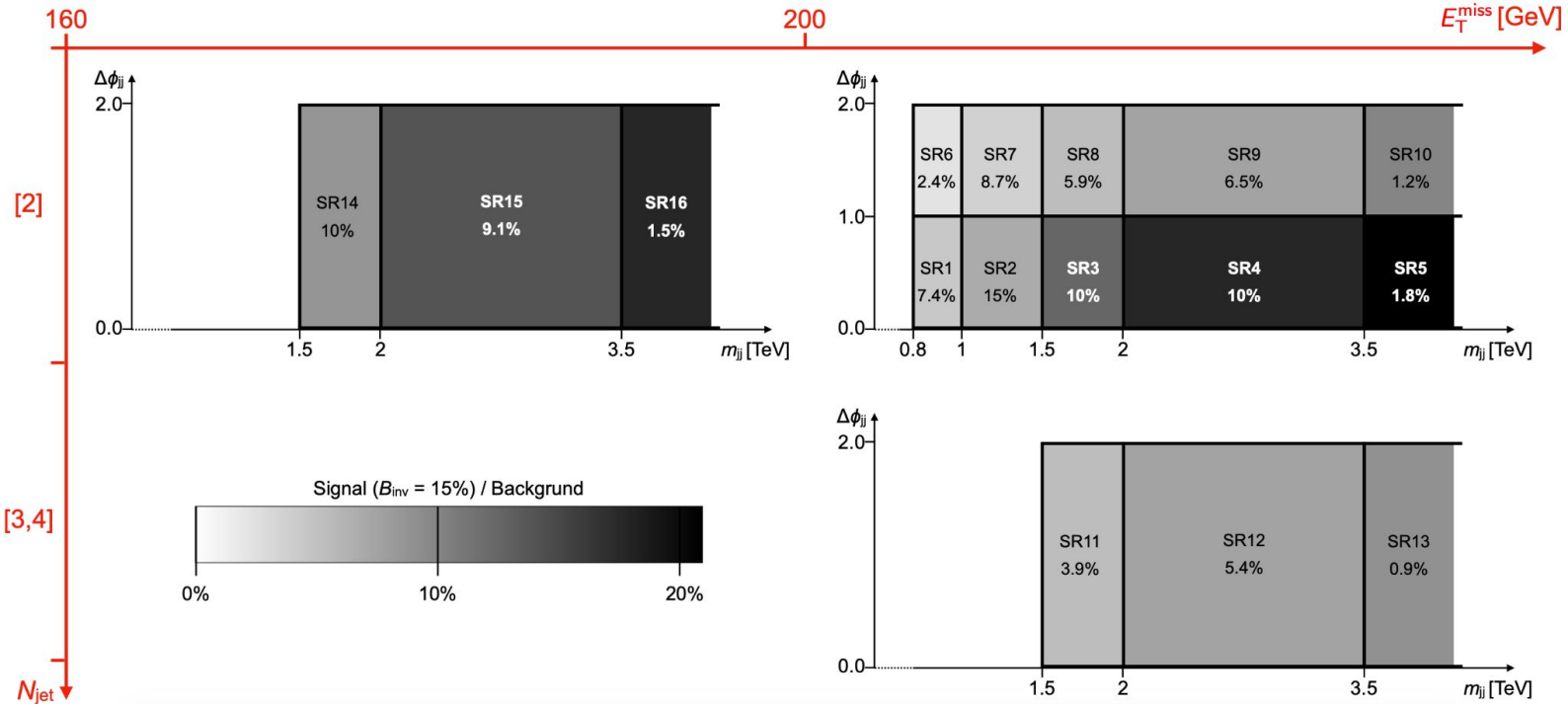
VBF+E_T^{miss}: Binning Strategy

Divide selected events into 16 bins ⇒ Improves sensitivity by adding shape info.

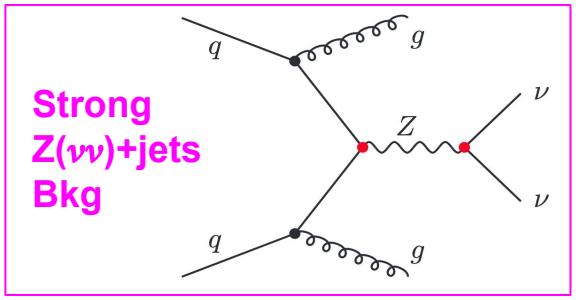
Binning variables:

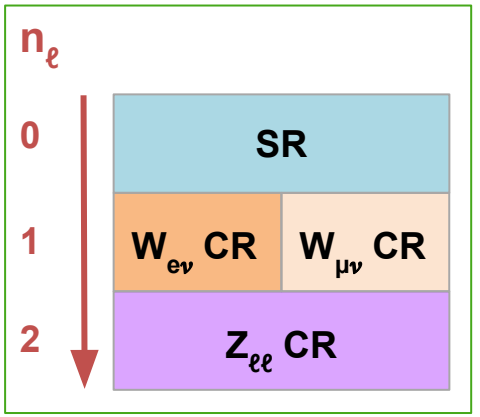
- E_T^{miss} (2 bins)
- Final-state jet multiplicity N_{jet} (2 bins)
- m_{jj}
- $\Delta\phi_{jj}$.



arXiv:2202.07953

VBF+E_T^{miss}





V+jets Bkg Estimation:

SM Z(νν)+jets and W(ℓν)+jets (V+jets) are dominant bkgs → simulated with MC.

- Using full *Run-2* dataset ⇒ important to minimize V+jets modelling uncertainties.
- Control regions (CRs) used for data-driven constraints on V+jets yields.
- Due to relatively low stats in $Z_{\ell\ell}$ CR, all V+jets bkgs constrained simultaneously in all CRs.
  - Requires precise NLO calculation of ratio $\mathcal{R}_{\mathrm{TH}}^{\mathrm{Z/W}}$ of Z to W cross sections.
  - Reweight all Z+jets events (depending on their m_{jj}) by:

    $\mathcal{R}_{\mathrm{TH}}^{\mathrm{Z/W}}(m_{\mathrm{jj}})/\mathcal{R}_{\mathrm{MC}}^{\mathrm{Z/W}}(m_{\mathrm{jj}})$ where $\mathcal{R}_{\mathrm{MC}}^{\mathrm{Z/W}}$ is the ratio for the nominal MC.

Dedicated NLO calculation of $\mathcal{R}_{\mathrm{TH}}^{\mathrm{Z/W}}$ in VBF-like phase space provided by collaborating theorists Jonas Lindert, Marek Schönherr and Stefano Pozzorini.

Multijet Bkg Estimation: also important due to large uncertainty.

- Estimated with two independent methods (simulation and dedicated CR)
- Use combination of both methods to get multijet estimate with minimal uncertainties.

Statistical Analysis:

- Apply same binning used in SR to all CRs.
- h→inv signal model simulated, assuming 100% B_{inv}.
- Simultaneous profiled likelihood fit of signal and SM backgrounds to data in all bins of SR and CRs.
- Floating fit parameters:
  - h→inv BF
  - V+jets normalization factor β_i in each bin i.

VBF+E_T^{miss}

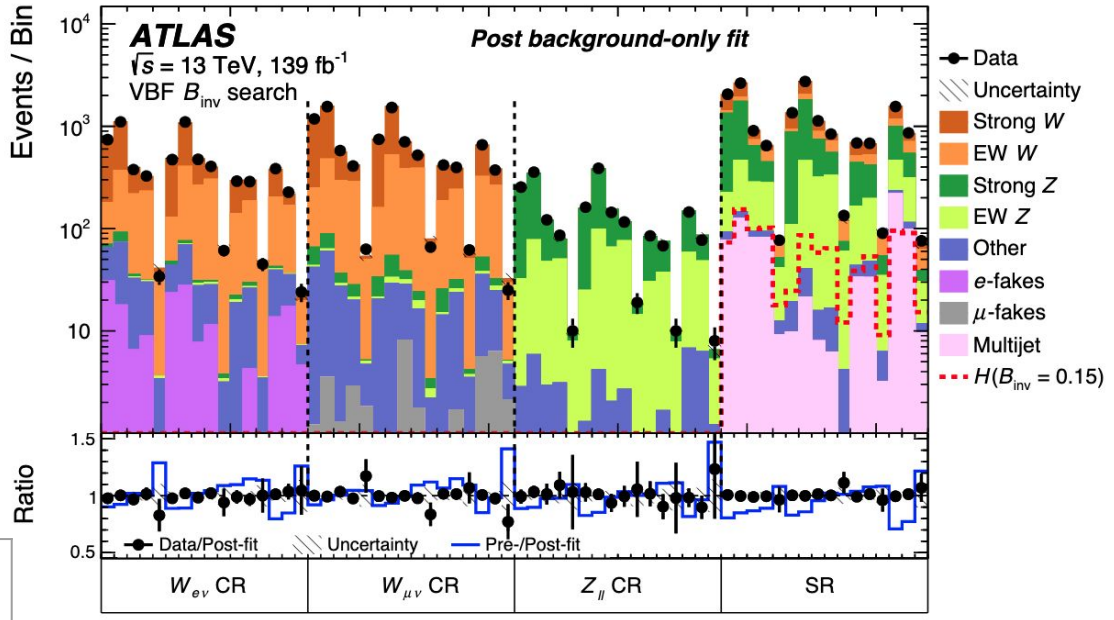
VBF+E_T^{miss} Result: Data consistent with SM bkg ⇒ upper limit placed on B_{inv} using CL_s method.

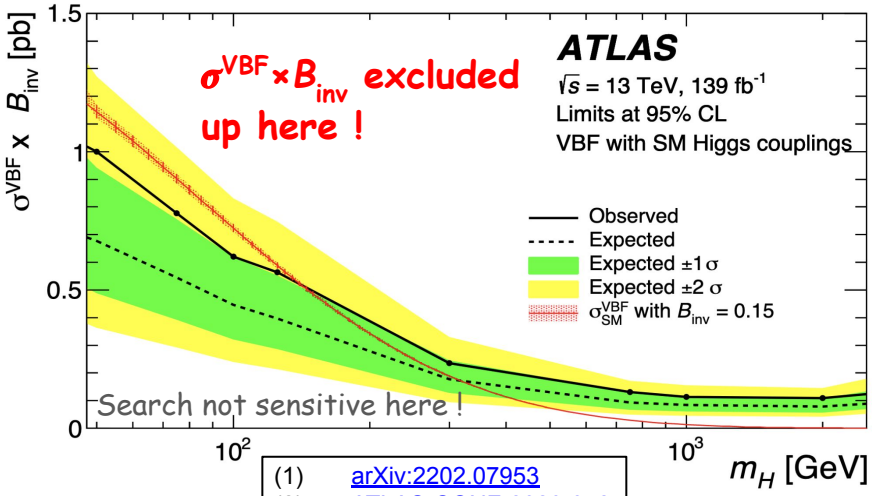
Combo: Recent combo of h→inv searches (ATLAS-CONF-2020-052, see backup)

⇒ sensitivity dominated by VBF+E_T^{miss}

	Publication	Expected B_{inv}^{upper}	Observed B_{inv}^{upper}
(1)	VBF+E_T^{miss}	10.3%	14.5%
(2)	h→inv combo	11%	11%
(3)	Z(ℓℓ)+E_T^{miss}	19%	19%
(4)	VBF+E_T^{miss}+γ	34%	37%

Constraints on $\sigma_{VBF}\times B_{inv}$ for new scalar mediator: Latest VBF+E_T^{miss} search also places upper bounds on $\sigma^{VBF}\times B_{inv}$ for new scalar mediator of variable mass (assume couplings otherwise follow SM Higgs).





(1) arXiv:2202.07953
(2) ATLAS-CONF-2020-052
(3) Phys. Lett. B 829 (2022)
(4) EPJC 82, 105 (2022)

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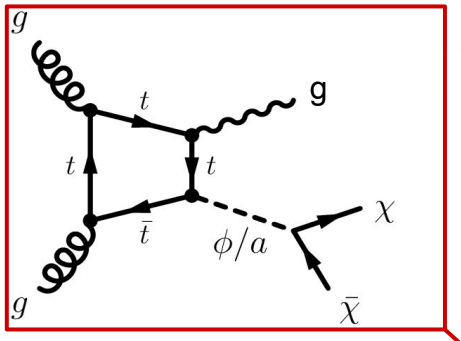
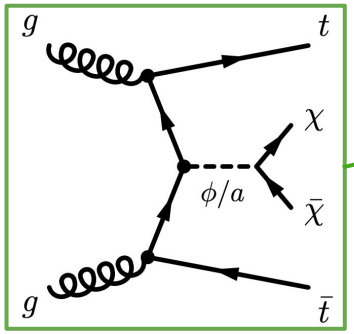
X+E_T^{miss} Bounds on New Spin-0 Mediators

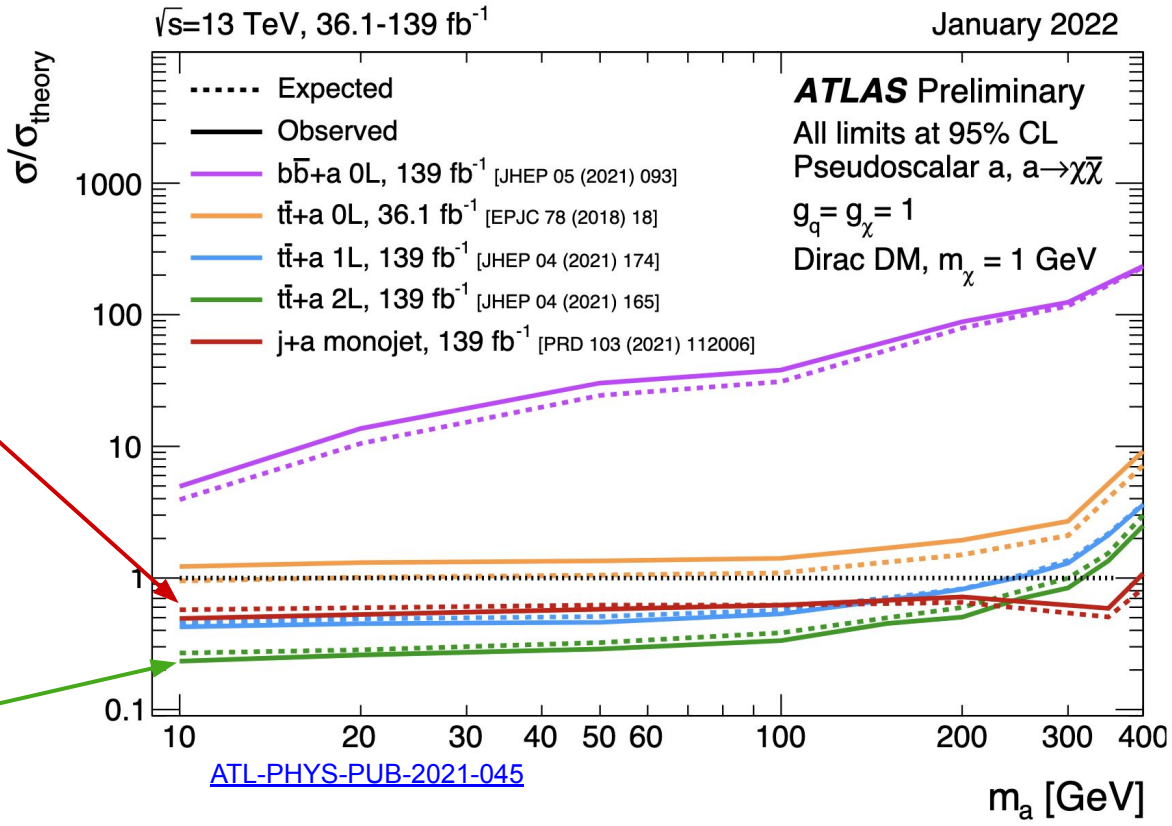
Tightest bounds(*) on simplified spin-0 mediator model come from searches in the tt+E_T^{miss} and jet+E_T^{miss} (PRD 103, 112006 (2021)) final states.

jet+E_T^{miss} signature



tt+E_T^{miss} signature





(*)Comparison of bounds depends on choice of couplings.

ATLAS-CONF-2022-007

$tt+E_T^{miss}$ Combination

Recently performed statistical combination of $tt+E_T^{miss}$ searches (ATLAS-CONF-2022-007).

General selections for $tt+E_T^{miss}$ final state:

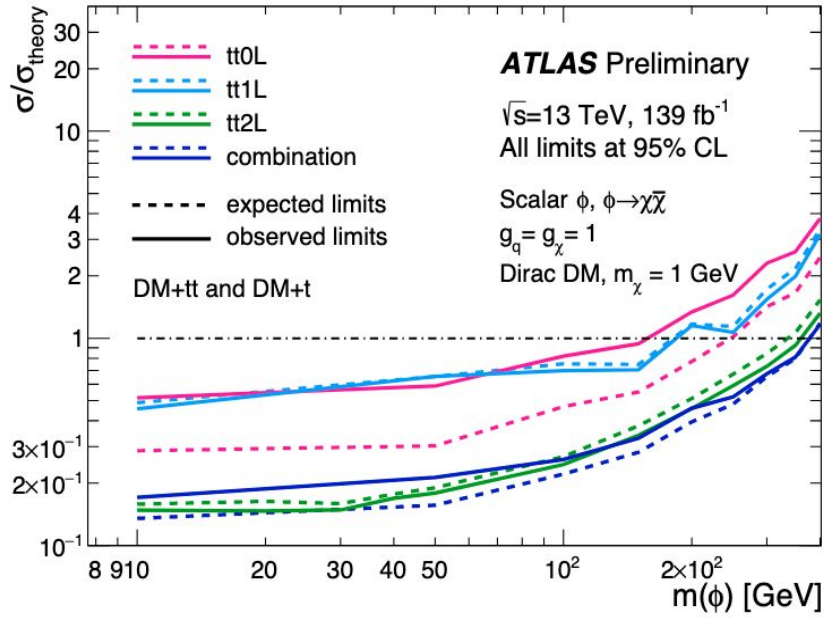
- ≥1 b-tagged jet ($t \rightarrow bW$ decay dominant)
- High E_T^{miss}

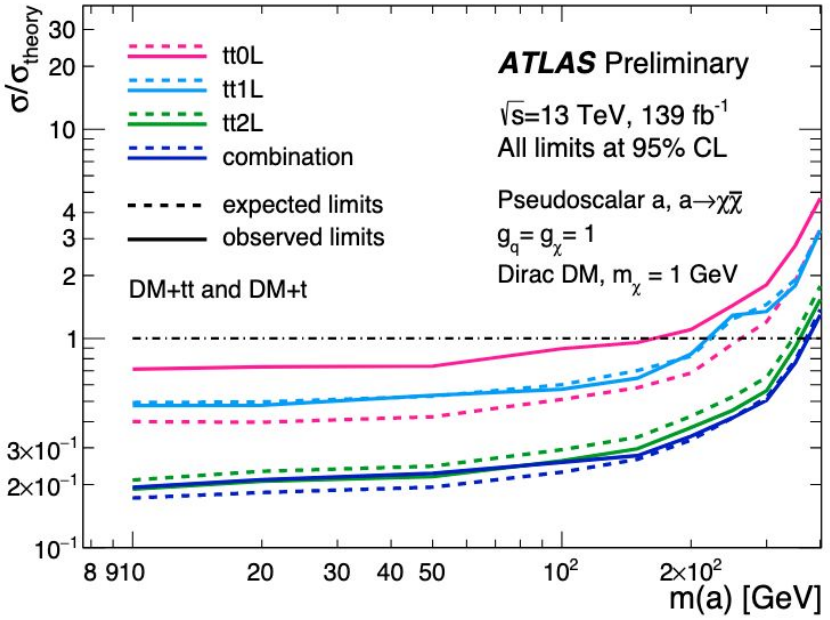
Combination:

- tt0L (EPJC 80, 737 (2020)): fully hadronic
  - Newly-added "tt0l-low" selection optimized at low E_T^{miss} to target low mediator masses,
- tt1L (JHEP 04, (2021) 174): semileptonic
- tt2L (JHEP 04, (2021) 165): fully leptonic
  - Fully-leptonic (tt2L) most sensitive to simplified spin-0 mediator model.

Results:

- Excluded mass range(*) of scalar (pseudoscalar) spin-0 mediator extended by 100 (30) GeV relative to tt2L alone.





(*)Mediator masses for which σ/σ_{theory}>1 are excluded.

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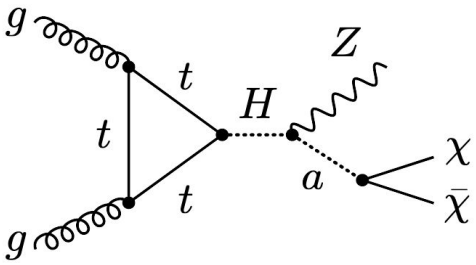
arXiv:1810.09420

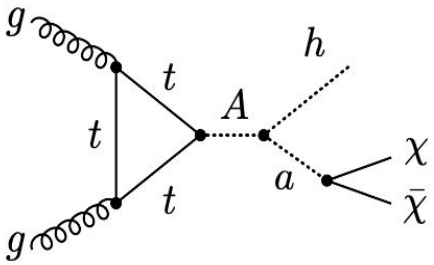
2HDM+a Model

- Extend the SM by postulating:
  - **Two** Higgs doublets
  - New pseudoscalar DM mediator “a”
- Predicts 5 Higgs bosons:
  - 2 scalars: h (SM Higgs), H (new particle)
  - 1 heavy pseudoscalar A
  - 2 charged Higgs $H^{\pm}$
- Adds several free parameters, incl.:
  - m_A, m_H, m_a
  - tanβ: ratio of VEVs of the two Higgs doublets
  - sinθ: Mixing angle between a and A
- Simplest gauge-invariant and renormalizable extension of simplified pseudoscalar DM mediator model.
- Wide variety of complementary signatures.
- Visible SM particle(s) produced by hard scatter rather than ISR.
- *Run-2* ATLAS data can probe 2HDM+a parameters consistent with observed DM relic density.

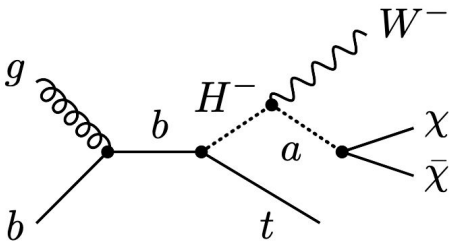
Z+E_T^{miss} Signature



h+E_T^{miss} Signature



tW+E_T^{miss} Signature



Benchmark Parameter Choices

$$M_H = M_A = M_{H^{\pm}}$$

$$\tan\beta = 1$$

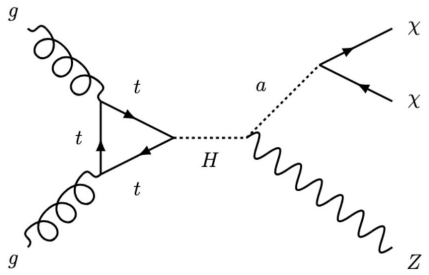
$$m_\chi = 10\,\text{GeV}$$

$$\sin\theta = 0.35$$

Phys. Lett. B 829 (2022)

$Z(\ell\ell)+E_T^{miss}$

2HDM+a signature (s-channel)



Strong constraints on 2HDM+a model.

⇒ Most recent search targets $Z\rightarrow\ell\ell$ decay.

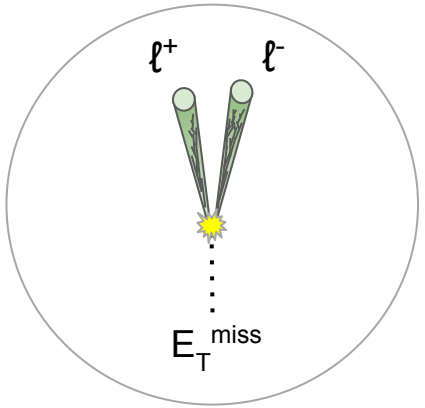
Event selection:

- **Signal topology:** collimated $\ell^+\ell^-$ pair, recoiling against E_T^{miss}.

  ⇒ Require:
  - Small $\Delta R_{\ell\ell}$
  - $m_{\ell\ell}$ near m_Z
  - large E_T^{miss}

n_ℓ	Same-flavour ℓℓ	Opposite-flavour ℓℓ
2	SR	eμ CR
3	3ℓ CR	
4	4ℓ CR	

Signal Topology in Detector



Background Estimation:

- Dominant SM background from ZZ($\ell\ell\nu\nu$), followed by WZ and Z+jets and non-resonant (WW, tt, single top, $Z\rightarrow\tau\tau$).
- All background processes modelled with MC simulation.
- CRs additionally defined for data-driven constraints.

CR	Constrains
eμ	Σ(non-resonant bkgs)
3ℓ	WZ bkg
4ℓ	ZZ bkg

Phys. Lett. B 829 (2022)

$Z(\ell\ell)+E_T^{miss}$

Fit strategy:

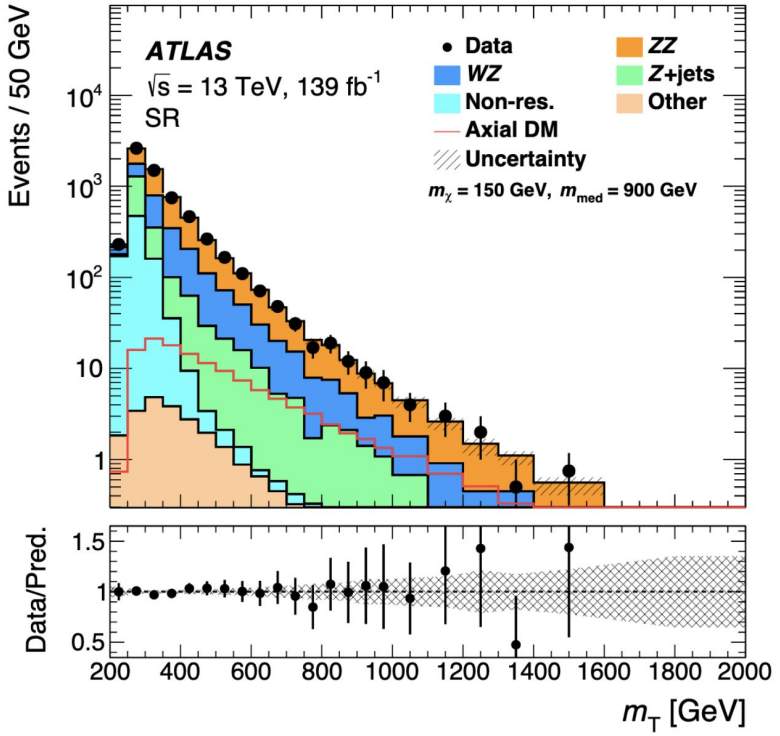
- Bin SR and eμ CR in ZZ m_T to improve shape discrimination:

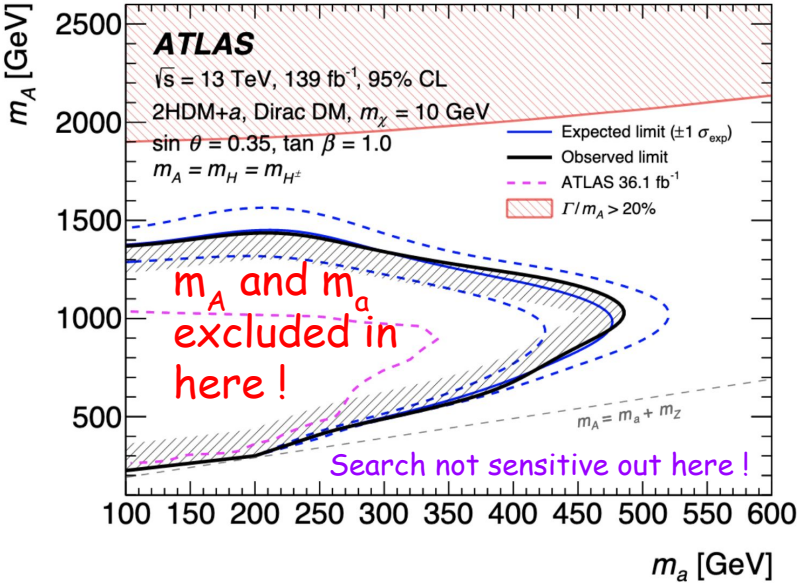
$$m_{\mathrm{T}} = \sqrt{\left[\sqrt{m_Z^2 + (p_{\mathrm{T}}^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_{\mathrm{T}}^{\mathrm{miss}})^2}\right]^2 - \left[\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right]^2}$$

- Bin 3ℓ CR and 4ℓ CR in E_T^{miss}.
- Simulate 2HDM+a signal model over range of m_a, m_A, tanβ, sinθ.
- For each parameter choice, simultaneous likelihood fit in SR and all CRs, fit for:
  - signal strength μ,
  - normalizations of WZ and Σ(non-resonant bkgs).

Results: Good agreement between data and SM background prediction.

⇒ Limits set on 2HDM+a model.

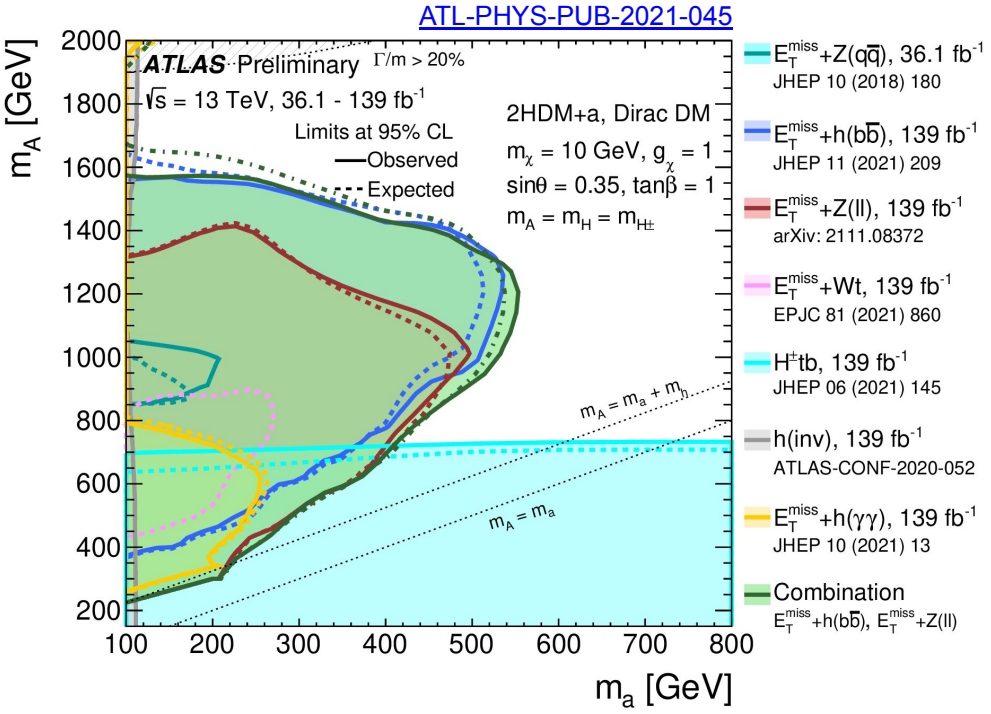




Summary of Constraints on 2HDM+a Model

- Tightest constraints with respect to m_a and m_A from statistical combination (ATL-PHYS-PUB-2021-045) of $Z(\ell\ell)+E_T^{miss}$ and $h(bb)+E_T^{miss}$.
- Parameter space also ruled out by direct searches for charged Higgs in $H^{\pm}\rightarrow tb$ channel.
- Search in the $tW+E_T^{miss}$ final state (EPJC 81, 860 (2021)) additionally provides constraints with respect to $m(H^{\pm})$

  → more recent result (ATLAS-CONF-2022-012) in backup.



Conclusions

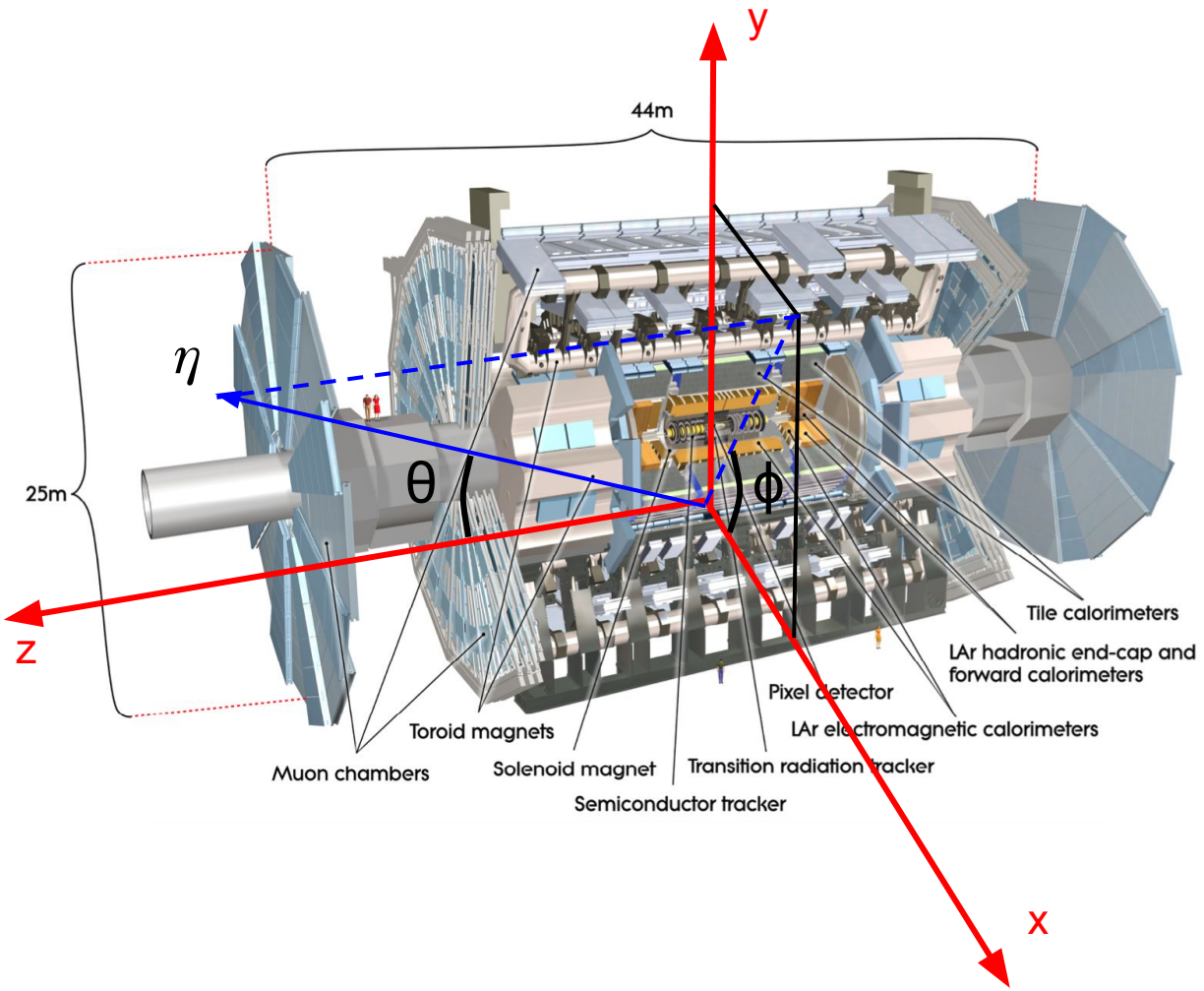
Presented recent results from the broad ATLAS dark matter search programme.

- Signature-driven approach → dedicated analyses probe specific final states.
- Large variety of final states probed → leave no stone unturned!
- Many DM search results with *Run-2* ATLAS data still to come.
  - Will both add new channels, and improve upon previously studied channels.

Backup

The ATLAS Detector

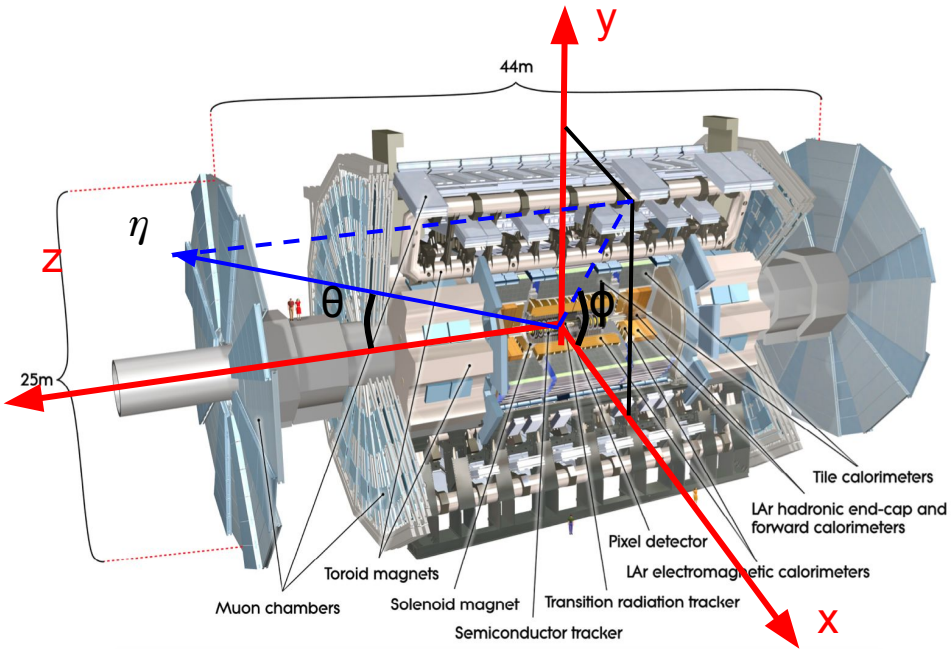
- General-purpose detector for studying particles produced by high-energy beam collisions at the LHC.
- Used both for precision standard model measurements and to search for new physics.



Pseudorapidity

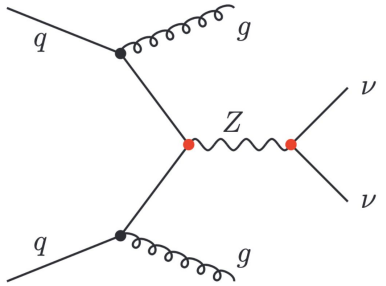
- Describes angle of particle relative to beam axis (z-axis).
- Changes Δ in pseudorapidity are Lorentz invariant under boosts along the longitudinal axis.

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

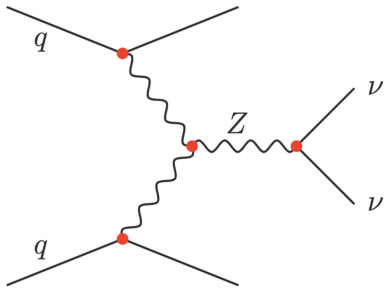


VBF+E_T^{miss}: Strong vs. EW W and Z Backgrounds

- **Strong:** Two electroweak (EW) vertices and two strong vertices in the hard scatter process.



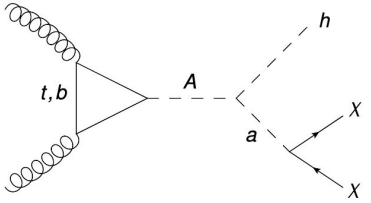
- **Weak:** Four electroweak (EW) vertices in the hard scatter process.



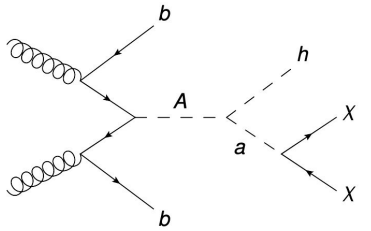
More info about variable-radius track jets in: JHEP 06 (2009) (059).

h(bb)+E_T^{miss}

2HDM+a ggF signature



2HDM+a bbA signature



- Can also probe the 2HDM+a model with h+E_T^{miss} final state.
- Most sensitivity from **h→bb** decay mode (JHEP 11 (2021) 209) ⇒ focus of next two slides.
- h→γγ also studied (JHEP 10 (2021) 013), with complementary sensitivity.

Event selection:

- At least two b-tagged jets recoiling against large E_T^{miss} with no leptons.
  - $\Delta\phi(jet_{1,2,3}, E_T^{miss}) > 20°$ reduces SM backgrounds with E_T^{miss} arising from jet mismeasurement.
- Divide events into two regions depending on N(b-tagged jets):
  - **2 b-tagged jets:** targets gluon-gluon fusion (ggF) signature
  - **≥3 b-tagged jets:** targets b-associated production (bbA) signature.
- Further divide into resolved and merged regions depending on final-state topology.

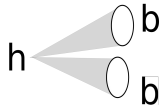
Background Estimation:

- Dominant SM background processes are tt and W/Z + heavy flavour quarks (W/Z+HF) ⇒ simulated with MC.
- 1μ and 2ℓ CRs for data-driven constraints of dominant bkgs.

2 b SR	2 b 1μ CR	2 b 2ℓ CR
3 b SR	3 b 1μ CR	3 b 2ℓ CR

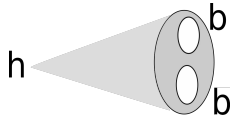
Resolved Region

- Less-boosted Higgs
- Reconstruct h as 2 small-radius b-tagged jets



Merged Region

- More-boosted Higgs
- Reconstruct h as 1 large-radius jet with 2 variable-radius track jets associated to Higgs.



CR	Constrains
1μ	tt and W+HF bkgs
2ℓ	Z+HF bkg

h(bb)+E_T^{miss}

Binning Strategy:

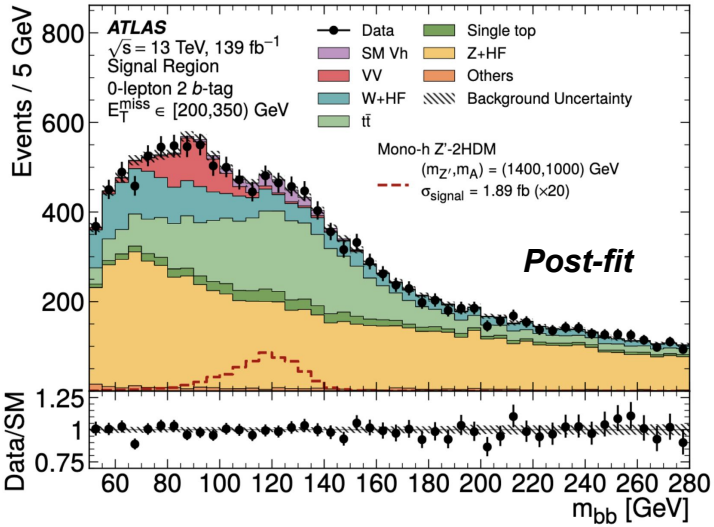
- Bin all SRs and CRs in E_T^{miss} (same binning across all regions) to improve shape discrimination.
- Additionally bin all SRs (but not CRs) in reconstructed Higgs mass m_{bb}.

Statistical Analysis:

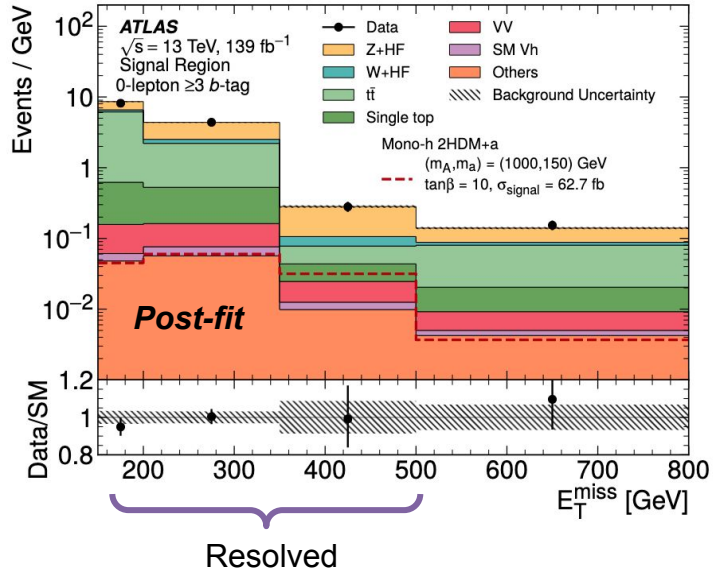
- 2HDM+a signal model simulated over range of m_a and m_A (ggF and bbA production modelled separately).
- At each modelled signal point, perform simultaneous likelihood fit in all bins of SRs and CRs.
- Floating parameters:
  - Signal strength μ
  - Four background normalization factors, which scale:
    - Z+HF with 2 b-tagged jets
    - Z+HF with ≥3 b-tagged jets
    - W+HF with ≥2 b-tagged jets
    - tt with ≥2 b-tagged jets

Result: No significant deviation from SM background expectations.

JHEP 11 (2021) 209

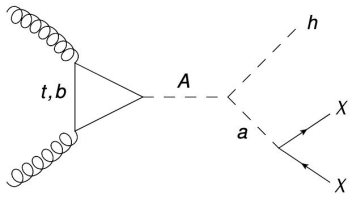


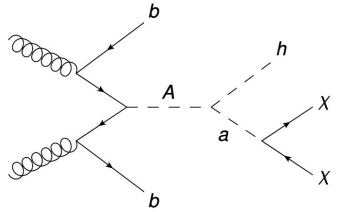
JHEP 11 (2021) 209



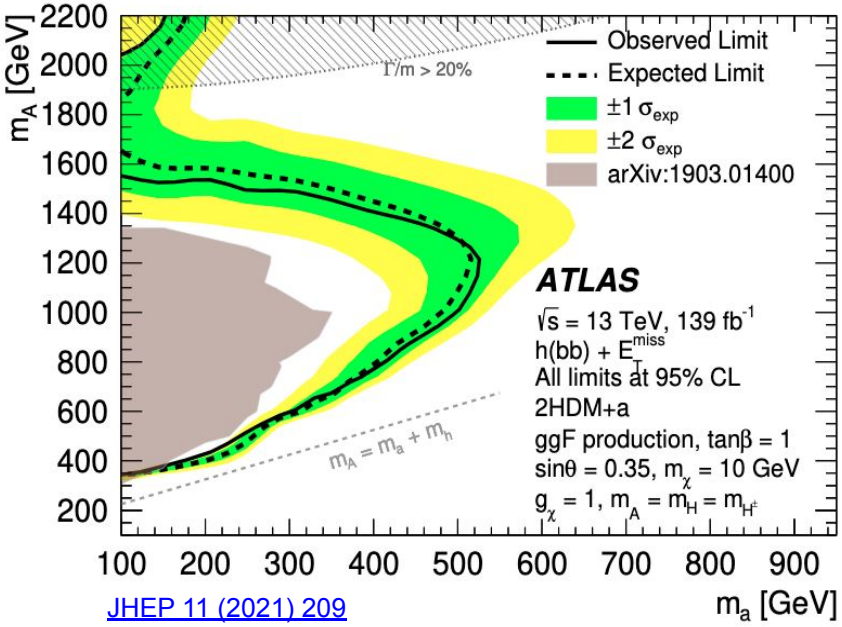
h(bb)+E_T^{miss}: Constraints on 2HDM+a Model

Exclusion limits placed in m_A vs. m_a plane for ggF and bbA production separately.



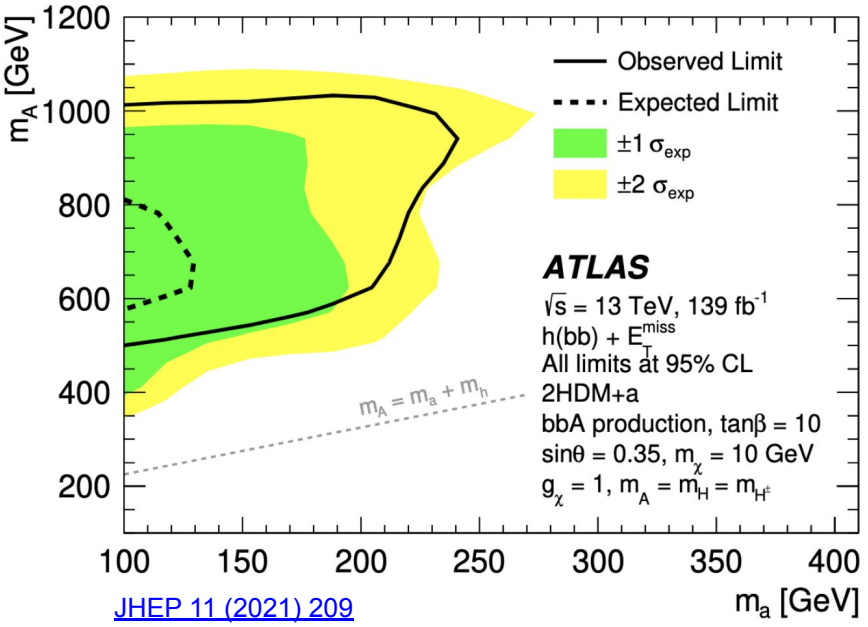


ggF Production



JHEP 11 (2021) 209

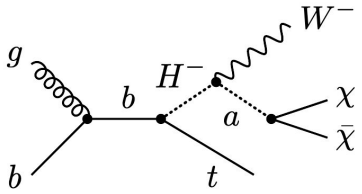
bbA Production



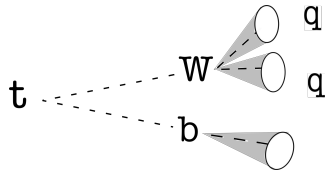
JHEP 11 (2021) 209

$tW+E_T^{miss}$

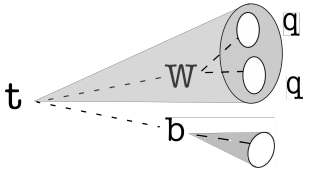
2HDM+a signature with $H^{\pm}$ mediator



W_{had} reco with 2 small-radius jets



W_{had} reco with 1 large-radius jet



A search performed in the $tW+E_T^{miss}$ channel (ATLAS-CONF-2022-012) provides a probe of $m(H^{\pm})$ in the 2HDM+a model.

⇒ Complements previous search (EPJC 81, 860 (2021)) by additionally considering fully-hadronic final state (tW_{0L}).

⇒ Performs statistical combination with tW_{2L} in previous search.

Event Selection:

- $t\rightarrow Wb$ decay proceeds with >99% BR ⇒ expect $Wb+W+E_T^{miss}$ final state.
- Require ≥1 high-p_T b-jet recoiling against large E_T^{miss} (≥250 GeV)
- Further divided into 1- and 2-lepton channels:
  - SR_{tW0L}: both final-state Ws decays hadronically
  - SR_{tW1L}: one final-state W decays leptonically ⇒ divide 1L SR into $t\rightarrow W(\ell\nu)b$ ($SR_{tW1L}^{lep.top}$) and $t\rightarrow W(jj)b$ ($SR_{tW1L}^{had.top}$)
- Previous search (EPJC 81, 860 (2021)) also considered:
  - SR_{tW2L}: both Ws decay leptonically.

Event Reconstruction:

- **New for this search:** high-p_T hadronically-decaying W_{had} can be reconstructed with a single large-radius jet (previously could only reconstruct W_{had} with two small-radius jets).

  ⇒ Event selection requires ≥1 large-radius jet consistent with W_{had} (“W-tagged”).

Background estimation:

- 6 control regions defined for data-driven constraints of dominant SM bkgs:
  - Z+jets, W+jets, tt, ttZ, single top

tW+E_T^{miss}: Statistical Analysis

Binning Strategy:

- Bin SR_{tW0L} and $SR_{tW1L}^{had.top}$ into 5 E_T^{miss} bins (no binning in $SR_{tW1L}^{lep.top}$ due to limited stats).
- No binning in CRs.

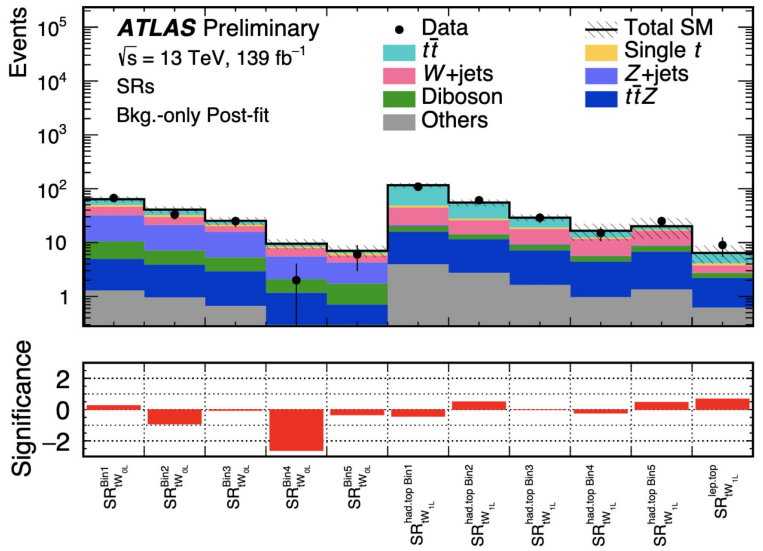
Background-only Fit:

- First, perform simultaneous likelihood fit in all CRs with bkg normalization parameters left floating.
  - Bkg norm factors: μ_{tt}^{tW0L}, μ_{tt}^{tW1L}, μ_{Z+jets}, μ_{W+jets}, $\mu_{single\ top}$, μ_{ttZ}.
  - Extrapolate fitted norm factors to SRs and compare with data ⇒ no significant deviations between data and SM bkg expectation.

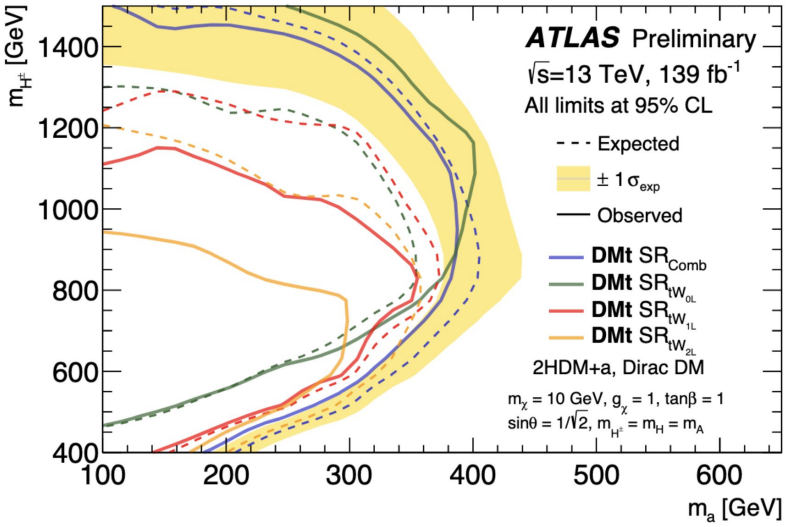
Exclusion Fit and Hypothesis Testing:

- Simulate 2HDM+a signal over range of m_a, $m(H^{\pm})$ and tanβ.
- Incorporate SR_{tW2L} from previous search.
- For each parameter choice, perform simultaneous **exclusion** likelihood fit in all SR bins and CRs with both 2HDM+a signal and SM bkgs.
  - Fit for 2HDM+a signal strength μ and all 5 bkg norm factors.
  - Use CLs method to test signal+SM bkg hypothesis against SM bkg-only to derive constraints on 2HDM+a model.

ATLAS-CONF-2022-012



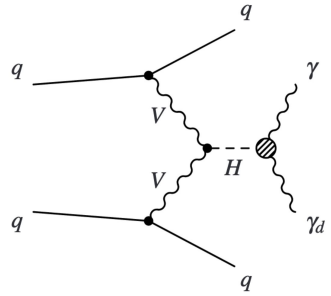
ATLAS-CONF-2022-012



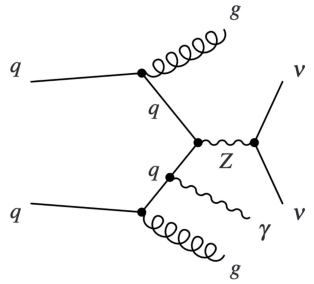
EPJC 82, 105 (2022)

VBF+E_T^{miss}+γ

VBF+E_T^{miss}+γ dark photon signature



Z(νν)γ+jets SM process



Newly-studied VBF+E_T^{miss}+γ final state probes semi-invisible decays of Higgs (or a new scalar mediator) to γ+(invisible particle).

Event Selection:

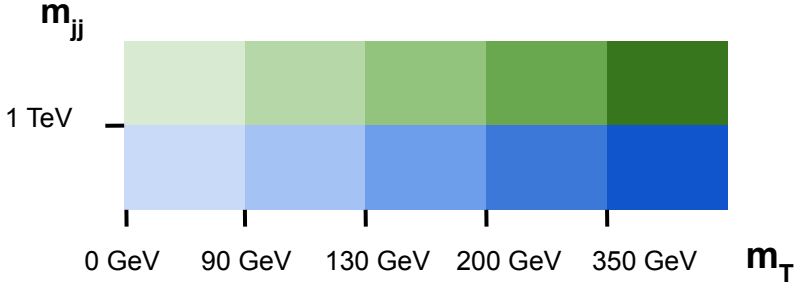
- Event selection similar to VBF+E_T^{miss}, additionally require 1 energetic final-state γ.
- Photon central in η relative to leading jets: C_γ > 0.4:

Binning $C_\gamma = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_\gamma - \frac{\eta_1+\eta_2}{2}\right)^2\right]$ where η_1, η_2 refer to leading two jets.

- Bin selected events in 10 bins according to:
  - m_{jj} (2 bins)
  - $m_T(\gamma, E_T^{miss})$ (5 bins):

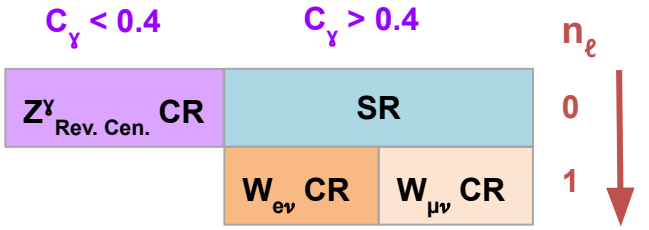
$$m_T(\gamma, E_T^{miss}) = \sqrt{2p_T^\gamma E_T^{miss}\left[1-\cos(\phi_\gamma - \phi_{E_T^{miss}})\right]}$$

Binning Strategy



Background Estimation:

- Dominant SM background processes are W(ℓν)γ+jets and Z(νν)γ+jets.
  - Modelled using Sherpa, Herwig and MadGraph+Pythia8.
  - 1-lepton $W_{e\nu}^{\gamma}$ and $W_{\mu\nu}^{\gamma}$ CRs used for data-driven constraint of W(ℓν)γ+jets.
  - Z(νν)γ+jets modelling checked with C_γ-reversed $Z^{\gamma}_{\text{Rev. Cen.}}$ CR (insufficient stats for data-driven constraint).
  - Fake-e CR with 1 lepton and low E_T^{miss} used to estimate rate of jets faking electrons in $W_{e\nu}^{\gamma}$ CR.

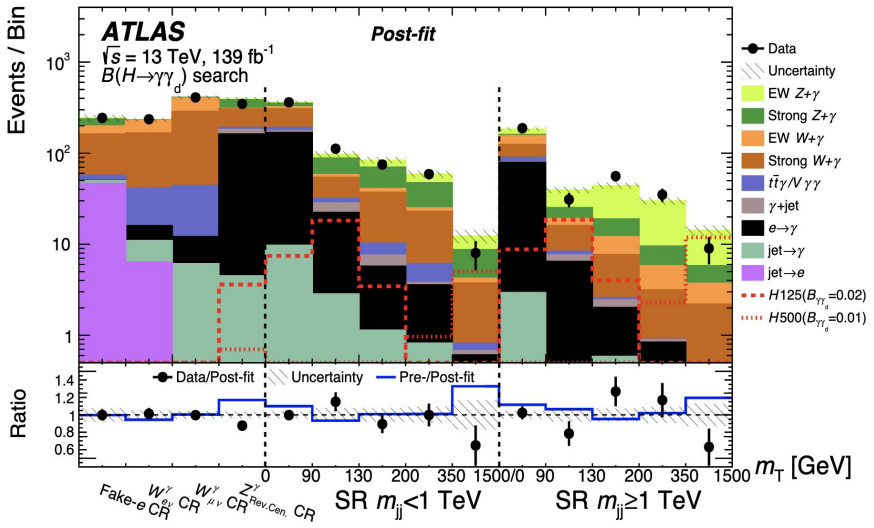


EPJC 82, 105 (2022)

VBF+E_T^{miss}+γ

Fit strategy:

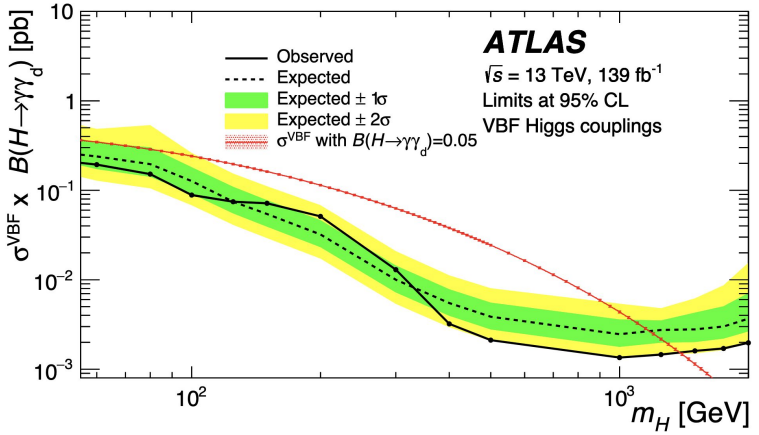
- Apply same binning in SR and all CRs.
- Simultaneous profiled likelihood fit in SR and CRs.
- Results interpreted in terms of Higgs (or new scalar mediator) decay to photon + inv. dark photon (γ_d).
- For signal process simulated at H masses from 60 GeV to 2 TeV, fit for:
  - Signal strength μ for H→γγ$_d$ process (100% BR).
  - Overall normalization $\beta_{W\gamma}$ of the Wγ+jets bkg.
- Statistical and systematic uncertainties incorporated as nuisance parameters.



Results: Good agreement between data and SM background predictions.

⇒ Set observed (expected) upper limit of 0.018 (0.017) on h→γγ$_d$ for m_h=125 GeV at 95% CL.

⇒ Also set 95% CL upper limit on σ_{VBF}×B(H→γγ$_d$) for VBF-produced Higgs with masses ranging from 60 GeV to 2 TeV.



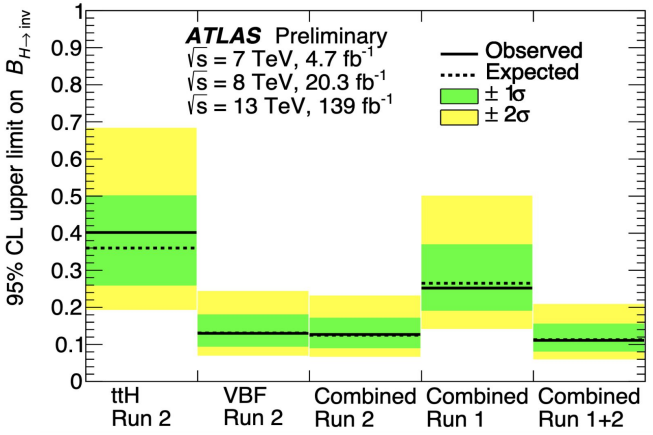
h→Invisible Combination

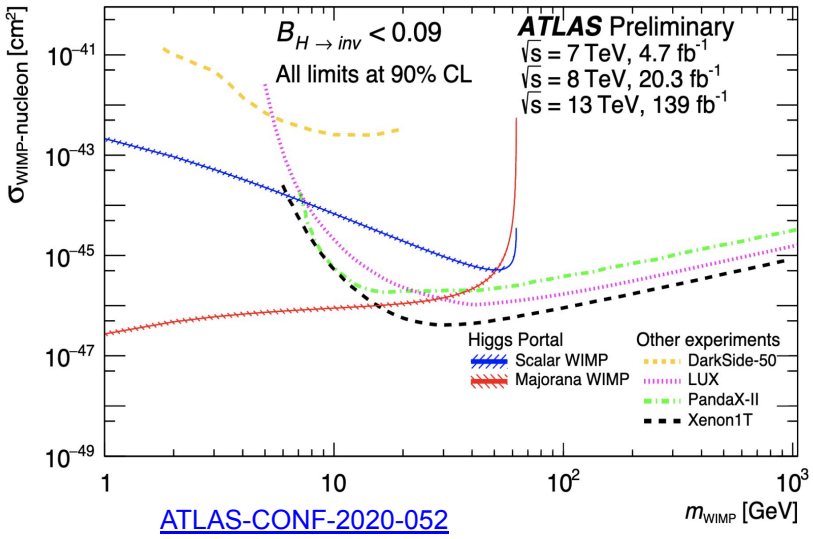
Combined all searches by ATLAS for h→inv in VBF+E_T^{miss} and tth final states (ATLAS-CONF-2020-052).

- Reinterpreted search for new phenomena in tth-0ℓ and tth-2ℓ final states.
- Combined limit: B_{inv} < 11% (95% CL) and B_{inv} < 9% (90% CL).
- Sensitivity dominated by VBF+E_T^{miss} final state.

- Translated into limits on spin-independent $\sigma_{WIMP\text{-}nucleon}$ vs. m_{WIMP} for comparison with direct detection searches.

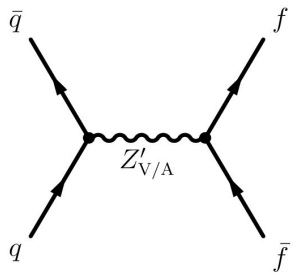
ATLAS-CONF-2020-052





ATLAS-CONF-2020-052

Inclusive Dijet Search



Idea: Search for a new candidate spin-1 DM mediator via its resonant production and decay back to SM particles.

- Reconstruct the m_{jj} spectrum above ~1 TeV, and search for a resonant peak.
- Most recent search reported in JHEP 04 (2020) 145.

Event Selection:

- ≥2 energetic final-state jets (jet p_T > 150 GeV).
- Require jets to be recoiling against one another ($|\Delta\phi_{jj}|$ > 1.0).

Background Estimation:

- SM Background dominated by multijet production.
  - Sliding-window fit applied to data to estimate SM contribution, using:

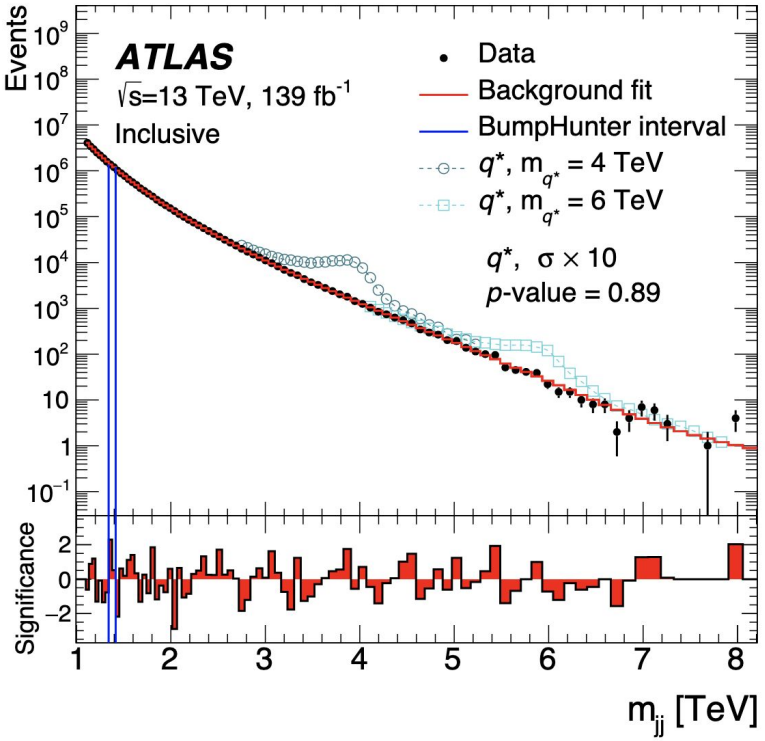
$$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4\ln x} \quad \text{where } x = m_{jj}/\sqrt{s}$$

  - Method validated using 37 fb^{-1} dataset (already published with no evidence of new physics).

Analysis and Interpretation:

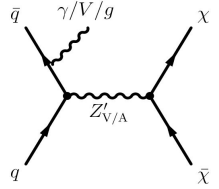
- Use BumpHunter to calculate significance of any localized excess.
  - No significant excesses found → place bounds on spin-1 mediator model using CL_s method.

JHEP 04 (2020) 145

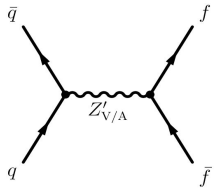


Bounds on New Spin-1 Mediators

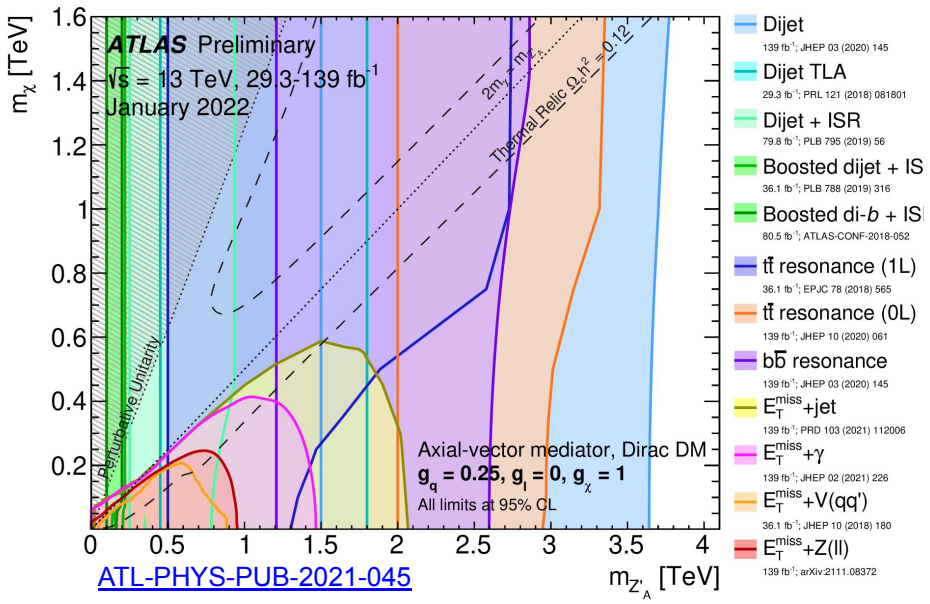
X+E_T^{miss} signature



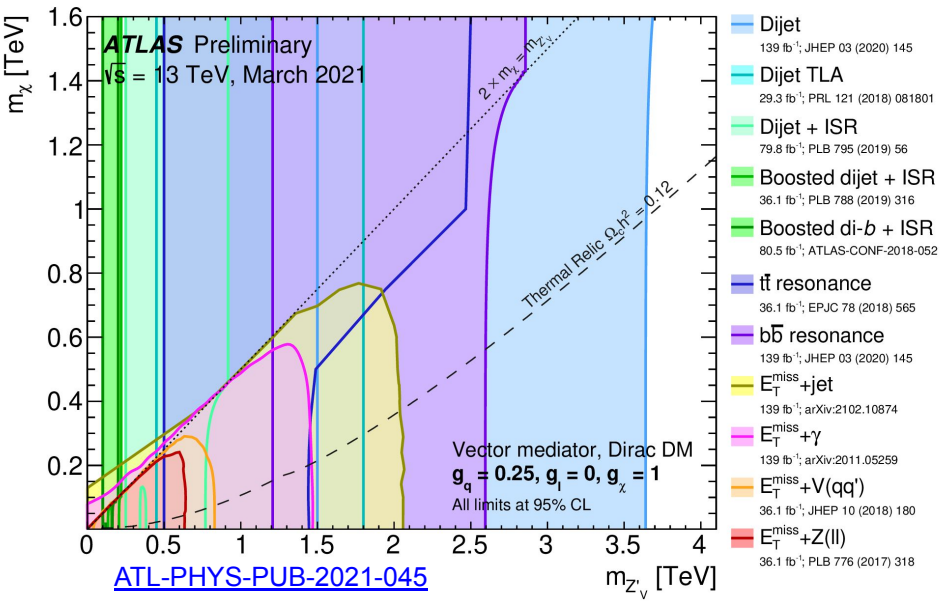
Resonance signature



Tightest bounds(*) on basic spin-1 Z' V/A mediator model set by inclusive dijet resonance searches (JHEP 04 (2020) 145) and jet+E_T^{miss} (PRD 103, 112006 (2021)).



Axial Vector Z'_A

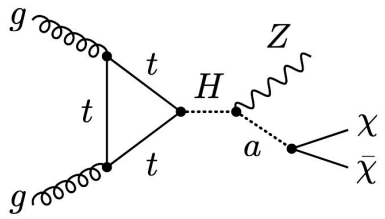


Vector Z'_V

(*)Comparison of bounds depends on choice of couplings.

2HDM+a Model

Z+E_T^{miss} Signature



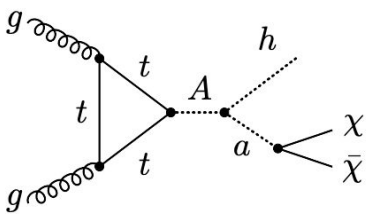
Constraints on simplified models dominated by jet+E_T^{miss} and tt+E_T^{miss}, but other X+E_T^{miss} final states can provide tighter constraints on more complex models such as 2HDM+a.

- Visible SM particle(s) produced by hard scattering process rather than ISR.

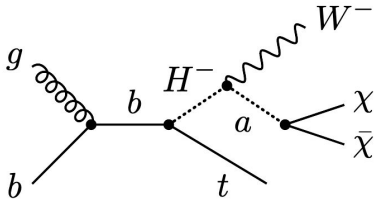
2HDM:

- Extend the SM by postulating **two** Higgs doublets.
- Predicts 5 Higgs bosons:
  - 2 scalars: h (SM Higgs), H (new particle)
  - 1 heavy pseudoscalar A
  - 2 charged Higgs $H^{\pm}$
- Adds several free parameters, incl.:
  - m_A, m_H
  - tanβ: ratio of VEVs of the two Higgs doublets

h+E_T^{miss} Signature



tW+E_T^{miss} Signature



2HDM+a (arXiv:1810.09420)**:**

- Adds a pseudoscalar DM mediator a to the 2HDM model.
- Simplest gauge-invariant and renormalizable extension of the simplified pseudoscalar DM mediator model.
- Additional free parameters, incl.:
  - m_a
  - sinθ: Mixing angle between a and A
- Wide variety of complementary signatures.

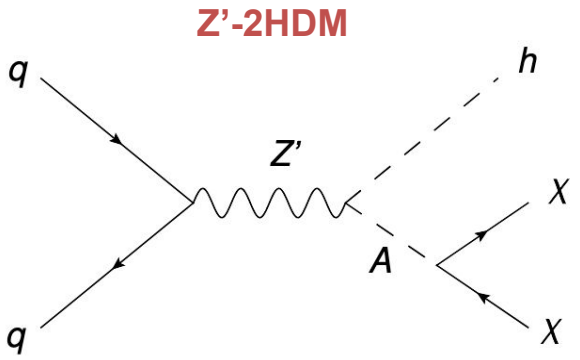
Benchmark Parameter Choices

$$M_H = M_A = M_{H^{\pm}}$$
$$\tan\beta = 1$$
$$m_\chi = 10\,\mathrm{GeV}$$
$$\sin\theta = 0.35$$

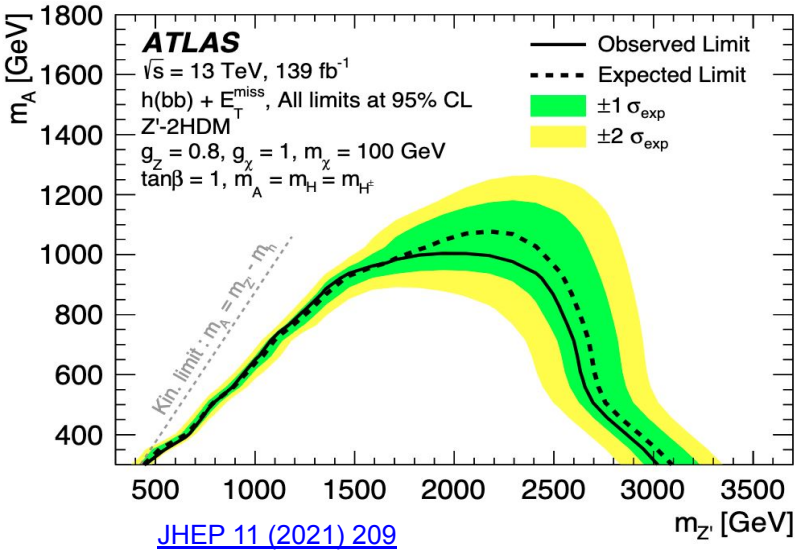
Z'-2HDM Model

Idea: Rather than adding a pseudoscalar DM mediator to the 2HDM model (i.e. 2HDM+a), instead add a vector DM mediator Z'.

- Note that, unlike 2HDM+a, Z'-2HDM is not a complete model.
- Used mainly as a benchmark for high-mass resonances.
- The mono-h(bb) search (JHEP 11 (2021) 209) places constraints on the Z'-2HDM model in addition to 2HDM+a.



Constraints on the Z'-2HDM Model by the mono-h(bb) Search



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