Searches for dark matter with the ATLAS detector

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For the ATLAS collaboration

SUSY 2021, Online

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Searching for Dark Matter is one of the main focuses at the LHC!

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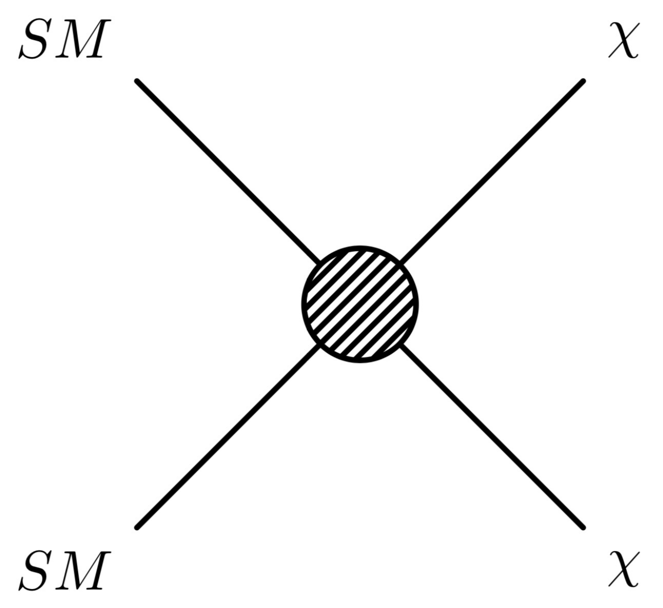
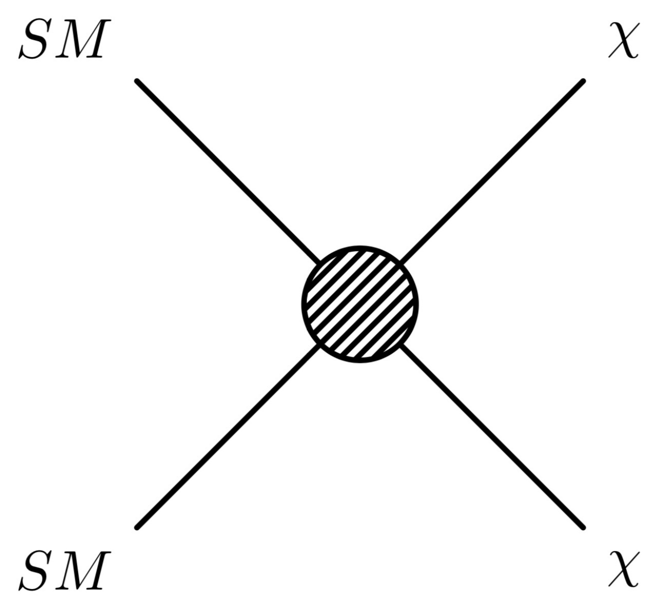


Searching for Dark Matter is one of the main focuses at the LHC!

Indirect detection



IceCube
MAGIC
HESS
...

Searching for Dark Matter is one of the main focuses at the LHC!

Indirect detection

IceCube
MAGIC
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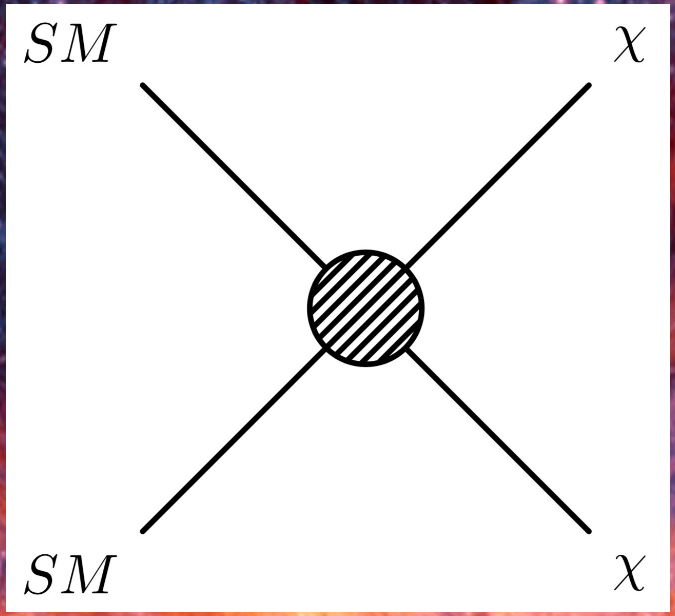

Direct detection

XENON
LUX
Panda-X
Picasso
...

Searching for Dark Matter is one of the main focuses at the LHC!

Indirect detection

IceCube
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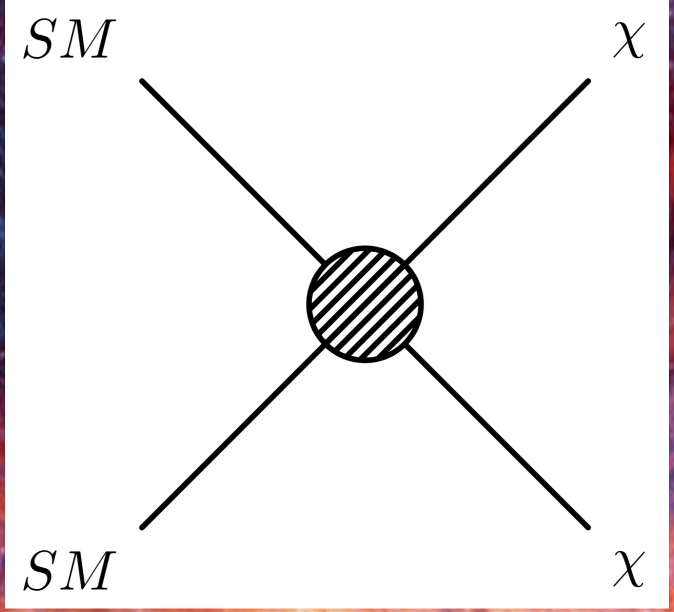

Direct detection

XENON
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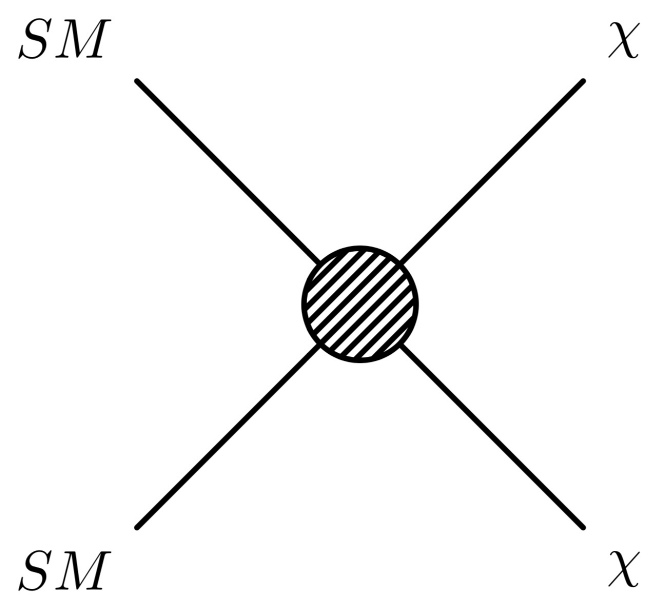
Collider

ATLAS
CMS
...

Searching for Dark Matter is one of the main focuses at the LHC!

DM can escape detectors

Indirect detection



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...

Direct detection

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LUX
Panda-X
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Collider

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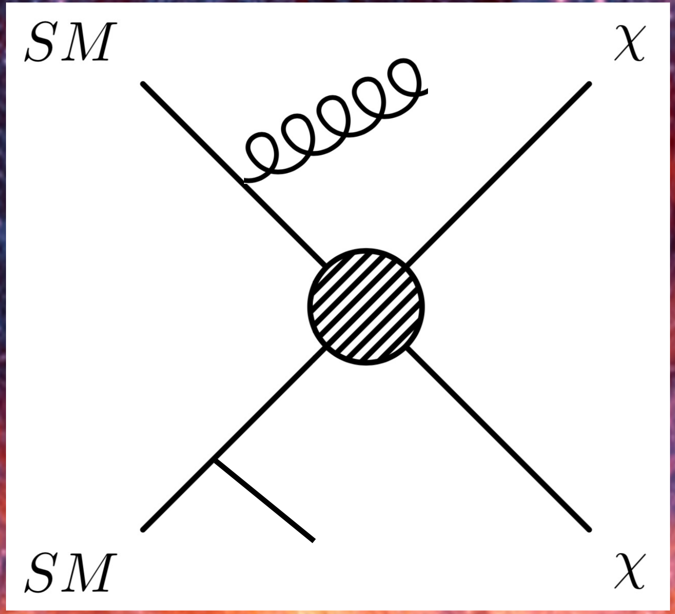
...

Searching for Dark Matter is one of the main focuses at the LHC!

DM can escape detectors
⇒<u>Measure the ISR or associated production</u>

Indirect detection



IceCube
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...

Direct detection

XENON
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ATLAS
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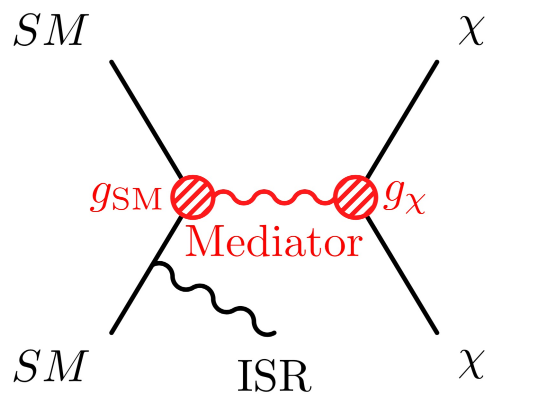
...

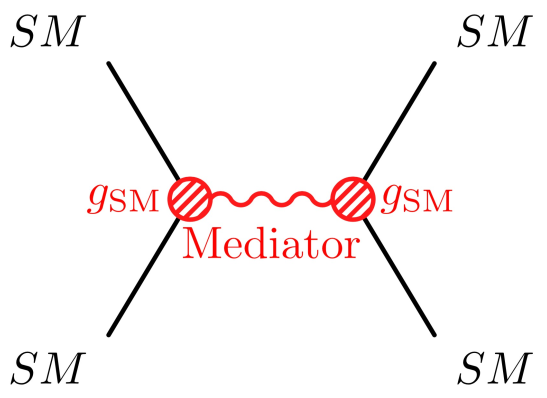
MET = missing transverse energy

Dark Matter searches with ATLAS

Simplified models



X + MET (mono-X) searches



Mediator (resonance) search

- The energy scale at run-2 ($\sqrt{s}$=13TeV) can be greater than the mediator mass
  - A more complex model than the EFT is needed…

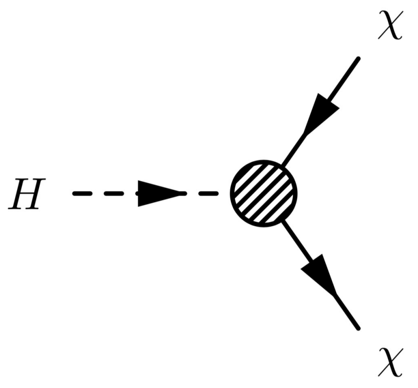
Other searches

SUSY

Long-lived particles

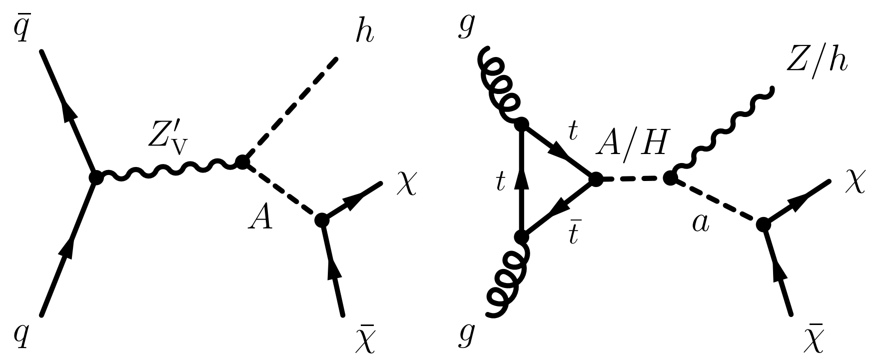
…

Higgs portal



Higgs invisible decay (with associated production)

Extended Higgs sector

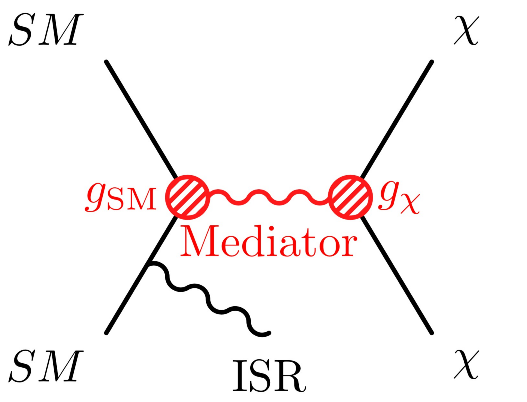


Two-Higgs-doublet Model extended with a **vector boson Z'** or a **pseudoscalar a** which mediates the interaction between SM and DM

MET = missing transverse energy

Dark Matter searches with ATLAS

Simplified models



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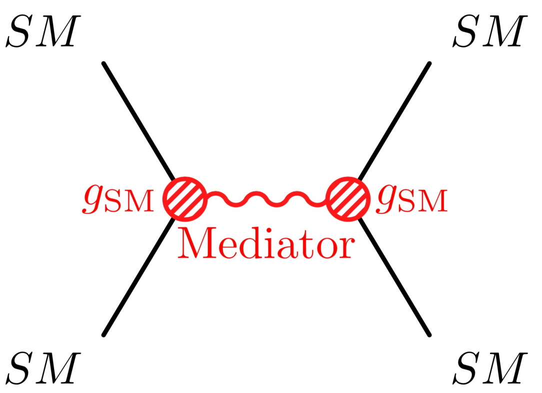

Mediator (resonance) search

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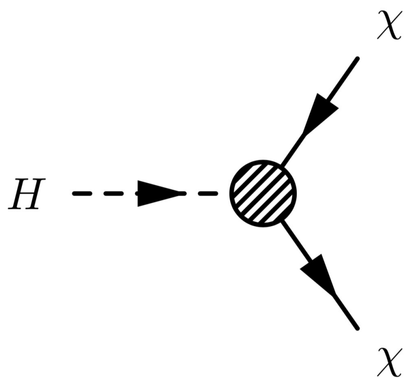
Other searches

…

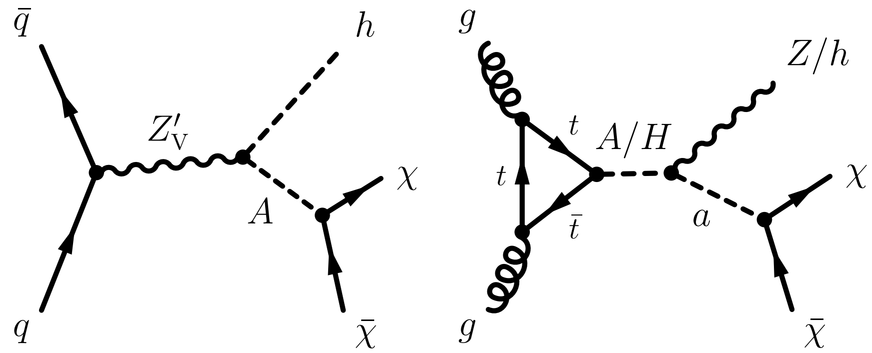
Recent run-2 results shown in the following

Higgs portal



Higgs invisible decay (with associated production)

Extended Higgs sector



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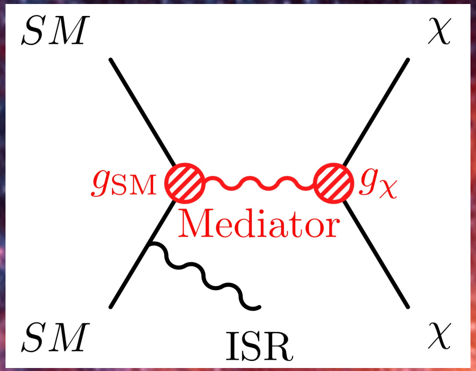
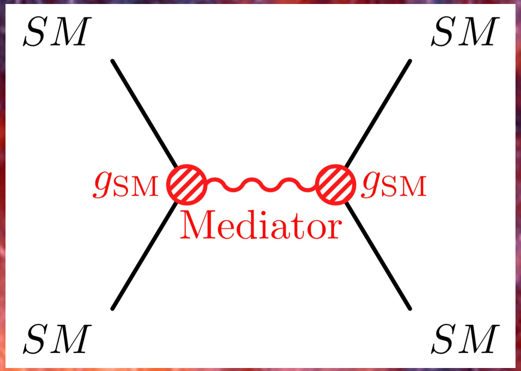
Simplified models





Mono-jet, 13TeV, 139fb^{-1}

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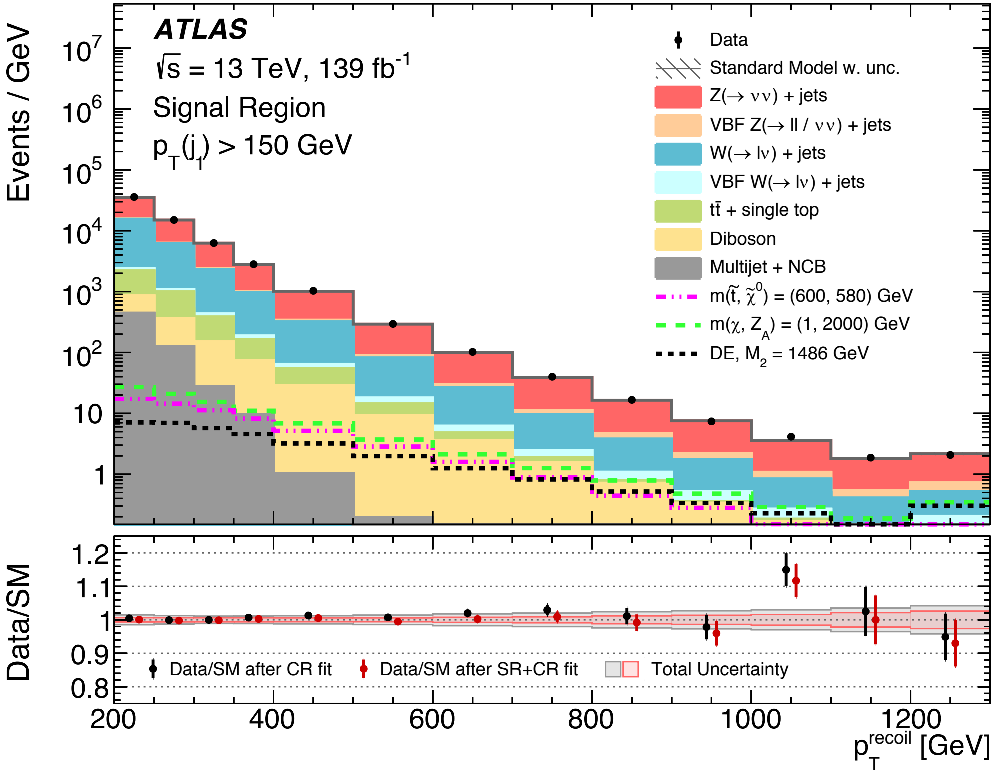
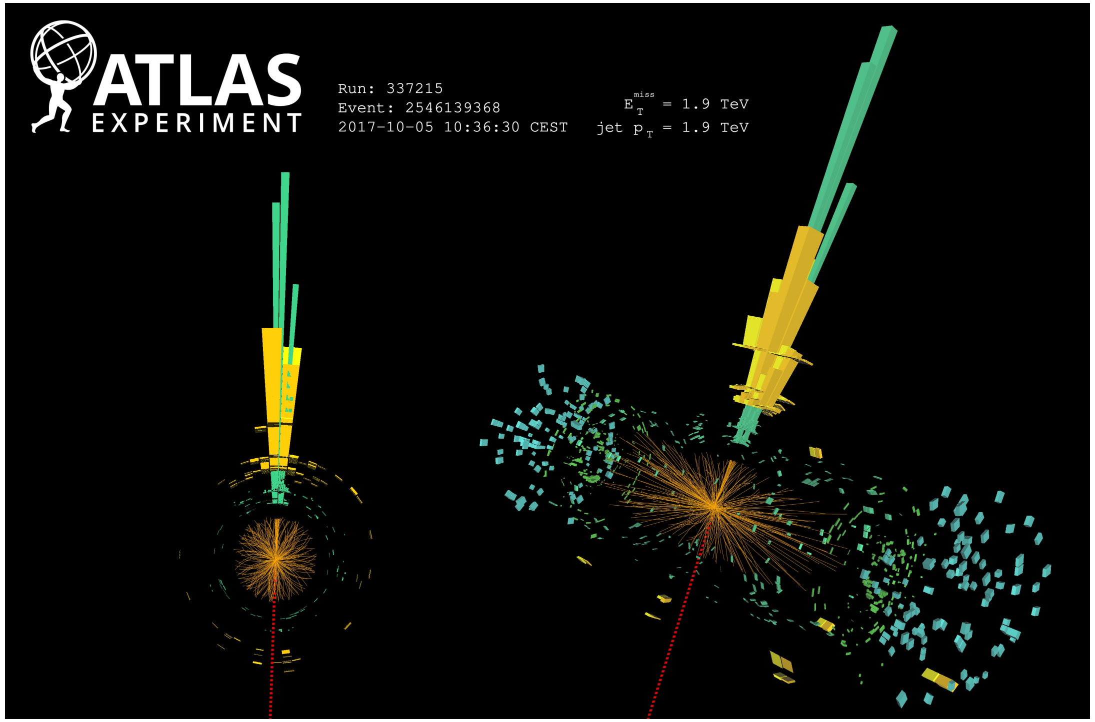
- The "golden" channel for WIMP searches
- Signal region requires:
  - MET > 200 GeV
  - A leading jet with p_T > 150 GeV, $|\eta|<2.4$
  - $\Delta\phi$(jet,MET) cuts to suppress multijet





- Background modeling:
  - V+jets, $t\bar{t}$, single-t modeled with 5 control regions
  - Multijet modeled with jet smearing method
- Main uncertainties:
  - Pile-up jets, MET, lepton in low MET region
  - Modeling of single-t and V+jets in high MET region
- Fit to the MET (or p_T(recoil)) spectrum in SR+CR

Mono-jet search, 13TeV, 139fb^{-1}

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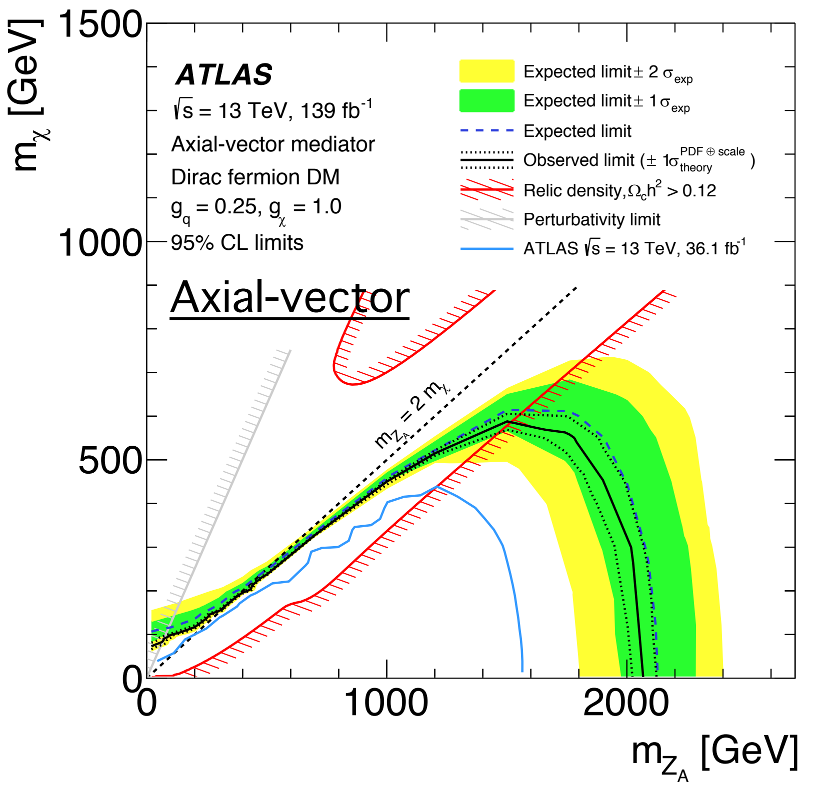
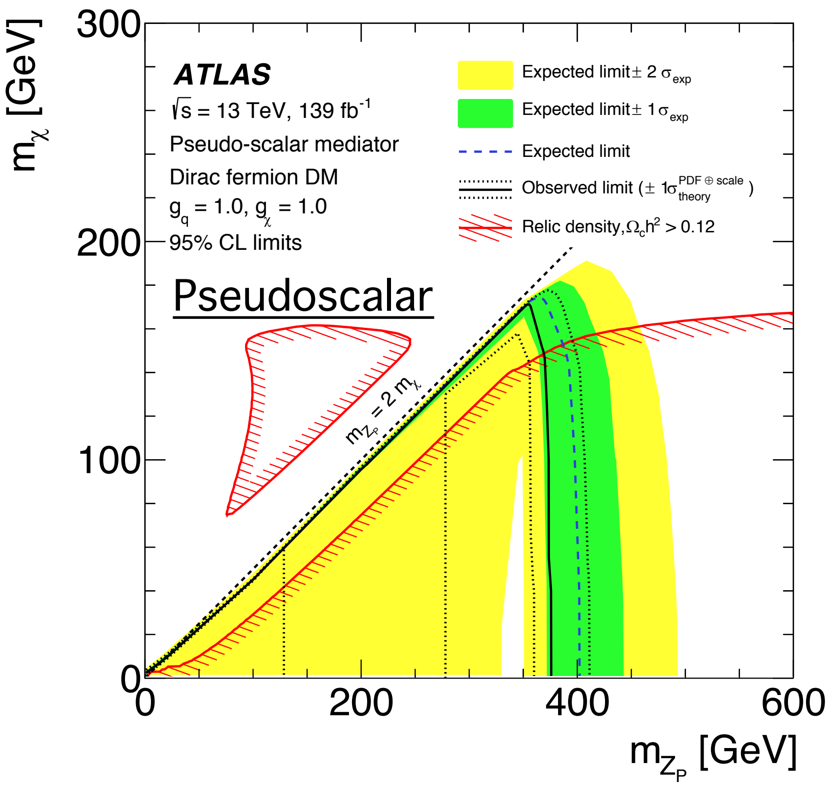
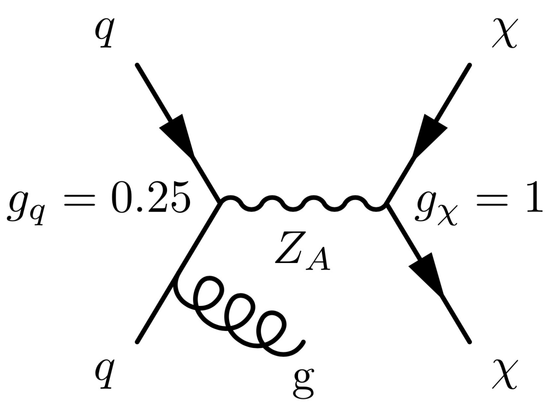
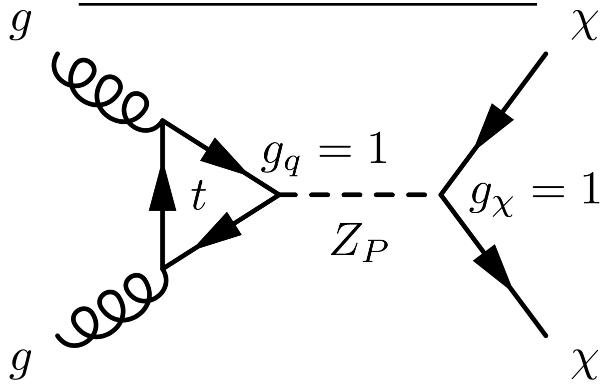




Axial-vector mediator

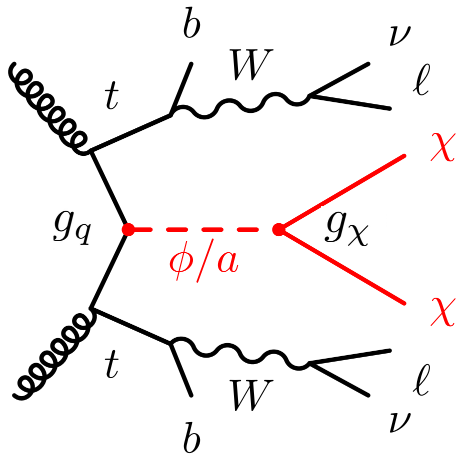


Pseudoscalar mediator

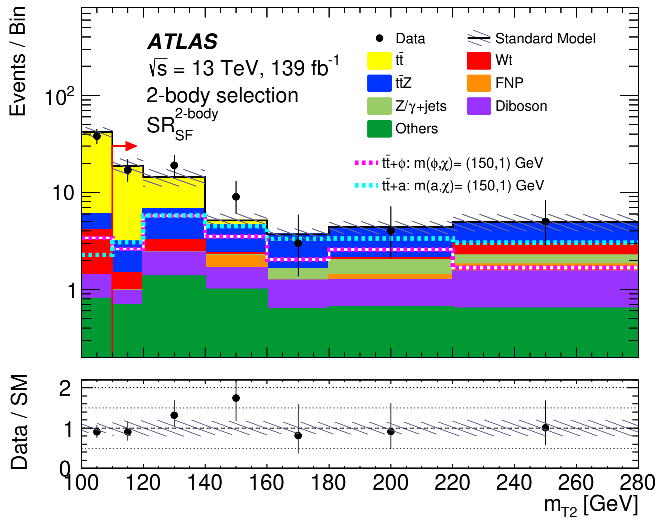


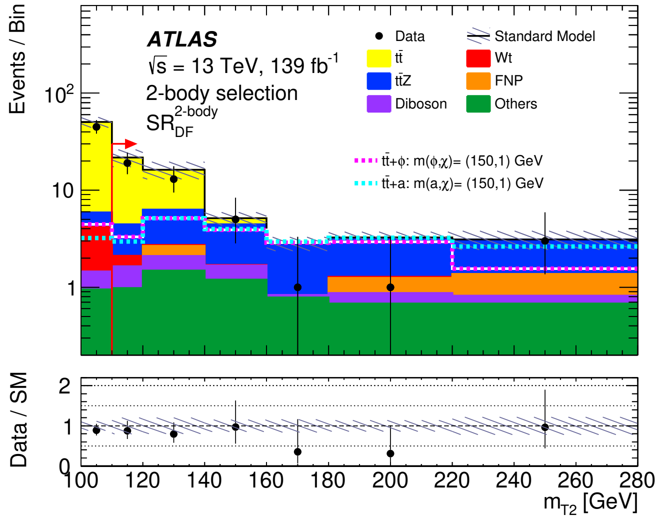
- No significant deviation from SM observed
- Simplified model with an axial vector mediator excluded up to m_{ZA} = 2.1 TeV
- First time having sensitivity to exclude simplified model with a pseudoscalar mediator (up to m_{ZP} = 376 GeV)

MET+$t\bar{t}$, 13TeV, 139fb^{-1}



- Sensitive to the associated scalar/pseudoscalar production with a pair of t-quarks
- $t\bar{t}$ decay fully- or semi-leptonically (fully-leptonic presented)
- Signal region requires:
  - 2 leptons, $pT_{l1(l2)}$>25(20), m_{ll}>20
  - ≥1 b-jets
  - MET significance > 12
  - Further cuts to suppress $t\bar{t}$ and DY





- A sophisticated variable m_{T2} used as final fit discriminant (definition in backup)
- Main backgrounds $t\bar{t}$ and $t\bar{t}Z$ modeled by control regions
- Main uncertainties include $t\bar{t}$, $t\bar{t}Z$ modeling and jet energy resolution and scale
- No significant deviation found

MET significance = MET / resolution

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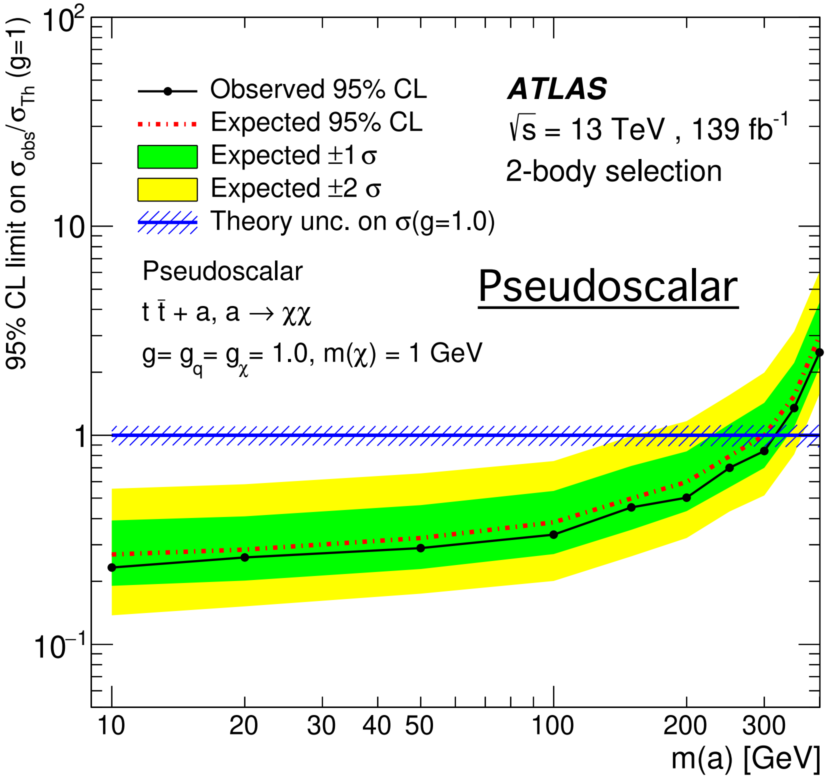
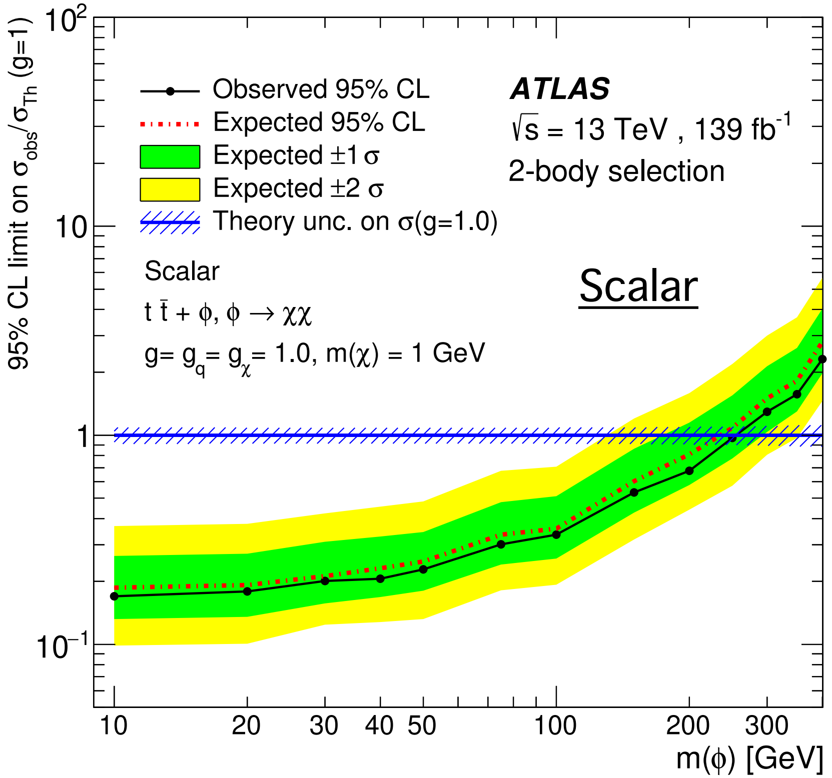
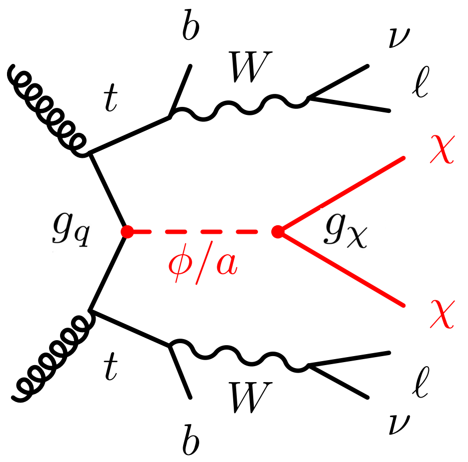
MET+$t\bar{t}$, 13TeV, 139fb^{-1}



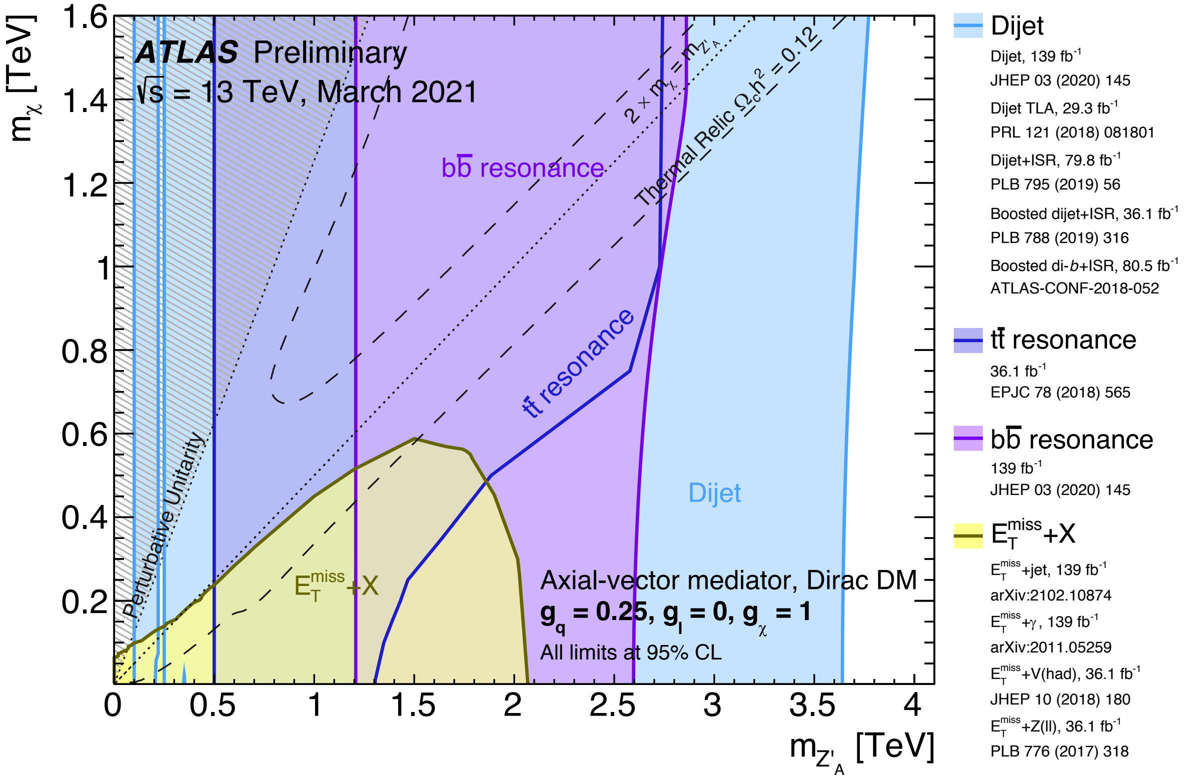


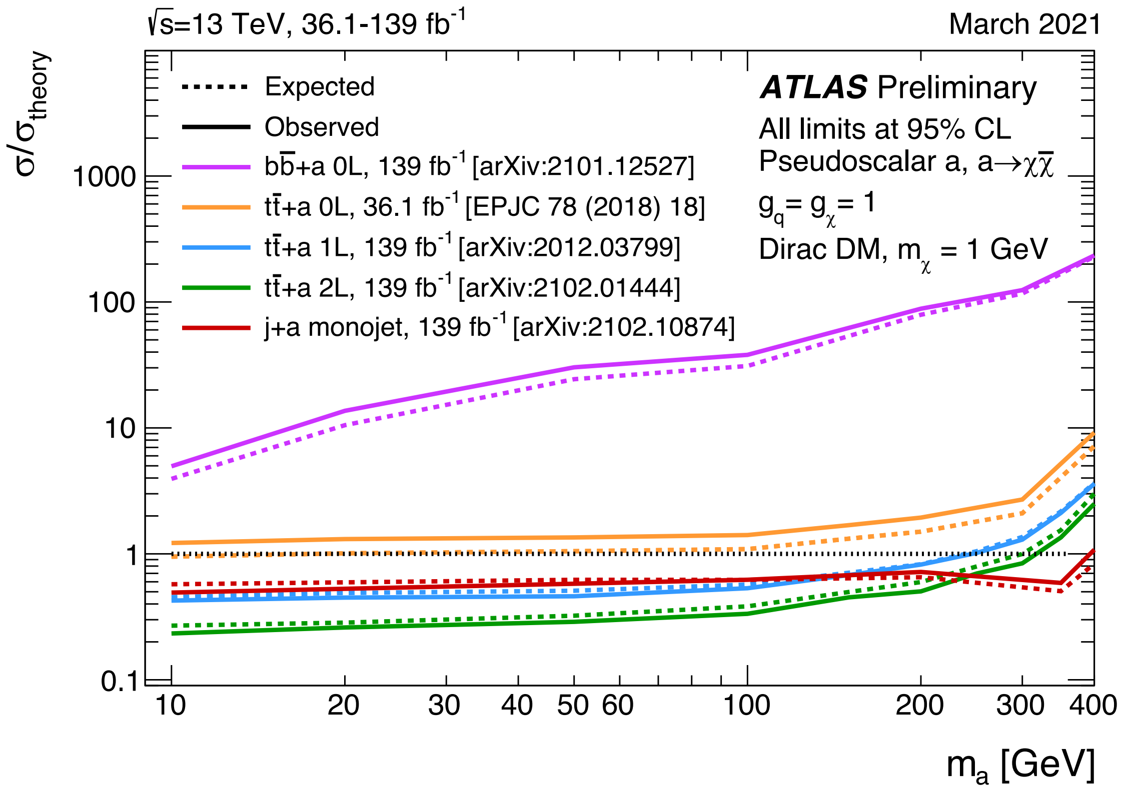


- Exclusion limits set on simplified models with a scalar or a pseudoscalar mediator
- Excluded for scalar (pseudoscalar) mediator masses up to 250 (300) GeV assuming $g_q = g_\chi = 1$

ATL-PHYS-PUB-2021-006

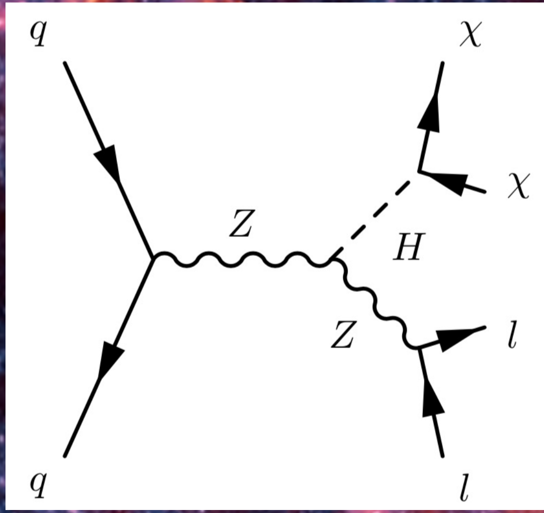
Summary of simplified models

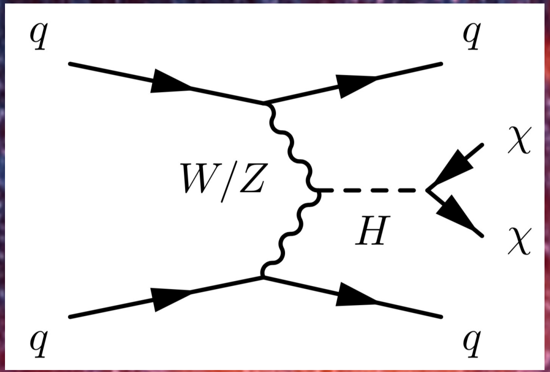


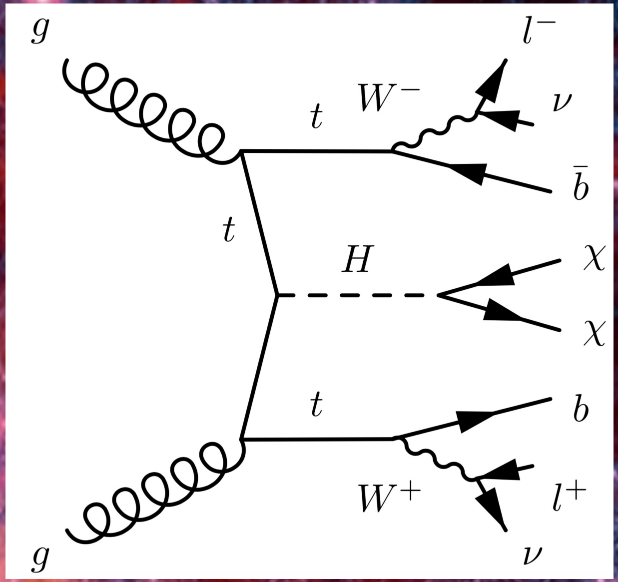


- Spin-1 mediator excluded for masses up to ~3.6 TeV mainly by di-jet search (for the given benchmark coupling strength)
- Mono-jet and MET+$t\bar{t}$ provide strongest limits on spin-0 mediator, excluding for masses up to ~376 GeV

Higgs portal (H→invisible)



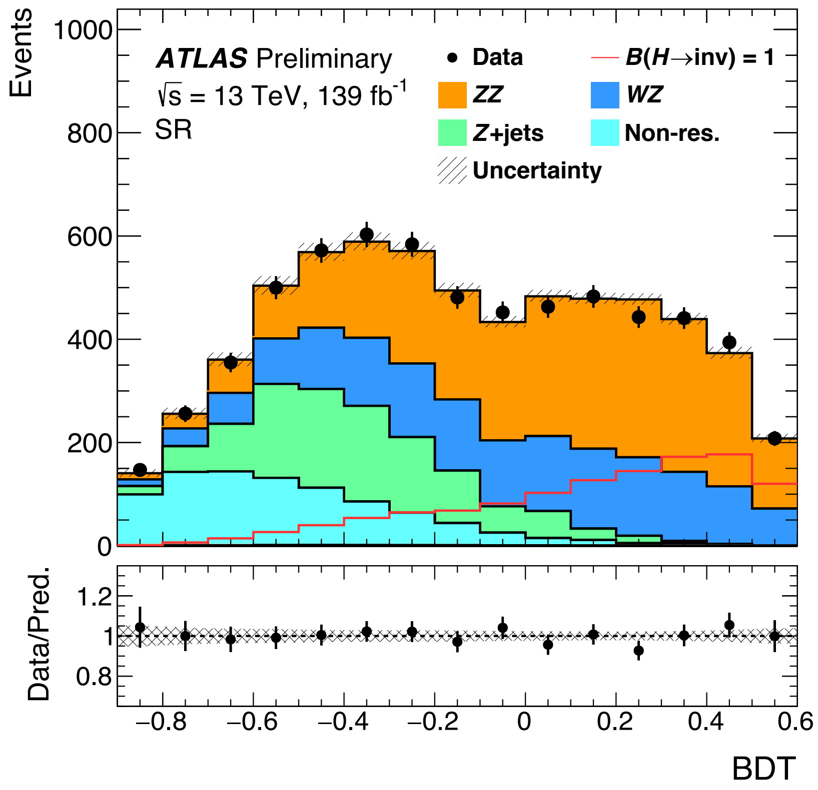


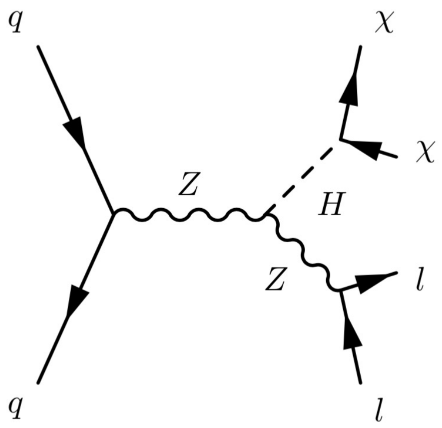


ATLAS-CONF-2021-029

Mono-Z (MET+Z), 13TeV, 139fb^{-1}

- Sensitive to Higgs invisible decay with ZH production and the extended Higgs sector (see slide 13)
- Focus on leptonic decay of Z
- Signal region requires:
  - 2 electrons or muons with opposite charges
  - $pT_{l1(l2)} > 30(20)$ GeV, $76 < m_{ll} < 106$ GeV, $\Delta R_{ll} < 1.8$
  - MET > 90 GeV, MET significance > 9
  - No b-jet
  - BDT trained with 8 variables for the Higgs invisible signal and used as the fit discriminant





- Dominant backgrounds include ZZ, WZ, Z+jets and non-resonant processes (WW + $t\bar{t}$ + single-t + $Z\rightarrow\tau\tau$)
  - Modeled with 3 control regions and 2 free normalization factors
- Main uncertainties include ZZ modeling and jet reconstruction
- Upper limits on $Br(H\rightarrow inv) = 18\%$

Other channels

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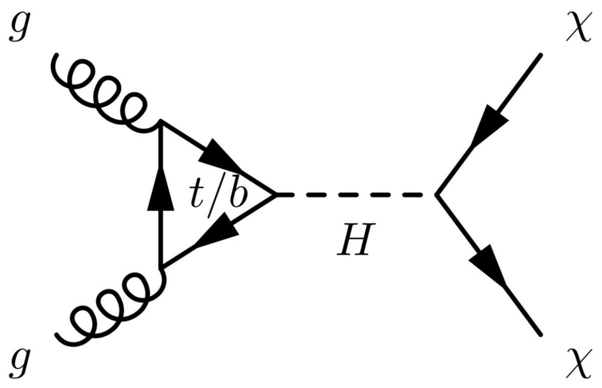
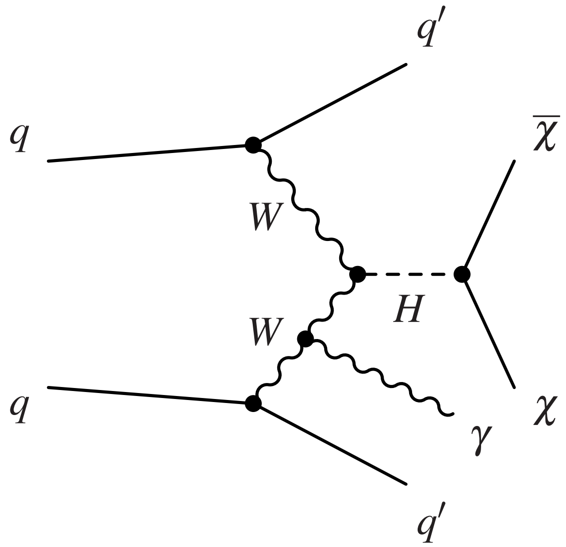
- Mono-jet (13TeV, 139fb^{-1}) can also be interpreted as H→invisible
  - Dominated by ggF (73%)
  - Upper limits on Br(H→inv) = 34%



ATLAS-CONF-2021-004

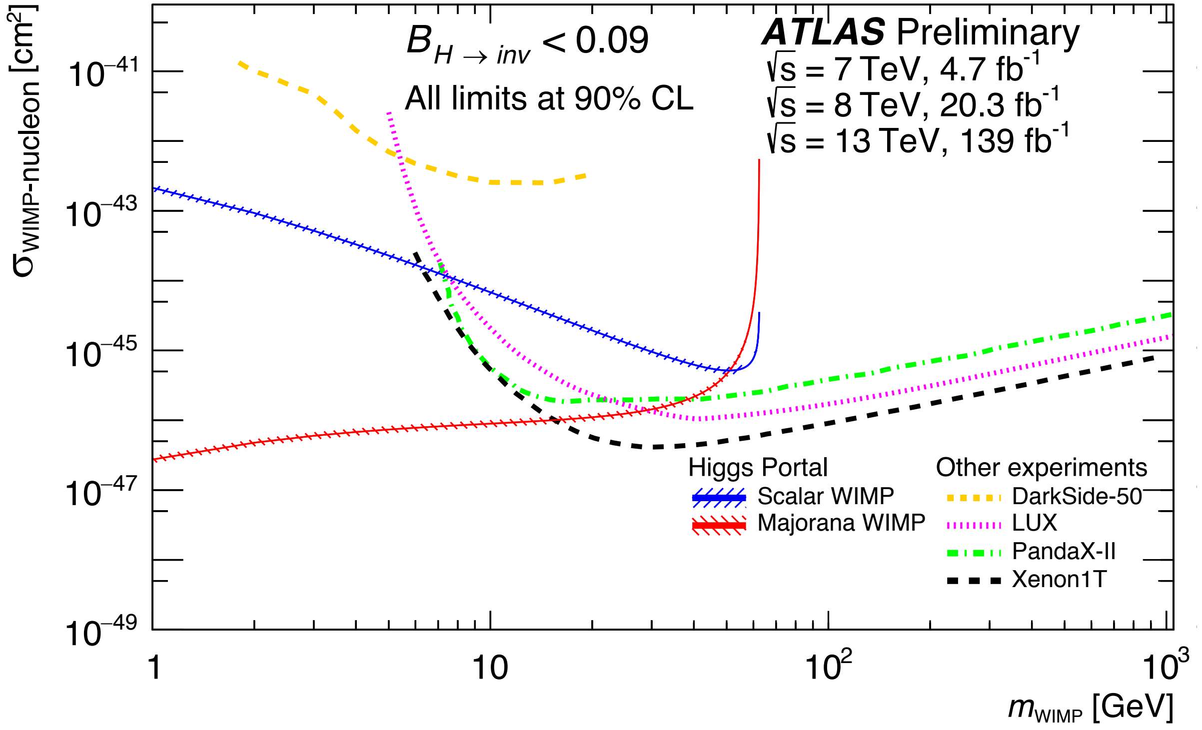


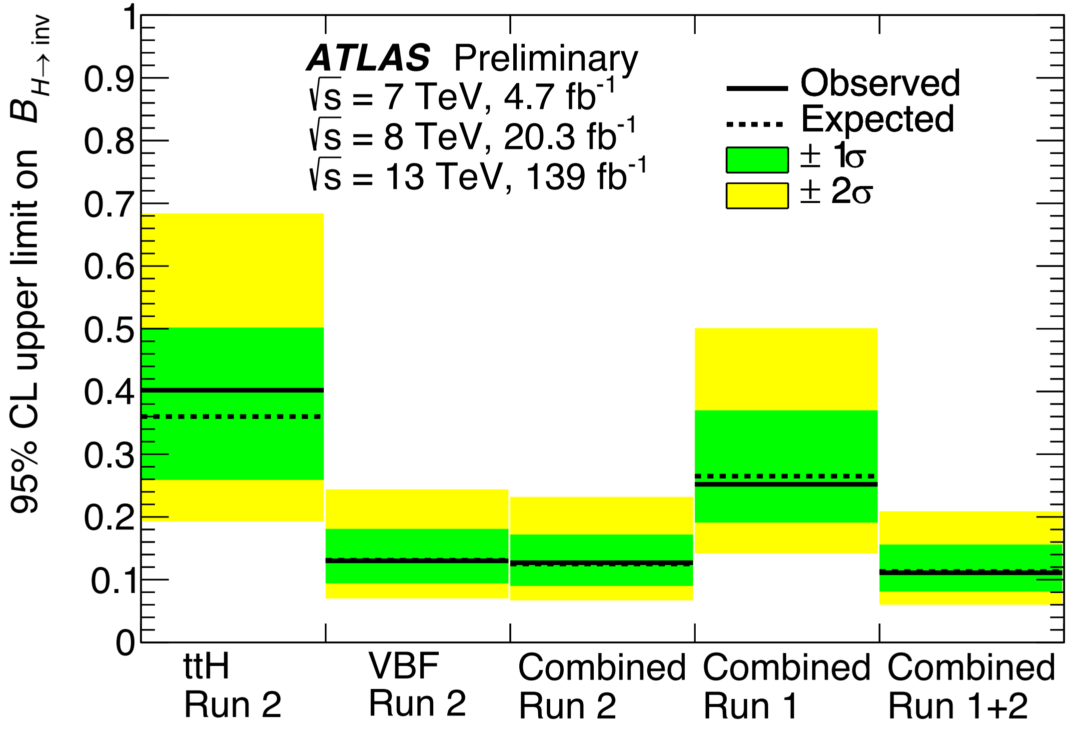
- VBF+MET+photon (13TeV, 139fb^{-1}) targets the H→invisible signal with the VBF production + photon
  - Significantly suppress the V+jet background by requiring an additional photon
  - Upper limits on Br(H→inv) = 37%

ATLAS-CONF-2020-052

H→invisible combination, 13TeV, 139fb^{-1}

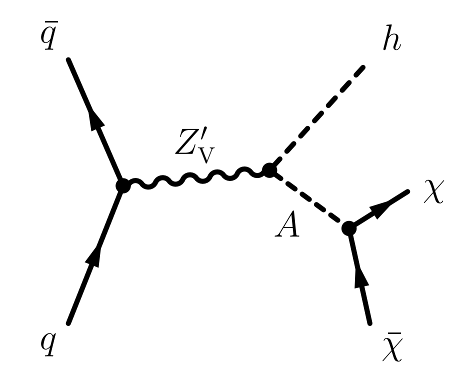
- Statistical combination of run-1 and run-2 results
  - Run-2 includes VBF and ttH channels (*other channels yet to be combined*)
  - Run-1 includes VBF and VH

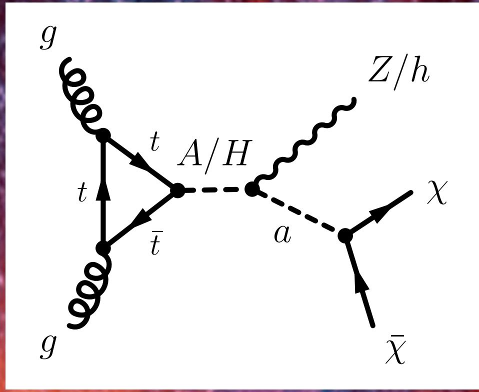




- **Upper limit on Br(H→inv) = 11%**
- Compared with constraints from direct search assuming H decays to a pair of DM particles that are either scalars or Majorana fermions

Extended Higgs sector





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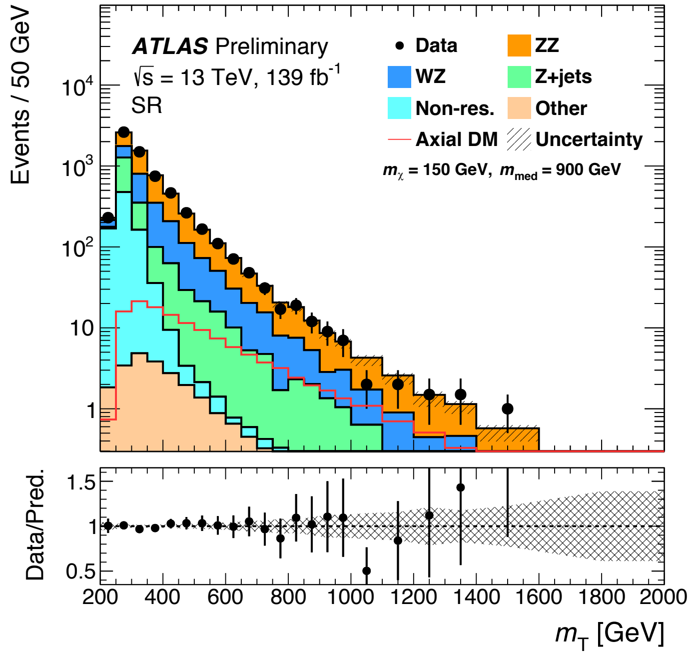
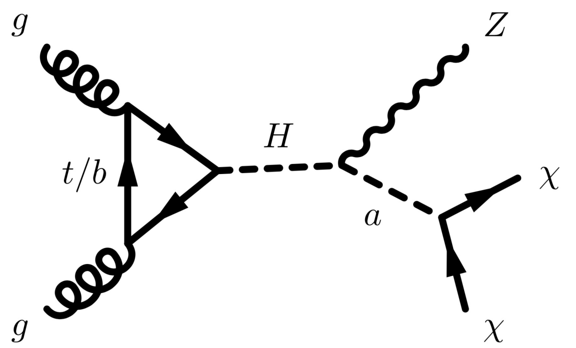
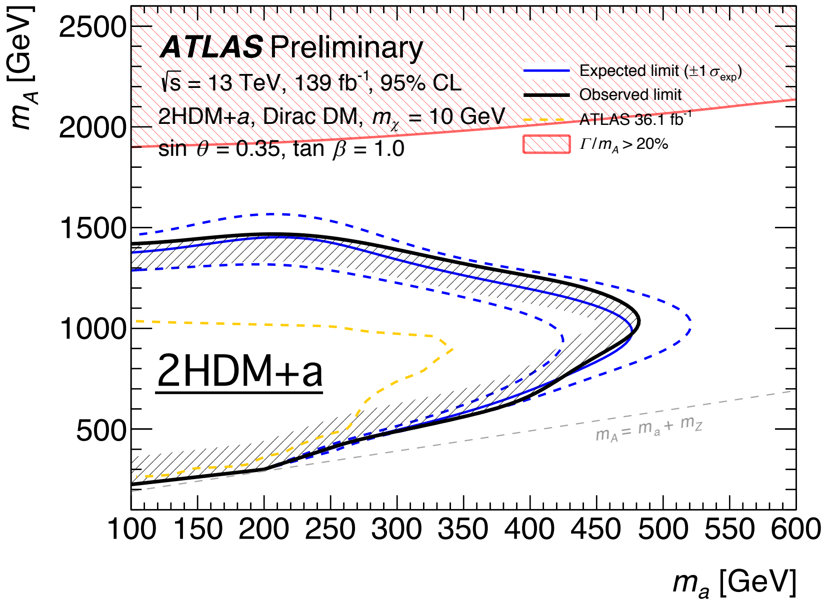
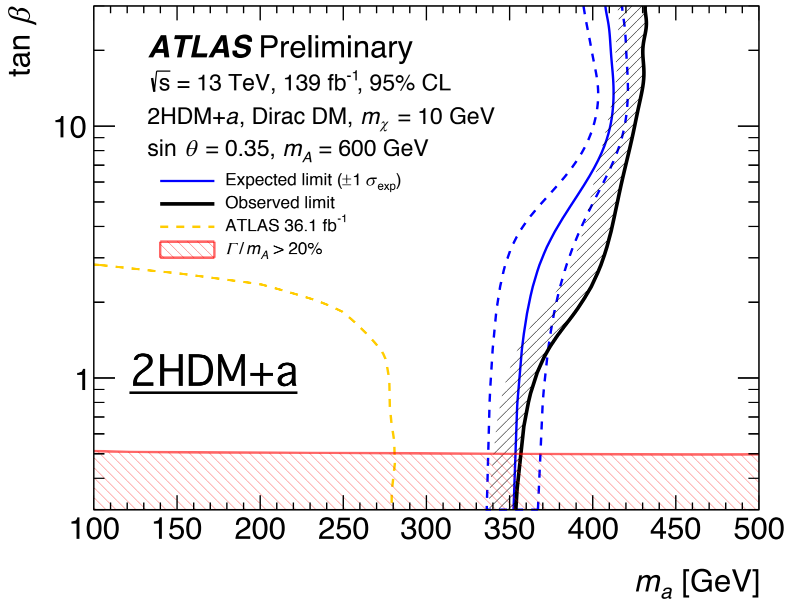
Mono-Z (MET+Z), 13TeV, 139fb^{-1}



- The mono-Z search can also be interpreted as the **2HDM+a signal**
- m_T(Z, MET) used as the fit discriminant (instead of BDT)
- Limits set on 2HDM+a in various parameter spaces (m_A, m_a, tanβ, sinθ)
- Large improvements compared to previous results!



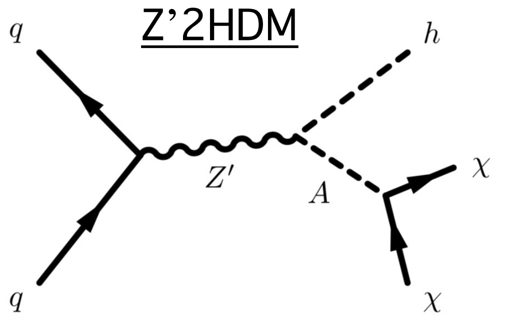


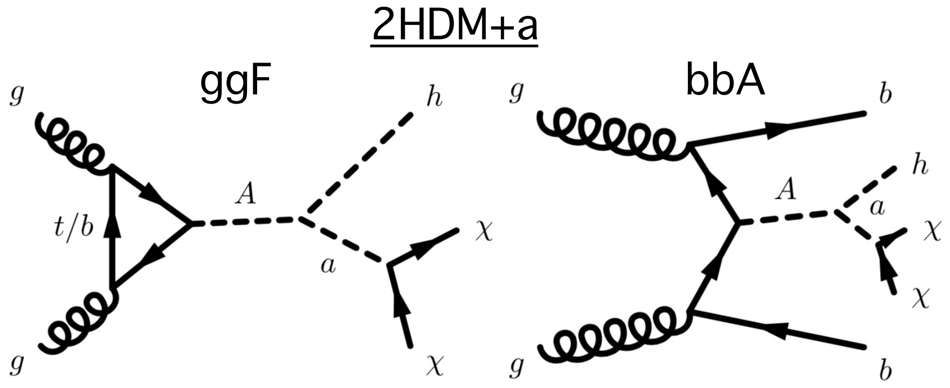


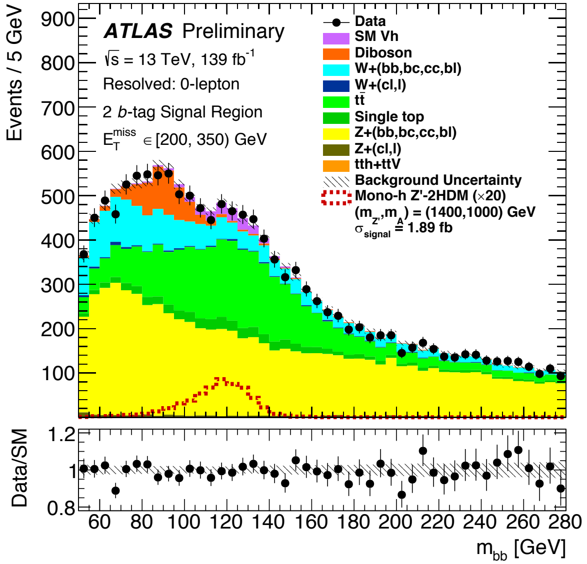
arXiv:2104.13240 ATLAS-CONF-2021-006

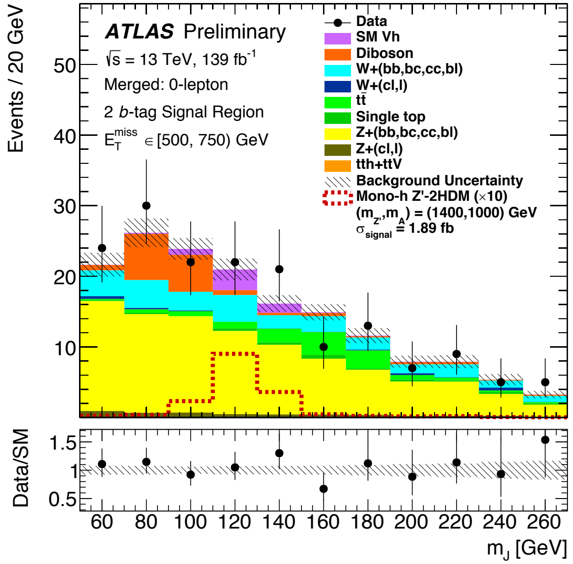
Mono-h (MET+h), 13TeV, 139fb^{-1}

- Sensitive to the Z'2HDM and 2HDM+a
- **h→bb** and h→$\gamma\gamma$ channels (**h→bb** presented)
- Select events with MET > 150 GeV, no lepton, and an h→bb candidate reconstructed with 2 methods:
  - **Resolved regime** (MET < 500 GeV): 2 b-tagged small-R jets (R=0.4)
  - **Boosted regime** (MET > 500 GeV): 1 large-R jet with 2 associated b-tagged variable-R track-jets









- Dominant backgrounds (Z/W+jets, $t\bar{t}$) modeled with control regions
- Fit to SR+CR in m_{bb}, MET and number of b-jets (2b and ≥3b); the additional ≥3b regions target the bbA production

Mono-h (MET+h), 13TeV, 139fb^{-1}

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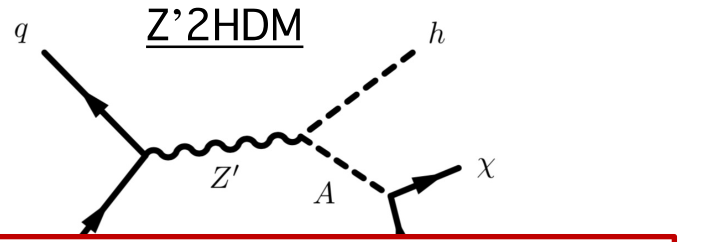

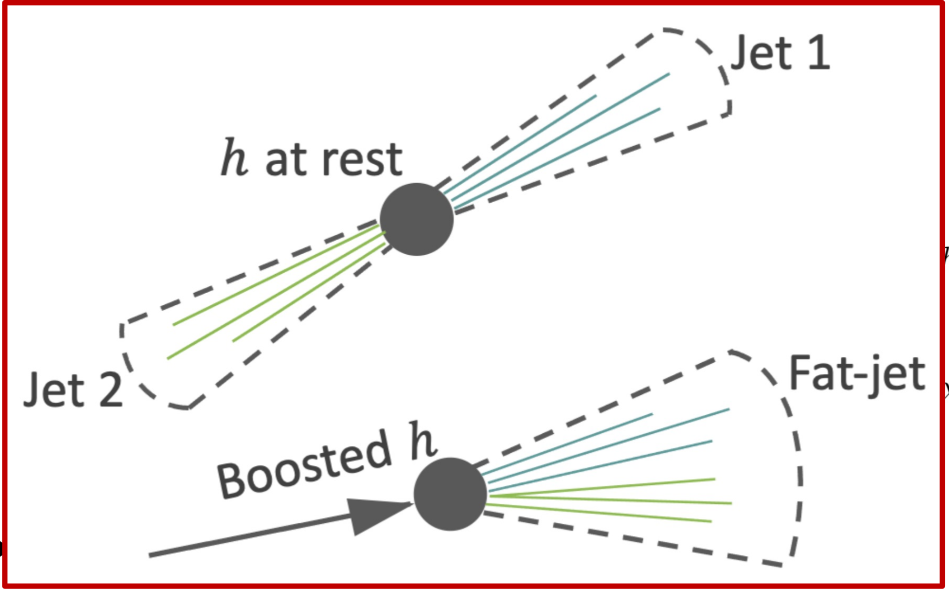

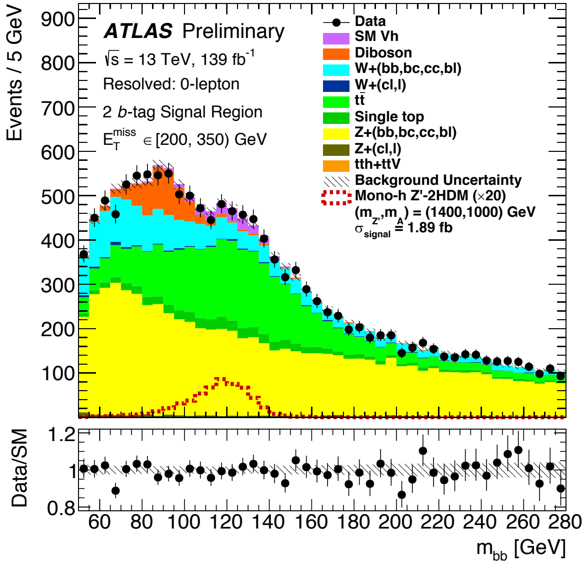

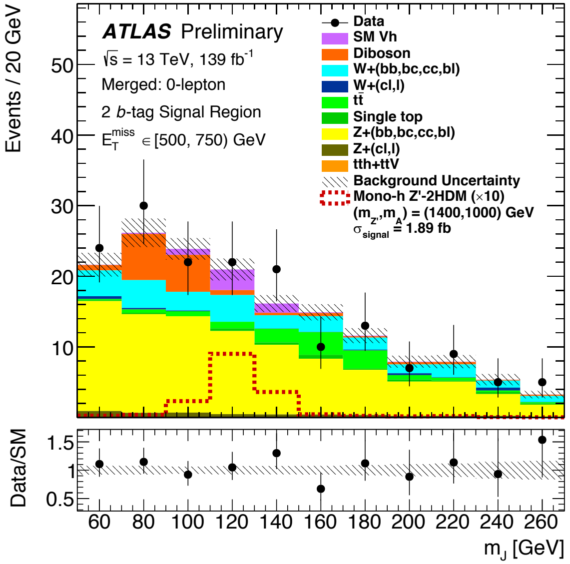

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arXiv:2104.13240 ATLAS-CONF-2021-006

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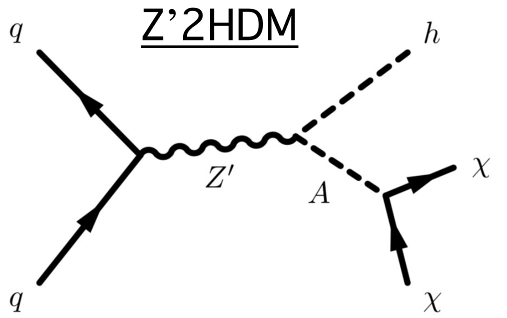
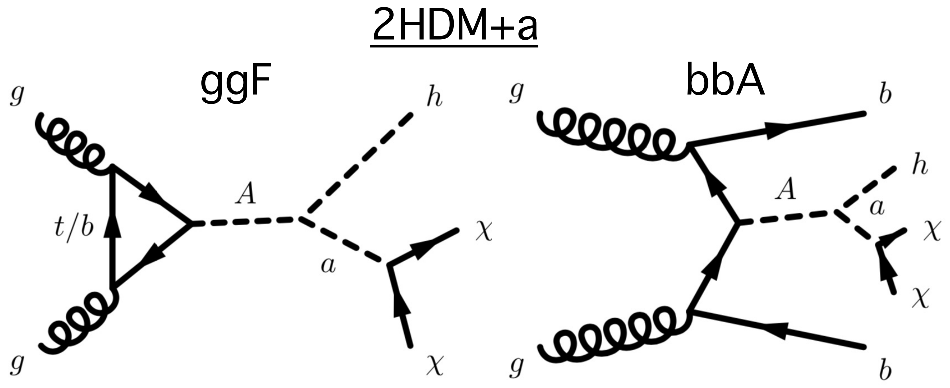
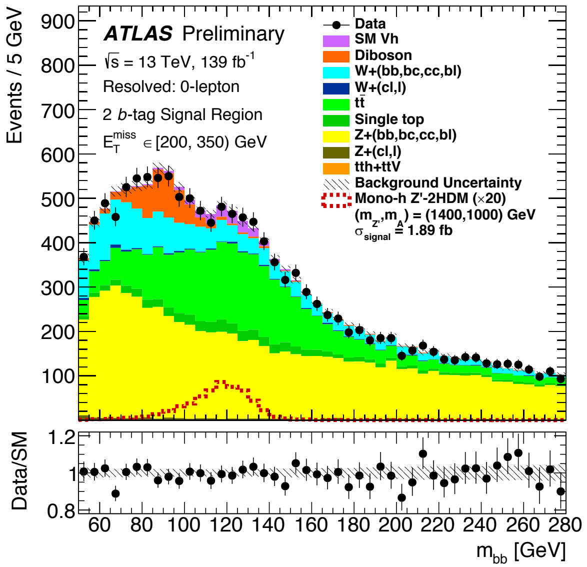
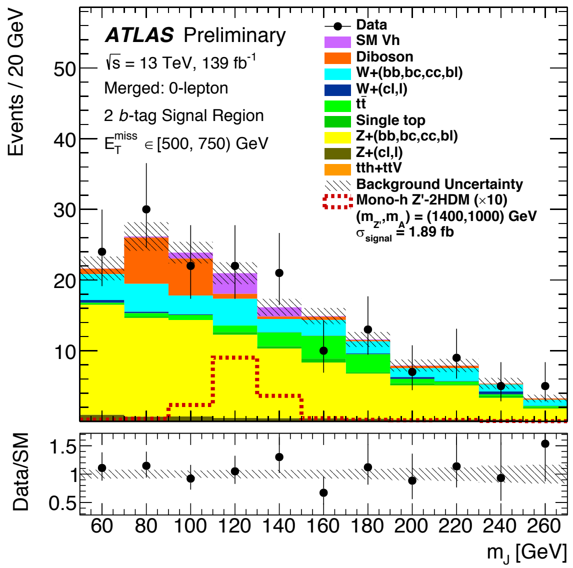
- **h→bb** and h→$\gamma\gamma$ channels (**h→bb** presented)
- Select events with MET > 150 GeV, no lepton, and an h→bb candidate reconstructed with 2 methods:
  - **Resolved regime** (MET < 500 GeV): 2 b-tagged small-R jets (R=0.4)
  - **Boosted regime** (MET > 500 GeV): 1 large-R jet with 2 associated b-tagged variable-R track-jets





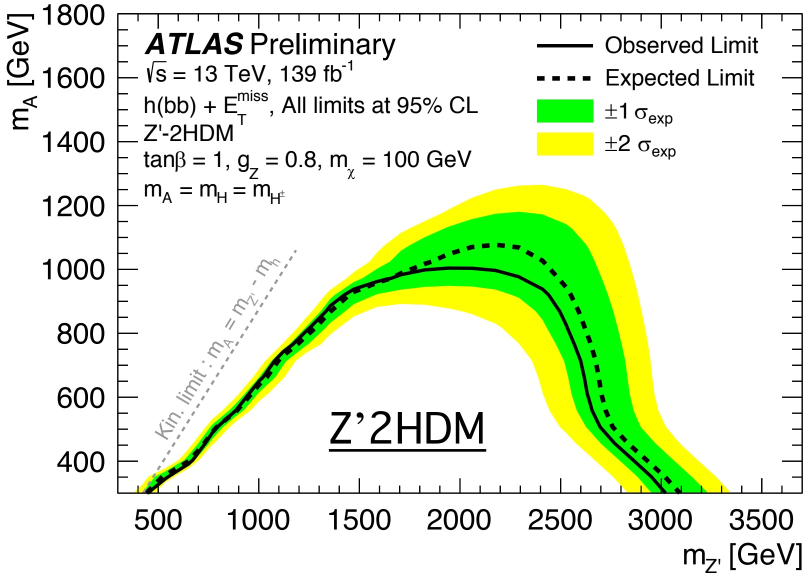




- Dominant backgrounds (Z/W+jets, $t\bar{t}$) modeled with control regions
- Fit to SR+CR in m_{bb}, MET and number of b-jets (2b and ≥3b); the additional ≥3b regions target the bbA production

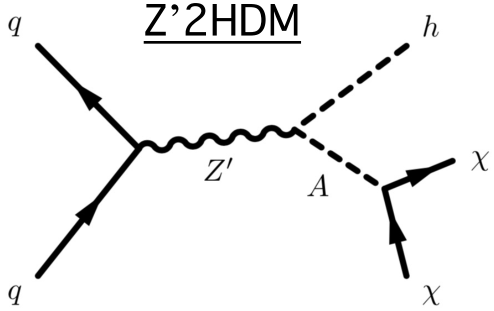
[arXiv:2104.13240](#) [ATLAS-CONF-2021-006](#)

Mono-h (MET+h), 13TeV, $139 fb^{-1}$

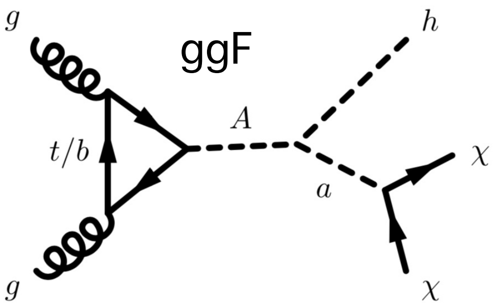


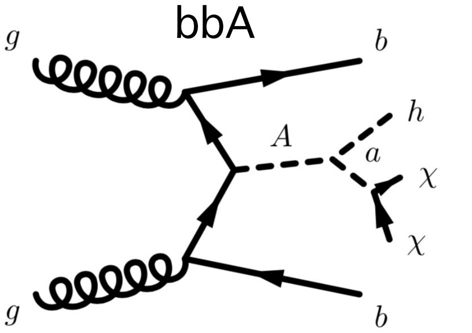
- Limits set on **Z'2HDM** and **2HDM+a with ggF or bbA** production
- Large improvements compared to previous result!
- First time reaching sensitivity to 2HDM+a bbA!

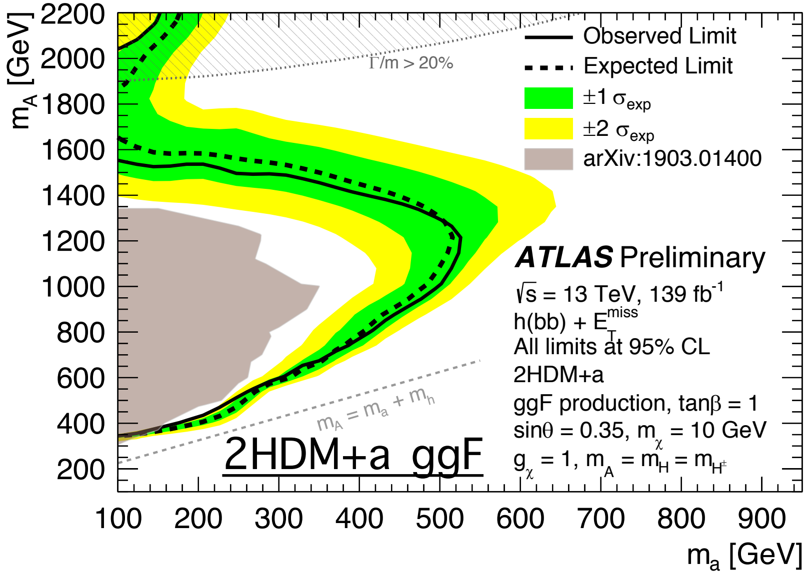
Z'2HDM

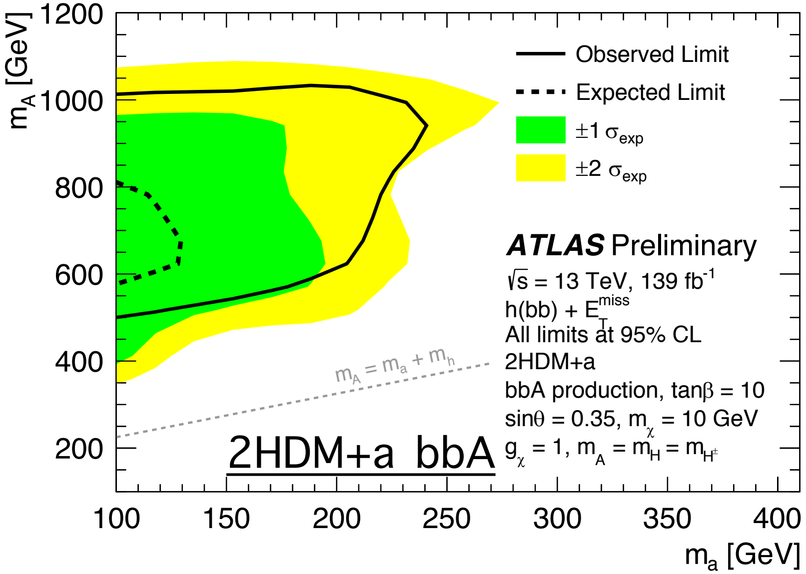


2HDM+a





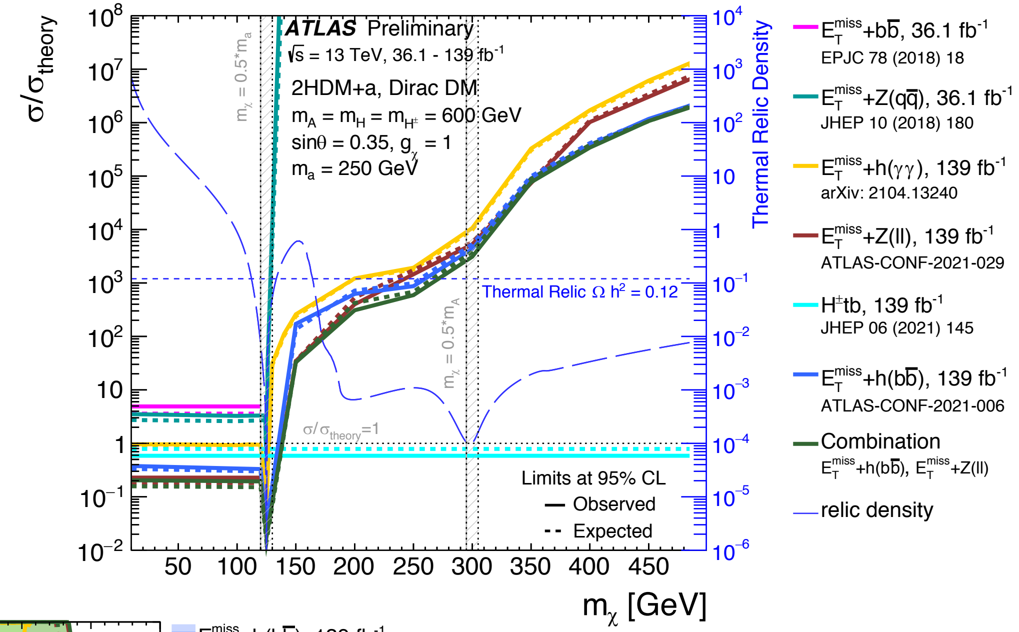


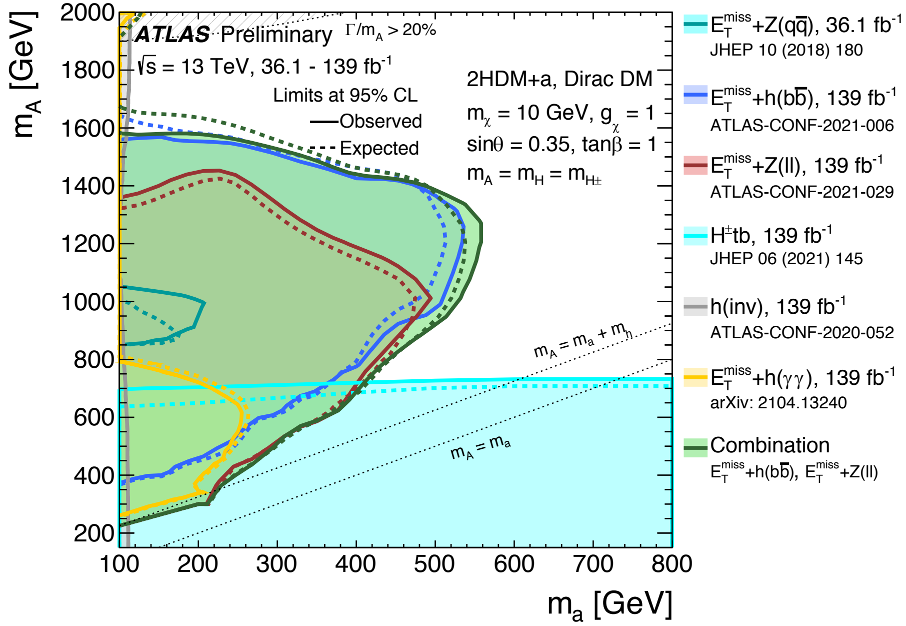


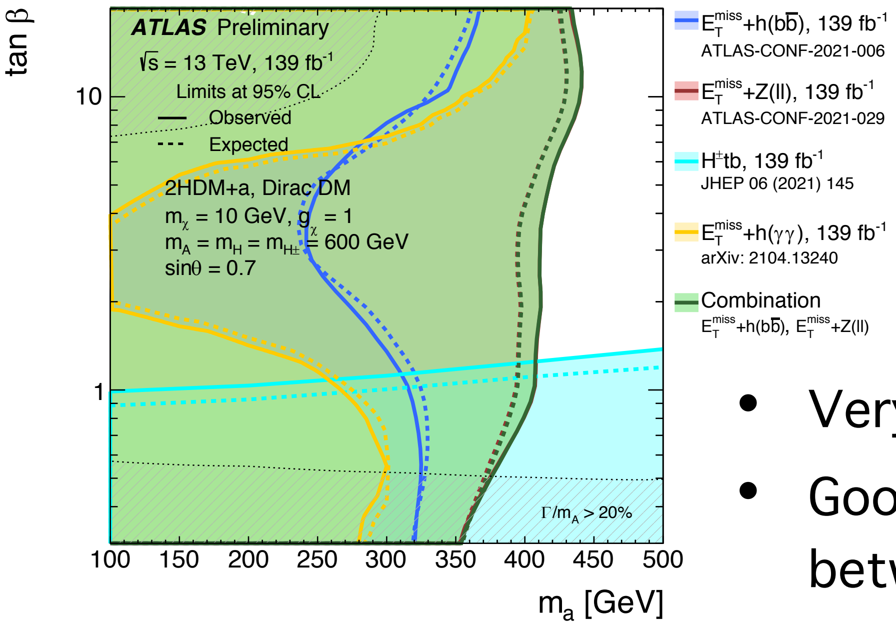
2HDM+a combination & summary

ATLAS-CONF-2021-036

- Updated with full run-2 (139 fb^{-1}) results:
  - First statistical combination: **mono-h(bb) + mono-Z**
  - Include **MET+Wt** channel and reinterpretation of **H±tb**
  - Include bb-initiated production of the 2HDM+a signal (in addition to gg-initiated)
  - Perform additional parameter scans (m_A, m_a, tanβ, sinθ, m_χ) wrt previous results (*JHEP 05 (2019) 142*)







- Very rich phenomenology
- Good complementarity between different channels

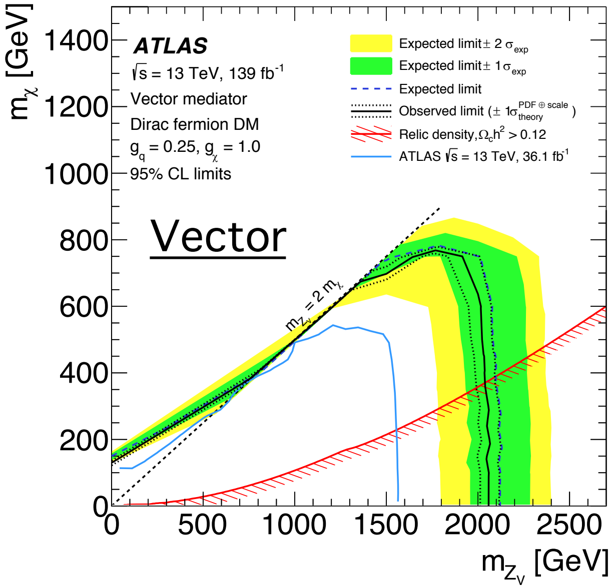
Summary

- Dark Matter searches with colliders are well physics-motivated and provide great complementarity to the direct/indirect searches
- Consider a wide variety of motivated simplified and more complete models
  - Simplified models with spin-0 or spin-1 mediators, Higgs portal, extended Higgs sector, etc.
  - Provide rich phenomenology and motivate a broad range of experimental techniques
- No deviation from SM has been found so far, yet…
  - More searches are ongoing with full run-2 data (stay tuned!)
  - Look forward to big surprise in the future!! (HL-LHC Projections: ATL-PHYS-PUB-2018-043, ATL-PHYS-PUB-2018-036, ATL-PHYS-PUB-2015-004, ATL-PHYS-PUB-2018-038, ATL-PHYS-PUB-2018-048)

Backup slides

Mono-jet search, 13TeV, 139fb^{-1}

Phys. Rev. D 103 (2021) 112006



Requirement	SR	$W \to \mu\nu$	$Z \to \mu\mu$	$W \to e\nu$	$Z \to ee$	Top
Primary vertex	at least one with ≥ 2 associated tracks with p_T > 500 MeV					
Trigger	E_T^{miss}			single-electron		E_T^{miss}, single-electron
p_T^{recoil} cut	E_T^{miss} > 200 GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(\mu) \rvert$ > 200 GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(\mu\mu) \rvert$ > 200 GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(e) \rvert$ > 200 GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(ee) \rvert$ > 200 GeV	$\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(\mu) \rvert$ > 200 GeV or $\lvert \mathbf{p}_T^{miss} + \mathbf{p}_T(e) \rvert$ > 200 GeV
Jets	up to 4 with p_T > 30 GeV, $\lvert\eta\rvert$ < 2.8					
$\lvert\Delta\phi(\text{jets}, \mathbf{p}_T^{recoil})\rvert$	> 0.4 (> 0.6 if 200 GeV < E_T^{miss} ≤ 250 GeV)					
Leading jet	p_T > 150 GeV, $\lvert\eta\rvert$ < 2.4, f_{ch}/f_{max} > 0.1					
b-jets	any	none	any	none	any	at least one
Electrons or muons	none	exactly one muon, with p_T > 10 GeV, 30 < m_T < 100 GeV; no electron	exactly two muons, with p_T > 10 GeV, 66 < $m_{\mu\mu}$ < 116 GeV; no electron	exactly one electron, tight, with p_T > 30 GeV, $\lvert\eta\rvert \notin$ (1.37, 1.52), tight isolation, 30 < m_T < 100 GeV; no muon	exactly two electrons, with p_T > 30 GeV, 66 < m_{ee} < 116 GeV; no muon	same as for $W \to \mu\nu$ or same as for $W \to e\nu$
τ-leptons	none					
Photons	none					

Source of uncertainty and effect on the total SR background estimate [%]			
Flavor tagging	0.1 – 0.9	τ-lepton identification efficiency	0.1 – 0.07
Jet energy scale	0.17 – 1.0	Luminosity	0.01 – 0.05
Jet energy resolution	0.15 – 1.3	Noncollision background	0.2 – 0.0
Jet JVT efficiency	0.01 – 0.03	Multijet background	1.0 – 0.0
Pileup reweighting	0.4 – 0.24	Diboson theory	0.01 – 0.22
E_T^{miss} resolution	0.34 – 0.04	Single-top theory	0.13 – 0.28
E_T^{miss} scale	0.5 – 0.25	$t\bar{t}$ theory	0.06 – 0.7
Electron and photon energy resolution	0.01 – 0.08	V+jets τ-lepton definition	0.04 – 0.16
Electron and photon energy scale	0.3 – 0.7	V+jets pure QCD corrections	0.24 – 1.1
Electron identification efficiency	0.5 – 1.0	V+jets pure EW corrections	0.17 – 2.2
Electron reconstruction efficiency	0.15 – 0.2	V+jets mixed QCD–EW corrections	0.02 – 0.7
Electron isolation efficiency	0.04 – 0.19	V+jets PDF	0.01 – 0.7
Muon identification efficiency	0.03 – 0.9	VBF EW V+jets backgrounds	0.02 – 1.1
Muon reconstruction efficiency	0.4 – 1.5	Limited MC statistics	0.05 – 1.9
Muon momentum scale	0.1 – 0.7		
Total background uncertainty in the Signal Region: 1.5%–4.2%			

- Main uncertainties:
  - Pile-up jets, MET, lepton in low MET
  - single-t and V+jets modeling in high MET

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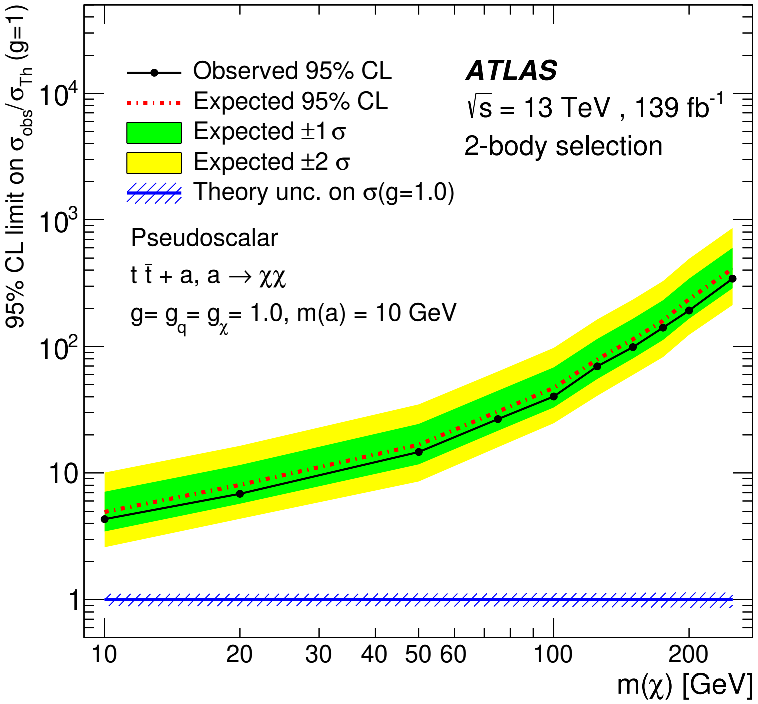
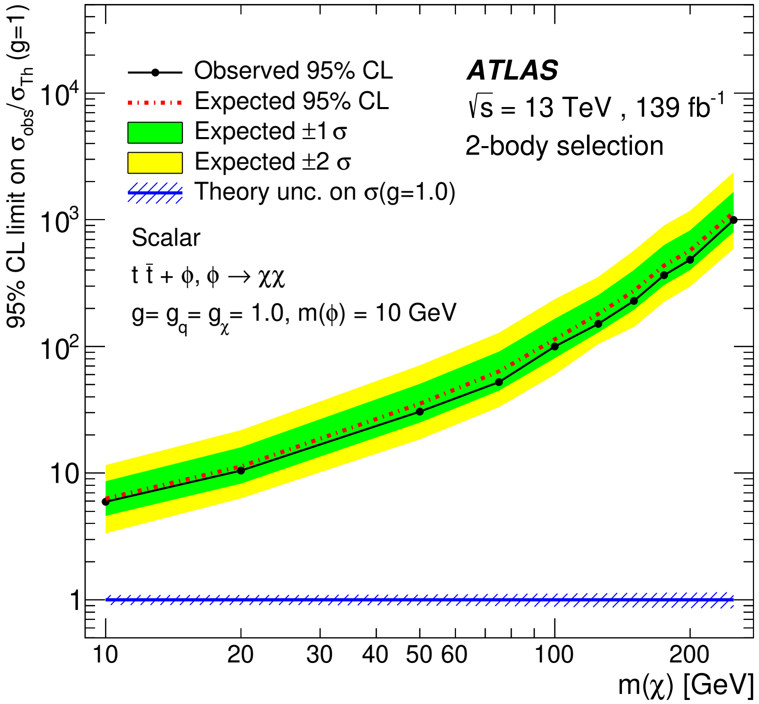
MET+$t\bar{t}$, 13TeV, 139fb^{-1}





	SR^{2-body}	
Leptons flavour	DF	SF
$p_T(\ell_1)$ [GeV]	> 25	
$p_T(\ell_2)$ [GeV]	> 20	
$m_{\ell\ell}$ [GeV]	> 20	
$\|m_{\ell\ell} - m_Z\|$ [GeV]	–	> 20
n_{b-jets}	≥ 1	
$\Delta\phi_{boost}$ [rad]	< 1.5	
E_T^{miss} significance	> 12	
$m_{T2}^{\ell\ell}$ [GeV]	> 110	

	$CR_{t\bar{t}}^{2-body}$	$CR_{t\bar{t}Z}$
Lepton multiplicity	2	3
Lepton flavour	DF	at least one SFOS pair
$p_T(\ell_1)$ [GeV]	> 25	> 25
$p_T(\ell_2)$ [GeV]	> 20	> 20
$p_T(\ell_3)$ [GeV]	–	> 20
$p_T(\ell_4)$ [GeV]	–	–
$m_{\ell\ell}$	> 20	–
$\|m_{\ell\ell} - m_Z\|$ [GeV]	–	< 20 for at least one SFOS pair
n_{b-jets}	≥ 1	≥ 2 with $n_{jets} \geq 3$
$\Delta\phi_{boost}$ [rad]	≥ 1.5	–
E_T^{miss} significance	> 8	–
$E_{T,corr}^{miss}$ [GeV]	–	> 140
$m_{T2}^{\ell\ell}$ [GeV]	[100, 120]	–
$m_{T2}^{4\ell}$ [GeV]	–	–

$$m_{T2}^{\ell\ell} = \min_{q_{T,1}+q_{T,2}=p_T^{miss}} \{\max[m_T(p_{T,\ell 1}, q_{T,1}), m_T(p_{T,\ell 2}, q_{T,2})]\}$$

represent the W mass from the t decays in the $t\bar{t}$ process. The value is expected to be higher in presence of additional invisible particles apart from the neutrinos from the W decays.

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MET+$t\bar{t}$, 13TeV, 139fb^{-1}

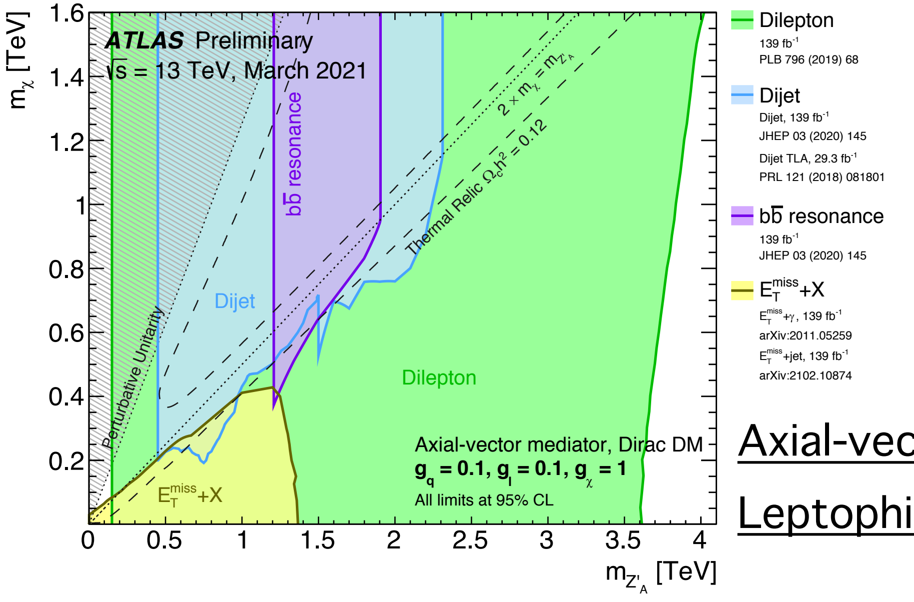
Signal Region	SR-SF$^{2-\text{body}}_{[110,120)}$	SR-SF$^{2-\text{body}}_{[120,140)}$	SR-SF$^{2-\text{body}}_{[140,160)}$	SR-SF$^{2-\text{body}}_{[160,180)}$	SR-SF$^{2-\text{body}}_{[180,220)}$	SR-SF$^{2-\text{body}}_{[220,\infty)}$
Total SM background uncertainty	19%	20%	17%	15%	15%	20%
VV theoretical uncertainties	–	2.4%	3.5%	4.9%	4.4%	7.1%
$t\bar{t}$ theoretical uncertainties	10%	11%	6.2%	–	1.7%	2.7%
$t\bar{t}Z$ theoretical uncertainties	1.0%	2.2%	4.2%	5.2%	5.0%	11%
$t\bar{t}$–Wt interference	–	–	–	–	1.0%	5.7%
Other theoretical uncertainties	1.0%	1.4%	2.7%	2.5%	2.6%	1.9%
MC statistical uncertainty	5.1%	5.4%	7.0%	7.7%	9.9%	8.7%
$t\bar{t}$ normalisation	7.6%	4.8%	1.0%	–	–	–
$t\bar{t}Z$ normalisation	1.1%	3.2%	5.6%	7.2%	6.4%	4.8%
Jet energy scale	11%	6.7%	9.6%	2.0%	3.4%	2.0%
Jet energy resolution	3.6%	13%	7.0%	6.1%	3.6%	7.7%
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	2.9%	3.6%	1.0%	4.1%	2.7%	1.2%
Lepton modelling	3.6%	1.8%	1.8%	3.8%	3.7%	6.4%
Flavour tagging	1.0%	1.0%	1.0%	2.6%	3.0%	2.4%
Pile-up reweighting and JVT	–	1.4%	1.0%	1.0%	1.7%	–
Fake and non-prompt leptons	–	–	1.1%	–	2.8%	4.3%

Signal Region	SR-DF$^{2-\text{body}}_{[110,120)}$	SR-DF$^{2-\text{body}}_{[120,140)}$	SR-DF$^{2-\text{body}}_{[140,160)}$	SR-DF$^{2-\text{body}}_{[160,180)}$	SR-DF$^{2-\text{body}}_{[180,220)}$	SR-DF$^{2-\text{body}}_{[220,\infty)}$
Total SM background uncertainty	20%	20%	15%	16%	14%	21%
VV theoretical uncertainties	1.0%	1.3%	2.6%	1.0%	2.0%	1.8%
$t\bar{t}$ theoretical uncertainties	9.6%	12%	7.6%	–	3.1%	–
$t\bar{t}Z$ theoretical uncertainties	1.2%	2.0%	5.3%	6.6%	5.7%	16%
$t\bar{t}$–Wt interference	–	–	–	–	–	–
Other theoretical uncertainties	1.0%	1.2%	2.8%	3.2%	2.7%	3.3%
MC statistical uncertainty	4.7%	5.0%	6.9%	8.2%	7.7%	6.6%
$t\bar{t}$ normalisation	7.2%	5.6%	1.2%	–	–	–
$t\bar{t}Z$ normalisation	1.4%	2.8%	6.9%	9.1%	7.3%	7.2%
Jet energy scale	8.5%	10%	2.5%	6.1%	1.0%	2.6%
Jet energy resolution	13%	6.6%	6.2%	4.3%	5.3%	2.0%
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	3.5%	6.1%	1.0%	2.2%	2.2%	1.0%
Lepton modelling	1.5%	1.1%	1.6%	1.3%	1.3%	1.0%
Flavour tagging	1.0%	1.0%	1.3%	2.0%	1.0%	1.0%
Pile-up reweighting and JVT	–	1.6%	1.0%	–	1.0%	–
Fake and non-prompt leptons	–	3.5%	–	–	7.1%	13%

- Main uncertainties include $t\bar{t}$, $t\bar{t}Z$ modeling and jet energy resolution and scale

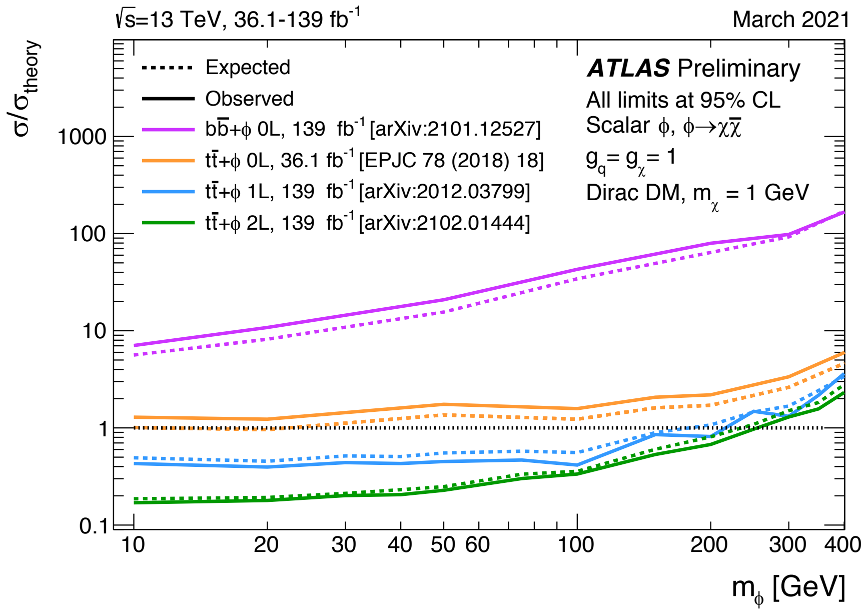
Summary of simplified models

ATL-PHYS-PUB-2021-006

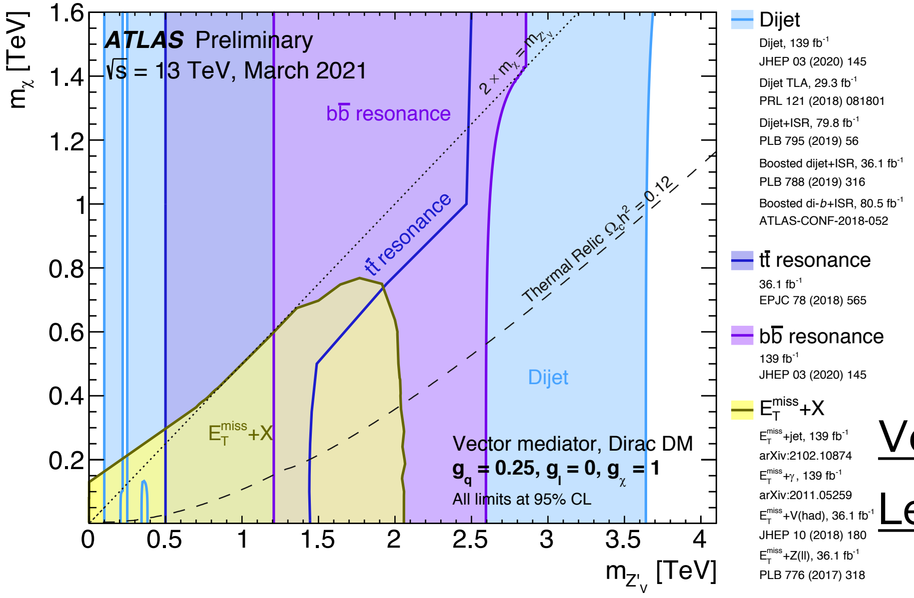


Axial-vector

Leptophilic

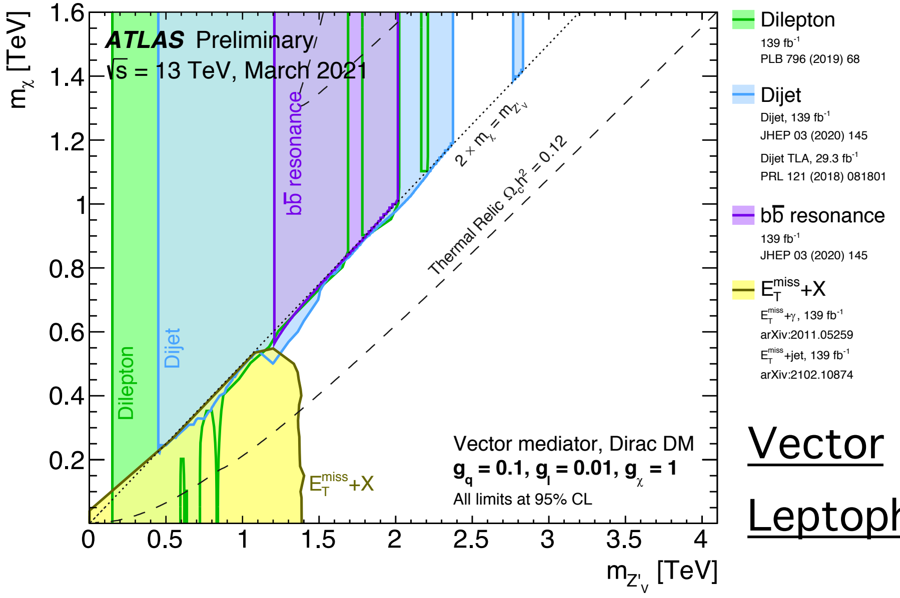


Scalar



Vector

Leptophobic

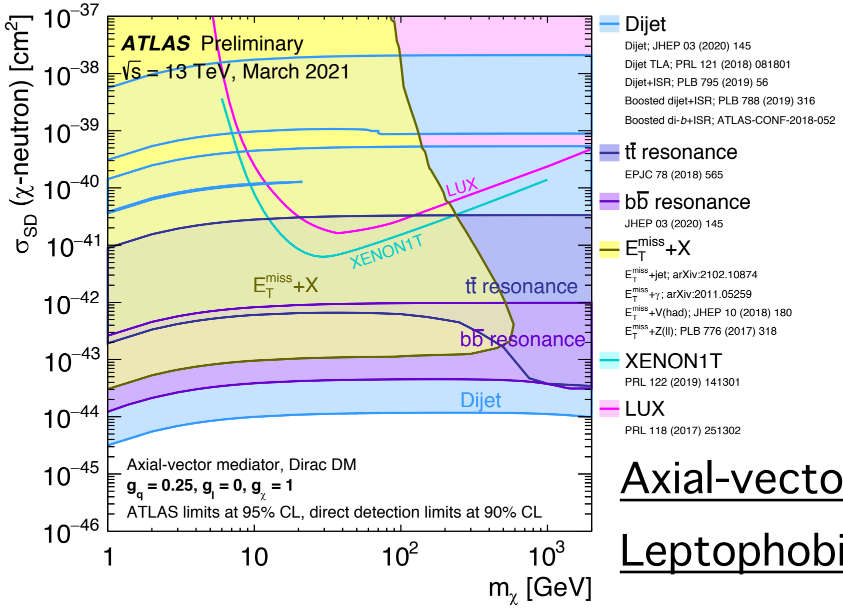


Vector

Leptophilic

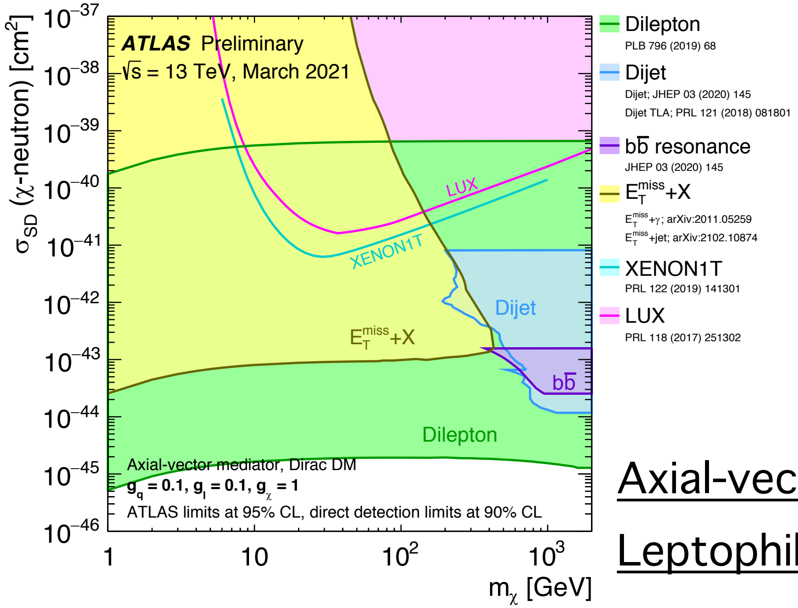
Summary of simplified models

ATL-PHYS-PUB-2021-006



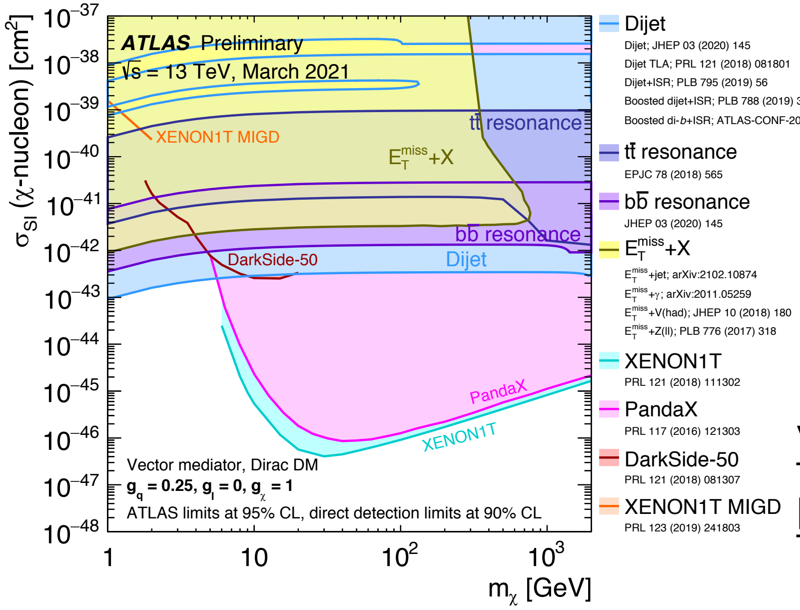
Axial-vector

Leptophobic



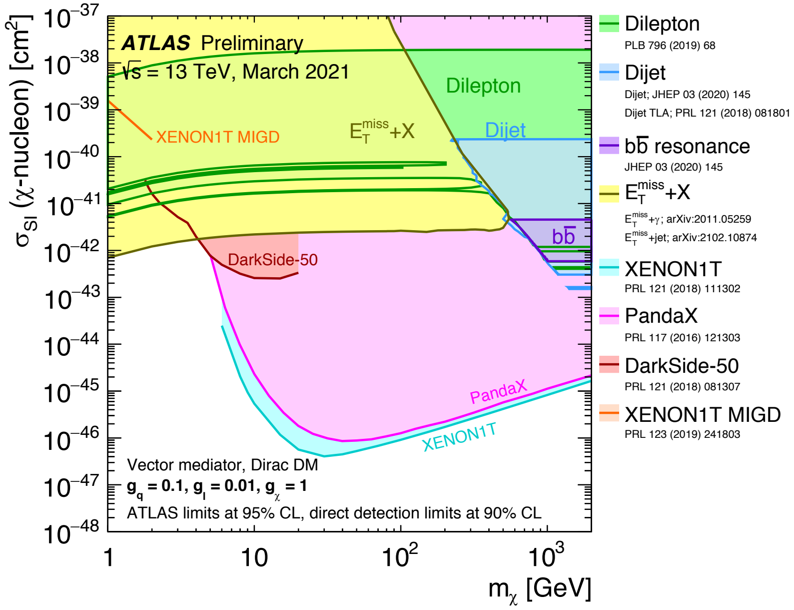
Axial-vector

Leptophilic



Vector

Leptophobic



Vector

Leptophilic

Mono-Z (MET+Z), 13TeV, $139fb^{-1}$

ATLAS-CONF-2021-029

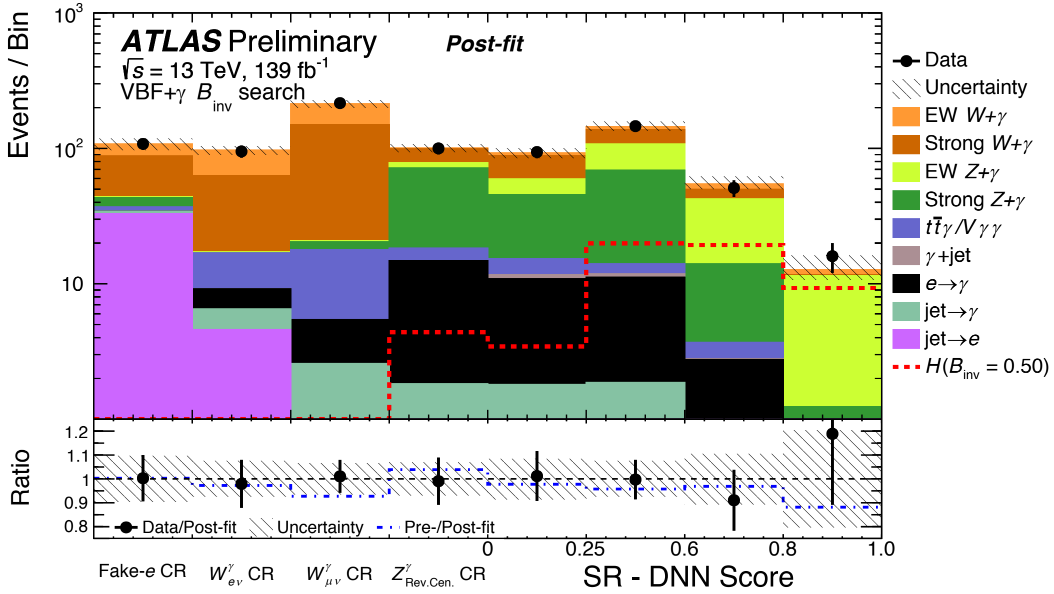
	SR	$e\mu$ CR	3ℓ CR	4ℓ CR
Observed events	6382	891	11415	314
Expected yields after fit	6385 ± 80	894 ± 29	11410 ± 110	295 ± 11
$ZH \to \ell\ell + \text{inv}$	-4 ± 110	-	-	-
$ZZ \to \ell\ell\nu\nu$	2669 ± 110	-	443.4 ± 7.5	-
WZ	1624 ± 28	11.59 ± 0.23	10646 ± 110	-
$Z + \text{jets}$	1110 ± 100	0.802 ± 0.018	237.6 ± 4.0	-
Non-resonant	876 ± 39	878 ± 29	-	-
$ZZ \to \ell\ell\ell\ell$	85.2 ± 5.5	-	-	295 ± 11
ttV	12.5 ± 1.1	1.769 ± 0.036	48.98 ± 0.82	-
Triboson	12.2 ± 1.4	2.886 ± 0.076	35.65 ± 0.60	-

Uncertainty source	$\Delta\mathcal{B}$ [%]
Statistical uncertainty	5.1
Systematic uncertainties	7.1
Theory uncertainties	4.9
Signal modelling	0.4
ZZ modelling	4.4
Non-ZZ background modelling	2.0
Experimental uncertainties (excl. MC stat.)	4.2
Luminosity, pile-up	1.5
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	3.5
Flavour tagging	0.4
Electrons, muons	1.2
MC statistical uncertainty	1.7
Total uncertainty	8.8

- Main uncertainties include ZZ modeling and jet reconstruction

VBF+MET+photon

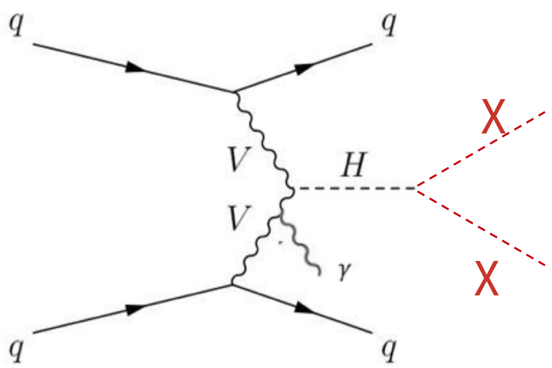
Variable	SR	$W^{\gamma}_{\mu\nu}$ CR	$W^{\gamma}_{e\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	Fake$-e$ CR
(j_1) [GeV]			> 60		
(j_2) [GeV]			> 50		
			2,3		
$N_{\text{b-jet}}$			< 2		
$\Delta\phi_{\text{jj}}$			< 2.5 [2.0]		
$\lvert\Delta\eta_{\text{jj}}\rvert$			> 3.0		
$\eta(j_1) \times \eta(j_2)$			< 0		
C_3			< 0.7		
m_{jj} []			> 0.25		
[GeV]	> 150	–	> 80	> 150	< 80
$E_{\text{T}}^{\text{miss,lep-rm}}$ [GeV]	–	> 150	> 150	–	> 150
$E_{\text{T}}^{\text{jets,no-jvt}}$ [GeV]			> 130		
$\Delta\phi(j_i, E_{\text{T}}^{\text{miss,lep-rm}})$			> 1.0		
N_γ			1		
(γ) [GeV]			> 15, < 110 [> 15, $<\max(110, 0.733 \times m_{\text{T}})$]		
C_γ	> 0.4	> 0.4	> 0.4	< 0.4	> 0.4
$\Delta\phi(\gamma, E_{\text{T}}^{\text{miss,lep-rm}})$			> 1.8 [–]		
N_ℓ	0	1 μ	1 e	0	1 e
(ℓ) [GeV]			> 30		



Source	1σ Uncertainty on $\mathcal{B}_{\text{inv}}$
Data stats.	0.106
$V\gamma$+jets theory	0.056
MC stats.	0.045
Jet Scale and Resolution	0.045
Photon	0.032
$e \to \gamma$, jet$\to e, \gamma$ Bkg.	0.026
Pileup	0.025
$W\gamma$+jets/$Z\gamma$+jets Norm.	0.021
	0.012
Signal theory	0.004
Lepton	0.002
Total	0.148

Region definition and categorization

VBF +MET +photon



- Signal region (SR)
  - n_{jet} = 2 or 3
  - $\Delta\eta_{jj} > 3$
  - m_{jj} > 250 GeV
  - $n_{\gamma} = 1$
  - MET > 150 GeV
  - Lepton veto
  - Detailed selections in backups

- Control regions (included in the statistical fitting)
  - W(→eν)γ+jets (require 1e)
  - W(→μν)γ+jets (require 1μ)

- Validation regions (not included in the statistical fitting)
  - Z(→ll)γ+jets (require 2l)
  - Fake-e (require 1 loose-e)

VBF+MET+photon region definition

VBF +MET +photon

Signal region

Jet cuts	
Cut	SR
N_{photon}	=1
$N_{baseline\text{-}lepton}$	=0
N_{jet}	=2,3
$N_{b\text{-}jet}$ (77% WP)	<2
$p_T(j_1)$	> 60 GeV
$p_T(j_2)$	> 50 GeV
MET	> 150 GeV
MET_CST_jet	> 120 GeV
$\eta(j_1) \times \eta(j_2)$	<0
$\Delta\eta(j_1,j_2)$	> 3.0
$\Delta\varphi(j_1,j_2)$	< 2
$\Delta\varphi(j_{1,2,3},\text{MET})$	> 1
abs. $\Delta\varphi(\text{MET,photon})$	> 1.8
Photon Centrality	> 0.4
Third jet centrality	< 0.7
$M(j_1,j_2)$	> 250 GeV
Photon p_T	< 110 GeV
abs(Photon Pointing)	< 250 mm

Lepton selections for signal region and control regions

Cut	*inv.*	$W(\to e\nu)\gamma$+ jets	$W(\to \mu\nu)\gamma$+ jets	$Z(\to \ell\ell)\gamma$+ jets
Lepton Flavours	0	e^-/e^+	μ^-/μ^+	$e^-,e^+/\mu^-,\mu^+$
"Veto" muons and electrons	0	1	1	2
"Signal" muons and electrons	0	1	1	2
$p_T(\ell_1)$	–	>30 GeV	>30 GeV	>30 GeV
$p_T(\ell_2)$	–	–	–	>4.5 GeV
$\lvert M(\ell\ell) - M_Z \rvert$	–	–	–	<25 GeV
E_T^{miss}(with leptons)	> 80 GeV	–	–	< 70 GeV

VBF+MET+photon background estimation

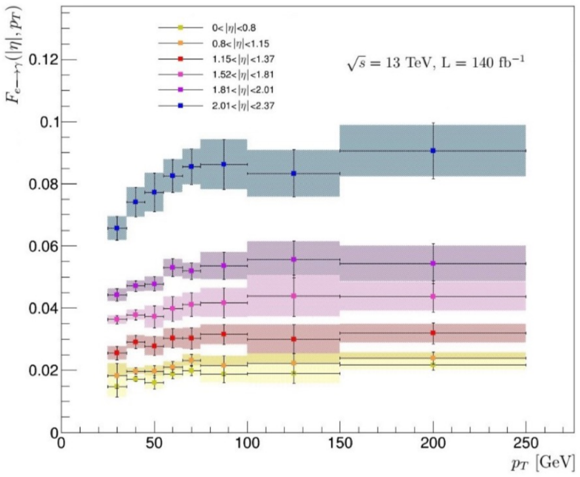
VBF +MET +photon

- Main backgrounds V+jets+photon modeled with MC

- V+jets (jet faking photon) estimated with ABCD method
- Electron faking photon ($We\nu$) estimated through Zee process in data
- Photon+jets estimated by jet smearing to increase statistics

Fake photons from electrons

- Estimating e → γ fake rate ($F_{e\rightarrow\gamma}$) in Z → ee events as function of |η| and p_T
- Using $F_{e\rightarrow\gamma}$ to rescale yields in a control sample of probe electrons
- Systematic uncertainties e.g. from:
  - background subtraction
  - energy scale of fake photon

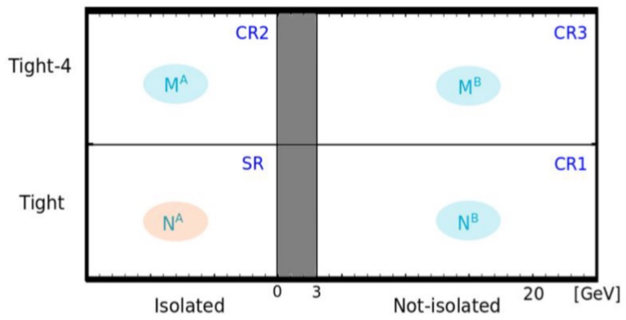


Fake photons from jets

- Estimated with ABCD method with inverted photon ID and isolation requirements

$$N^A_{sig} = N^A - N^A_{bkg} = N^A - N^B \frac{M^A}{M^B}$$

- Dominant systematic uncertainties:
  - Photon ID
  - CR statistics



Ref: Andrea's slides

Jay Chan (Wisconsin)

VBF+MET+photon DNN

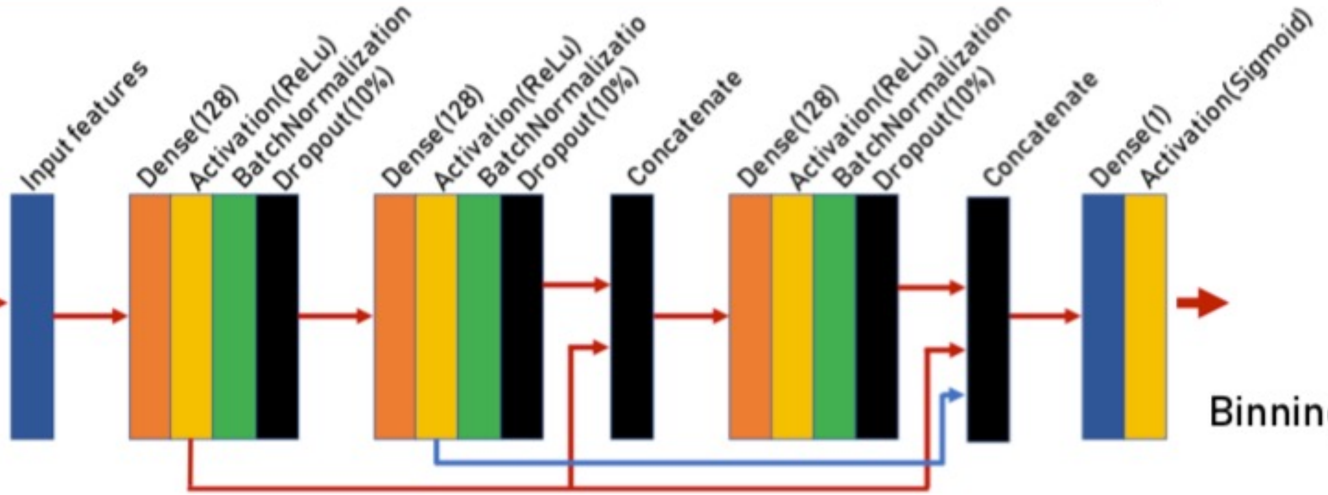
VBF +MET +photon

- Alternative approach to the Cutbased analysis (m_{jj} fit)

Training sample pre-selections (looser than SR/VR):

- n_{ph}=1
- n_{jet}= 2/3
- $E_T^{miss,no-lep}$ > 140 GeV
- γ+jet sample excluded

Input features
1. $\Delta\eta_{jj}$
2. $\Delta\varphi_{jj}$
3. m_{jj}
4. $E_T^{miss,no-lep}$
5. $\eta(\gamma)$
6. $p_T(j_1)$
7. $p_T(j_2)$
8. $\eta(j_2)$



Output:
1 ~ signal
0 ~ bkg

Binning = [0, 0.25, 0.6, 0.8, 1]

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Ref: Luigi's slides

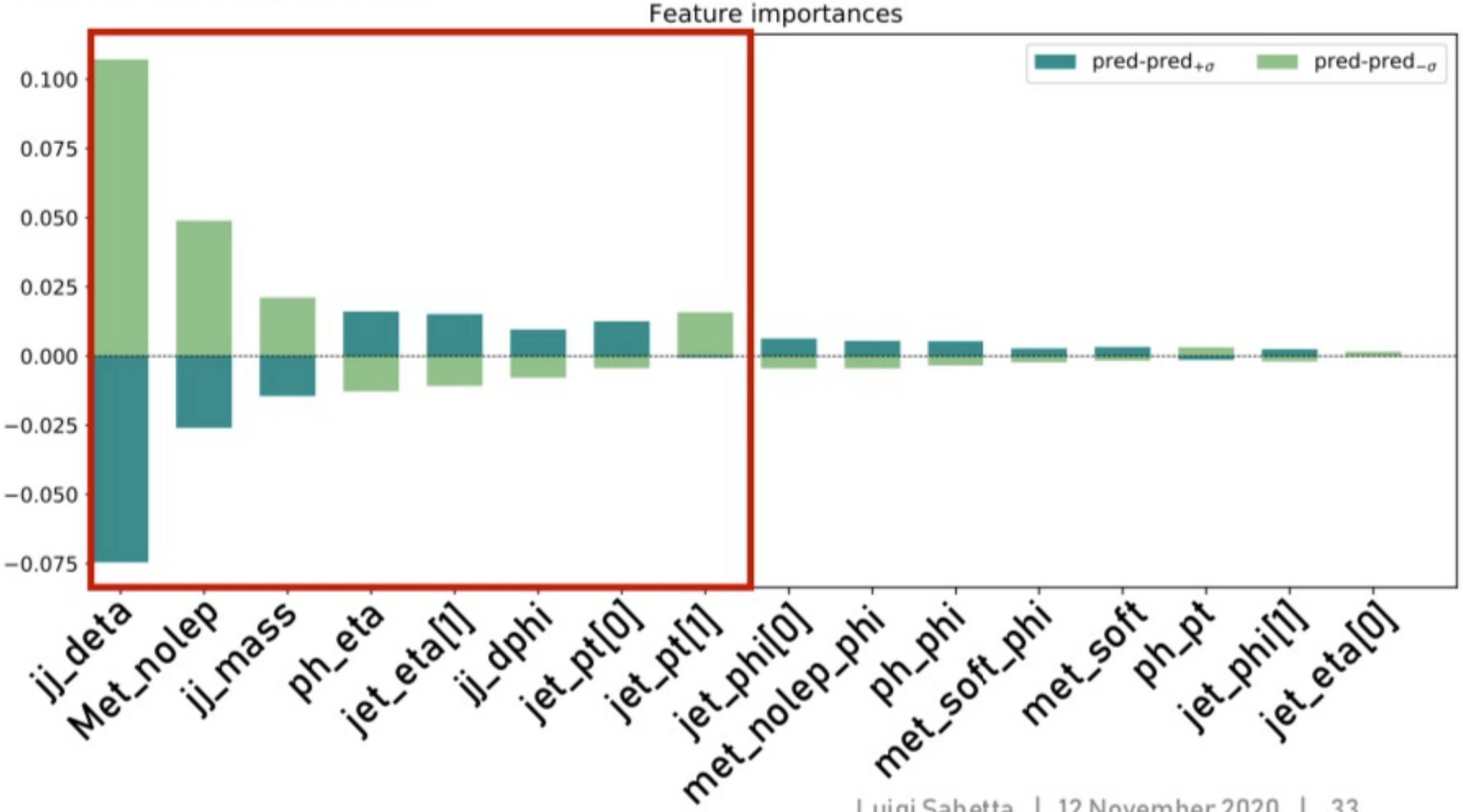
VBF+MET+photon DNN

VBF
+MET
+photon

Feature chosen via a backward elimination process:

1) Each feature is varied up and down by 10% and the average variation of DNN output interpreted as feature importance

2) The least important feature is removed and the model retrained with the new set of features



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Ref: Luigi's slides

arXiv:2104.13240 ATLAS-CONF-2021-006

Mono-h (MET+h), 13TeV, 139fb^{-1}

Resolved	Merged
Primary E_T^{miss} trigger	
Data quality selections	
$E_T^{miss} > 150$ GeV	
Lepton veto & extended τ-lepton veto	
$\Delta\phi(\text{jet}_{1,2,3}, E_T^{miss}) > 20°$	
$E_T^{miss} < 500$ GeV	$E_T^{miss} > 500$ GeV
At least 2 small-R jets	At least 1 large-R jet
At least 2 b-tagged small-R jets	At least 2 b-tagged associated variable-R track jets
$p_{T h} > 100$ GeV if $E_T^{miss} < 350$ GeV $p_{T h} > 300$ GeV if $E_T^{miss} > 350$ GeV	—
$m_T^{b,min} > 170$ GeV	—
$m_T^{b,max} > 200$ GeV	—
$\mathcal{S} > 12$	—
$N_{\text{small-}R\text{ jets}} \leq 4$ if 2 b-tag $N_{\text{small-}R\text{ jets}} \leq 5$ if ≥ 3 b-tag	—
$50\text{ GeV} < m_h < 280\text{ GeV}$	$50\text{ GeV} < m_h < 270\text{ GeV}$

	0 lepton	**1 muon**	**2 leptons**
Aim	Signal regions	$t\bar{t}$ and W+HF control region	Z+HF control region
Fitted observable	m_h distribution	Muon charge (2 b-tag) Yields (≥ 3 b-tag)	Yields
b-tag multiplicities	resolved (small-R jets): 2, ≥ 3 merged (variable-R track jets): 2 (inside Higgs candidate), ≥ 3 (2 inside Higgs candidate)		
E_T^{miss} proxy	E_T^{miss}	$E_{T,\text{lep. invis.}}^{miss}$	$E_{T,\text{lep. invis.}}^{miss}$
Bins in E_T^{miss} proxy	resolved: [150, 200], [200, 350] and [350, 500] GeV 2 b-tag merged signal regions (0 lepton): [500, 750] and [750, ∞) GeV Other merged regions: [500, ∞) GeV		

Source of uncertainty	Fractional squared uncertainty on μ		
	Z'-2HDM signals, $(m_{Z'}, m_A)$ [GeV]		
	(800, 500)	(1400, 1000)	(2800, 300)
Z+HF normalisation	0.11	0.03	<0.01
W+HF normalisation	0.02	0.01	<0.01
$t\bar{t}$ normalisation	0.16	0.04	<0.01
Z modelling uncertainties	0.02	0.07	<0.01
W modelling uncertainties	<0.01	0.01	<0.01
$t\bar{t}$ modelling uncertainties	0.13	0.05	<0.01
Single t modelling uncertainties	0.18	0.02	<0.01
Other modelling uncertainties	0.05	0.01	<0.01
Jets	0.20	0.06	0.01
b-tagging	0.01	0.01	0.04
E_T^{miss} soft term and pile-up	<0.01	<0.01	<0.01
Other experimental systematic uncertainties	0.01	<0.01	<0.01
Signal systematic uncertainties	<0.01	<0.01	<0.01
MC sample statistics	0.08	0.07	0.11
Statistical uncertainty	0.27	0.61	0.79
Total systematic uncertainties	0.73	0.39	0.21

- Main uncertainties include modeling of Z+jets and jet energy resolution

[ATLAS-CONF-2021-036]

2HDM+a combination & summary

- Target the DM model: 2HDM+a (arXiv:1701.07427)
  - Based on the type-II Two-Higgs-Doublet Model with an additional pseudoscalar mediating the interaction between SM and fermionic DM
  - The simplest gauge-invariant and UV-complete extension to the simplified model with a pseudoscalar mediator
  - Considered as a benchmark by LHC DM Working Group (arXiv:1810.09420)
  - Rich in phenomenology and offers various signatures and complementary exclusion from different experiments
- Previous results summarized in the 36 fb^{-1} DM summary paper
- New results with 139 fb^{-1}:
  - First statistical combination: MET+h(bb) + MET+Z(ll)
  - Include MET+Wt channel and reinterpretation of $H^{\pm}tb$
  - Include bb-initiated production of the 2HDM+a signal (apart from gg-initiated)
  - Perform 4 additional parameter scans

ATLAS-CONF-2021-036

2HDM+a combination & summary

Parameters	Description
m_h, m_H, $m_{H\pm}$, m_A, m_a	Masses of the Higgs bosons h, H, $H^{\pm}$, A, and the additional pseudoscalar mediator a
m_χ	Mass of the Dark Matter particle χ
g_χ	Yukawa coupling constant between a and χ
ν	Electroweak VEV
tanβ	Ratio of the VEVs of the two Higgs doublets
α, θ	Mixing angles between CP-even and CP-odd eigenstates
λ_{p1}, λ_{p1}, λ_3	Three quartic couplings between the scalar doublets and the mediator

→

Conditions	• Alignment limit: $\cos(\beta-\alpha)=0$, m_h=125 GeV, ν=246 GeV • $g_\chi=1$ • $\lambda_{p1}=\lambda_{p1}=\lambda_3=3$ • $m_H=m_{H\pm}=m_A$
Remaining parameters	m_A, m_a, m_χ, θ, tanβ

- The 2HDM+a is fully defined by 14 parameters
- Reduced to 5 free parameters with experimental constraints and phenomenological considerations: mA, m_a, m_χ, θ, tanβ

2HDM+a combination & summary

ATLAS-CONF-2021-036

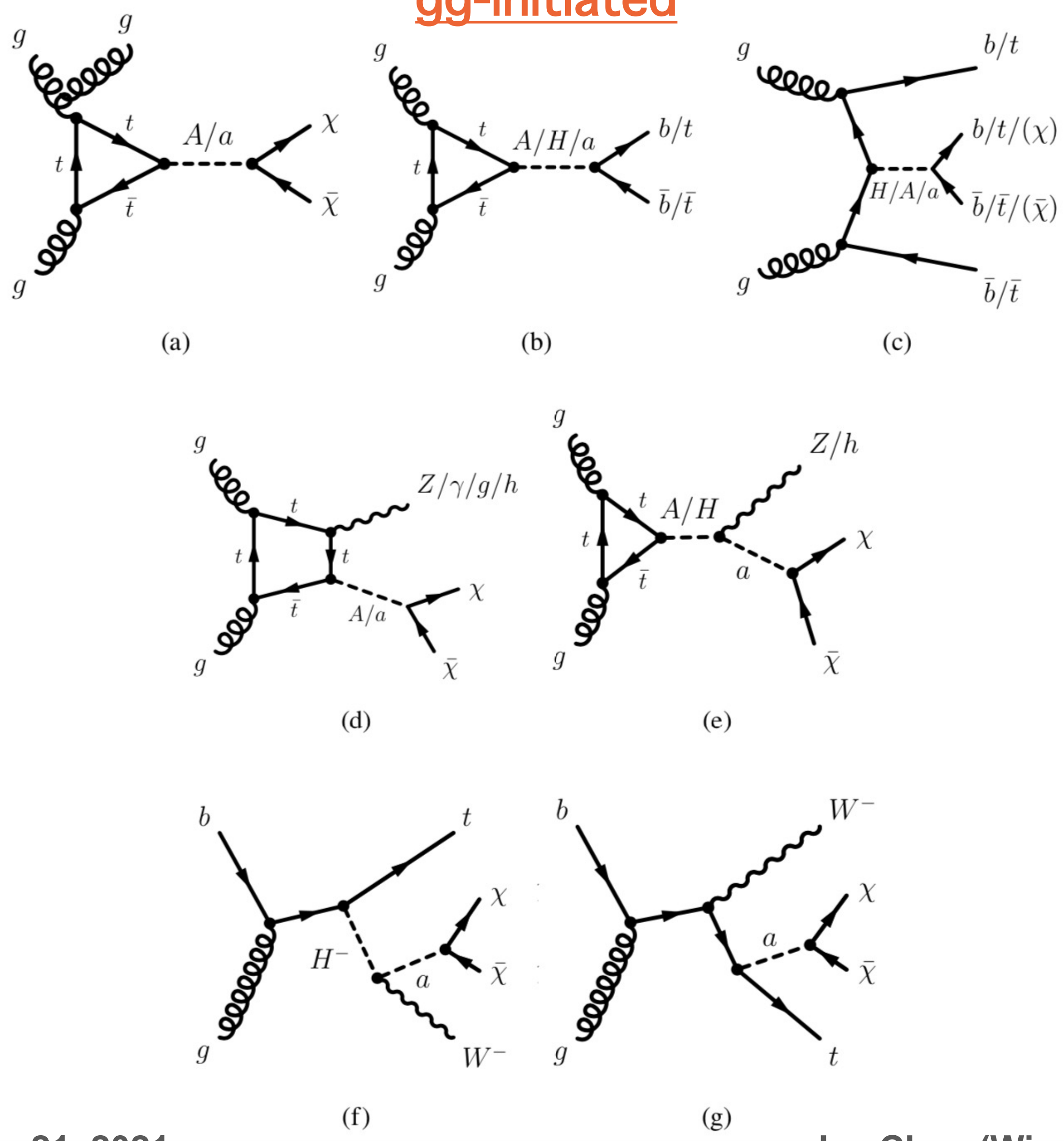
Index	Description
Scan 1	2D scan in (m_a-m_A) with tanβ=1, m_χ=10 GeV and (a.) sinθ=0.35 (b.) sinθ=0.7
Scan 2	2D scan in (m_a-tanβ) with m_A=0.6 TeV, m_χ=10 GeV and (a.) sinθ=0.35 (b.) sinθ=0.7
Scan 3	1D scan in sinθ with tanβ=1 and (a.) m_A=0.6 TeV, m_a=200 GeV (low-mass scan) (b.) m_A=1 TeV, m_a=350 GeV (high-mass scan)
Scan 4	1D scan in m_χ with m_A=0.6 TeV, m_a=250 GeV, tanβ=1, sinθ=0.35
Scan 5	2D scan in (m_A-tanβ) with m_a=250 GeV, m_χ=10 GeV and (a.) sinθ=0.35 (b.) sinθ=0.7

- 5 parameter scans recommended by LHC DM WG + 4 additional scans

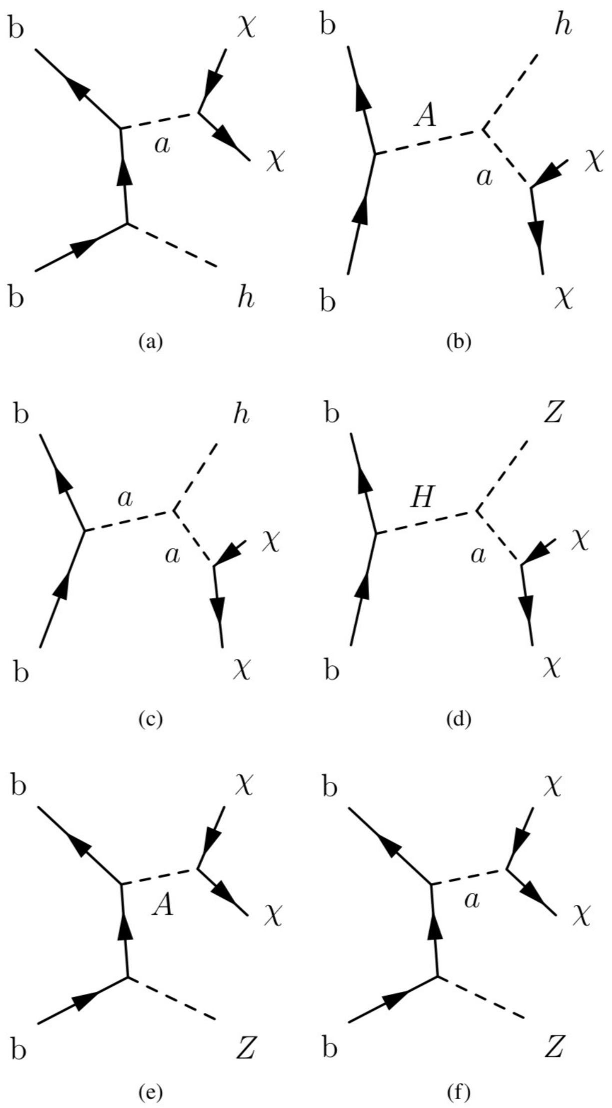
2HDM+a combination & summary

ATLAS-CONF-2021-036

gg-initiated

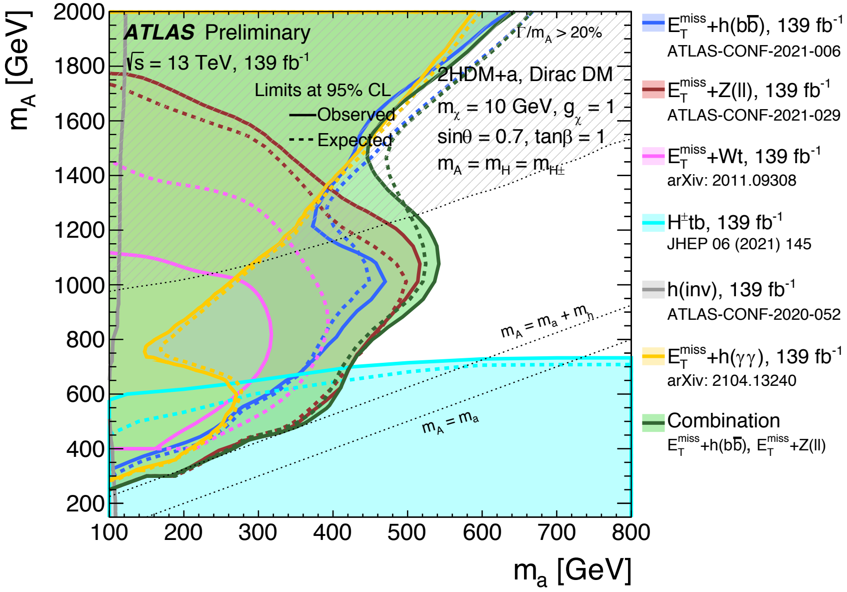


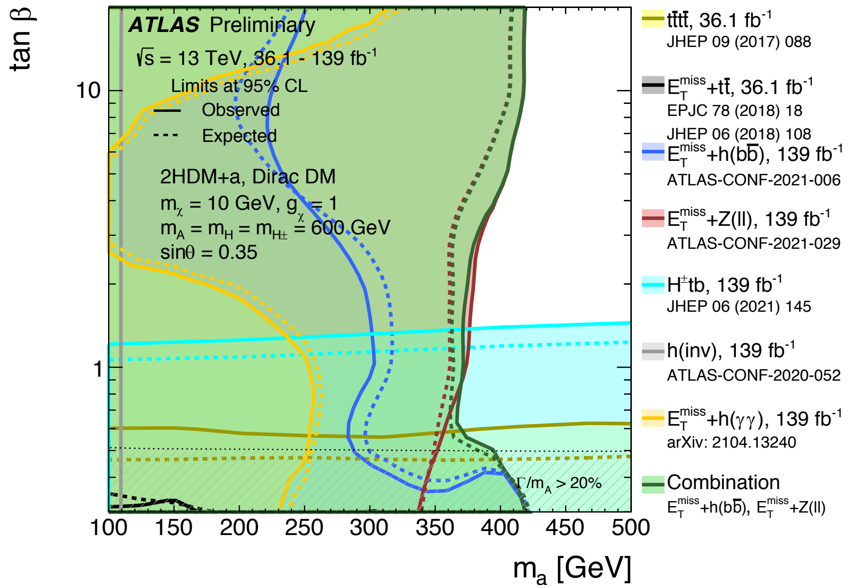
bb-initiated

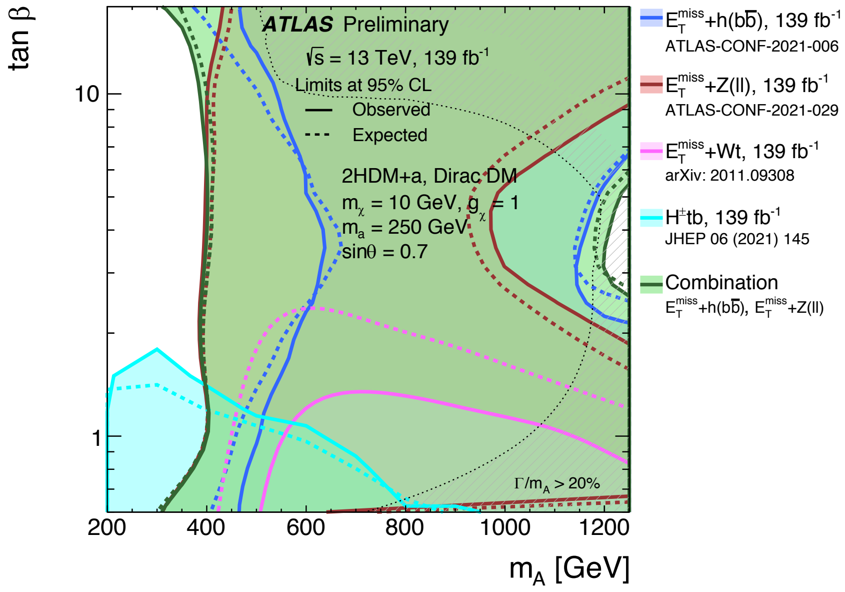


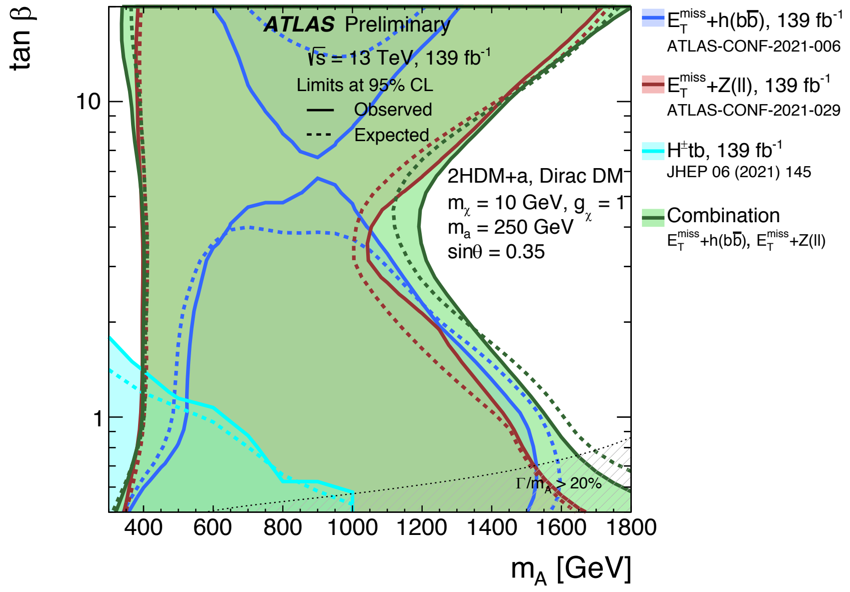
ATLAS-CONF-2021-036

2HDM+a combination & summary



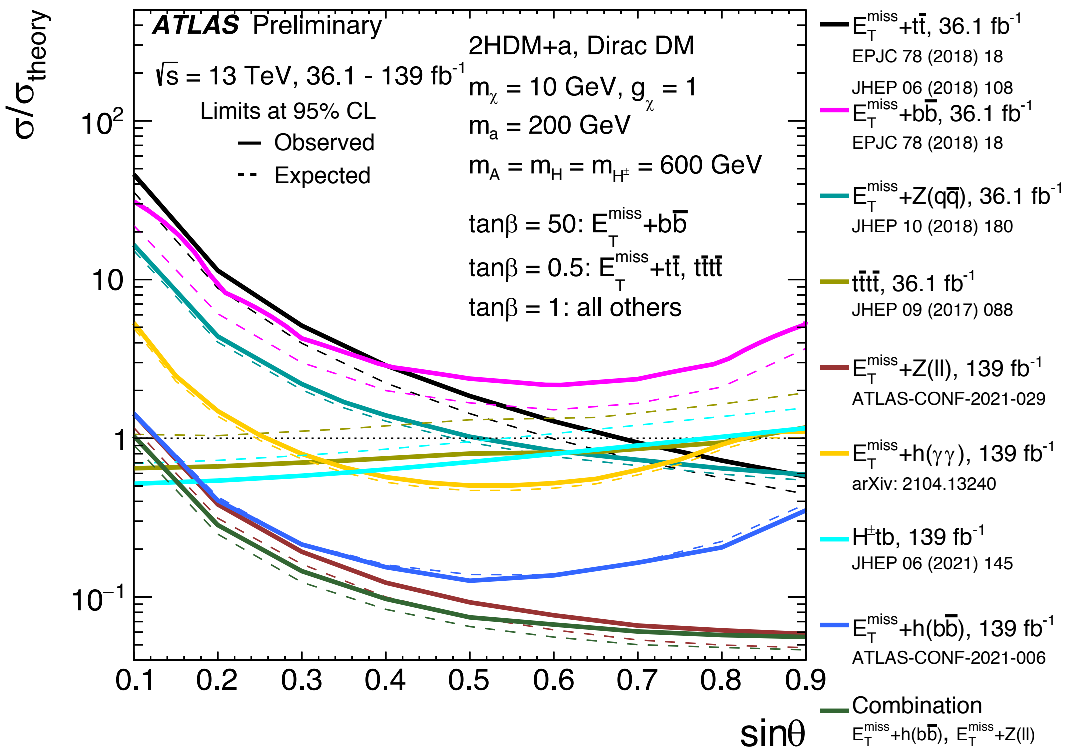


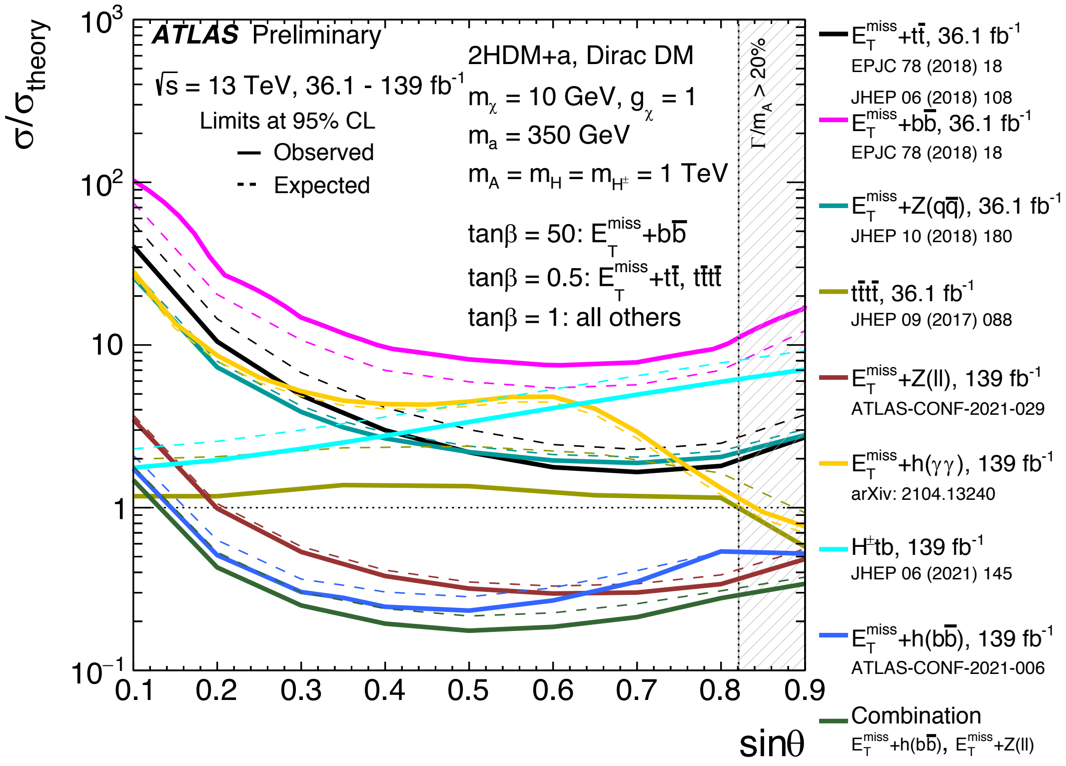




2HDM+a combination & summary

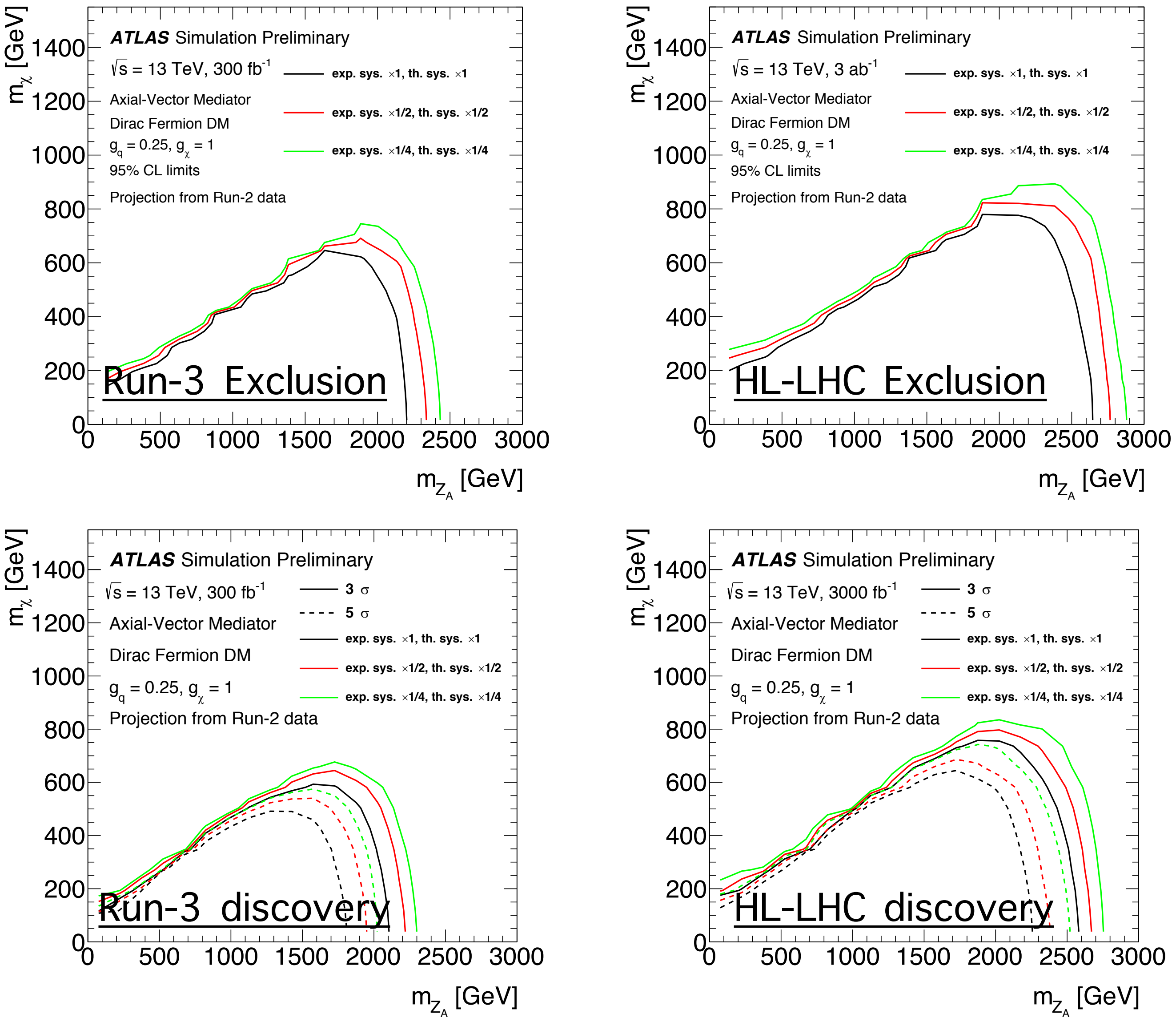
ATLAS-CONF-2021-036





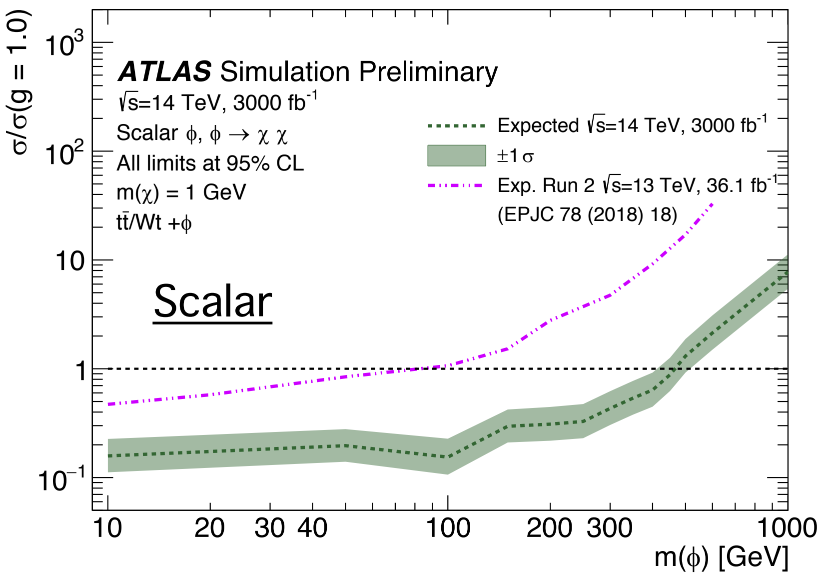
Mono-jet projection

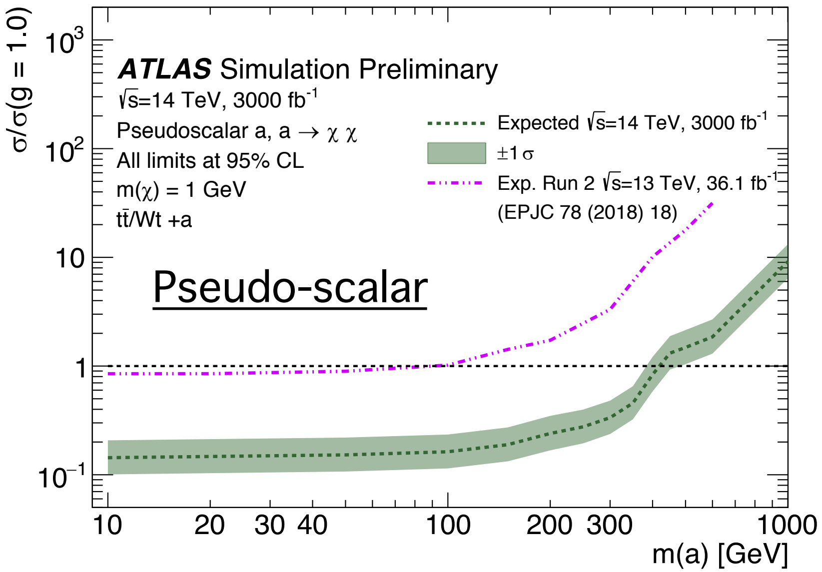
ATL-PHYS-PUB-2018-043

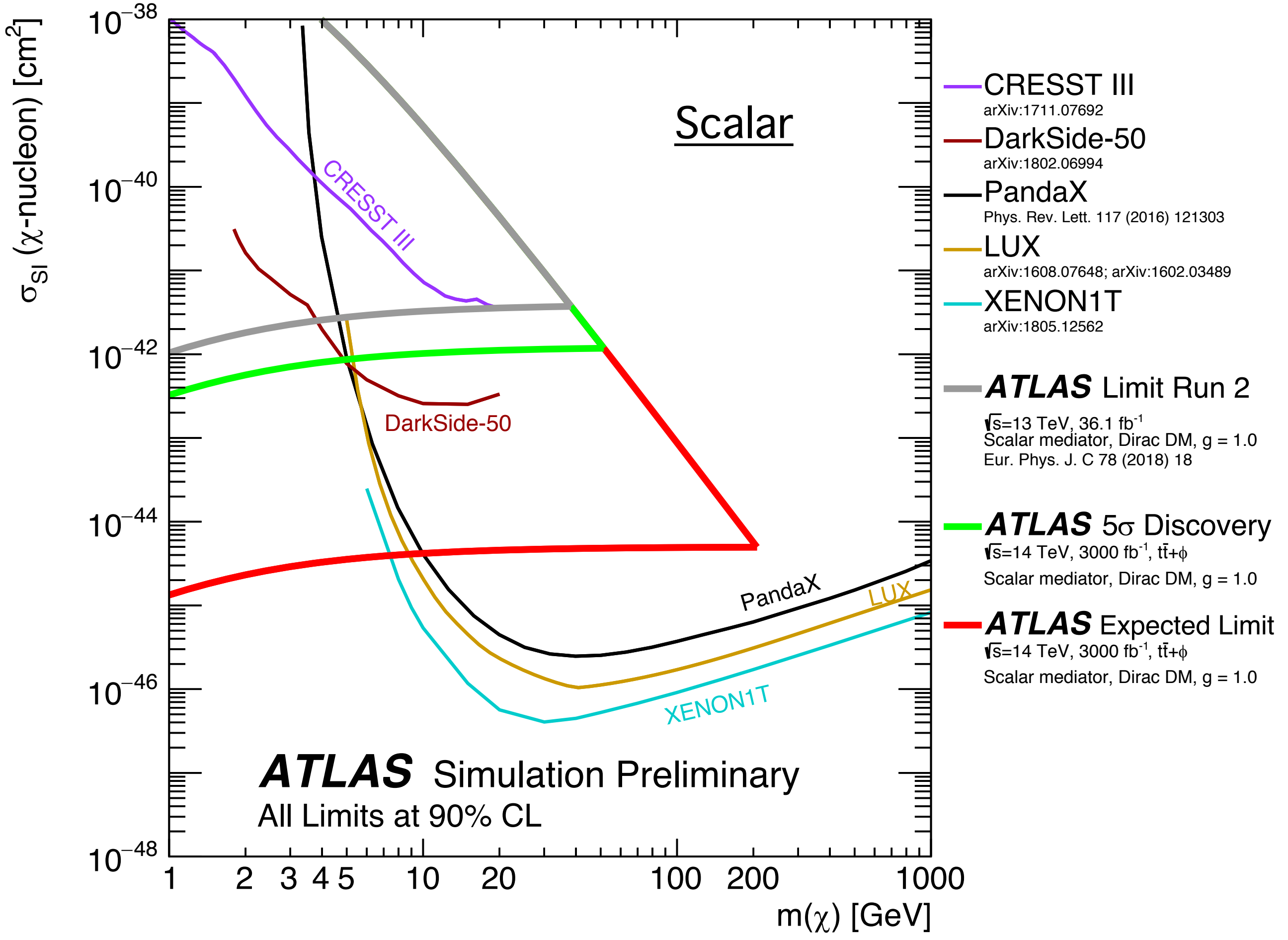


MET+heavy-flavor projection

ATL-PHYS-PUB-2018-036

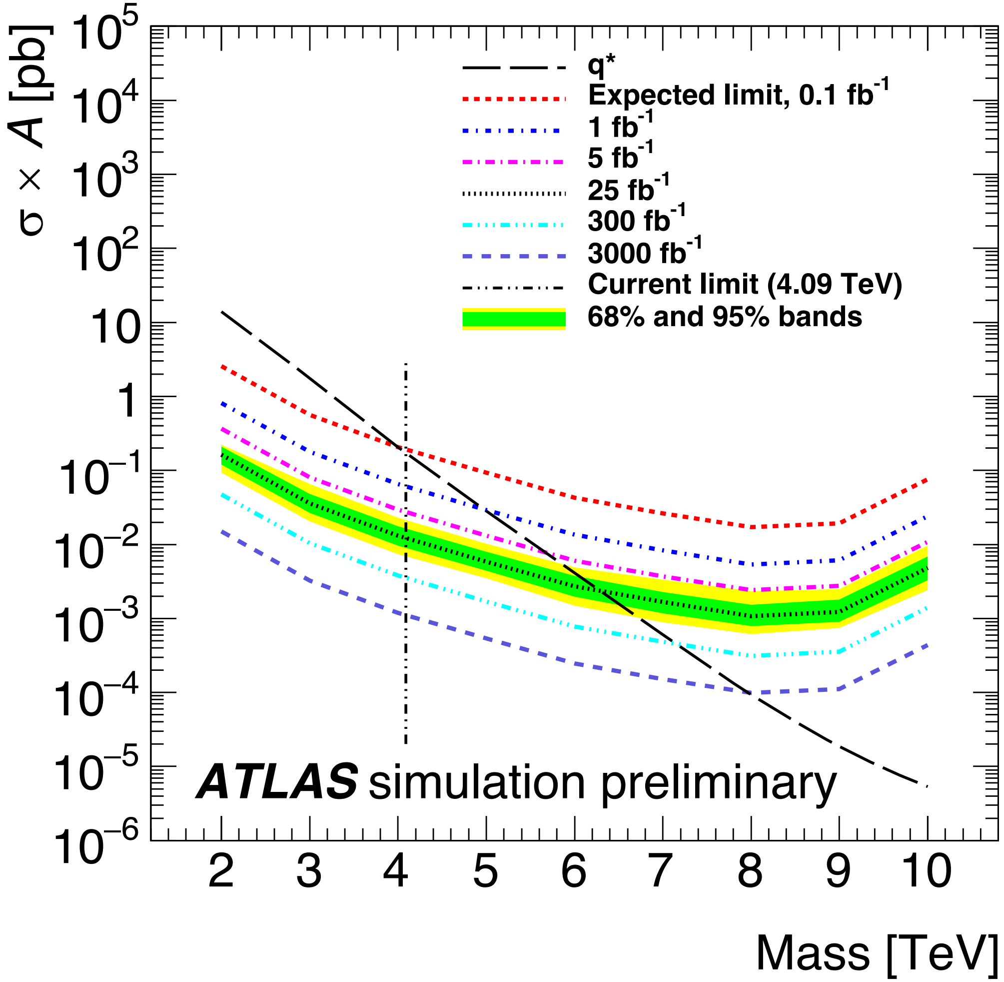






Di-jet projection

ATL-PHYS-PUB-2015-004



- The projection is performed on the excited quarks model instead of simplified models