Search for Higgs→ invisible decays & dark matter with Z(ll)+MET final state with the ATLAS detector

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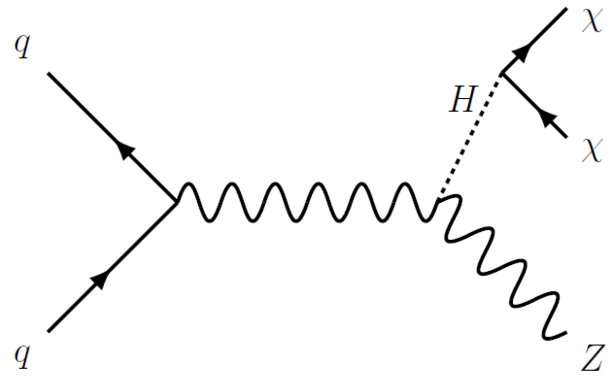
Motivation

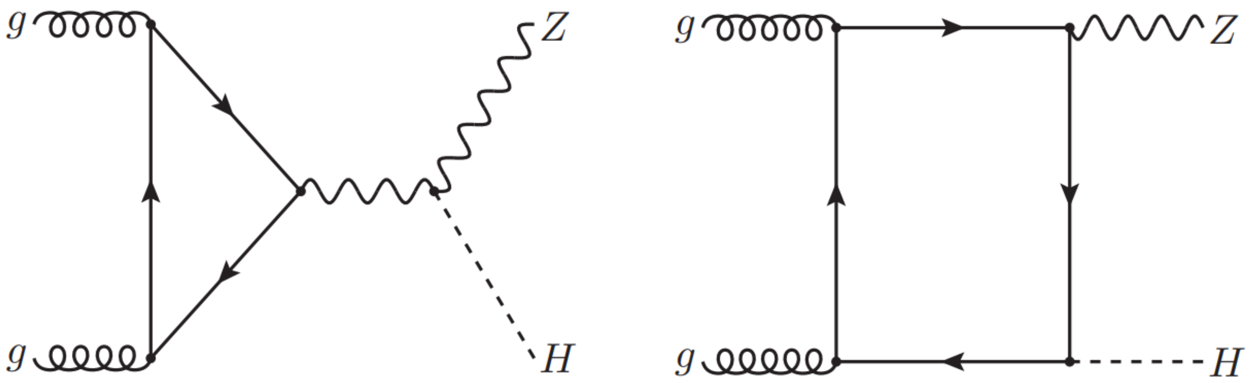
- From Astrophysics observations, dark matter (DM) particles only have gravitational interaction, and maybe weak interaction.
- Higgs boson can couple to massive particles, therefore it could have coupling with the dark matter particles. Higgs can be a bridge between Standard Model (SM) particles and BSM DM particles
- We search for DM through Higgs decays to invisible particles associate with Z production
- This search is based on the full dataset of 139 fb^{-1} collected from 2015-2018 at 13 TeV with the ATLAS detector.

Introduction

- In Standard Model(SM), Higgs can decay to invisible 4−$neutrino$ final state.
  - H -> ZZ* -> 4 υ , $\mathrm{BR}_{Hinv}^{SM} \approx 0.1\%$
- Beyond Standard Model(BSM), Higgs could decay to Dark Matter particles which cannot be detected by the ATLAS detector.
  - $\mathrm{BR}_{Hinv}^{total} = \mathrm{BR}_{Hinv}^{SM} + \mathrm{BR}_{Hinv}^{BSM}$ > 0.1%
  - Current combined ATLAS limit of $\mathrm{BR}_{Hinv}^{total}$ <11% (ATLAS-CONF-2020-052)
- This analysis uses the following channels of Higgs production (χ denotes DM particle)



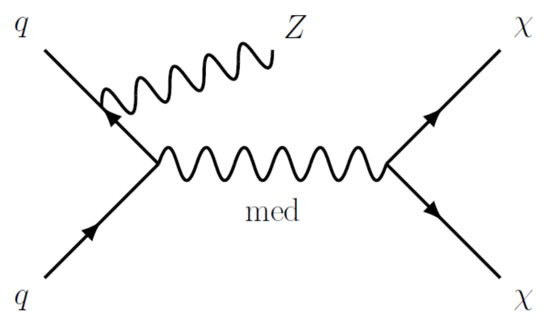
Main production of ZH (qq -> ZH)

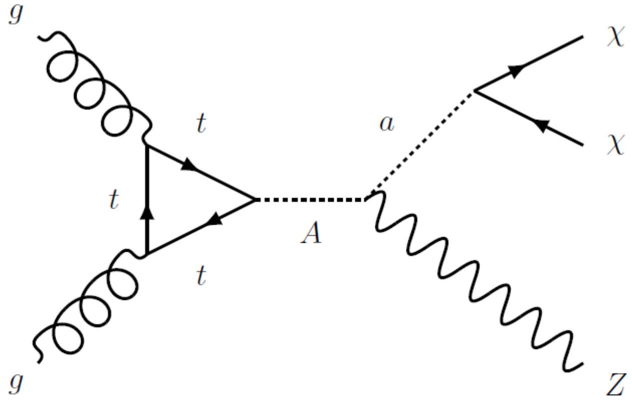


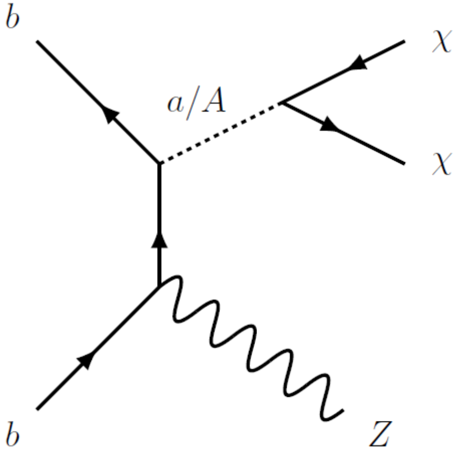
ZH production through gg ZH

DM Model

- Simplified DM Model
  - DM is produced through a mediator particle (couples to SM particles)
    - the mediator mass
    - DM particle masses
    - the mediator couplings g_χ, g_{q}, and g_l
  - Search in a parameter space {m_χ, m_{med}} with g_i fixed
- 2-Higgs-Doublet Models
  - CP-conserving type II 2HDM with parameters:
    - m_A: mass of the pseudo-scalar Higgs boson
    - m_a: mass of the additional pseudo-scalar
    - $\tan\beta$: ratio of the two Higgs doublets
    - $\sin\theta$: mixing angle between the two CP-odd weak spin-0 eigenstates
  - Following recommendations in the following paper
    - T. Abe et al., LHC Dark Matter Working Group: Next-generation spin-0 dark matter models, Phys. Dark Univ. 27 (2020) 100351, arXiv: 1810.09420 [hep-ex].

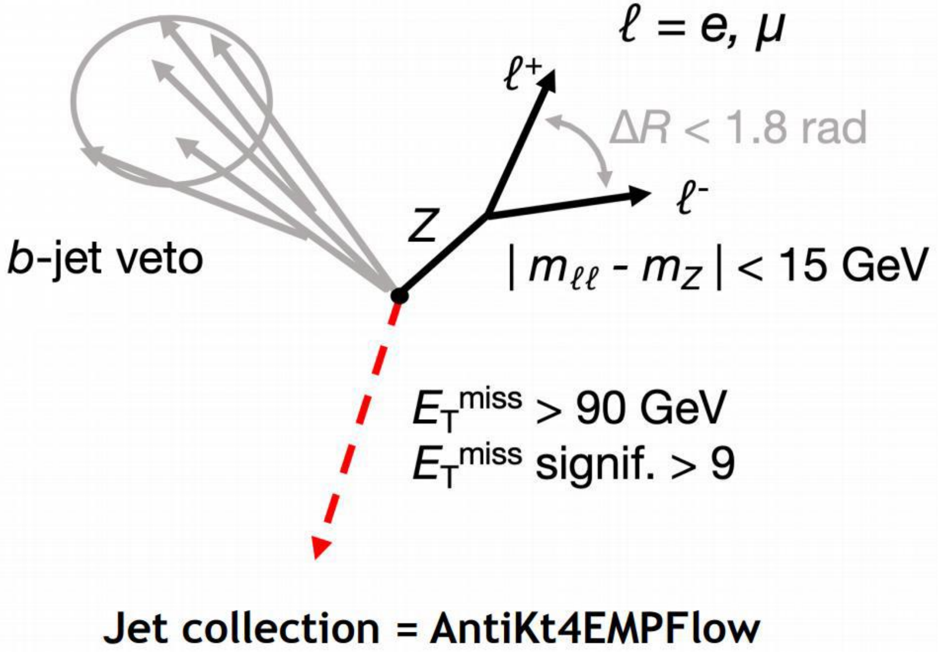






Event Selection (ZH→ ll+MET)

Selection criteria	Background reduced
$p_T^{\ell_1}$ ($p_T^{\ell_2}$) > 30 (20) GeV	—
Veto events with $p_T^{\ell_3}$ > 7 GeV	WZ
76 < $m_{\ell\ell}$ < 106 GeV	Non-resonant $\ell^+\ell^-$
Veto events with a b-jet	Single top, $t\bar{t}$
$E_{\mathrm{T}}^{\mathrm{miss}}$ > 90 GeV	Z+jets
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 9	Z+jets
$\Delta R(\ell\ell)$ < 1.8	Z+jets, non-resonant $\ell^+\ell^-$



Background

- Major backgrounds are from following processes
  - ZZ and WZ processes (Z -> ll, real MET)
  - Non-Z two leptons (Same-Flavor-Opposite-Sign leptons, MET) (WW, ttbar, tW, Z -> ττ)
  - Z+jets (Z -> ll, MET from jet mismeasurement)
- Other minor background
  - W+jets, ttV, ttVV
- Use Control Region(CR) method to estimate the background from ZZ, WZ and non-Z lepton pair.

Background	Contribution/%	CR in simultaneous fit
ZZ	44	4l CR
WZ	26	3l CR
Non-res. ll	14	eμ CR
Z+jets	15	MC Simulation / CR validation
Others	<1	MC Simulation

3l & 4l Control Region Definitions

3l CR

- WZ process
- Event selection requires SFOS pair, and one additional lepton.
- Select W(lv) with $m_T(W) \; > 60 \; GeV$
  - $m_T(W)$:

$$m_T(W) = \sqrt{2p_T^{\ell} E_{\mathrm{T}}^{\mathrm{miss}}(1 - cos\Delta\phi)}$$

4l CR

- ZZ process
- Randomly assign one Z boson as invisible Z
- Slightly loose lepton Pt selection
- Inherit other selections from SR (signal region)

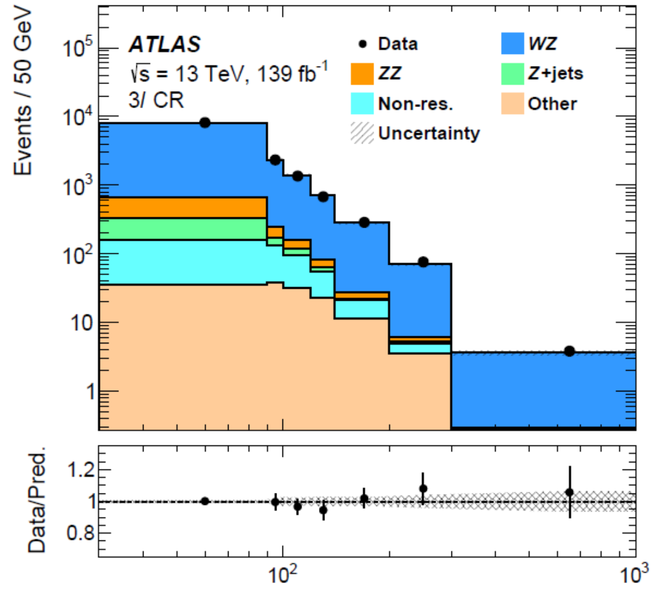
eμ CR

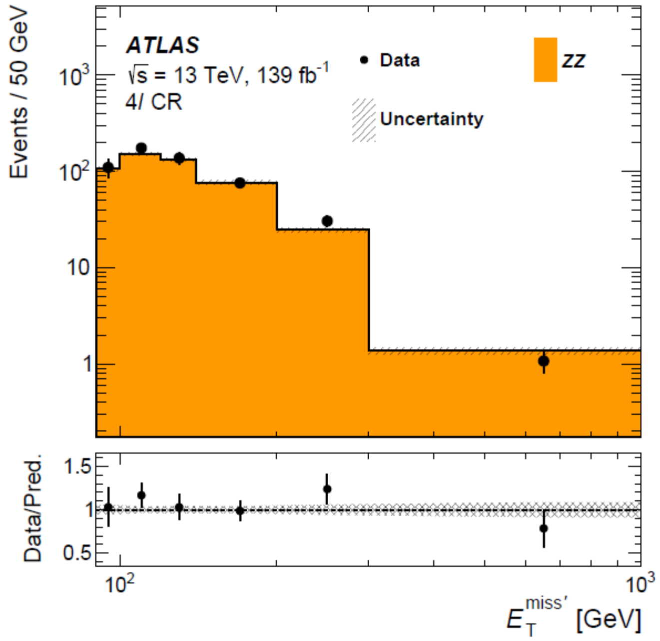
- WW, tt, tW, Zττ process
- Event selection requires OFOS pair (eμ)

SR & CR Definitions

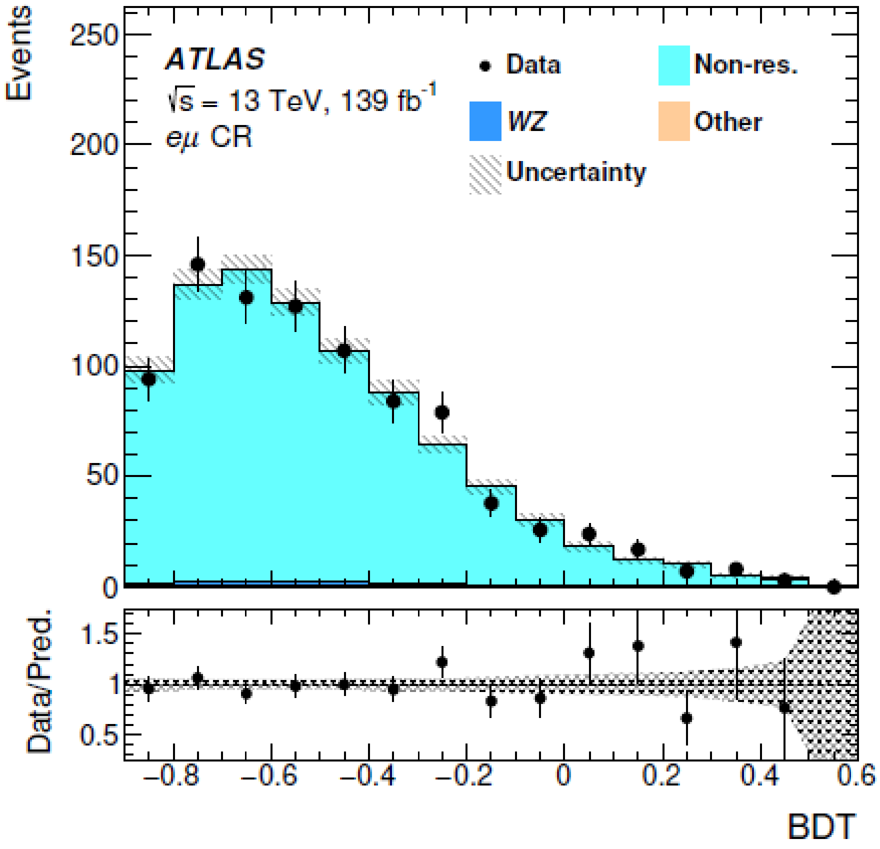
SR	$e\mu$ CR	$3l$ CR	$4l$ CR
Vertex with ≥ 2 tracks with $p_{\mathrm{T}} > 1$ GeV			
Jet Cleaning			
Single lepton trigger			
Trigger matching			
Electron crack region veto			
SFOS dilepton pair	OFOS dilepton pair	SFOS pair plus an additional lepton	2 SFOS dilepton pairs
Lepton $p_{\mathrm{T}} > 30, 20$ GeV		Lepton $p_{\mathrm{T}} > 30, 20, 20$ GeV	Lepton $p_{\mathrm{T}} > 27, 15, 15, 7$ GeV
3rd lepton veto with Loose ID and $p_{\mathrm{T}} > 7$ GeV		4th lepton veto with Loose ID and $p_{\mathrm{T}} > 7$ GeV	5th lepton veto with Loose ID and $p_{\mathrm{T}} > 7$ GeV
$76 < m_{ll} < 106$ GeV	$76 < m_{e\mu} < 106$ GeV	$76 < m_{ll,SFOS} < 106$ GeV	Both pairs with $76 < m_{ll} < 106$ GeV
b-jet veto ($p_{\mathrm{T}} > 20$ GeV, $\|\eta\| < 2.5$, MV2c10, 85% WP)			
Region-specific selections			
$E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV		$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}\,'} > 90$ GeV
$\Delta R(\ell\ell) < 1.8$		$m_T(W) > 60$ GeV	$\Delta R(\ell\ell)\ < 1.8$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 9		$E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 3	$E_{\mathrm{T}}^{\mathrm{miss}}$ si gnificance' > 9

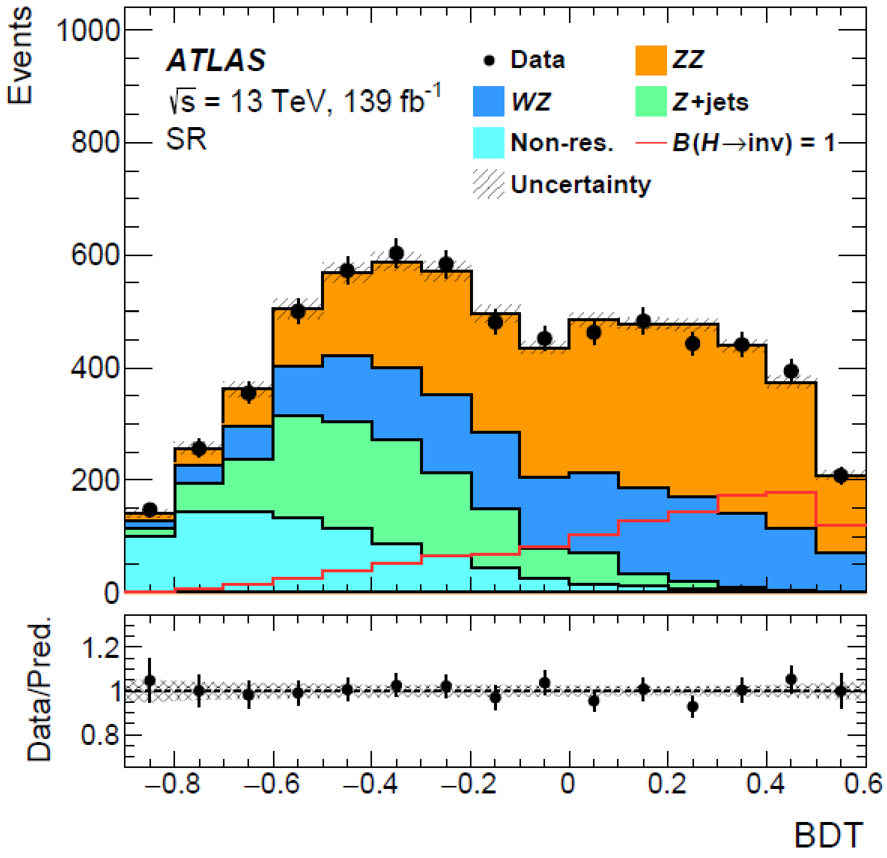
Background – Data vs Prediction





H -> invisible post-fit distributions





- BDT was trained to further separate signal and background
- BDT training variables can be found in backup slide

Yield of selected events in CRs and SR

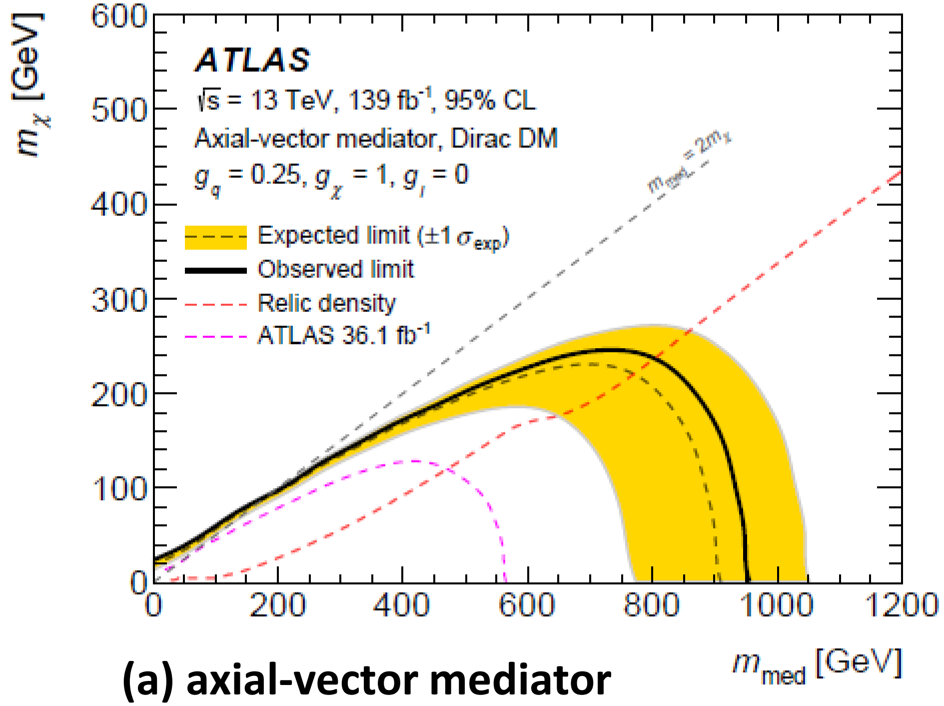
	SR	$e\mu$ CR	3ℓ CR	4ℓ CR
Observed events	6382	891	11622	314
Expected yields after fit	6385 ± 81	895 ± 29	11620 ± 110	296 ± 11
$ZH \rightarrow \ell\ell + \mathrm{inv}$	4 ± 110	-	-	-
$ZZ \rightarrow \ell\ell\nu\nu$	2681 ± 110	0.763 ± 0.064	2.61 ± 0.18	-
WZ	1595 ± 34	11.6 ± 1.1	10623 ± 150	-
$Z + \mathrm{jets}$	1111 ± 100	0.79 ± 0.30	235 ± 89	-
Non-resonant	881 ± 39	876 ± 29	220 ± 31	-
$ZZ \rightarrow 4\ell$	85.8 ± 5.5	0.621 ± 0.056	443 ± 40	295 ± 11
$t\bar{t} + V$	12.7 ± 2.8	1.76 ± 0.41	53 ± 12	-
Triboson	13.0 ± 6.2	3.1 ± 1.4	44 ± 20	0.48 ± 0.23

- Fitting SR and CRs simultaneously
- Floating Normalization factors for WZ and non-Z(ll) processes

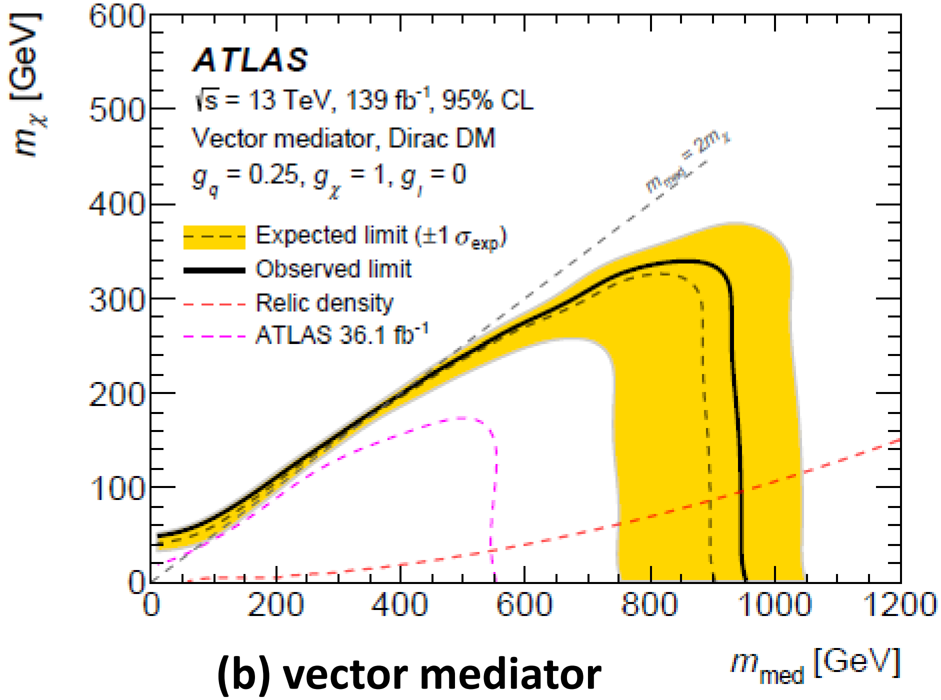
	Asimov	Data
Hinv BR Limit (95% CL)	0.19	0.19

Limits – Simplified DM Models

$$g_\chi = 1.0$$
$$g_q = 0.25$$
$$g_\ell = 0$$

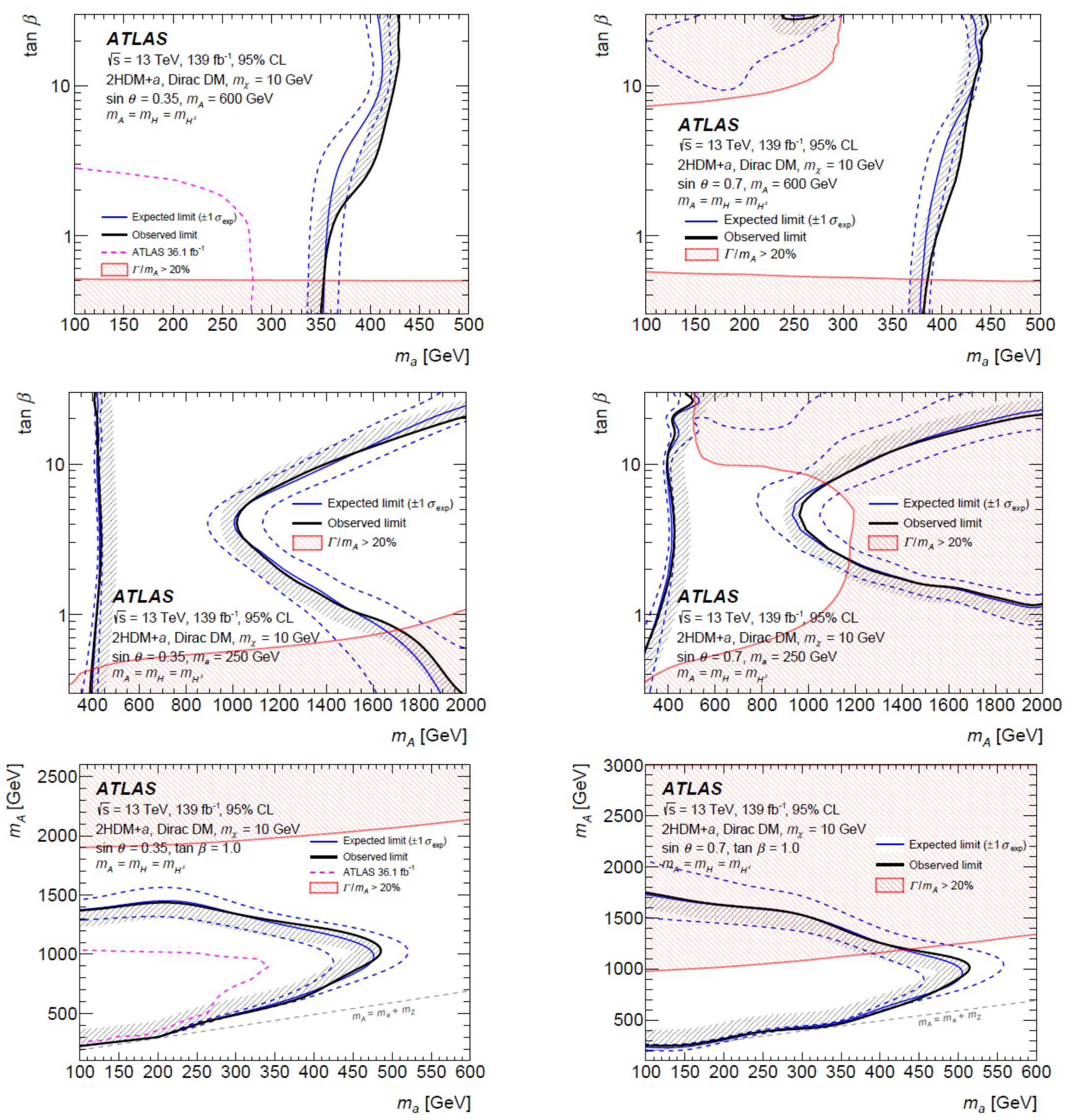


(a) axial-vector mediator



(b) vector mediator

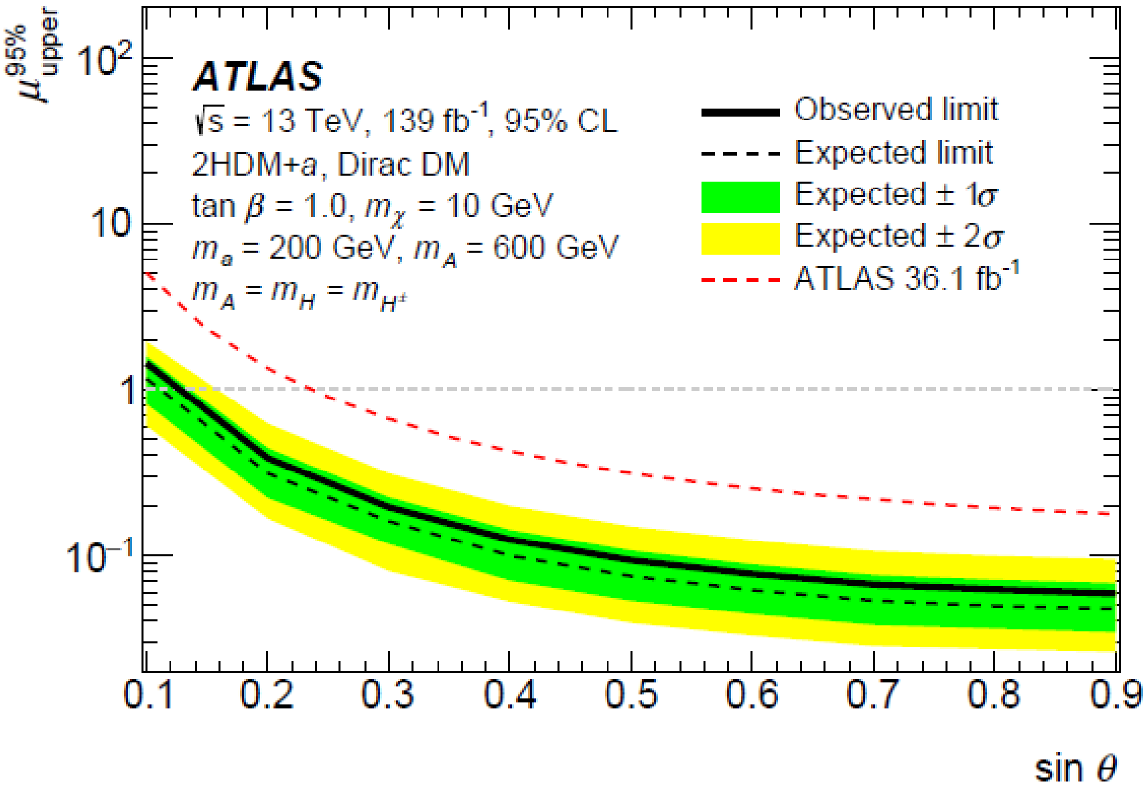
Results – Limits on 2HDMa Models

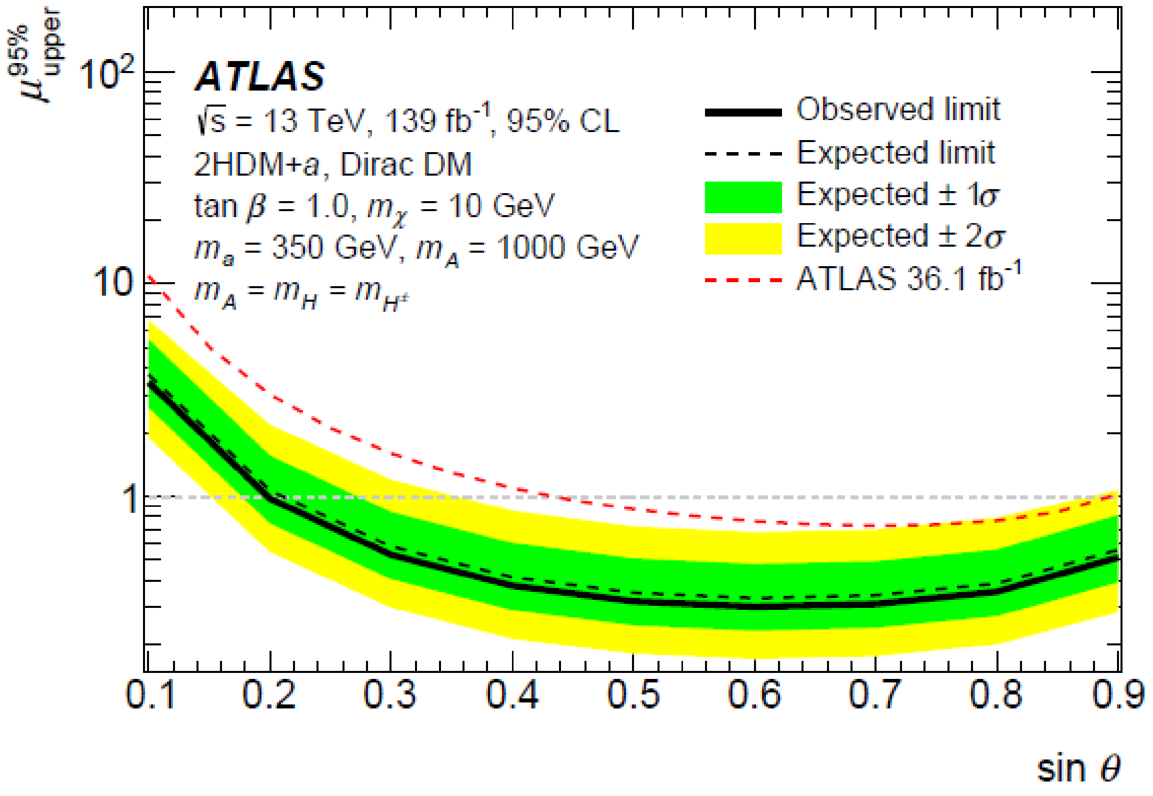


Magenta line: ATLAS Collaboration, *Constraints on mediator-based dark matter and scalar dark energy models using √s = 13 TeV pp collision data collected by the ATLAS detector* JHEP **05** (2019) 142,arXiv: 1903.01400 [hep-ex].

Scan Strategy: T. Abe et al., LHC Dark Matter Working Group: Next-generation spin-0 dark matter models, Phys. Dark Univ. 27 (2020) 100351, arXiv: 1810.09420 [hep-ex].

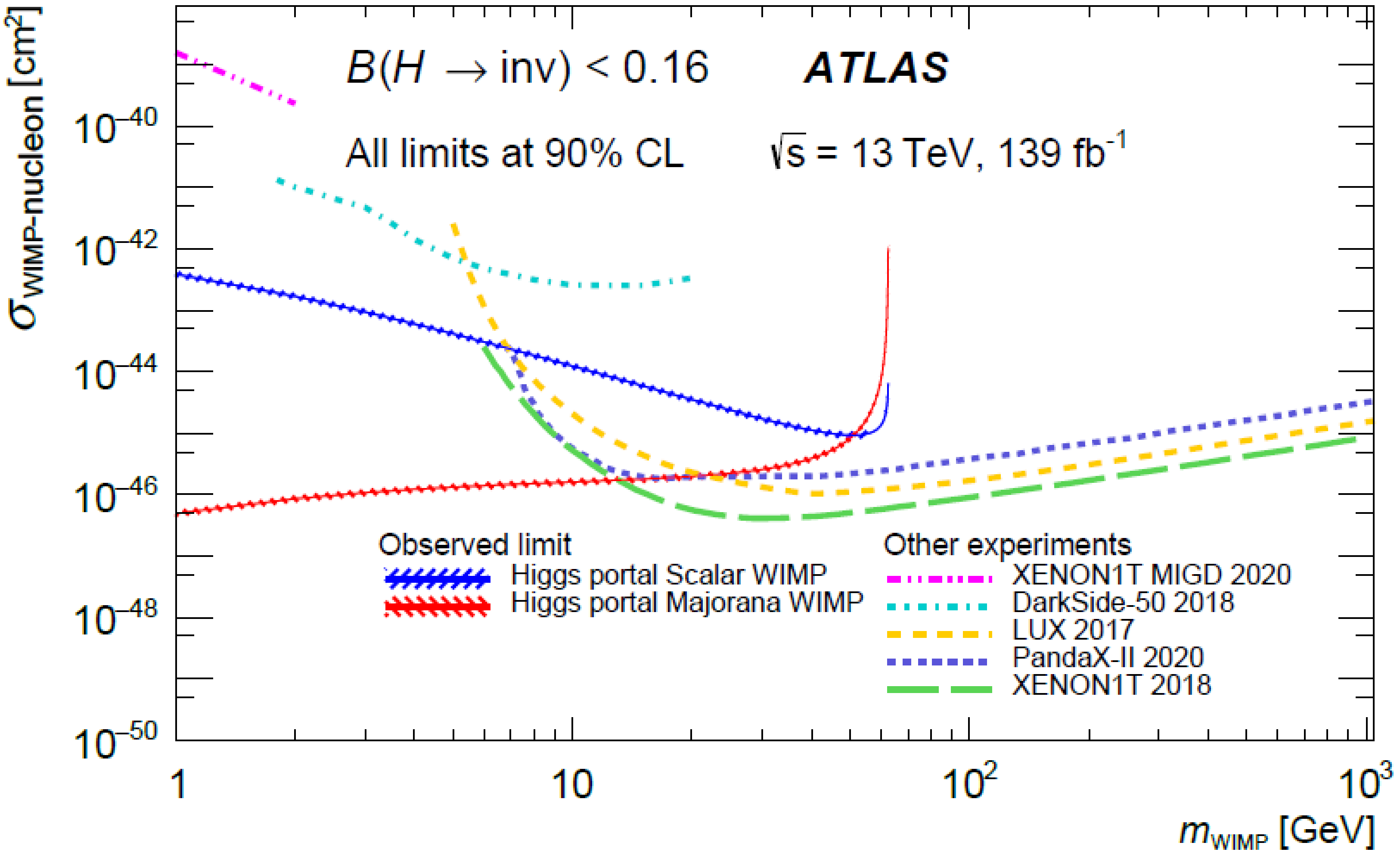
Limits on signal strength - 2HDMa Models





Red line: ATLAS Collaboration, *Constraints on mediator-based dark matter and scalar dark energy models using* s = 13 *TeV* pp *collision data collected by the ATLAS detector*, JHEP **05** (2019) 142,arXiv: 1903.01400 [hep-ex].

Cross-section Limit Comparison



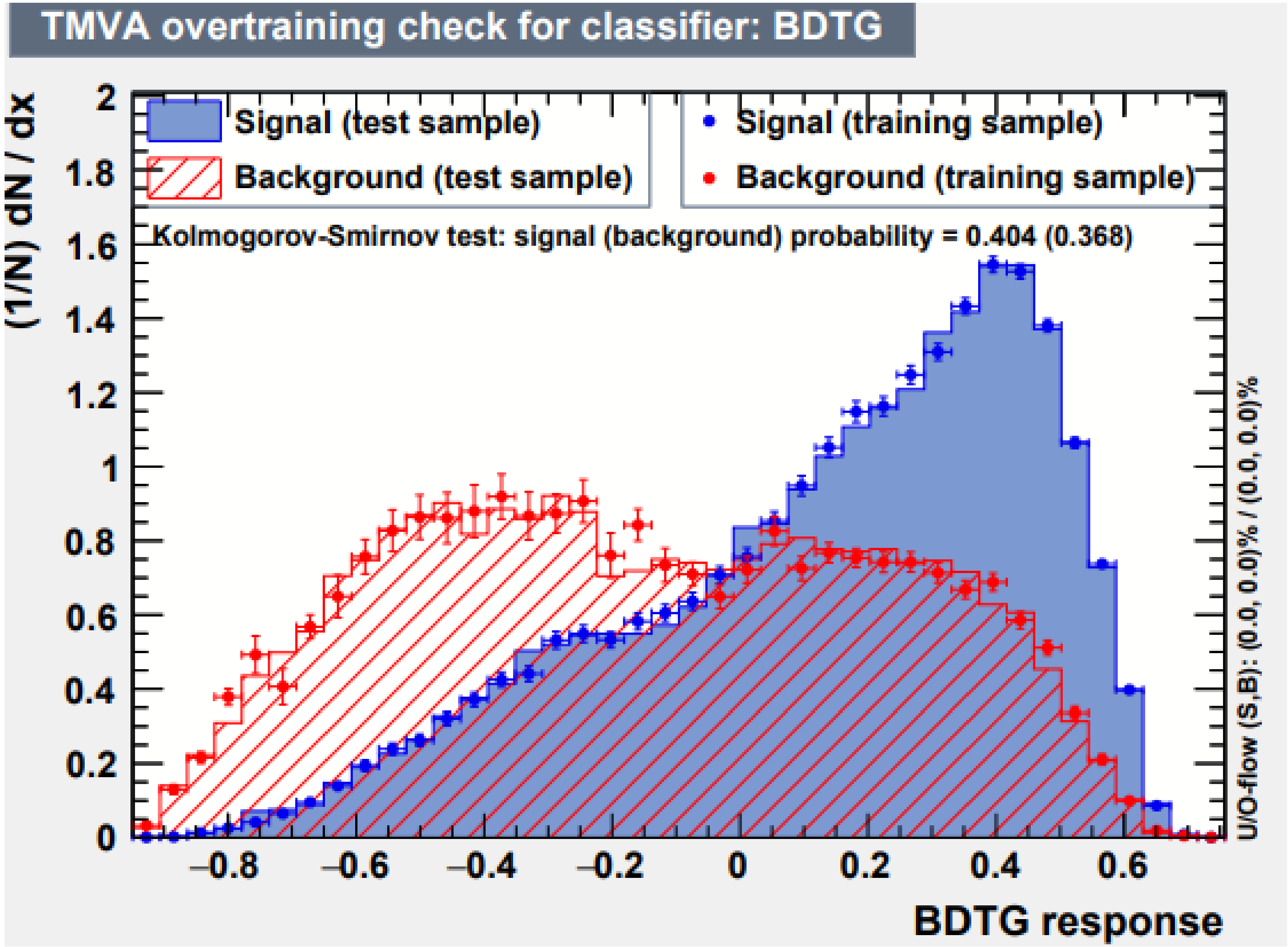
Summary

- We use full Run-2 dataset to search for dark matter production associate with Z → ll
- Background processes estimated through the CR method and MC simulation. Good agreement found between data and estimation in the CRs(No data excess in the SR over the background predictions).
- Set the observed limit on BR of H → invisible decay:
  - 0.19 (exp.), 0.19 (obs.) [95% C.L.]
- This result significantly improved sensitivity in comparison of the early Run-2 result:
  - 0.39 (exp.), 0.67 (obs.)

Backup

BDT

- To further separate the Higgs invisible signal and background, BDT is used as the Signal Region(SR) discriminant variable
- BDT input variables:
  - Z rapidity
  - ΔR(ll)
  - ΔΦ(MET, Z_pT)
  - MET Significance
  - Fractional pT
  - HT
  - MET/HT
  - M(ll)



BDT Response with Final SR Selection

Uncertainties

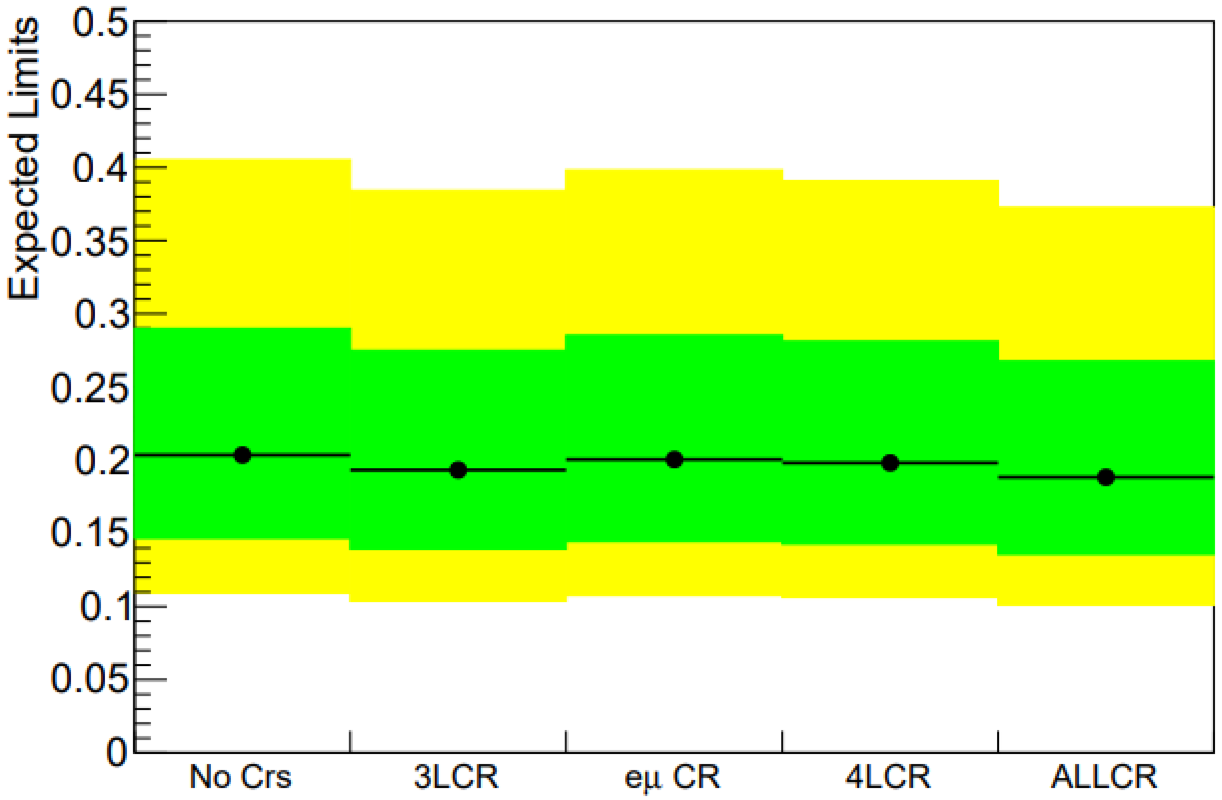
Uncertainty source	$\Delta\mathcal{B}$ [%]
Statistical uncertainty	5.1
Systematic uncertainties	7.4
Theory uncertainties	4.9
Signal modelling	0.4
ZZ modelling	4.4
Non-ZZ background modelling	2.1
Experimental uncertainties (excl. MC stat.)	4.6
Luminosity, pile-up	1.5
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.0
Flavour tagging	0.4
Electrons, muons	1.2
MC statistical uncertainty	1.6
Total uncertainty	9.0

Fit

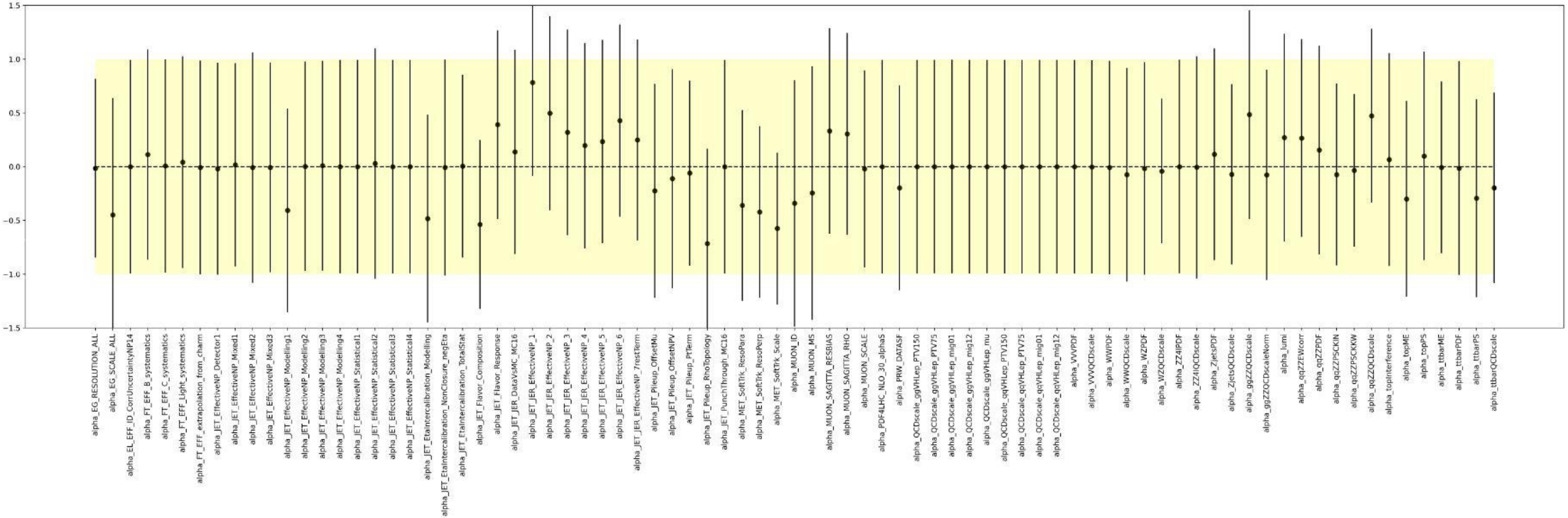
- Use TRexFitter to perform the simultaneous fit with control regions used in addition to the signal region.
- Set floating normalization factors in WZ and eμ CR.

Channel	BR limit	μ_{WZ}	μ_{em}
comb	0.190	1.000 ± 0.071	1.000 ± 0.118

The right plot shows the Higgs boson to invisible particles branching ratio for TRExFitter fits that include no control regions, 3l, eμ, 4l and all control regions.

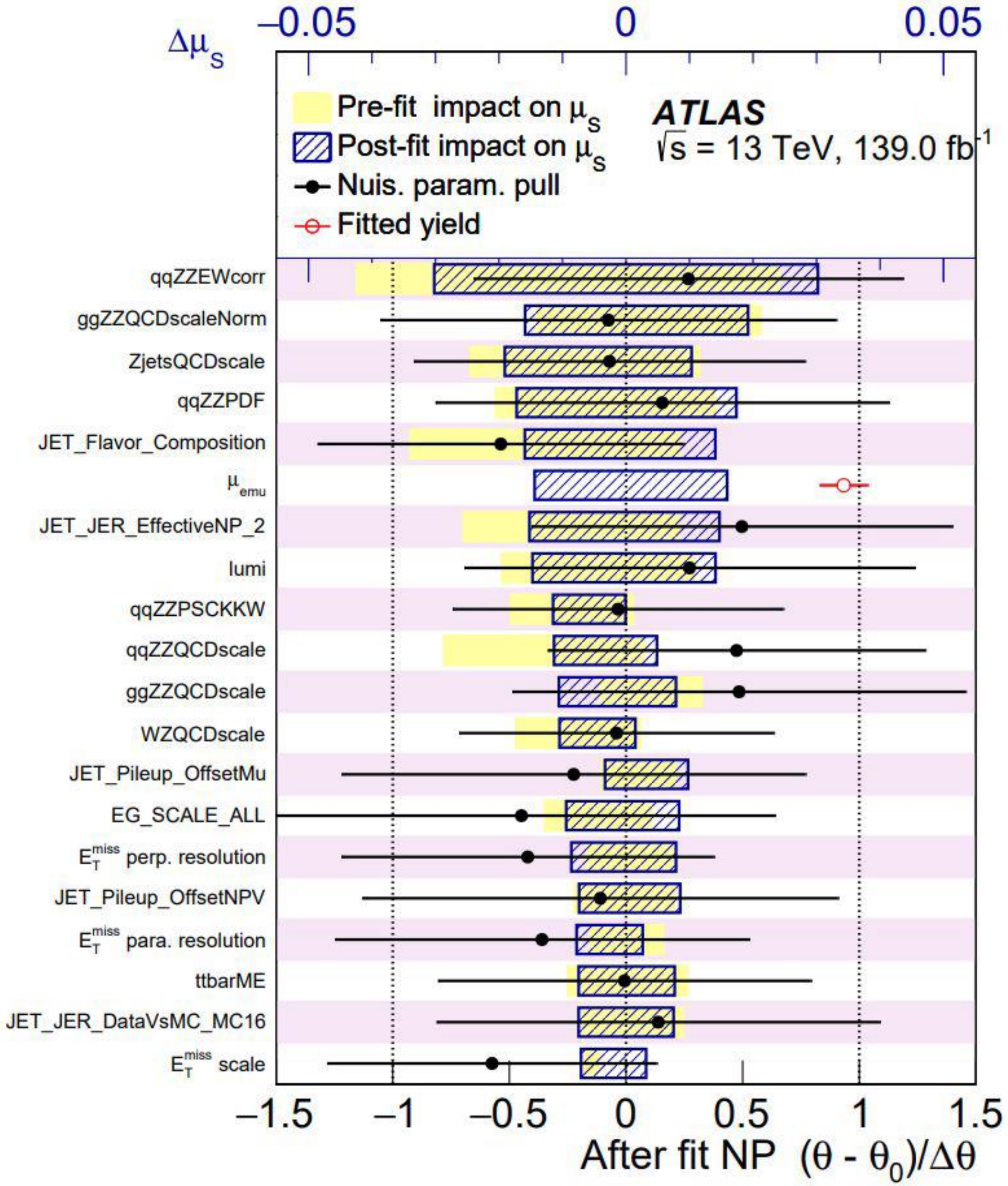


Fit



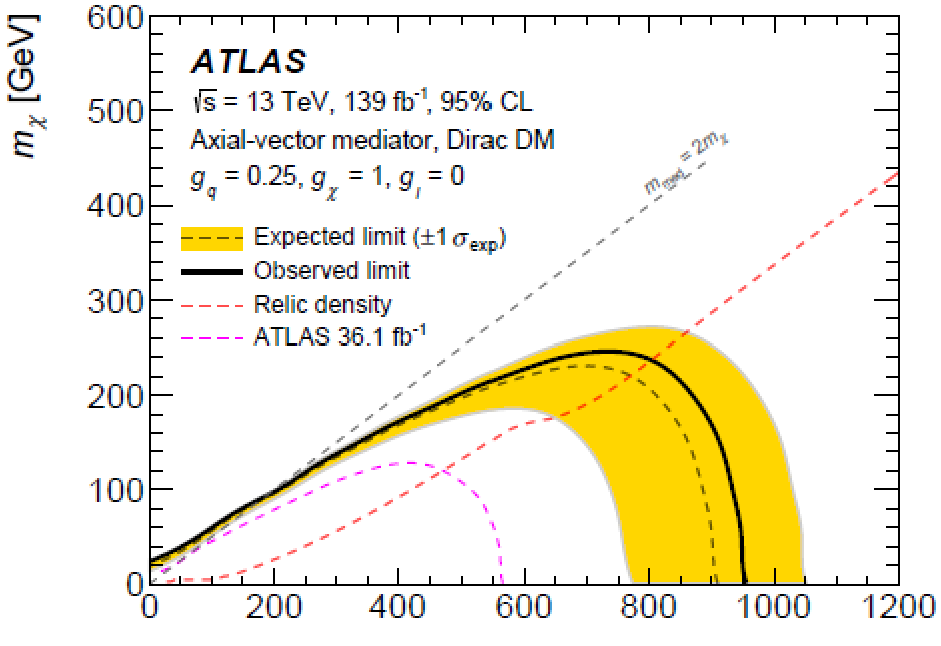
Pulls for H -> invisible fit

Fit

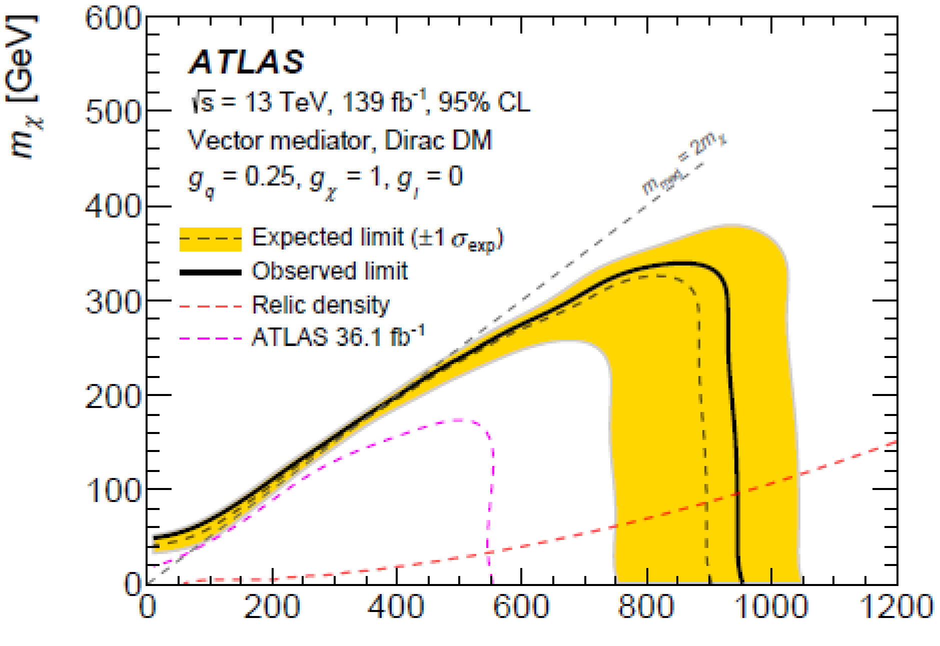


	SigXsecOverSM	JET_Flavor_Composition	JET_Flavor_Response	JET_Pileup_RhoTopology	MET_ResoPara	MET_ResoPerp	MET_Scale	WZ_PDF	WZ_QCDscale	ZjetsQCDscale	emu_WWQCD	emu_ttbarME	emu_ttbarPS	emu_ttbarQCD	ggZZ_QCDscale_Norm	qqZZ_EWcorr	qqZZ_QCDscale	SigXsecOverSM for EMU	SigXsecOverSM for WZ
SigXsecOverSM	100.0	15.9	0.7	5.1	-5.0	-6.8	-0.5	-7.1	7.1	17.8	0.3	-8.6	1.1	-3.6	-20.5	-33.9	-15.7	15.4	-0.7
JET_Flavor_Composition	15.9	100.0	20.0	-24.3	11.6	8.2	-13.2	-0.0	-22.3	14.0	-2.2	-7.9	2.2	-5.7	1.9	-1.1	6.5	20.8	22.2
JET_Flavor_Response	0.7	20.0	100.0	10.0	-1.9	-1.0	5.3	0.9	14.6	-3.3	1.4	5.8	-3.3	3.5	-0.1	0.6	0.3	-0.9	-12.2
JET_Pileup_RhoTopology	5.1	-24.3	10.0	100.0	2.9	-0.5	-3.7	-0.0	-9.2	-0.5	-1.3	-4.0	2.0	-2.8	0.4	-0.2	1.8	16.4	9.3
MET_ResoPara	-5.0	11.6	-1.9	2.9	100.0	-19.2	26.5	-0.4	-15.5	-6.8	2.6	4.9	-0.6	5.2	-1.5	0.1	-4.8	-7.6	12.5
MET_ResoPerp	-6.8	8.2	-1.0	-0.5	-19.2	100.0	25.0	-0.5	-16.0	-19.5	-1.5	1.4	0.0	0.9	-2.5	1.2	-11.8	-4.7	13.3
MET_Scale	-0.5	-13.2	5.3	-3.7	26.5	25.0	100.0	0.4	23.9	21.7	-0.4	-3.2	3.9	-3.0	0.6	-1.7	3.6	4.6	-19.5
WZ_PDF	-7.1	-0.0	0.9	-0.0	-0.4	-0.5	0.4	100.0	-4.3	-0.8	0.0	0.1	-0.1	0.0	-0.2	0.1	-0.6	0.4	-43.4
WZ_QCDscale	7.1	-22.3	14.6	-9.2	-15.5	-16.0	23.9	-4.3	100.0	-3.5	1.8	4.9	-1.7	2.3	0.3	0.0	-1.9	-7.5	-85.2
ZjetsQCDscale	17.8	14.0	-3.3	-0.5	-6.8	-19.5	21.7	-0.8	-3.5	100.0	-8.0	-1.8	8.4	-9.9	-0.1	3.5	-6.7	18.5	9.1
emu_WWQCD	0.3	-2.2	1.4	-1.3	2.6	-1.5	-0.4	0.0	1.8	-8.0	100.0	-9.9	5.6	-8.7	-0.2	0.2	-2.1	-30.2	-1.7
emu_ttbarME	-8.6	-7.9	5.8	-4.0	4.9	1.4	-3.2	0.1	4.9	-1.8	-9.9	100.0	9.7	-19.1	-1.1	0.3	-4.9	-37.2	-5.9
emu_ttbarPS	1.1	2.2	-3.3	2.0	-0.6	0.0	3.9	-0.1	-1.7	8.4	5.6	9.7	100.0	12.2	0.3	-0.5	2.8	-28.1	2.1
emu_ttbarQCD	-3.6	-5.7	3.5	-2.8	5.2	0.9	-3.0	0.0	2.3	-9.9	-8.7	-19.1	12.2	100.0	-0.6	0.3	-3.9	-57.8	-2.9
ggZZ_QCDscale_Norm	-20.5	1.9	-0.1	0.4	-1.5	-2.5	0.6	-0.2	0.3	-0.1	-0.2	-1.1	0.3	-0.6	100.0	0.3	-1.5	2.4	0.3
qqZZ_EWcorr	-33.9	-1.1	0.6	-0.2	0.1	1.2	-1.7	0.1	0.0	3.5	0.2	0.3	-0.5	0.3	0.3	100.0	-22.0	-0.2	0.5
qqZZ_QCDscale	-15.7	6.5	0.3	1.8	-4.8	-11.8	3.6	-0.6	-1.9	-6.7	-2.1	-4.9	2.8	-3.9	-1.5	-22.0	100.0	11.8	5.3
SigXsecOverSM for EMU	15.4	20.8	-0.9	16.4	-7.6	-4.7	4.6	0.4	-7.5	18.5	-30.2	-37.2	-28.1	-57.8	2.4	-0.2	11.8	100.0	11.5
SigXsecOverSM for WZ	-0.7	22.2	-12.2	9.3	12.5	13.3	-19.5	-43.4	-85.2	9.1	-1.7	-5.9	2.1	-2.9	0.3	0.5	5.3	11.5	100.0

Reference



(a) axial-vector mediator



(b) vector mediator

Red Line: *Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for dark matter mediators in visible and invisible decay channels and calculations of the thermal relic density*,
Phys. Dark Univ. **26** (2019) 100377, arXiv: 1703.05703 [hep-ex].
Magenta line: ATLAS Collaboration, *Search for an invisibly decaying Higgs boson or dark matter candidates produced in association with a Z boson in pp collisions at s = 13 TeV with the ATLAS detector*,
Phys. Lett. B **776** (2018) 318, arXiv: 1708.09624 [hep-ex].