Search for invisible decays of the Higgs boson and for dark matter with the ATLAS detector

Chuanshun Wei

University of Michigan

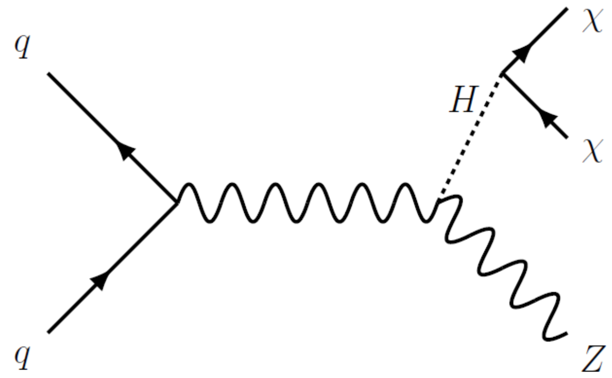
07/14/2021

Motivation

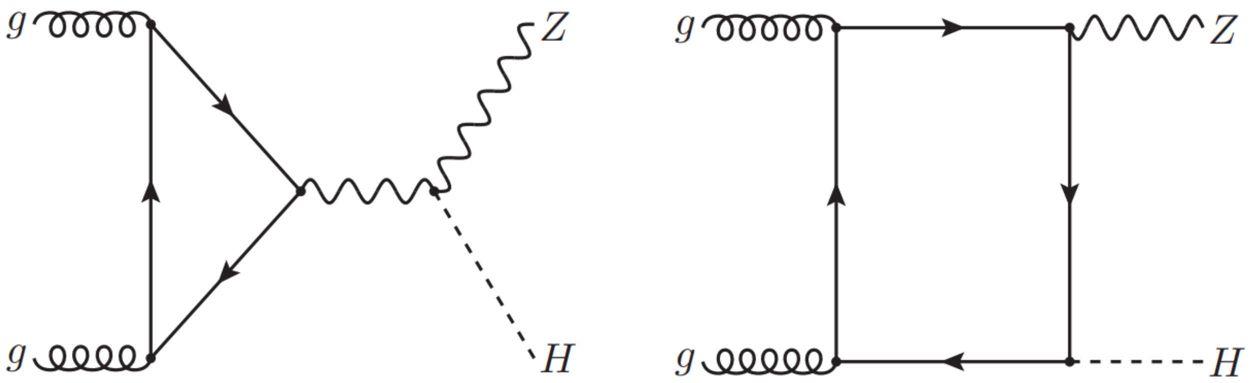
- From Astrophysics observations, dark matter particles only have gravitational interaction, and maybe weak interaction.
- Higgs boson can couple to massive particles, therefore it could have coupling with the dark matter particles. Higgs can be a bridge between Standard Model particles and BSM DM particles
- We search for DM through Higgs decays to inviable 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 4υ final state.
  - H -> ZZ* -> 4 υ , $\mathrm{BR}_{Hinv}^{SM} \approx 0.001$
- Beyond Standard Model(BSM), Higgs could decay to Dark Matter(DM) particles which cannot be detected by the ATLAS detector.
  - $\mathrm{BR}_{Hinv}^{total} = \mathrm{BR}_{Hinv}^{SM} + \mathrm{BR}_{Hinv}^{BSM} > 0.001$
- This analysis uses the following channels of Higgs production



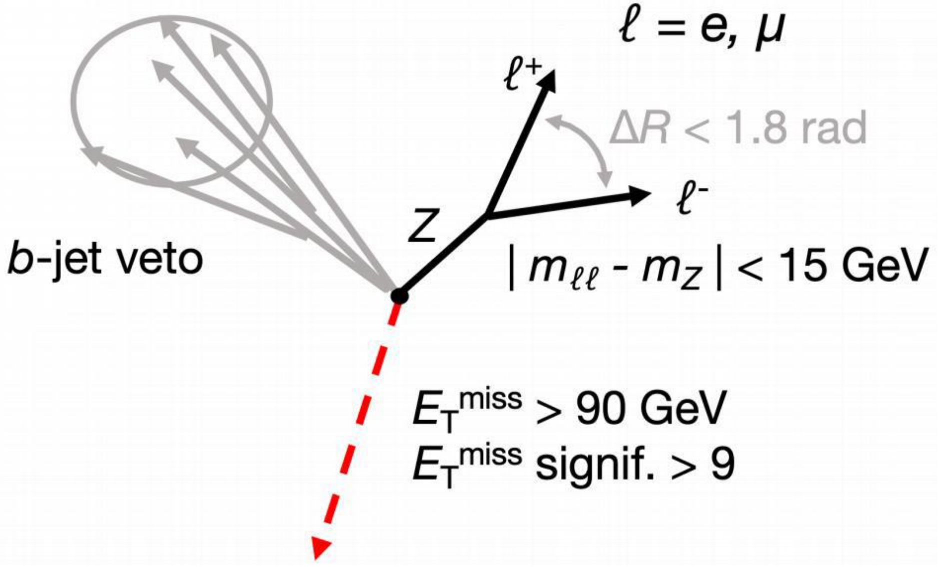
Main production of ZH (qq -> ZH)



ZH production through gg ZH

Event Selection

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 $\ell^+\ell^-$



Jet collection = AntiKt4EMPFlow

Background

- Major backgrounds are from following processes
  - ZZ and WZ processes (Z -> ll, real MET)
  - Non-Z two leptons (SFOS 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 CR Definition

3l CR

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

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

4l CR

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

Three Lepton CR event selection
Two same flavor opposite-sign (SFOS) leptons (e^+e^- OR $\mu^+\mu^-$)
Single lepton trigger fired by one of the SFOS leptons
One additional lepton with $p_T > 20$ GeV
Veto of any additional lepton with Loose ID and $p_T > 7$ GeV
$76 < M_{\ell\ell,SFOS} < 106$ GeV
mT (W)> 60 GeV
$E_T^{miss} > 30$ GeV
E_T^{miss}-Significance > 3
b-jet Veto

4ℓ CR definition
Two Same flavour Opposite sign dilepton pairs($\ell^\pm\ell^\mp\ell^\pm\ell^\mp$)
Leptons $p_T > 27, 15, 15, 7$ GeV
Veto any additional lepton with Loose ID and p_T >7 GeV
Both dileptons pair with $76 < M_{\ell\ell} < 106$ GeV
$E_T^{miss'} > 90$ GeV
$\Delta R_{\ell\ell} < 1.8$
$E_T^{miss'}$-significance > 9
b-jet Veto

eμ CR Definition

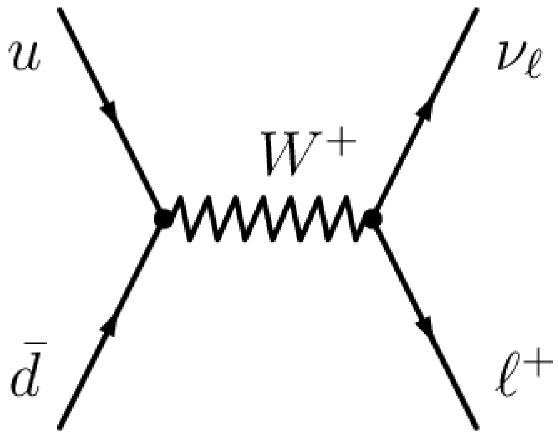
eμ CR

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

$e\mu$CR definition
Two Opposite flavour Opposite sign leptons ($e^{\pm}\mu^{\mp}$)
Veto any additional lepton with Loose ID and $p_{\rm T}$ >7 GeV
$76 < M_{e\mu} < 106$ GeV
$E_{\rm T}^{\rm miss} > 90$ GeV
$\Delta R_{e\mu} < 1.8$
$E_{\rm T}^{\rm miss}$-significance > 9
b-jet Veto

Data Driven Method on eμ CR

- WW, tt, tW, Zττ processes could give non-negligible contribution to the SR
- The contribution of these backgrounds can be estimated from data through eμ CR
- In eμ CR, those processes have high purity
- eμ events: μμ events: ee events = 2: 1: 1



Data Driven Method on eμ CR

- eμ events: μμ events: ee events = 2: 1: 1
- Detector efficiency for ee/mm are not the same, need to include the correction factor
- Considering the difference in the electron/muon reconstruction efficiency
  - Define ε-factor:

$$\epsilon^2 = \frac{N_{ee}}{N_{\mu\mu}}$$

  - Apply eμ CR ε-factor on SR:

$$N^{e\mu}_{SRee} = \frac{1}{2} \times \epsilon \times N^{data,sub}_{e\mu}$$

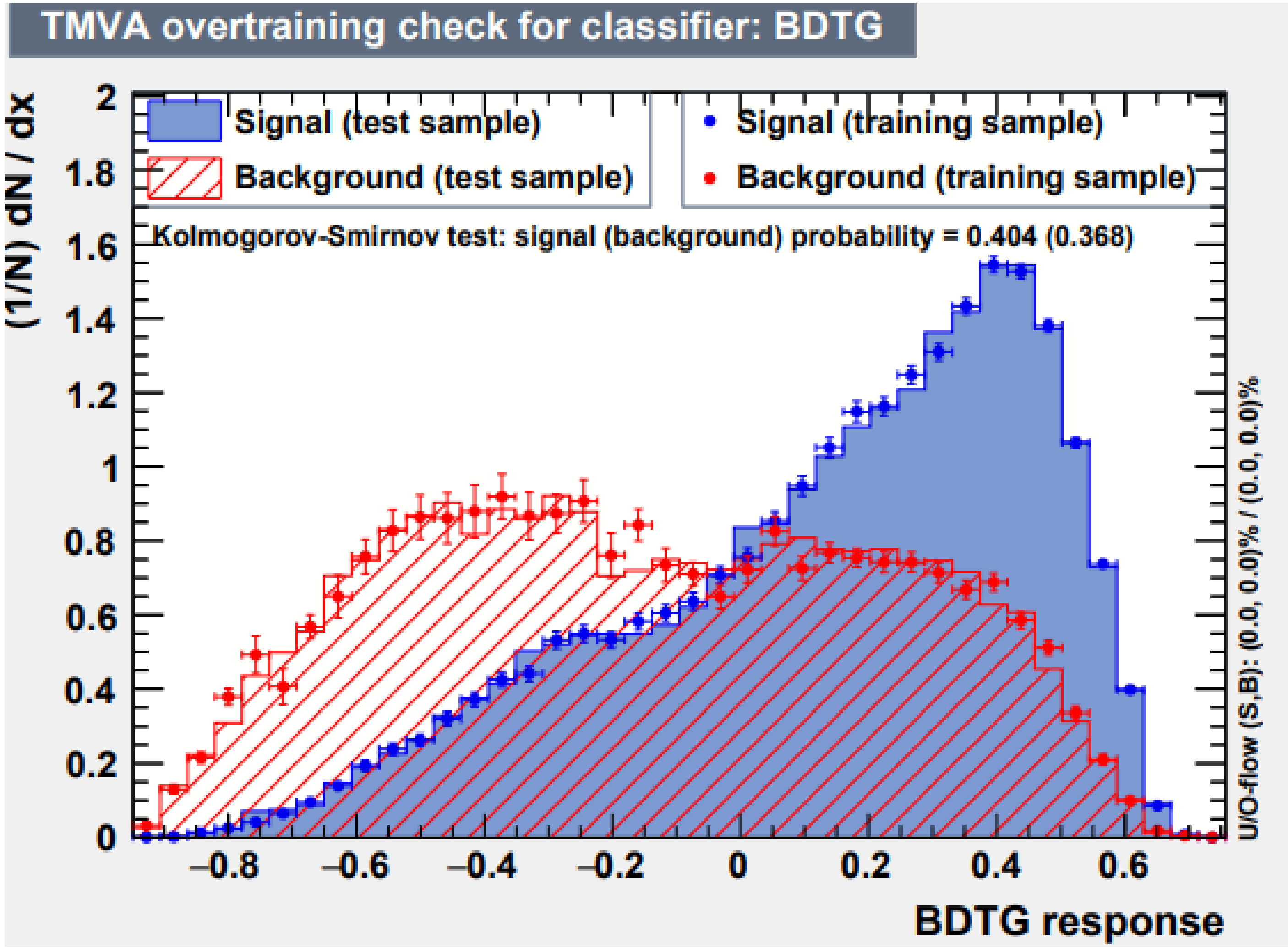
$$N^{e\mu}_{SR\mu\mu} = \frac{1}{2} \times \frac{1}{\epsilon} \times N^{data,sub}_{e\mu}$$

  - For non-WW, tt, tW, Zττ background, use Monte Carlo/Data-Driven method to get the estimation, subtracted from Data

$$N^{data,sub}_{e\mu} = N^{data}_{e\mu} - N^{other}_{sub}$$

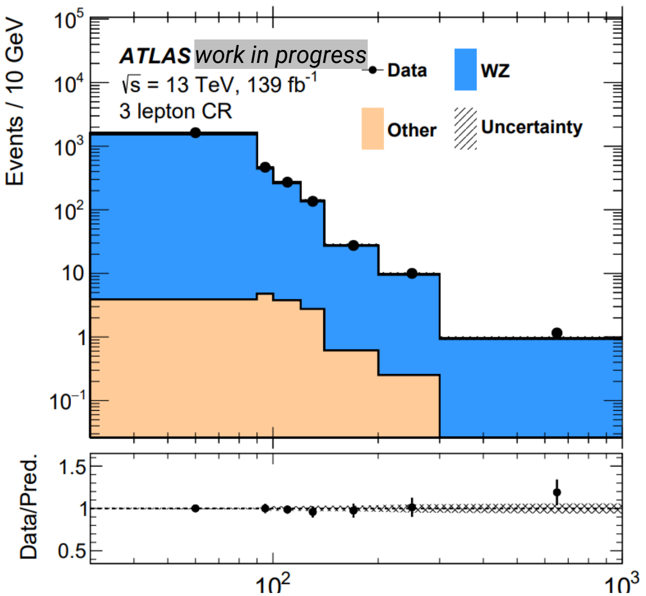
BDT

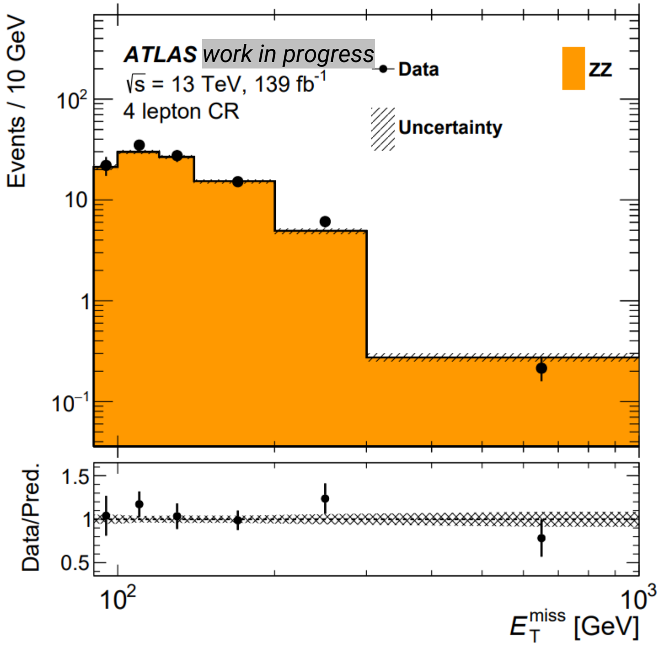
- To further separate the Higgs invisible signal and background, BDT is used as the Signal Region(SR) discriminant variable
- BDT input variables:
    - Z rapidity
    - ΔR(ll)
    - ΔΦ(MET, Z_pT)
    - MET Significance
    - Fractional pT
    - HT
    - MET/HT
    - M(ll)

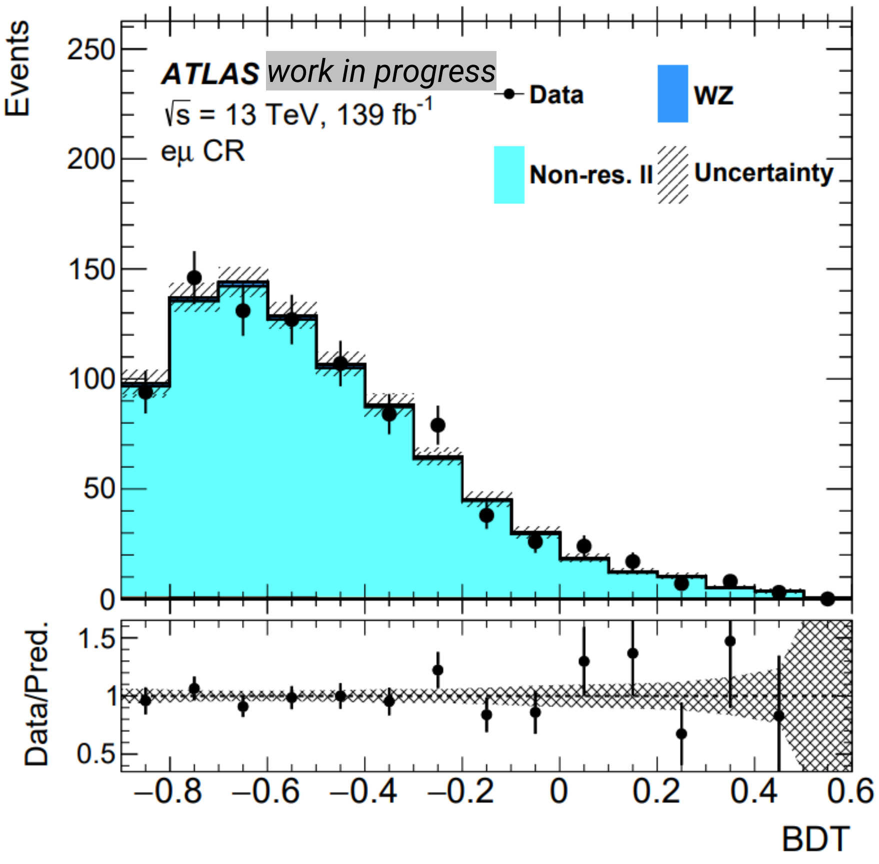


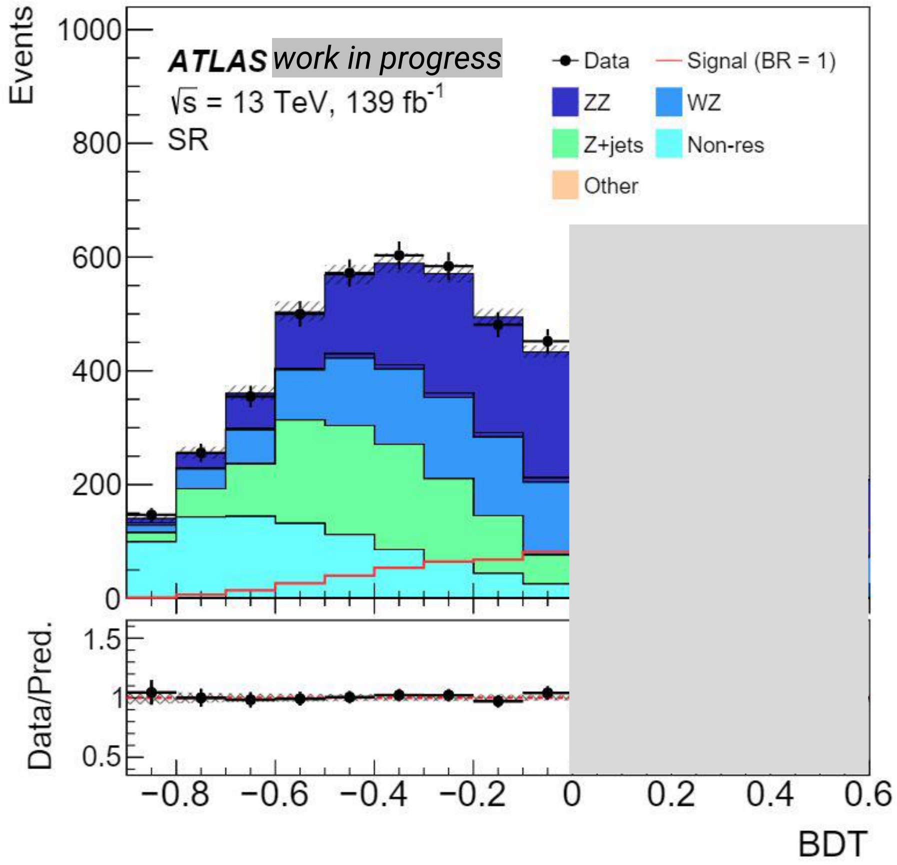
BDT Response with Final SR Selection

Background – Data vs Prediction









H -> invisible post-fit distributions

Results

Define μ here

	Asimov	Data
μ(WZ)	1.000±0.071	*work in progress*
μ(eμ)	1.000±0.118	
μ(Sig)	0.000±0.091	
BR Limit (95% CL)	0.183	

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

	Signal Region	Control Region em	Control Region 3l	Control Region 4l
Observed events	*work in progress*	891	11415	314
Yields after fit		894.41 ± 29.41	11411.80 ± 106.86	294.61 ± 11.29
$ZH(inv)$		0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$		0.00 ± 0.00	443.38 ± 7.51	0.00 ± 0.00
$ZZ4\ell$		0.00 ± 0.00	0.00 ± 0.00	294.61 ± 11.29
WZ		11.59 ± 0.23	10646.16 ± 107.71	0.00 ± 0.00
Non-res ll		875.39 ± 29.42	0.00 ± 0.00	0.00 ± 0.00
$ttV(V)$		1.77 ± 0.04	48.98 ± 0.82	0.00 ± 0.00
Z+jets		0.80 ± 0.02	237.64 ± 4.03	0.00 ± 0.00
$Z\tau\tau$		1.98 ± 0.38	0.00 ± 0.00	0.00 ± 0.00
VVV		2.89 ± 0.08	35.65 ± 0.60	0.00 ± 0.00
Yields before fit	5920.87 ± 536.95	916.25 ± 127.58	11235.38 ± 934.91	273.32 ± 18.39
$ZH(inv)$	0.00 ± 0.12	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	2502.84 ± 164.34	0.00 ± 0.00	441.26 ± 7.74	0.00 ± 0.00
$ZZ4\ell$	80.24 ± 7.09	0.00 ± 0.00	0.00 ± 0.00	273.32 ± 18.39
WZ	1563.06 ± 146.24	11.55 ± 0.24	10473.39 ± 934.67	0.00 ± 0.00
Non-res ll	905.91 ± 127.98	897.61 ± 127.54	0.00 ± 0.00	0.00 ± 0.00
$ttV(V)$	10.89 ± 1.36	1.76 ± 0.04	48.75 ± 0.85	0.00 ± 0.00
Z+jets	843.91 ± 320.04	0.80 ± 0.02	236.51 ± 4.15	0.00 ± 0.00
$Z\tau\tau$	2.18 ± 0.55	1.65 ± 0.44	0.00 ± 0.00	0.00 ± 0.00
VVV	11.84 ± 1.43	2.88 ± 0.08	35.48 ± 0.62	0.00 ± 0.00

Summary

- We use full run-2 dataset to search for Higgs decays to inviable particles associate with Z production
- Background processes estimated through CR method and MC simulation. Good agreement found between data and estimation in CRs.
- Expected Branch Ratio limit for h→invisible: 0.18. Significant improvement compared to early run-2 result: 0.39(exp.), 0.67(obs.).

Backup

Backup

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, Pileup	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

work in progress

SR CR Definition Compare

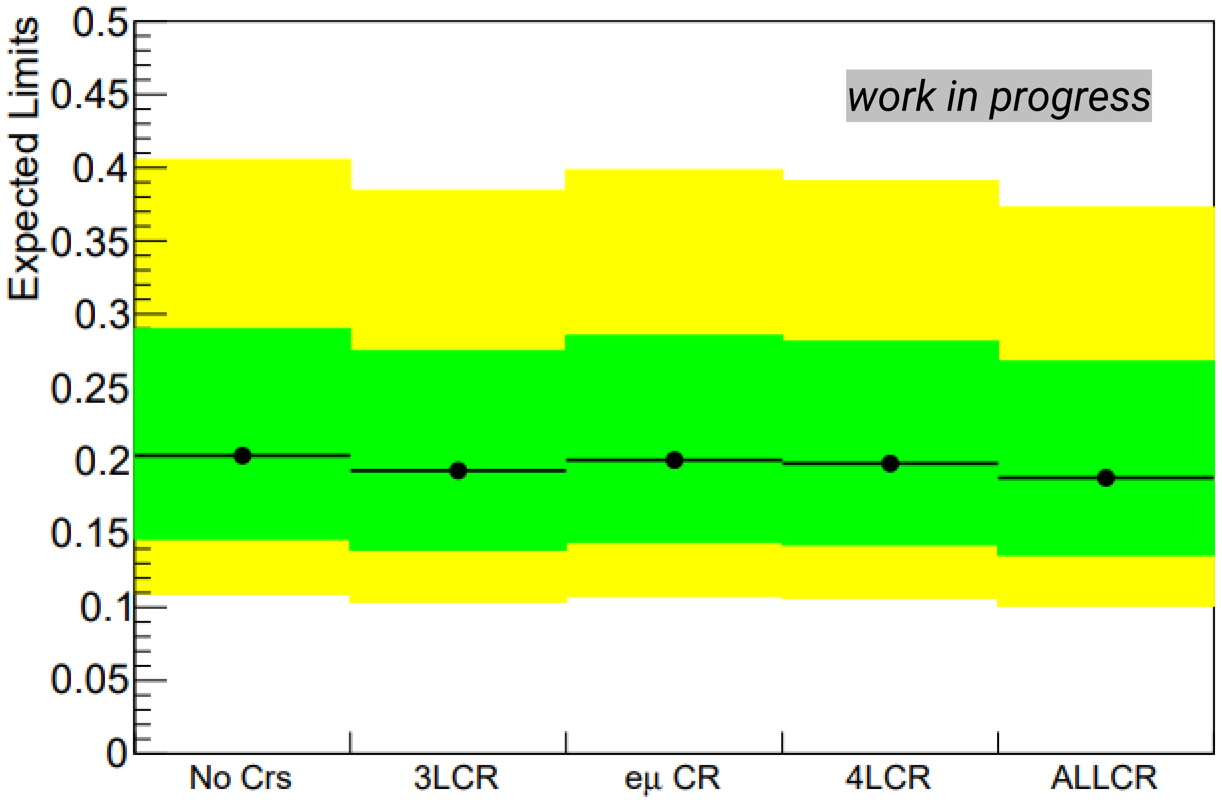
SR	$e\mu$ CR	$3l$ CR	$4l$ CR
Vertex with ≥ 2 tracks with $p_T > 1$ GeV			
Jet Cleaning			
Single lepton trigger			
Trigger matching			
Electron crack region veto			
SFOS dilepton pair	OFOS dilepton pair	SFOS pair plus an additional lepton	2 SFOS dilepton pairs
Lepton $p_T > 30, 20$ GeV		Lepton $p_T > 30, 20, 20$ GeV	Lepton $p_T > 27, 15, 15, 7$ GeV
3rd lepton veto with Loose ID and $p_T > 7$ GeV		4th lepton veto with Loose ID and $p_T > 7$ GeV	5th lepton veto with Loose ID and $p_T > 7$ 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 ($p_T > 20$ GeV, $\|\eta\| < 2.5$, MV2c10, 85% WP)			
Region-specific selections			
$E_T^{miss} > 90$ GeV		$E_T^{miss} > 30$ GeV	$E_T^{miss}{}' > 90$ GeV
$\Delta R(\ell\ell) < 1.8$		$m_T(W) > 60$ GeV	$\Delta R(\ell\ell) < 1.8$
E_T^{miss} significance > 9		E_T^{miss} significance > 3	E_T^{miss} si gnificance' > 9

Fit

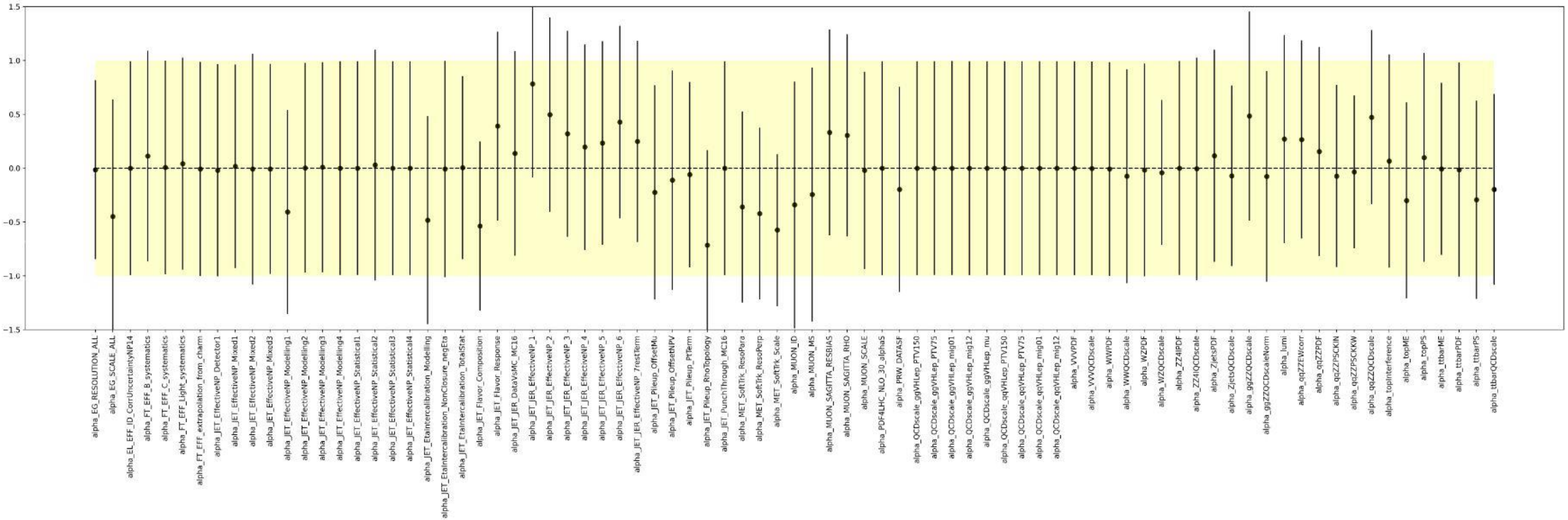
- Use TRexFitter to perform the simultaneous fit with control regions used in addition to the signal region.
- Set floating normalization factors in WZ and eμ CR.

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.

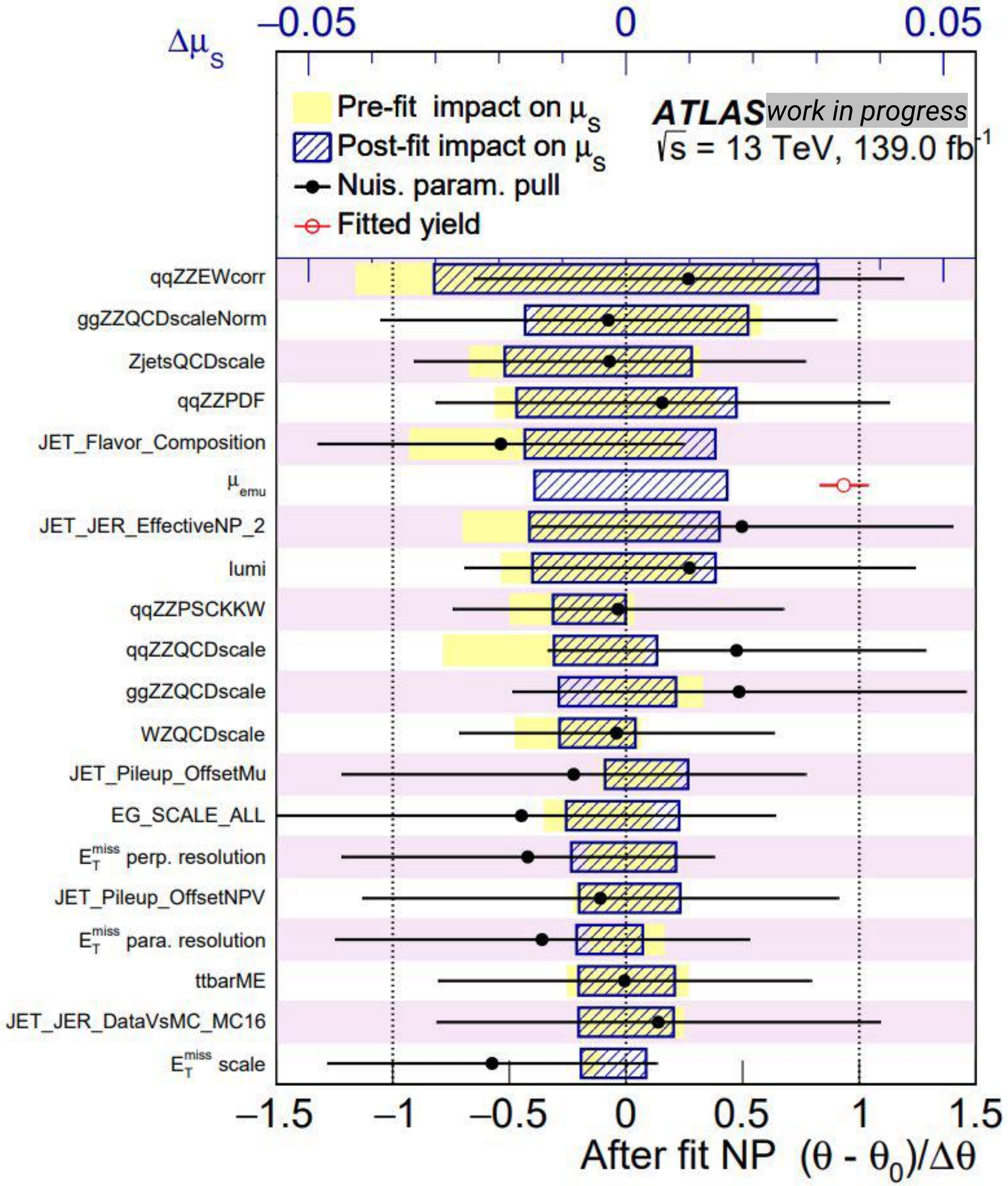


Fit



Pulls for H -> invisible fit
(Work in Progress)

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