$X \rightarrow Sh \rightarrow \gamma\gamma + 1/2L$

Search for X->SH model in the final states of two photons and multiple leptons with the ATLAS detector at the LHC

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IHEP

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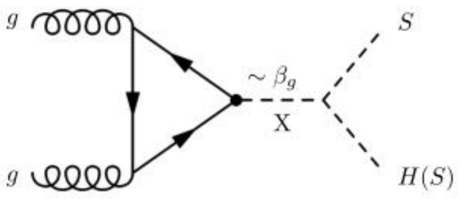
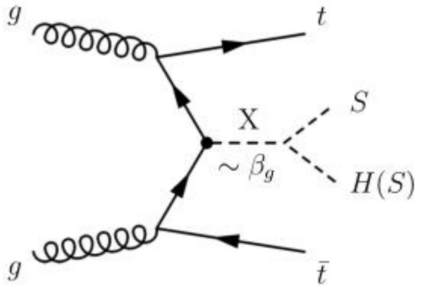
Nanjing, CLHCP2021

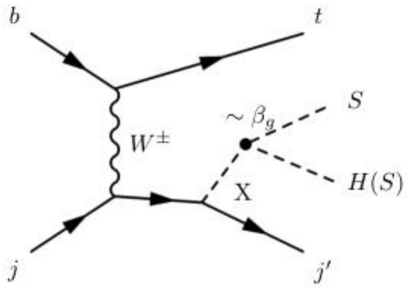
Introduction



(a) Gluon fusion (ggF).



(b) Top pair associated production (ttH).

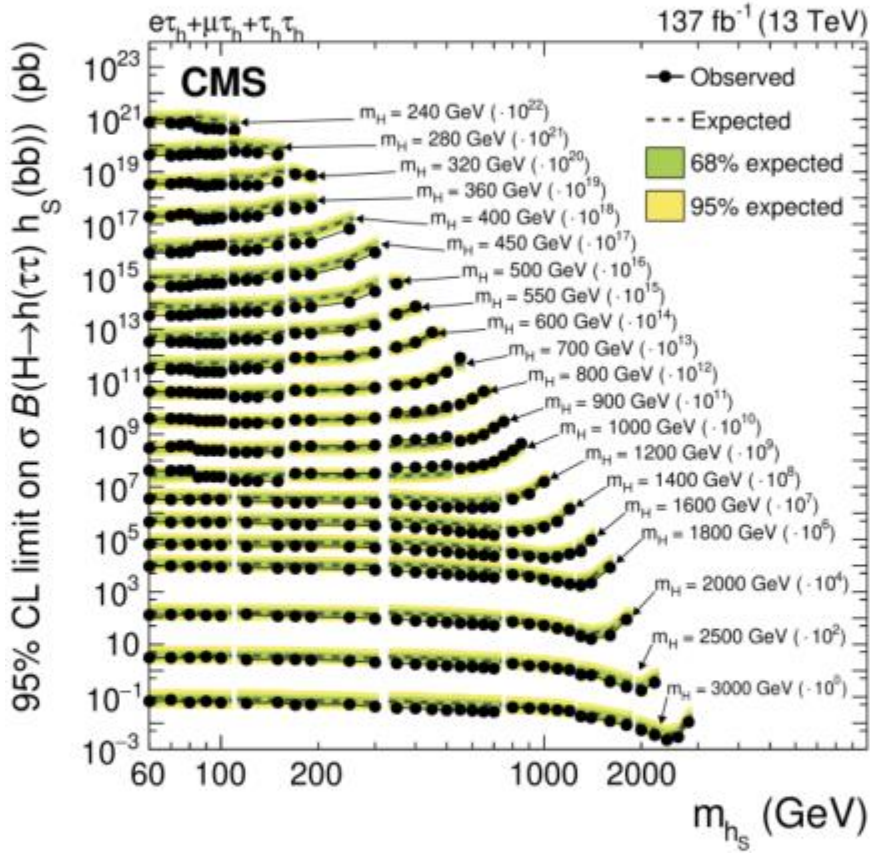


(c) Single top associated production (tH).

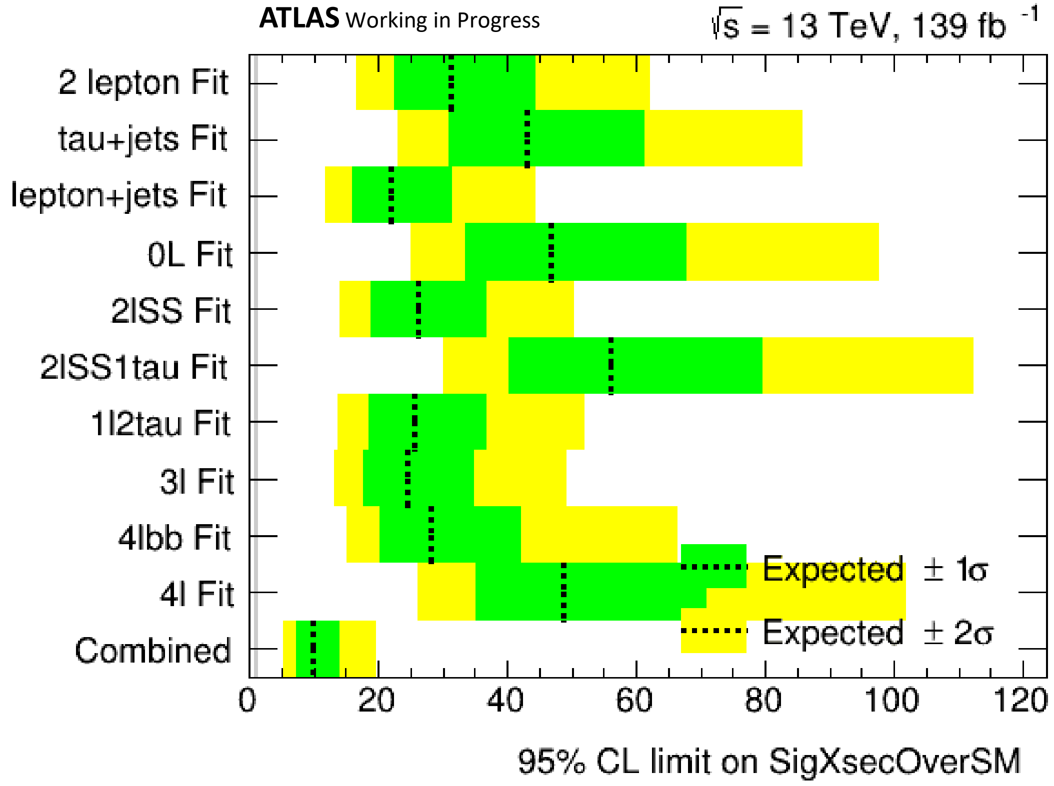
- BSM Extended 2HDM+S model
- X → Sh process would be an alternative higgs pair production.
  - Heavy cp-even scalar X decay into Higgs + Higgs-like scalar S.
  - For $m_S > m_{125}$, S would decay into WW and ZZ dominantly. Multilepton channels benefit from large branch ratio.
  - Higgs diphoton gives excellent clean spectrum and clear signature.

Related Study

CMS SH->bbtautau, JHEP 11 (2021) 057

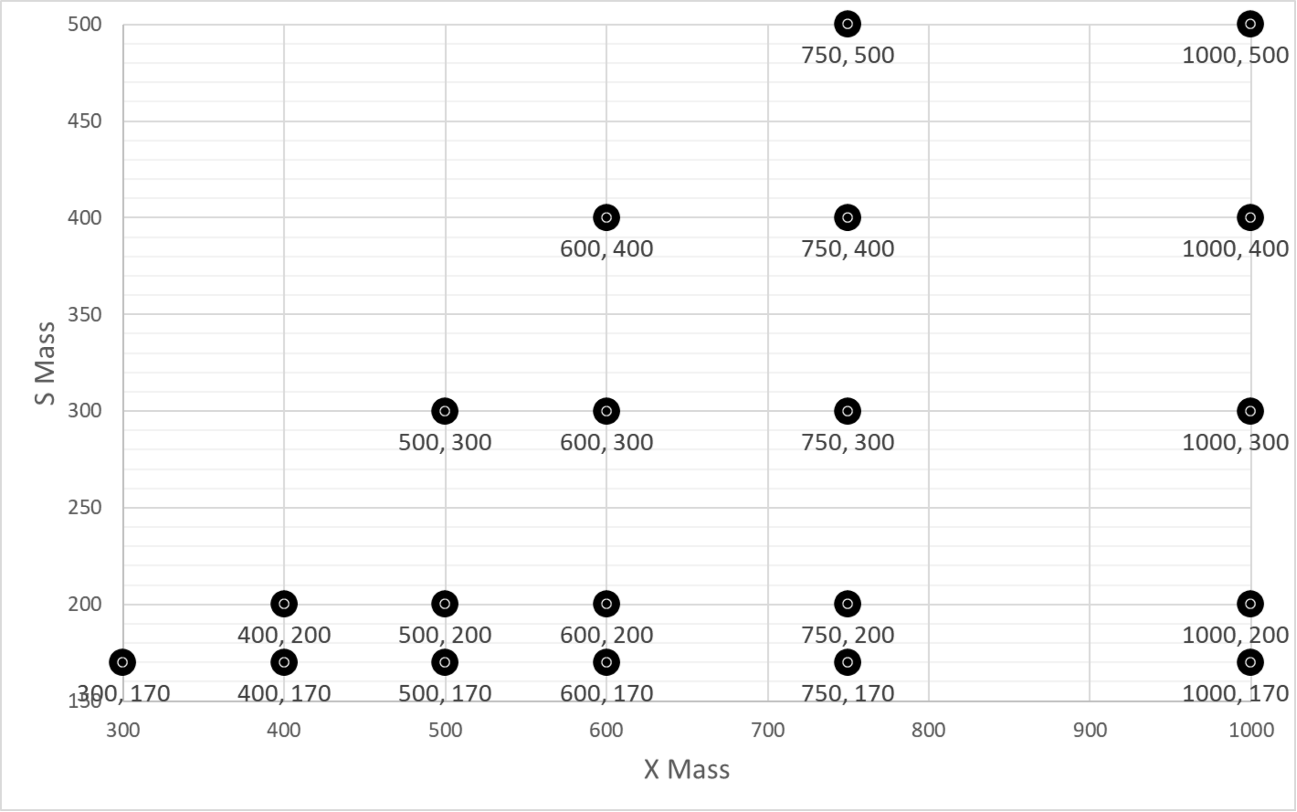


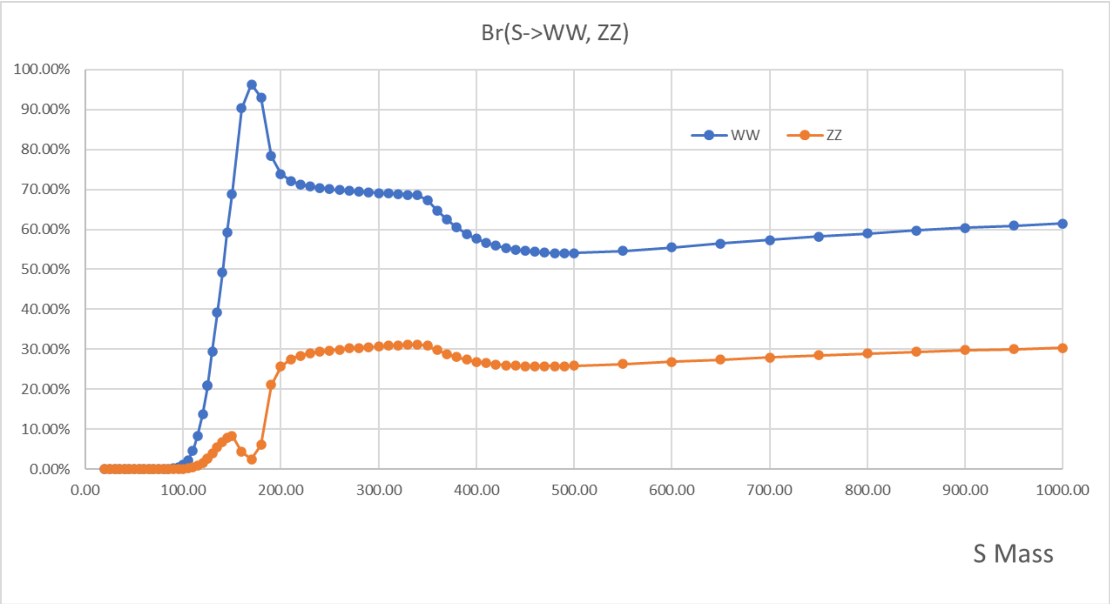
ATLAS HH multilepton, on going



X-S Mass Grid

- 20 mass points has been chosen:
- S mass from 170 to 500 GeV
- X mass from 300 to 1000 GeV
  - Samples are generated with WW1l, WW2l and ZZ2l. Cross talks are considered.





CERN YR4, (without NLO EW corrections)
among S[170, 500], WW and ZZ are dominant decays.

Selection

- Good event
  - GRL, Pass the trigger, detector DQ……
- 2 tight photons
  - Diphoton triggers used
    - ${\gamma_1}_{Pt} > 35GeV,\ {\gamma_2}_{Pt} > 25GeV;$
  - Tight ID, Tight ISO.
- At least 1 lepton
  - e/muon pt>10 GeV;   PID: medium;
    - Hadronic tau not included.
- B-veto
  - B-77 veto to avoid the overlap.

- Regions defined:
  - WW1l: 1 e/muon + 2 central jets;
    - Central jet: pt>25 GeV, |eta|<2.5, pass overlap removal;
  - WW2l: 2 same flavor, OS leptons
    - Z-veto, $|m_{ll} - 91| > 10\ \mathrm{GeV}$

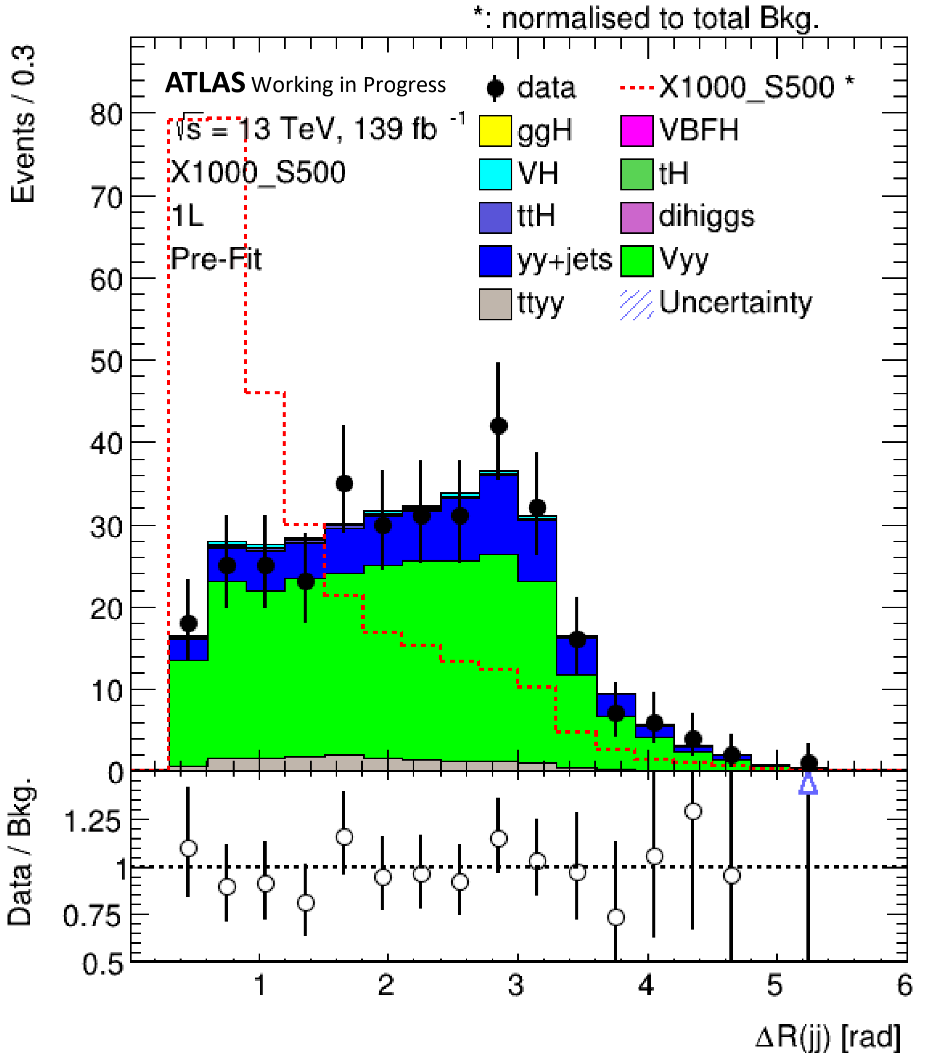
These 2 have enough statistics, use BDT to improve sensitivity.

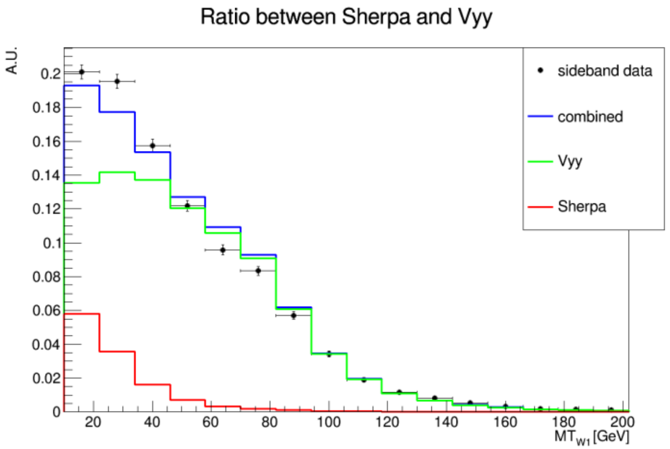
  - WW1e1m: OS 1 electron 1 muon;
  - ZZ2l: 2 same flavor, OS leptons
    - In Z peak: $|m_{ll} - 91| < 10\ \mathrm{GeV}$

Limited statistics, used for number counting.

Sideband Data/MC consistence

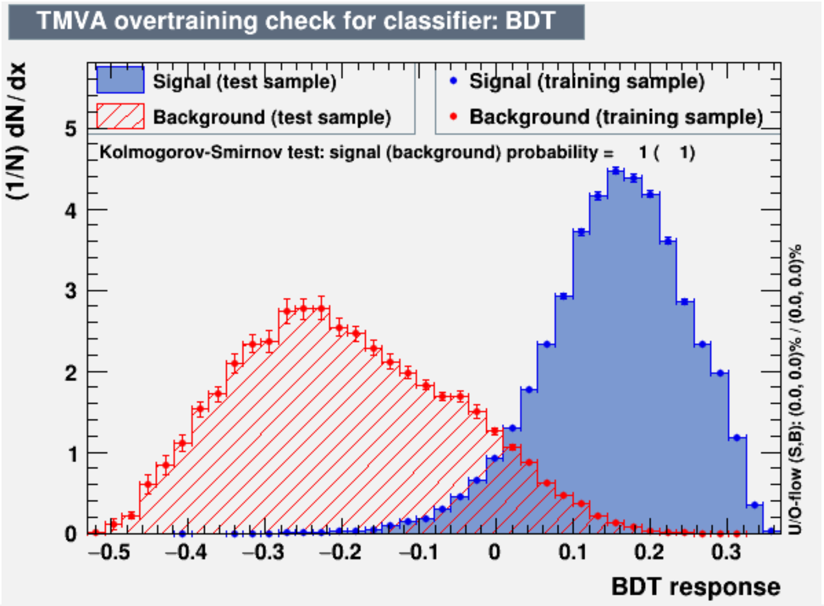
- As our limited data yield, we use yy+jets(known as "Sherpa") and Vyy continuum MC in the BDT training.
- For 1l case the ratio of Sherpa and Vyy are fitted by variable MT_W.
- For 2l case, Vyy are scaled with MT_W mass bins.
- After tuning, The discrepancy between data and MC would be acceptable.

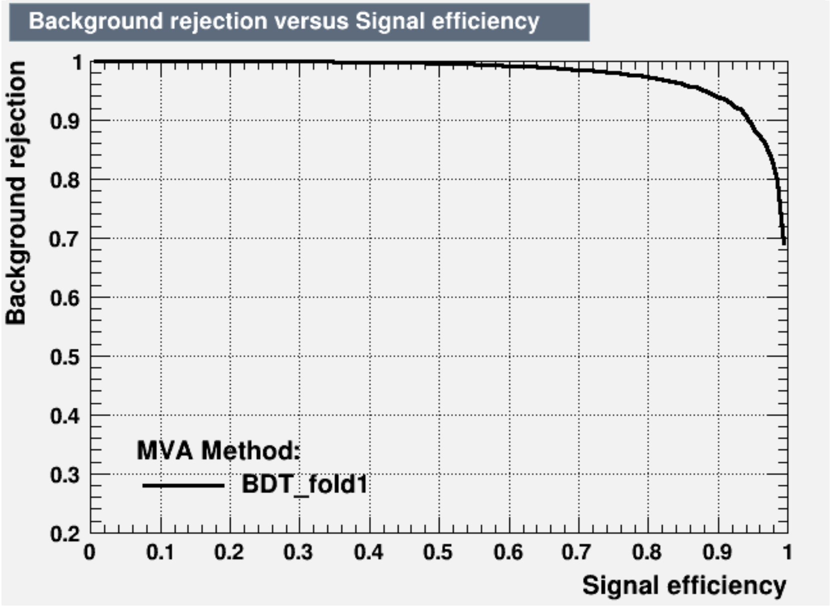




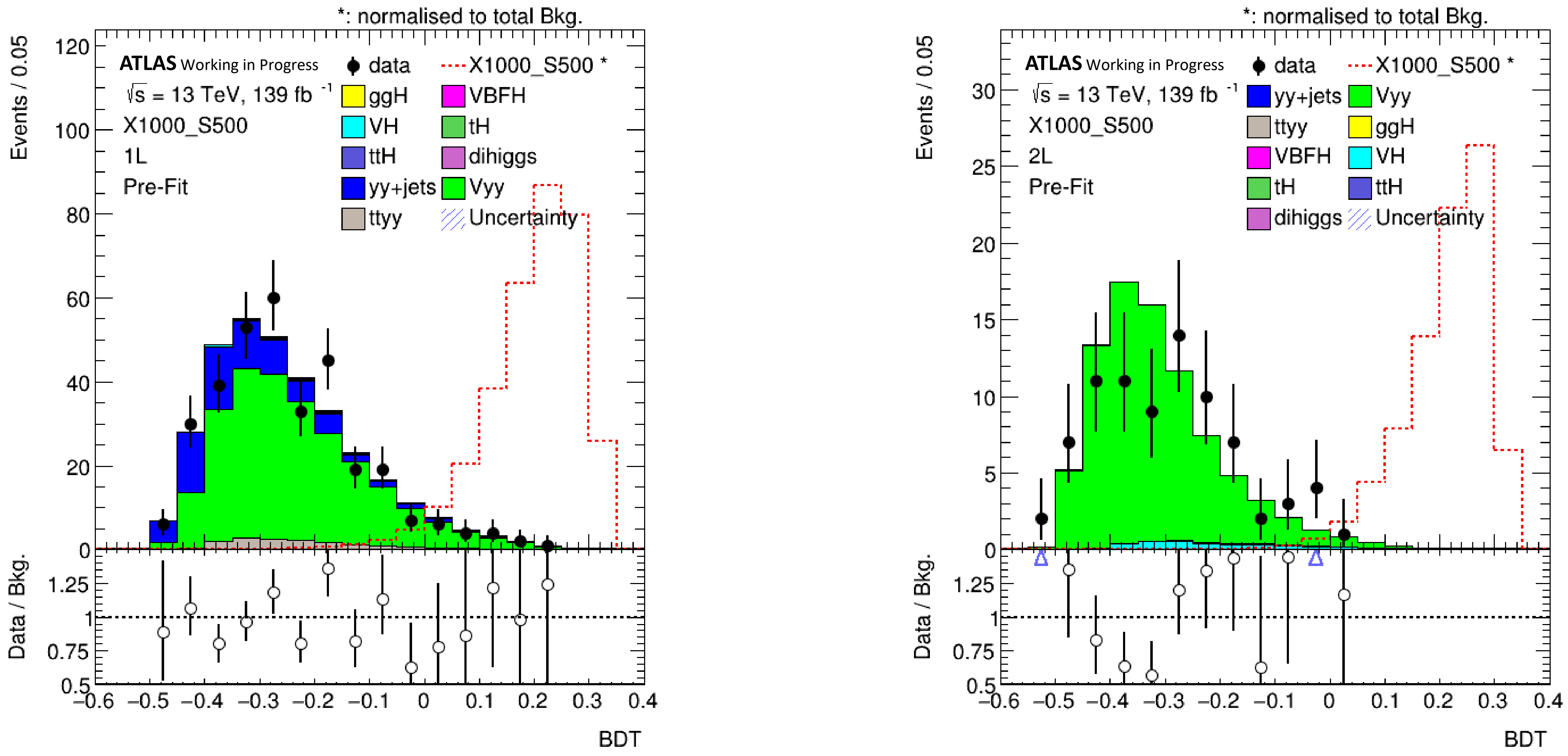
BDT training

- Signal MC, yy+jets, Vyy, ttyy, SM single Higgs and SM dihiggs used.
- 1 lepton 14 variables and 2lepton 11 variables.
- Cross validation method + 4 folds
- Parameterized X mass used
  - 20 signals samples, grouped by their S mass, using their true X mass in the BDT training. While background X mass randomly assigned
  - When applying BDT, background use the same X mass information as signals.
  - In this case, we have 5 individual BDT training but would have all different BDT output for different signals.





BDT outputs



*: normalised to total Bkg.
ATLAS Working in Progress
√s = 13 TeV, 139 fb -1
X1000_S500
1L
Pre-Fit
data
X1000_S500 *
ggH
VBFH
VH
tH
ttH
dihiggs
yy+jets
Vyy
ttyy
Uncertainty
Events / 0.05
Data / Bkg.
BDT
*: normalised to total Bkg.
ATLAS Working in Progress
√s = 13 TeV, 139 fb -1
X1000_S500
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Pre-Fit
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X1000_S500 *
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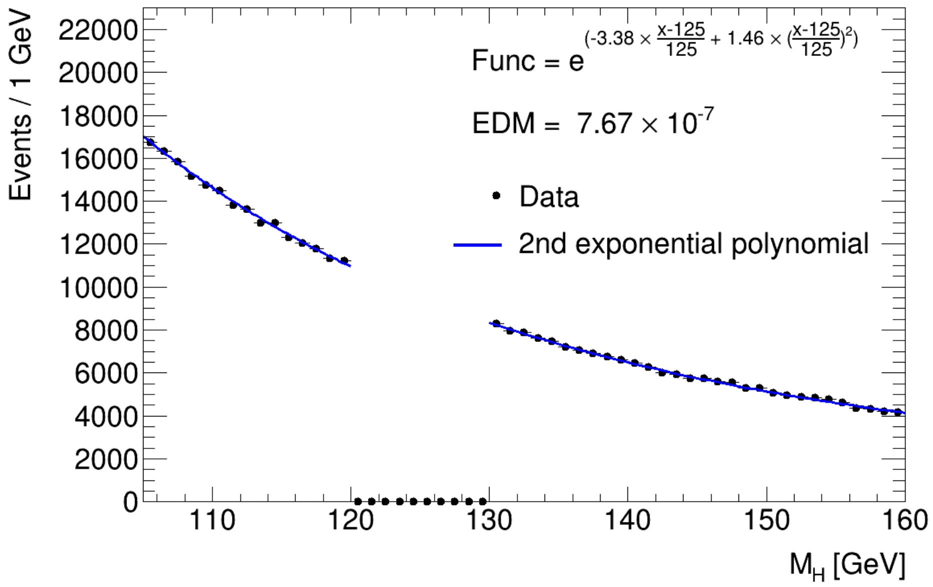
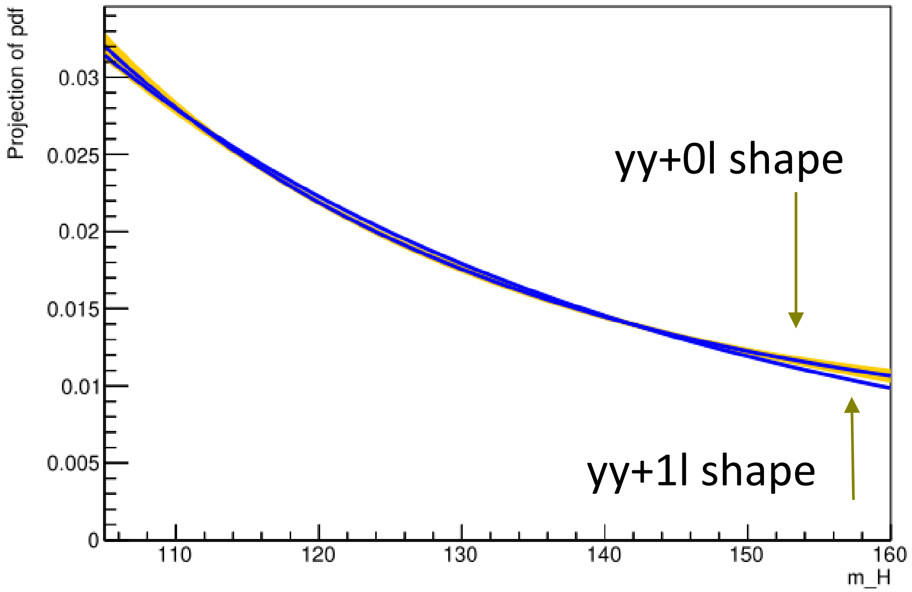
VH
tH
ttH
dihiggs
Uncertainty
Events / 0.05
Data / Bkg.
BDT

Background modelling

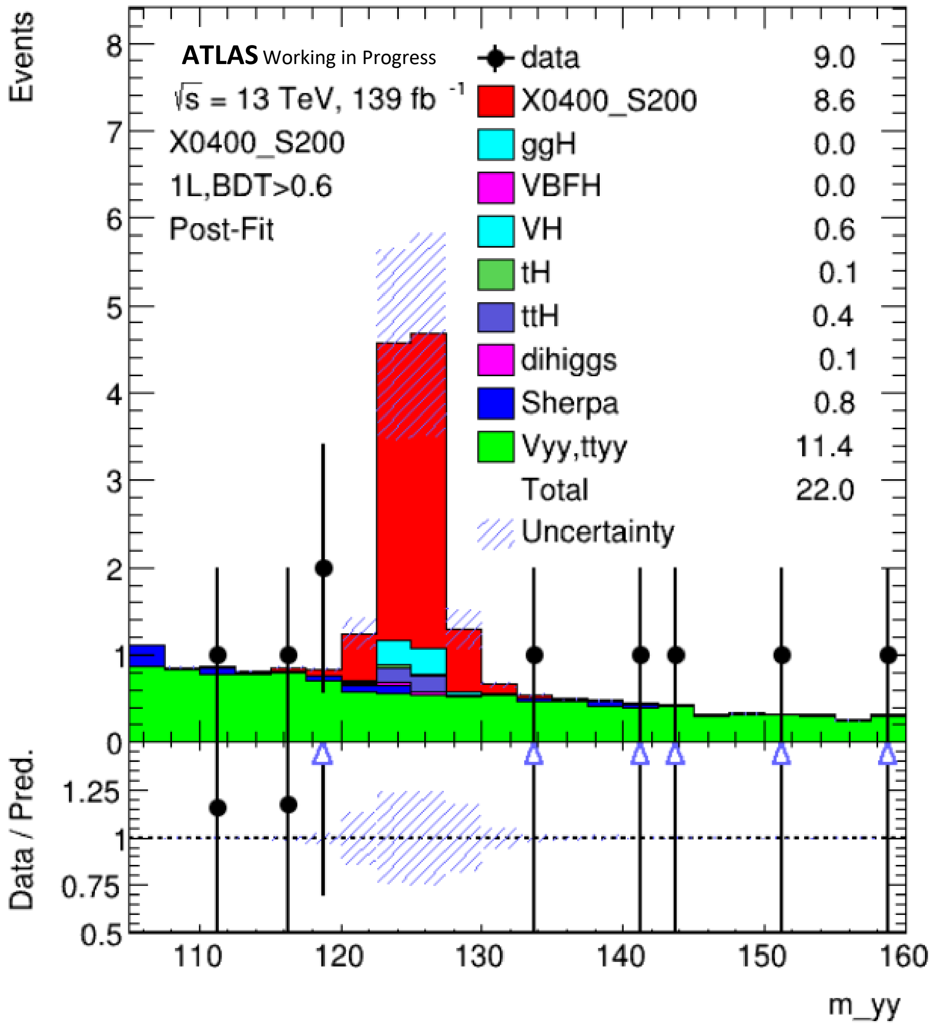




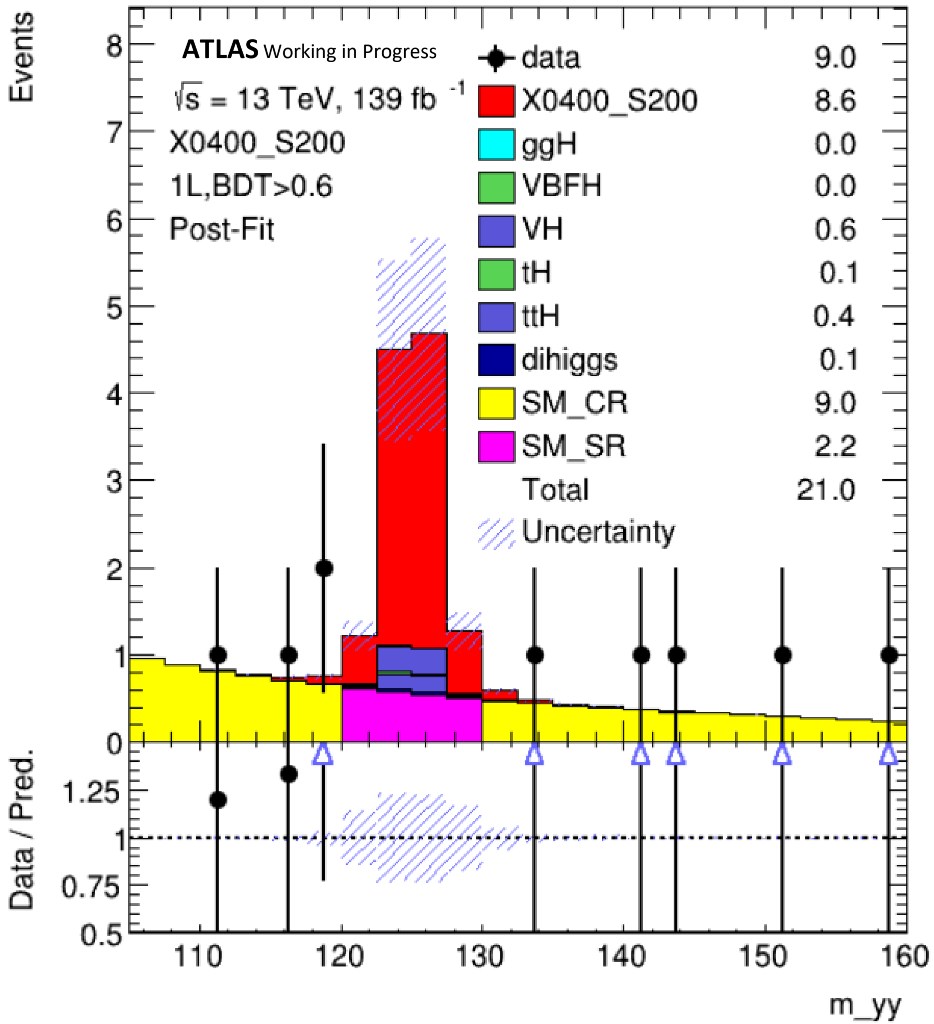
- Use 0 lepton data-side band control region as shape.
  - 2nd exponential polynomial function used.
- All the region, 1l and 2l, assumed to share the same shape.
  - Proper reweighting in N_jets
  - Using 0l to simulate the multilepton shape is reliable, and the bias could be implemented.
  - Lepton dependance introduced as uncertainty, up to 5%.

Mass distribution

Using continuum MC



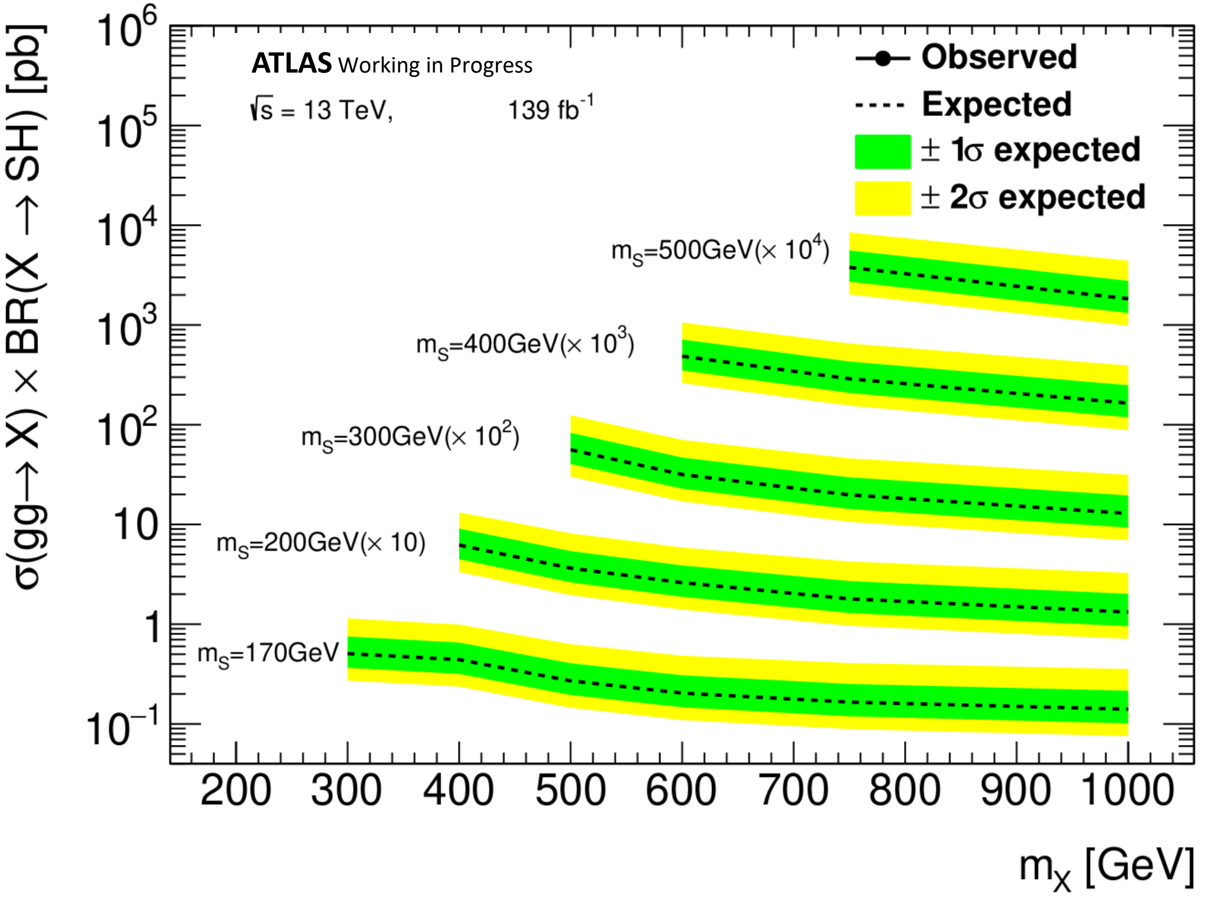
Using shape from 0L shape.



Stat-only results

POI set to cross section (X->SH).

	Smass=170	200	300	400	500
Xmass=300	455.39				
Xmass=400	415.37	611.81			
Xmass=500	260.57	360.98	535.75		
Xmass=600	204.50	260.83	309.04	452.33	
Xmass=750	170.40	178.81	200.69	275.96	349.24
Xmass=1000	141.30	138.62	132.78	162.42	184.70



Best limit in (X1000, S300) for 132.78fb, worst one in (X400, S200) for 611.81fb.

Among all 4 regions, 1l channel is dominant.
With only 1lepton category, Limit: 155fb.
With 1l+2l, without ZZ2l and WW1e1m, Limit: 139fb.

Systematics

- Following dihiggs combination scenario, 105 CP NPs introduced.
  - Also for Lumi, theoretic uncertainties and Br(S->WW and ZZ)
  - Lepton dependance, and impact for different bkg function form studied in the SS test.
- Statistics dominant
  - No NP has >5% impact in the pre-fit yields except for PRW_dataSF(11%).
  - No >5% impact in the post-fit.
  - Importing systematics led (X1000, S300) 12% worse, to 148fb.

Summary

- Study on $X \rightarrow Sh \rightarrow \gamma\gamma + 1/2L$ is done from X(300, 1000) and S(170, 500).
  - Best result could be achieved in (X1000, S300) for 132fb(stat only) and 148fb(sys).
- Systematics study done.
  - Interpolation to the whole plane, independent POI…… in the plan.
- Will EB soon and targeting Moriond 2022.

Thanks a lot for your attention!

Backups

m_X	300	400	400	500	500	500	600	600	600	600
m_S	170	170	200	170	200	300	170	200	300	400
WW1l, DSID	800943	800944	800945	800946	800947	800948	800949	800950	800951	800952
All events	100	100	100	100	100	100	100	100	100	100
No duplicates	100	100	100	100	100	100	100	100	100	100
GRL	100	100	100	100	100	100	100	100	100	100
Pass trigger	77.56	82.25	81.14	88.92	88.45	83.35	91.86	91.69	90.37	84.82
Detector DQ	77.56	82.25	81.14	88.92	88.45	83.35	91.86	91.69	90.37	84.82
Has PV	77.56	82.25	81.14	88.92	88.45	83.35	91.86	91.69	90.37	84.82
2 loose photons	58.57	59.26	59.46	60.98	61.10	61.23	63.06	63.11	62.69	62.65
Trigger match	53.29	54.64	54.12	58.45	58.19	55.83	61.60	61.46	60.02	57.10
tight ID	45.04	46.47	46.07	49.67	49.36	47.09	52.24	52.01	50.49	47.84
isolation	36.73	39.99	38.98	44.28	43.61	39.70	47.45	46.98	44.37	40.26
rel. pT cuts	34.16	35.51	34.57	39.95	39.10	35.11	43.62	43.15	39.97	35.50
m_{yy} in [105, 160]GeV	33.81	35.18	34.16	39.51	38.59	34.34	43.21	42.64	39.11	34.43
b-veto	30.75	31.49	30.52	34.97	34.19	30.35	38.03	37.52	34.18	30.19
At least 1lep	19.32	19.81	20.30	21.27	22.71	20.67	21.92	24.46	23.73	20.55
pass WW1l	11.01	13.12	13.85	15.20	16.58	16.11	16.27	18.60	18.92	16.95
WW2l, DSID	800963	800964	800965	800966	800967	800968	800969	800970	800971	800972
All events	100	100	100	100	100	100	100	100	100	100
No duplicates	100	100	100	100	100	100	100	100	100	100
GRL	100	100	100	100	100	100	100	100	100	100
Pass trigger	84.51	87.68	87.25	91.92	91.75	89.45	93.83	93.99	93.39	91.03
Detector DQ	84.51	87.68	87.25	91.92	91.75	89.45	93.83	93.99	93.39	91.03
Has PV	84.51	87.68	87.25	91.92	91.75	89.45	93.83	93.99	93.39	91.03
2 loose photons	58.15	57.75	58.43	59.10	58.94	60.23	60.91	60.68	60.45	61.59
Trigger match	53.03	53.45	53.28	56.75	56.22	55.25	59.63	59.21	58.15	56.72
tight ID	45.22	45.74	45.55	48.59	48.07	47.34	50.94	50.69	49.77	48.45
isolation	38.12	39.65	39.06	43.23	42.55	40.57	45.96	45.60	43.99	41.37
rel. pT cuts	35.49	34.90	34.68	38.88	38.01	35.87	42.10	41.73	39.45	36.56
m_{yy} in [105, 160]GeV	34.79	34.22	33.88	38.02	36.96	34.43	41.17	40.68	37.95	34.67
b-veto	33.56	32.74	32.39	36.23	35.17	32.95	39.05	38.65	36.08	32.96
At least 2lep	17.14	18.06	18.12	20.55	20.72	19.45	22.16	23.23	22.35	20.15
pass WW2l	17.01	17.90	17.60	20.34	20.09	18.95	21.90	22.44	21.73	19.76
pass ZZ2l	0.07	0.10	0.43	0.13	0.52	0.40	0.14	0.65	0.46	0.23
WW2l-em	8.46	8.91	8.85	10.17	10.27	9.64	10.96	11.50	11.02	10.03
fall to 1lepton category	11.93	10.51	10.99	11.07	11.14	10.93	11.54	11.82	11.33	10.58
ZZ2l, DSID	800983	800984	800985	800986	800987	800988	800989	800990	800991	800992
All events	100	100	100	100	100	100	100	100	100	100
No duplicates	100	100	100	100	100	100	100	100	100	100
GRL	100	100	100	100	100	100	100	100	100	100
Pass trigger	77.68	81.12	80.26	87.03	86.52	81.65	89.98	89.82	88.24	82.69
Detector DQ	77.68	81.12	80.26	87.03	86.52	81.65	89.98	89.82	88.24	82.69
Has PV	77.68	81.12	80.26	87.03	86.52	81.65	89.98	89.82	88.24	82.69
2 loose photons	53.42	53.66	54.13	54.92	55.21	55.79	56.92	57.19	56.96	57.33
Trigger match	48.43	49.46	49.14	52.63	52.49	50.88	55.57	55.65	54.47	52.29
tight ID	40.75	41.91	41.52	44.61	44.41	42.81	46.87	46.93	45.85	43.71
isolation	32.83	35.78	34.68	39.36	38.81	35.77	42.31	42.05	39.74	36.32
rel. pT cuts	30.54	31.61	30.81	35.43	34.77	31.78	38.92	38.53	35.90	32.00
m_{yy} in [105, 160]GeV	29.93	30.98	30.14	34.67	33.94	30.73	38.17	37.69	34.73	30.70
b-veto	25.04	24.53	23.71	26.65	25.77	22.89	28.65	28.14	25.25	21.89
At least 2lep	12.82	12.97	12.87	13.79	13.86	13.75	14.16	14.69	15.67	13.50
pass WW2l	10.13	9.66	6.13	9.94	6.21	5.69	9.99	6.26	6.18	5.16
pass ZZ2l	2.64	3.24	6.68	3.77	7.60	7.99	4.08	8.35	9.40	8.25
WW2l-em	0.07	0.09	0.08	0.09	0.09	0.13	0.11	0.11	0.14	0.11
fall to 1lepton category	8.52	8.06	7.69	8.76	8.32	6.26	9.56	9.20	6.33	5.53

Table 6: Efficiencies in percent for event selection for signals.

X	750	750	750	750	750	1000	1000	1000	1000	1000
S	170	200	300	400	500	170	200	300	400	500
WW1l, DSID	800953	800954	800955	800956	800957	800938	800939	800940	800941	800942
All events	100	100	100	100	100	100	100	100	100	100
No duplicates	100	100	100	100	100	100	100	100	100	100
GRL	100	100	100	100	100	100	100	100	100	100
Pass trigger	93.90	93.92	93.60	92.95	90.06	95.70	95.56	95.69	95.69	95.31
Detector DQ	93.90	93.92	93.60	92.95	90.06	95.70	95.56	95.69	95.69	95.31
Has PV	93.90	93.92	93.60	92.95	90.06	95.70	95.56	95.69	95.69	95.31
2 loose photons	66.12	65.98	65.50	64.81	63.87	70.26	70.03	69.93	69.35	68.60
Trigger match	65.35	65.15	64.43	63.04	60.41	69.85	69.62	69.50	68.81	67.87
tight ID	55.30	55.05	54.46	52.80	50.27	59.30	58.99	58.67	58.08	56.94
isolation	51.01	50.75	49.51	46.92	43.19	55.65	55.44	54.89	53.74	51.84
rel. pT cuts	47.92	47.61	46.04	43.00	38.47	53.12	52.95	52.20	50.81	48.79
m_{yy} in [105, 160]GeV	47.57	47.12	45.22	41.89	37.09	52.87	52.51	51.55	49.92	47.62
b-veto	41.45	41.08	39.16	36.33	32.17	45.53	45.14	44.30	42.94	40.86
1lep	21.69	25.62	27.08	24.90	21.87	19.71	25.60	30.14	29.57	27.95
pass WW1l	16.62	20.31	22.32	20.98	18.68	15.49	20.95	25.37	25.19	24.01
WW2l, DSID	800973	800974	800975	800976	800977	800958	800959	800960	800961	800962
All events	100	100	100	100	100	100	100	100	100	100
No duplicates	100	100	100	100	100	100	100	100	100	100
GRL	100	100	100	100	100	100	100	100	100	100
Pass trigger	95.43	95.31	95.49	95.37	94.10	96.61	96.77	96.84	96.88	96.82
Detector DQ	95.43	95.31	95.49	95.37	94.10	96.61	96.77	96.84	96.88	96.82
Has PV	95.43	95.31	95.49	95.37	94.10	96.61	96.77	96.84	96.88	96.82
2 loose photons	63.62	63.33	63.21	62.85	62.67	67.11	67.07	67.16	66.86	66.30
Trigger match	62.94	62.62	62.21	61.51	59.53	66.77	66.70	66.76	66.37	65.70
tight ID	53.72	53.75	53.21	52.64	50.85	57.43	57.28	57.33	56.91	56.27
isolation	49.43	49.29	48.39	47.13	44.22	53.56	53.49	53.36	52.56	51.50
rel. pT cuts	46.18	46.00	44.78	42.90	39.40	50.90	50.75	50.38	49.46	48.15
m_{yy} in [105, 160]GeV	45.32	44.96	43.35	40.95	37.02	50.16	49.81	49.12	47.84	46.02
b-veto	42.79	42.47	41.01	38.49	35.14	46.94	46.63	46.05	44.92	43.22
At least 2lep	23.96	25.67	26.20	24.56	22.24	24.54	28.04	29.91	29.17	28.33
pass WW2l	23.65	24.75	25.38	24.11	21.87	24.14	26.97	28.89	28.49	27.84
pass ZZ2l	0.17	0.74	0.63	0.29	0.16	0.22	0.86	0.80	0.42	0.22
WW2l-em	11.90	12.65	12.93	12.22	11.08	12.22	13.90	14.75	14.40	14.12
fall to 1lepton category	12.27	12.52	12.14	11.62	10.76	13.54	13.04	12.99	12.88	12.34
ZZ2l, DSID	800993	800994	800995	800996	800997	800978	800979	800980	800981	800982
All events	100	100	100	100	100	100	100	100	100	100
No duplicates	100	100	100	100	100	100	100	100	100	100
GRL	100	100	100	100	100	100	100	100	100	100
Pass trigger	92.35	92.38	91.98	90.73	87.54	94.41	94.56	94.45	94.11	93.63
Detector DQ	92.35	92.38	91.98	90.73	87.54	94.41	94.56	94.45	94.11	93.63
Has PV	92.35	92.38	91.98	90.73	87.54	94.41	94.56	94.45	94.11	93.63
2 loose photons	59.89	60.04	59.63	59.11	58.35	63.46	63.58	63.61	63.33	62.62
Trigger match	59.27	59.25	58.55	57.46	55.16	63.09	63.17	63.14	62.80	61.87
tight ID	49.98	50.14	49.17	48.08	45.78	53.39	53.43	53.22	52.85	51.68
isolation	45.90	46.00	44.42	42.29	38.80	49.83	49.88	49.41	48.66	46.80
rel. pT cuts	42.91	42.97	41.25	38.70	34.58	47.48	47.40	46.85	46.02	43.98
m_{yy} in [105, 160]GeV	42.22	42.23	40.22	37.43	33.09	46.95	46.78	45.99	44.92	42.68
b-veto	30.66	30.57	28.53	26.06	22.68	33.10	32.64	31.58	30.64	28.72
At least 2lep	13.68	14.63	17.85	16.51	14.55	12.22	13.08	19.37	19.46	18.42
pass WW2l	9.64	6.18	6.58	5.93	5.20	8.72	5.85	6.76	6.58	6.17
pass ZZ2l	3.95	8.36	11.15	10.48	9.25	3.39	7.12	12.48	12.72	12.14
WW2l-em	0.11	0.13	0.17	0.18	0.16	0.12	0.10	0.20	0.21	0.21
fall to 1lepton category	10.88	10.59	6.77	5.98	5.06	12.07	12.17	7.12	6.21	5.84

Table 7: Efficiencies in percent for event selection for signals.(Continued)

BDT variables

Following 13 variables are used for WW1l BDT training:

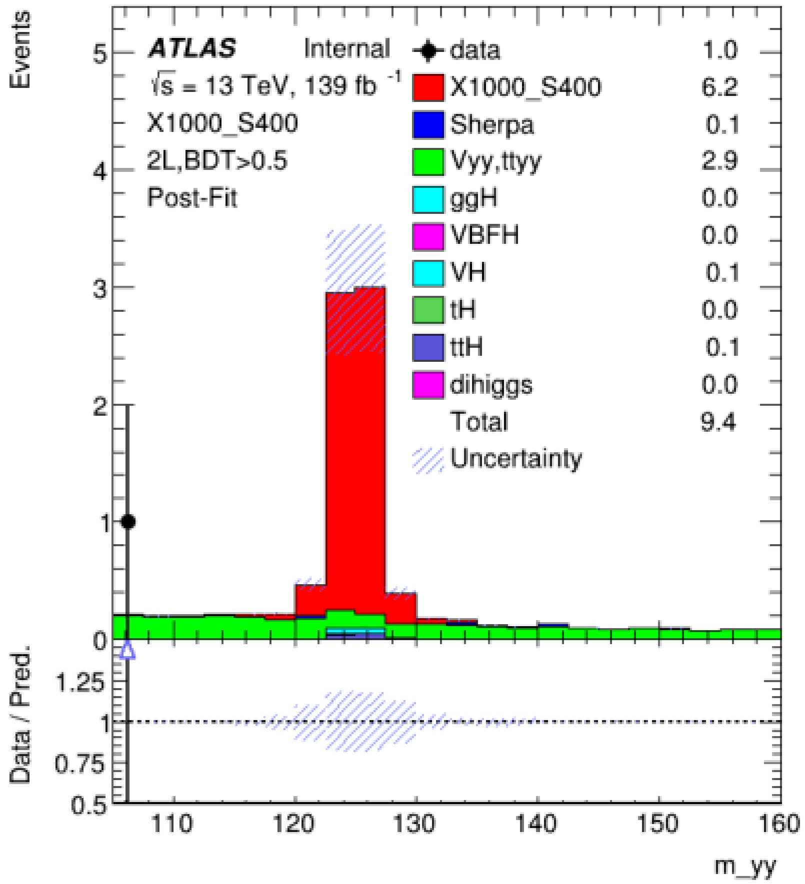
- $\Delta R(j, j)$, the angular difference between two jets.
- $\Delta R(S)$, the angular difference between two bosons from S decay (aka $\Delta R(V, V)$).
- $\Delta R(X)$, the angular difference between H and S from X decay (aka $\Delta R(S, H)$).
- $\Delta R(\ell\nu)$, the angular difference between signal lepton and neutrino from W decay (aka $\Delta R(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$).
- $\Delta\Phi(\gamma\gamma, \ell_1)$, the polar angle difference between di-photon system and signal lepton.
- $E_{\mathrm{T}}^{\mathrm{miss}}$, the missing transverse momentum.
- $p_{\mathrm{T}}(\gamma\gamma)$, the transverse momentum of the di-photon system.
- $p_{\mathrm{T}}(S)$, the transverse momentum of di-jets+ℓ+$E_{\mathrm{T}}^{\mathrm{miss}}$ system.
- $p_{\mathrm{T}}(jj)$, the transverse momentum of di-jets system.
- $p_{\mathrm{T}}(\ell_1)$, the transverse momentum of signal lepton.
- $\Delta m(X, S)$, the mass difference between reconstructed X and S particles.
- $m_W(jj)$, the hadronic W boson system reconstructed from di-jets which has the closet mass to the W boson mass.
- $m_{\mathrm{T}}(W_1)$, the transverse mass of the leptonically decay W boson (reconstructed from signal lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$).

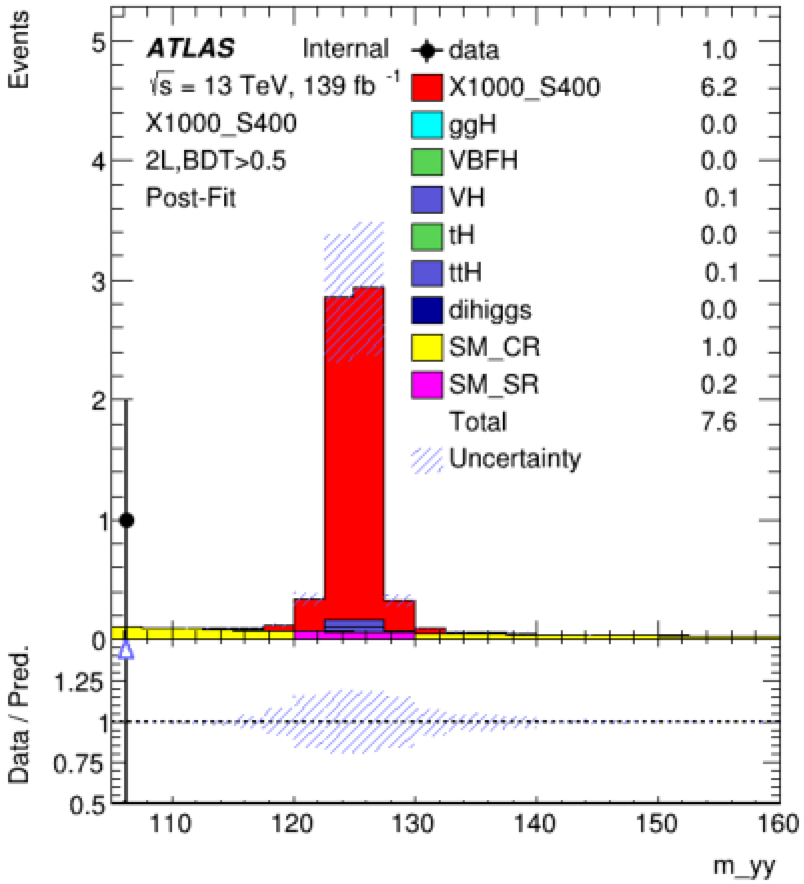
Following variables are used for WW2l BDT training:

- $\Delta R(l, j))$, the angular difference between lepton and jet.
- ΔS, the angular difference between two bosons from S decay (aka $\Delta R(V, V)$).
- ΔX, the angular difference between H and S from X decay (aka $\Delta R(S, H)$).
- $\Delta\Phi(\gamma\gamma, \ell_1)$, the polar angle difference between di-photon system and leading signal lepton.
- $E_{\mathrm{T}}^{\mathrm{miss}}$, the missing transverse momentum.
- $p_{\mathrm{T}}(\gamma\gamma)$, the transverse momentum of the di-photon system.
- $p_{\mathrm{T}}(\ell_1)$, the transverse momentum of leading signal lepton.
- $p_{\mathrm{T}}(\ell\nu)$, the transverse momentum of ℓ_1+$E_{\mathrm{T}}^{\mathrm{miss}}$ system.
- $\Delta m(X, S)$, the mass difference between reconstructed X and S particles.
- $m_{\mathrm{T}}^{W_1}$, the transverse mass of the leptonically decay W boson (reconstructed from signal lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$).
- $m_{\ell\ell}$, the invariant mass of di-leptons system.

2l distribution

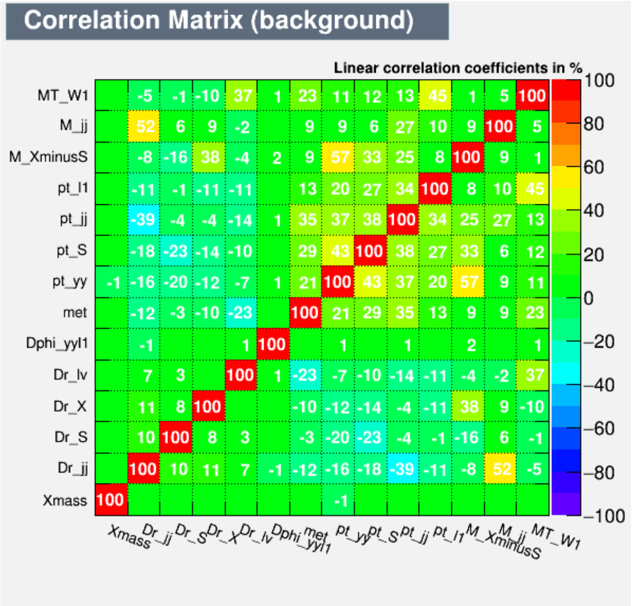
For 2l, ww1e1m, zz2l regions, the spectrum is clear.



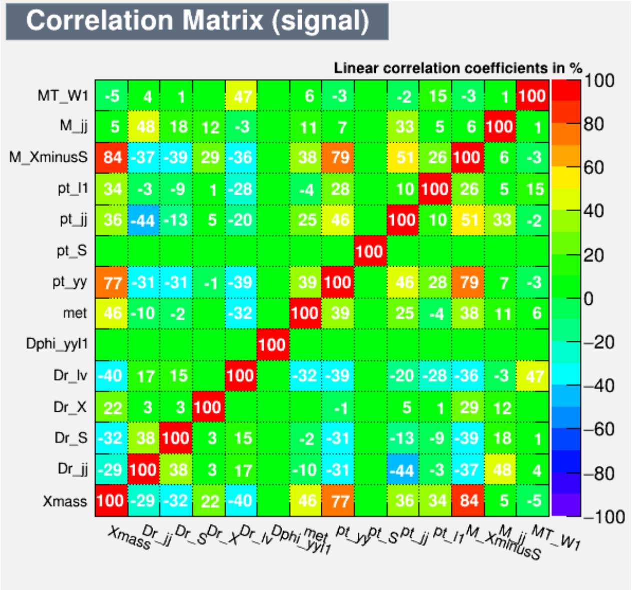


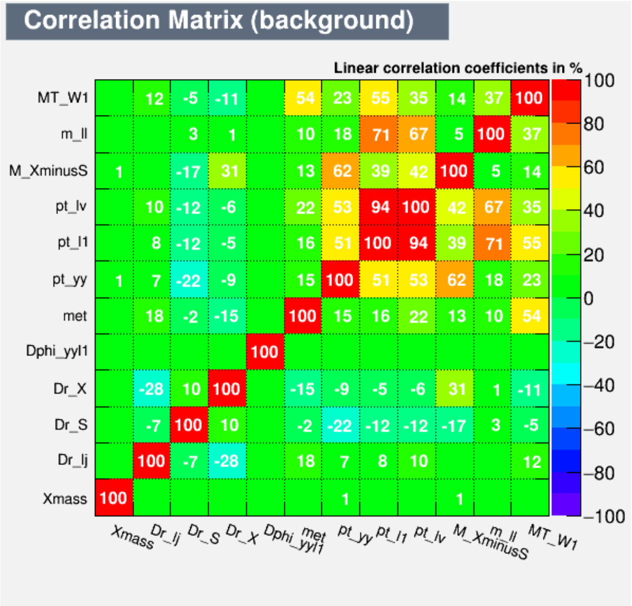
Variable Correlation

All the variables in the BDT has small correlation compared to m_yy.

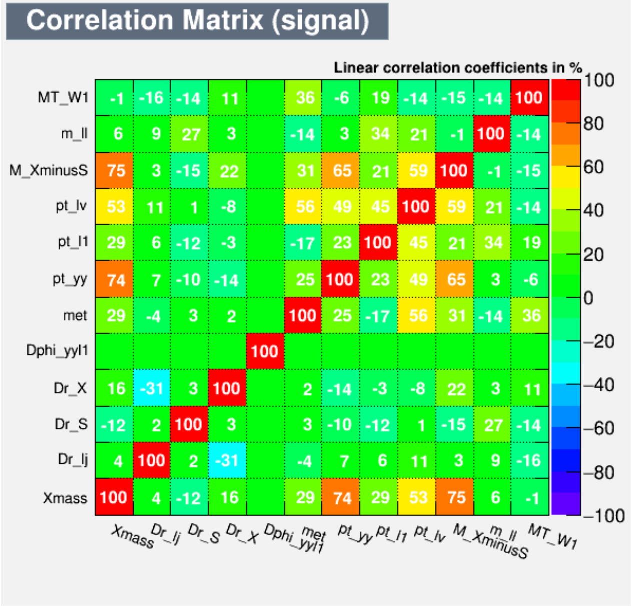


1 lepton bkg: S400 signal





2 lepton bkg: S400 signal



Analysis Team

ANA-HDBS-2021-23-INT1
CDS:2779977

ATLAS EXPERIMENT

ATLAS Note

ANA-HDBS-2021-23-INT1

September 26, 2021

Draft version 0.1

Search for $X \rightarrow SH$ model in the final states of two photons and multiple leptons using 139 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13 TeV recorded with the ATLAS detector at the LHC

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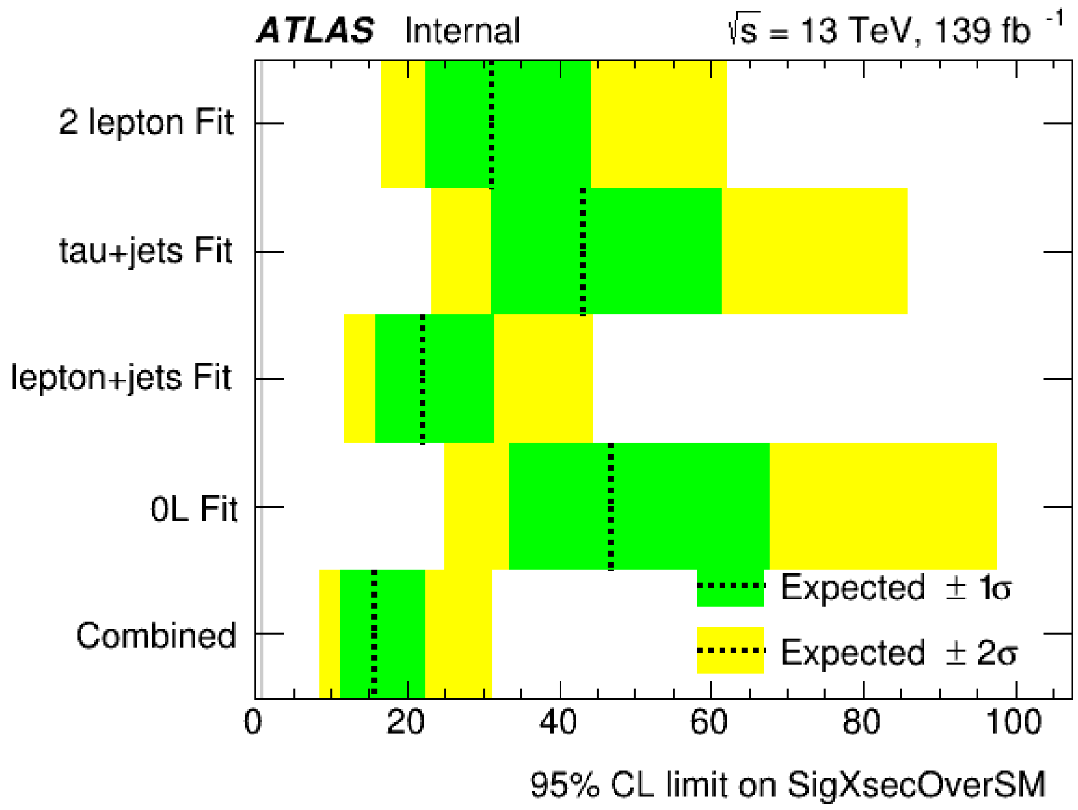
This note presents a search for a new heavy scalar particle X decaying into a Standard Model Higgs boson and a singlet scalar particle S using 139 fb^{-1} of proton-proton collision data at the centre-of-mass energy of 13 TeV recorded with the ATLAS detector at LHC. The explored X mass range varies from 300 GeV to 1000 GeV, with the corresponding S mass range being from 170 GeV to 500 GeV. This search uses the event signature of two photons from the Higgs boson decay and one or two leptons (e or μ) coming from the process of $S \rightarrow WW/ZZ$. The observed (expected) upper limits at the 95% confidence level on the cross-section for $gg \rightarrow X \rightarrow Sh$ is between X fb (133 fb) and Y fb (612 fb).

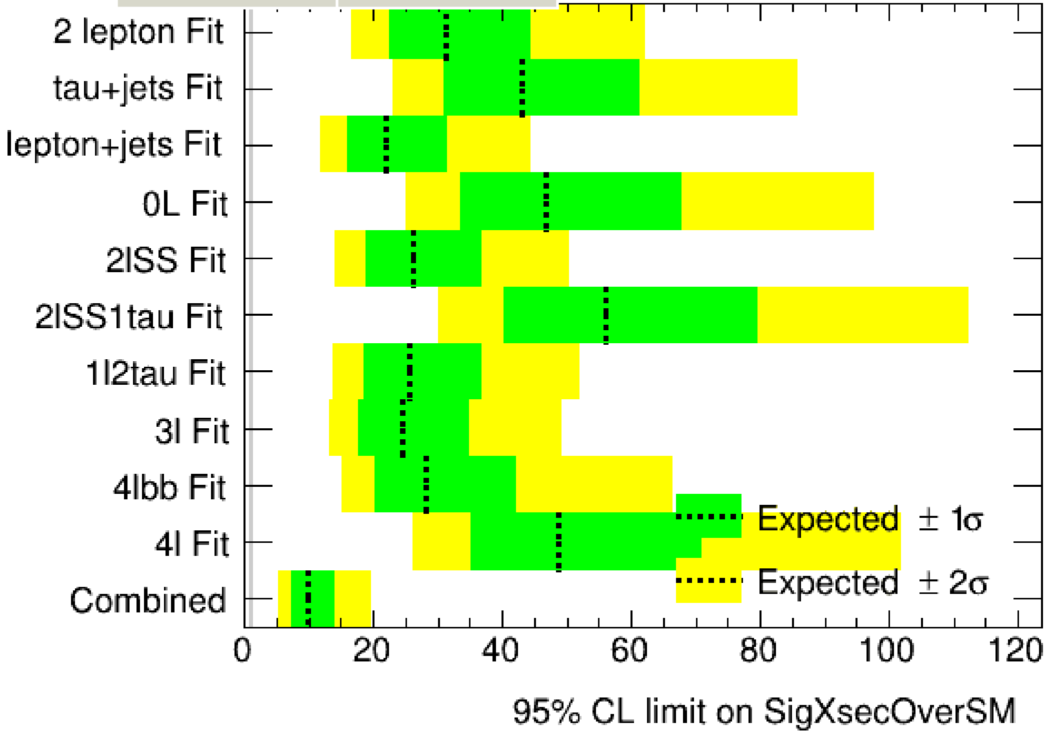
List of contributions

Yaquan Fang	Contact editor, optimisation, supervision of IHEP students
Kaili Zhang	Contact editor, optimization, plots production, signal/background estimation, systematics and limit setting
Zhijun Liang	Analysis Optimization for BDT and supervision of Bo Liu
Bo Liu	Analysis Strategy and editor of the note
Xinchou Lou	Statisics and supervisiion of Shuiting Xin
Qiyu Sha	signal sample preparation
Shuiting Xin	Preparation of Samples
Wei-Ming Yao	the optimiazation of BDT analysis and editor of the note

Dihiggs multilepton:

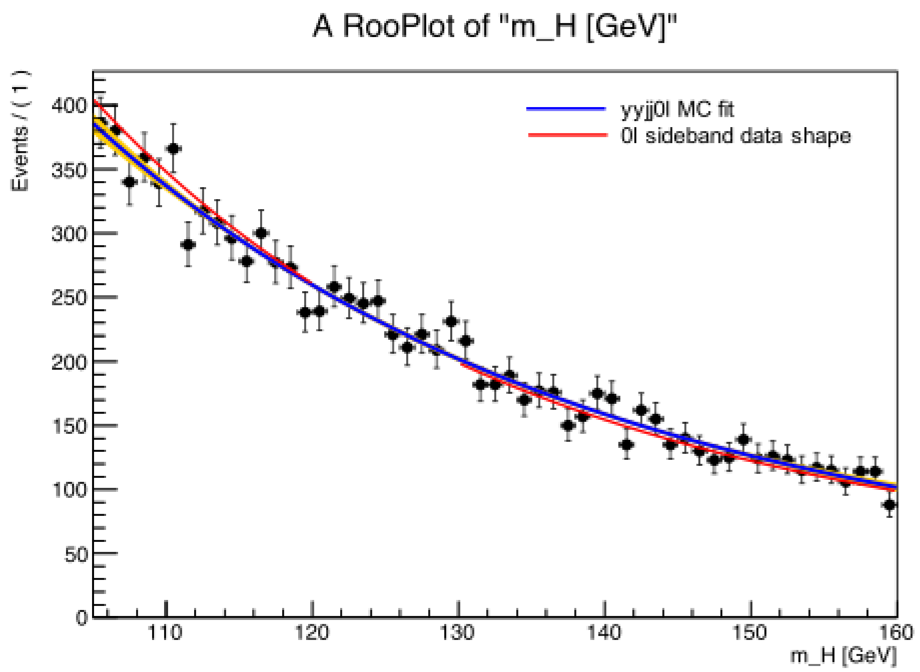
Channels	Upper limit	Channels	Upper limit
Yy+2 lepton	33	3L	25
Yy+Lepton+jets	23	2LSS	26
Yy+Tau+jets	42	1L2tau	26
YY+0L	47	4Lbb	28
Combined	15.69	2LSS1tau	56
		4L	49
		Combined	10.73

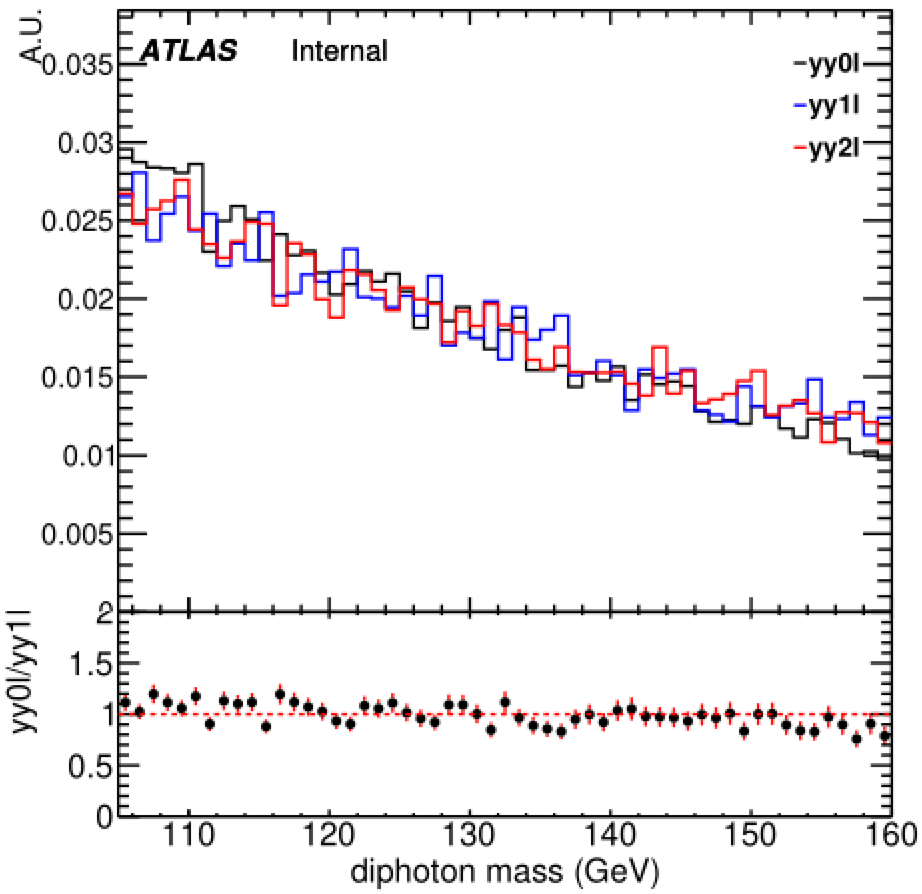




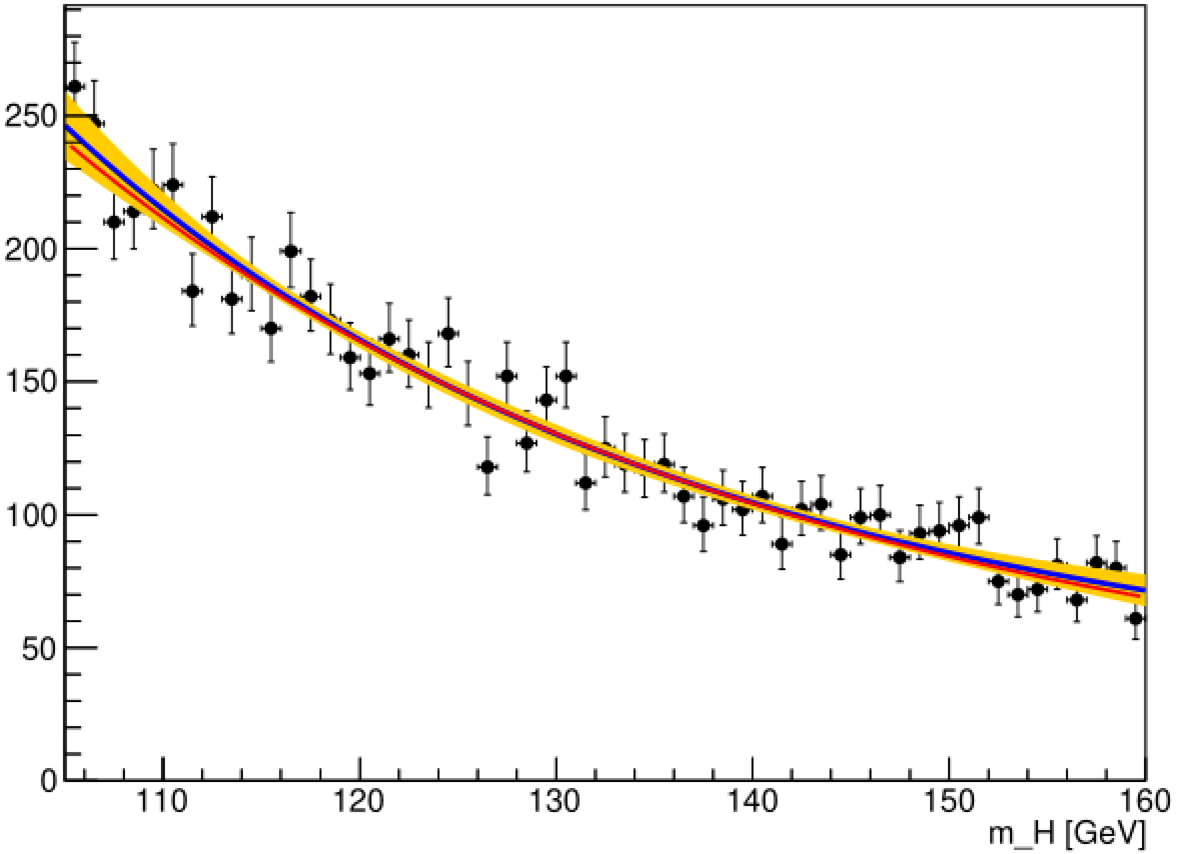
Total multi lepton: 8.40.

Background modelling





2l lepton dependance



the derivation between 0l and 2l:

[105, 160]: 3.29%

[120, 130]: 0.65%