Higgs pair searches with $WW\gamma\gamma \to l\nu qq\gamma\gamma$ (unblinding approval)

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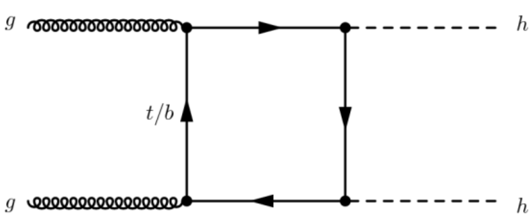
On behalf of the analysis team

Sunday, June 18, 2017

HGamma group meeting

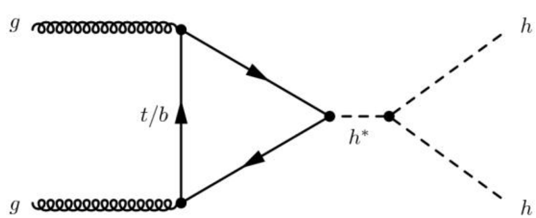
Motivation

- Higgs pair production has a small XS in the SM (~33 fb @ 13 TeV)
- BSM can effectively enhance Higgs pair production.
  - non-resonance: altering tth coupling, Higgs self-coupling.
  - resonance: BSM resonance decay, such as heavy Higgs in the 2HDM.



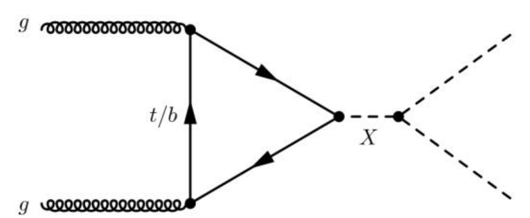
(a)

Non-resonance



(b)

Non-resonance



(c)

resonance

Introduction

- Large BR from $h \rightarrow WW$ and clean signature from $h \rightarrow \gamma\gamma$
- Search for Higgs pair via $WW\gamma\gamma$ with the final state $l\nu qq\gamma\gamma$
  - Explore non-resonance production
  - Explore resonance in low mass region
    - Mass of resonances: 260, 300, 400 and 500 GeV

Background

- Continuum background, dominant one
  - Data sideband
- SM h background
  - tth, Wh, Zh, ggh, VBF
  - Estimated by MC
- SM hh background for resonant searches
  - Estimated by MC

Object definitions

Photons:

PID: Tight; Iso: FixedCutLoose;

$|\boldsymbol{\eta}| \in [\mathbf{0}, \mathbf{1.37}] \cup [\mathbf{1.52}, \mathbf{2.37}]$;

Rel. p_T cut:

$\frac{E_T(\gamma 1)}{m(\gamma\gamma)} \geq \mathbf{0.35}$, $\frac{E_T(\gamma 2)}{m(\gamma 1\gamma 2)} \geq \mathbf{0.25}$

$m(\gamma 1\gamma 2) \in [\mathbf{105}, \mathbf{160}]$ **GeV**

Electrons:

$E_T > \mathbf{10}$ **GeV;**

$|\boldsymbol{\eta}| \in [\mathbf{0}, \mathbf{1.37}] \cup [\mathbf{1.52}, \mathbf{2.47}]$;

$|d_0|$ **significance** $< \mathbf{5}$;

$|z_0| < \mathbf{0.5}$ **mm;**

PID: Medium; Iso: Loose

Jets:

AntiKt4EMTopoJets

$p_T > \mathbf{25}$ **GeV;** $|\boldsymbol{\eta}| < \mathbf{2.5}$;

$JVT < \mathbf{0.59}$ ($p_T < \mathbf{60}$ **GeV** & $|\boldsymbol{\eta}| < \mathbf{2.4}$)

Muons:

$E_T > \mathbf{10}$ **GeV;** $|\boldsymbol{\eta}| \in [\mathbf{0}, \mathbf{2.7}]$;

$|d_0|$ **significance** $< \mathbf{3}$; $|z_0| < \mathbf{0.5}$ **mm;**

PID: Medium; Iso: GradientLoose

Follow HGam recommendations except the central jets

Selections

- Start with diphoton selections used in Hgam
  - Trigger: HLT_g35_loose_g25_loose
- At least one lepton
- At least two central jets, $|\eta| < 2.5$
- B-Veto, B-tagger: MV2c10, WP: 70%
- $p_T(\gamma\gamma) > 100$ GeV for non-res, mh400 and mh500

- [SR] Signal Region (above)
- [CR] Control Region ($N(lep) = 0$)

CUTS
All Events
Duplicate
GRL
Pass Trigger
Detector Quality
Has PV
2 loose photons
Trigger Match
Tight ID
Isolation
Rel.Pt cuts
$105 < m_{\gamma\gamma} < 160$ GeV
At least two central jets
B-veto
At least 1 lepton
$pT_{\gamma\gamma} > 100$ GeV

Cut flow for signal

EFFICIENCY	Non-res (%)	mX260 (%)	mX300 (%)	mX400 (%)	mX500 (%)
All Events	100	100	100	100	100
Duplicate	100	100	100	100	100
GRL	100	100	100	100	100
Pass Trigger	73.76	68.47	69.37	71.76	74.41
Detector Quality	73.76	68.47	69.37	71.76	74.41
Has PV	73.76	68.47	69.37	71.76	74.41
2 loose photons	59.14	56.39	55.80	57.26	59.59
Trigger Match	58.82	56.10	55.51	56.95	59.29
Tight ID	48.71	45.35	44.74	46.89	49.50
Isolation	43.96	38.53	38.59	41.98	44.99
Rel.Pt cuts	40.43	36.13	35.04	38.24	41.76
$105 < \mathrm{m}_{\gamma\gamma} < 160$ GeV	40.27	36.03	34.96	38.09	41.56
At least 1 lepton	17.5	16.55	15.84	17.39	17.90
At least two central jets	11.12	6.50	7.61	10.37	11.96
B-veto	10.47	6.18	7.18	9.77	10.28
$p_T(\gamma\gamma) > 100$ GeV	8.69	-	-	7.90	10.45

Cut flow for SM single Higgs background

EFFICIENCY	ggh (%)	VBF (%)	Wh (%)	Zh (%)	tth (%)
All Events	100	100	100	100	100
Duplicate	100	100	100	100	100
GRL	100	100	100	100	100
Pass Trigger	59.58	61.30	56.63	56.10	72.70
Detector Quality	59.58	61.30	56.63	56.10	72.70
Has PV	59.58	61.30	56.63	56.10	72.70
2 loose photons	49.75	51.16	44.49	45.15	58.31
Trigger Match	49.66	51.03	44.33	45.03	57.89
Tight ID	43.11	44.12	38.05	38.68	48.22
Isolation	38.57	39.85	33.53	34.03	39.78
Rel.Pt cuts	35.80	36.20	30.72	31.09	36.35
$105 < \mathrm{m}_{\gamma\gamma} < 160$ GeV	35.80	36.16	30.50	30.89	35.86
At least 1 lepton	0.0224	0.0394	5.28	2.34	11.0
At least two central jets	0.00421	0.0111	0.537	0.383	10.2
B-veto	0.00375	0.0103	0.511	0.346	1.77
$p_T(\gamma\gamma) > 100$ GeV	0.00196	0.00568	0.274	0.166	1.04

Signal and background yields

$\mathcal{L}$: 36.1 fb-1

Yields	ggh	VBF	Wh	Zh	tth	SM hh
B-veto	0.153	0.032	0.58	0.253	0.743	0.055
$p_T(\gamma\gamma) >$ 100 GeV	0.079	0.018	0.311	0.121	0.437	0.045

The $\sigma(pp \to hh)$ or $\sigma(pp \to X \to hh)$ is assumed as 1 pb.

Yields	Non-res	mX260	mX300	mX400	mX500
B-veto	1.732	0.962	1.120	1.623	1.873
$p_T(\gamma\gamma) >$ 100 GeV	1.357	-	-	1.233	1.633

Optimization

- Optimize based on $\sqrt{2 \times [(S+B) \times ln\left(\frac{S+B}{B}\right) - S]}$ or expected limits.
- No significant improvements on $\Delta R(l, jj)$
- No significant improvements on $m(ljj)$
- $\Delta R_{min}(l, j)$, not promising
- No selections on the $\Delta R(l, jj), m(ljj)$ and $\Delta R_{min}(l, j)$

- Tight ID leptons: no significant improvements, ~3%, choose medium ID leptons
- ≥ 1 lepton or $= 1$ lepton: no significant improvements, choose ≥ 1 lepton

mX500	MediumID leptons	TightID leptons
Limits	6.31	6.12

Limits	mX260	mX500
≥ 1 lepton	12.42	4.22
1 lepton	12.19	4.15

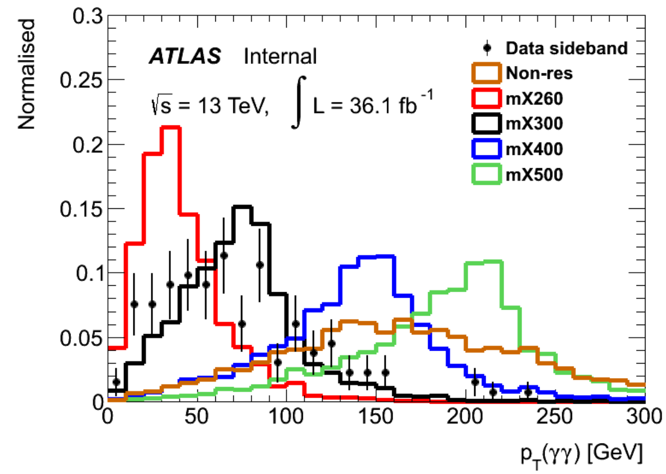
$p_T(\gamma\gamma)$ selection

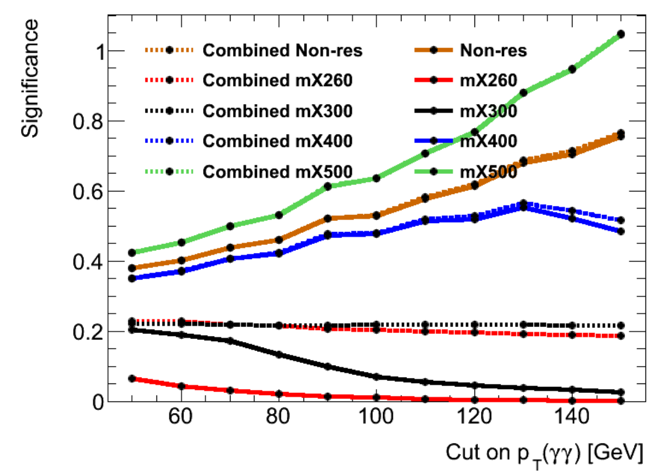
Applying cut on $p_T(\gamma\gamma)$ to mX500

mX500	$p_T(\gamma\gamma) >$ 100 GeV	$p_T(\gamma\gamma) >$ 80 GeV	$p_T(\gamma\gamma) >$ 50 GeV
Limits	4.22	4.64	5.42

With sys, shape fitting
Applying $p_T(\gamma\gamma) > 100$ GeV gives the best limit for mX500

Apply the $p_T(\gamma\gamma)$ cut to mX400, mX500 and non-resonance
No $p_T(\gamma\gamma)$ cut on mX260 and mhX300

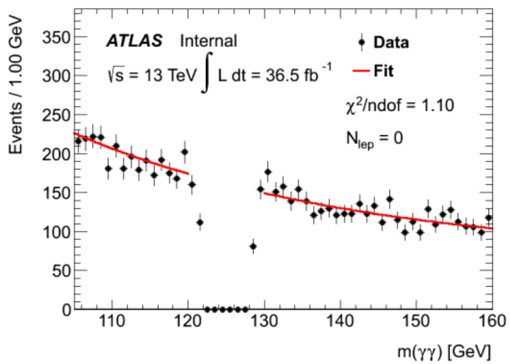


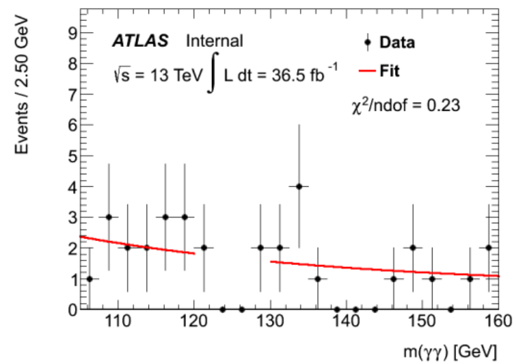


Model of continuum background

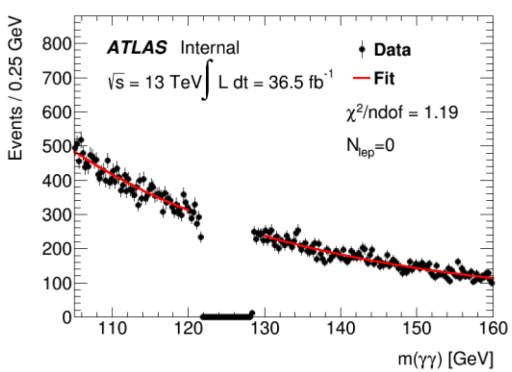
Model: $e^{c_1 m_{\gamma\gamma} + c_2 {m_{\gamma\gamma}}^2}$

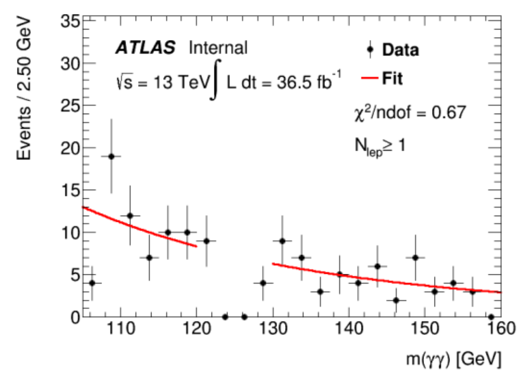
Fit to the high statistical region (0Lep) with c1 and c2 floating to get the c1 and c2. Fit to the 1lep using c1 and c2 obtained. Check the chi2/ndof in both of the regions.





$p_T(\gamma\gamma) > 100$ GeV





No $p_T(\gamma\gamma)$cut

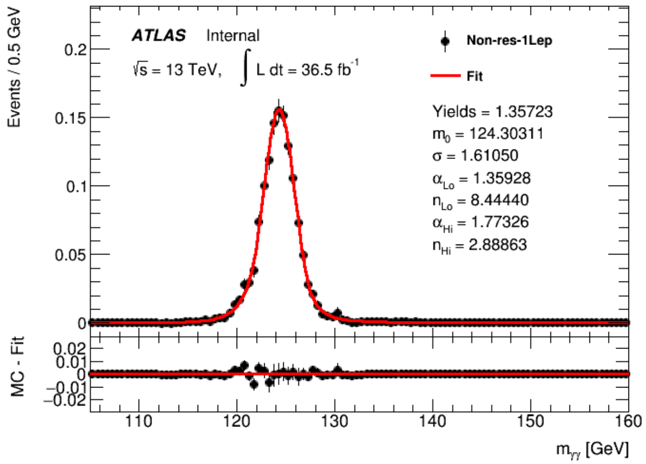
Spurious signal

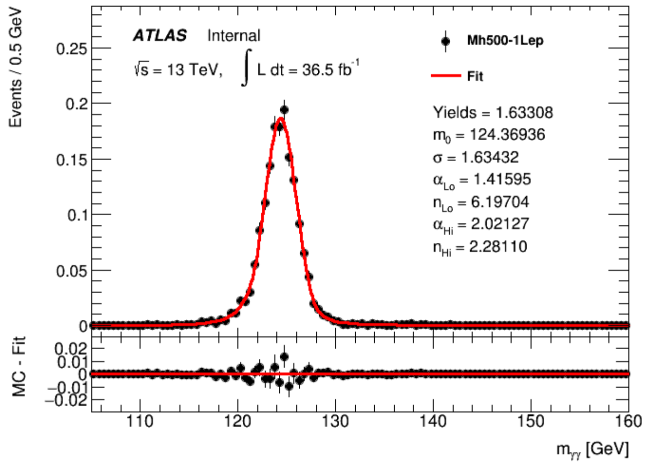
Passing one of the following two criteria:
$Max(N_{ss}/\Delta N_{ss}) < 20\%$
$Max(N_{ss}/N_{S,exp}) < 10\%$
N_{ss}: spurious signal
ΔN_{ss}: error on the spurious signal
$N_{S,exp}$: expected number of signal events

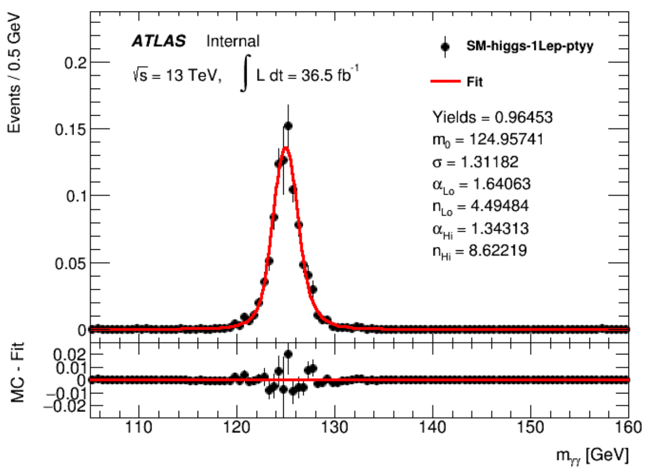
$m_h \in [105, 160]$ GeV
Step: 0.5 GeV
Max are extracted in [120, 130] GeV
Fit to one-lep regions

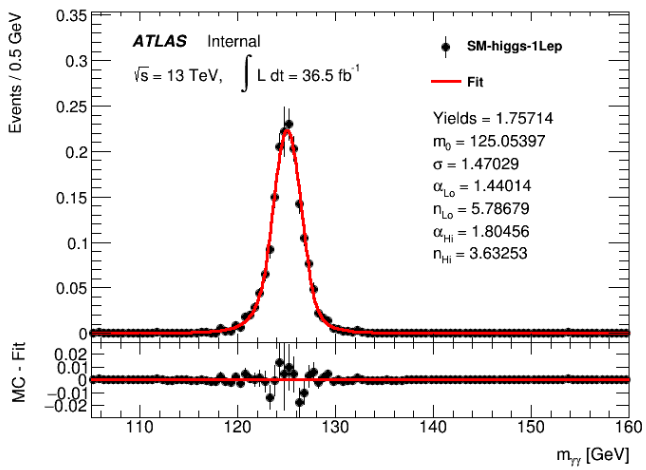
SS	Function	N_{ss}	Max $(N_{ss}/\Delta N_{ss})$	Max $(N_{ss}/N_{S,exp})$	Status
Non-res	ExpPoly2	-0.260	-0.106	-0.322	Pass
mX260	ExpPoly2	-0.439	-0.105	-0.848	Pass
mX300	ExpPoly2	-0.459	-0.109	-0.807	Pass
mX400	ExpPoly2	-0.265	-0.106	-0.343	Pass
mX500	ExpPoly2	-0.260	-0.106	-0.322	Pass

Signals model









Systematics

- **Photons**
  - **5 NPs, scale, resolution, ID, Iso**
- **Jets**
  - **21 NPs + JVT + JER**
- **Flavor tagging**
  - **14 NPs**
- **PU reweighting**
  - **1 NPs**
- **Electrons**
  - **3 NPs, ID, ISO, Reco**
- **Muons**
  - **11 NPs**

Theory

  - **SCALE, PDF, α_S, EFT, BR($h \rightarrow \gamma\gamma$), BR($h \rightarrow WW$) for different processes**
- **Luminosity**
  - **1 NP, 3.2%**
- **Trigger**
  - **1 NP, 0.4%**
- **Spurious signal**
  - **1 NP**
- **W/Zh generator**
  - **2 NPs, caused by that the jets in the Pythia8 is derived from parton shower for W/Zh processes, 22.7%/7.38%**

Fit strategy

Expected limits	Non-res	mX260	mX300	mX400	mX500
Strategy 1	**5.35767**	**13.4825**	**11.4673**	**6.01451**	**4.41402**
Strategy 2	**5.57175**	**14.4944**	**12.2967**	**6.2738**	**4.58404**
Strategy 3	**5.3401**	**13.352**	**11.3597**	**5.97878**	**4.38764**
Strategy 4	**5.35149**	**13.4493**	**11.4445**	**5.99255**	**4.39667**

95% CL upper limits on the $\sigma(pp \to X \to hh)$ or $\sigma(pp \to hh)$

Continuum background model: ExpPoly2, $\exp(c_1 \times m_{\gamma\gamma} + c_2 \times m_{\gamma\gamma}^2)$

Same Spurious Signals

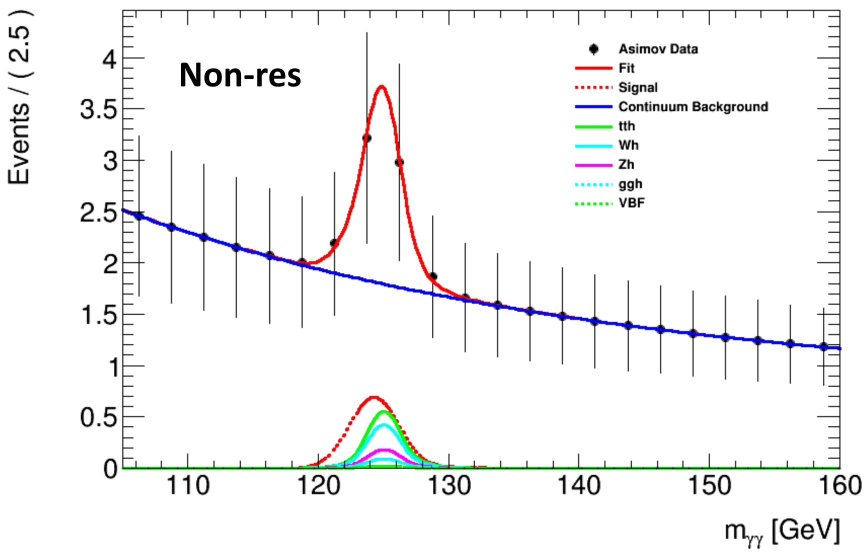
Strategy 1: Fit to 1lep region, the **c1 and c2 are fixed** from 0lep region, **nConBkgSR floating**

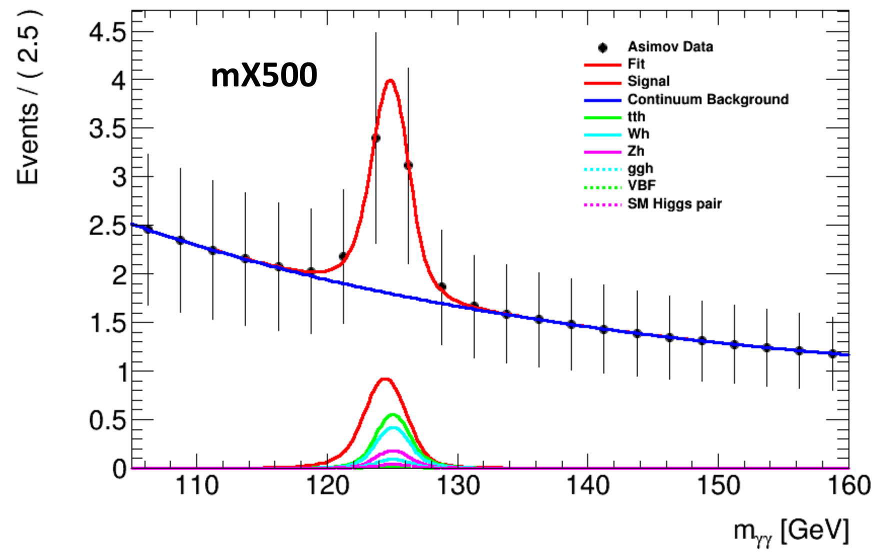
Strategy 2: Fit to 1lep region, the **c1 and c2 are floating, nConBkgSR floating**

Strategy 3: Fit to the 1Lep and 0Lep regions simultaneously with **nConBkgSR (continuum BKG in 1Lep) constrained** by nConBkgCR (continuum BKG in 0Lep), nConBkgSR = Transfer factor * nCongBkgCR. **c1 and c2 floating.**

Strategy 4: Fit to the 1Lep and 0Lep regions simultaneously with **floating nConBkgSR and nConBkgCR**. **c1 and c2 floating.**

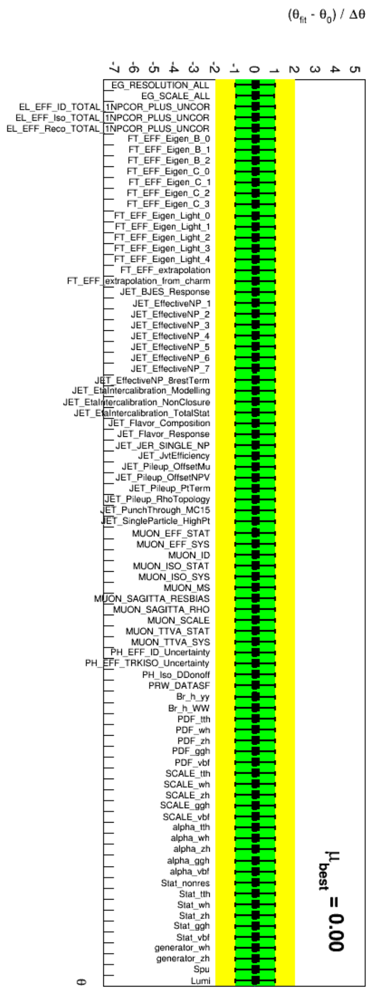
Final fits

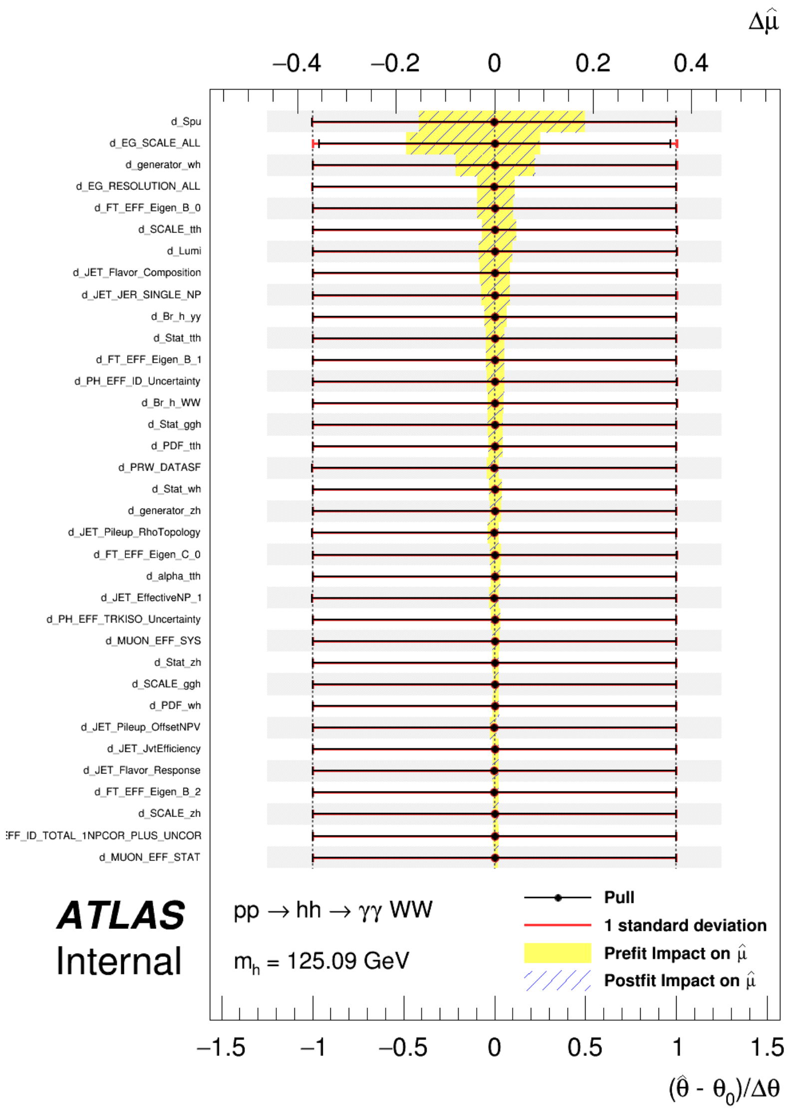




- Plots show the fits **with $\boldsymbol{\mu = 1}$**.
- The **yields and shapes are fixed** for **signal, SM single Higgs processes, SM Higgs pair (for resonance searches).**
- The $\boldsymbol{c_1, c_2}$ and the **normalization** in model of **continuum background** are **floating**.

NPs pulls and ranking





NPs pull look OK

The top five NPs in the ranking plot: spurious signal, EG_SCALE_ALL generator_wh, EG_RESOLUTION_ALL, FT_EFF_Eigen_B_0

Limits setting

Expected Limits	Non-res	mX260	mX300	mX400	mX500
Median	5.6	14.5	12.3	6.3	4.6

- 95% CL upper limits. Limits on $pp \to X \to hh$ / $pp \to hh$. Unit is pb. All of systematic/statistic/spurious signals have been included.

- Continuum background model: ExpPoly2; SM h background models: DSCB; SM hh background (for resonance) model: DSCB; Signal models: DSCB

Summary

- Ready to unblinding
- Almost all the materials are done
- Supporting note: ATL-COM-PHYS-2016-1406
- The theoretical uncertainties on the acceptance are missed
- New samples for SM single Higgs processes

Backup

Di-photon purity

MC Samples

DSID	Process	Generator	Tags
341069	tth	Pythia8EvtGen A14NNPDF23LO	e3796_s2608_s2183_r6765_r6282_p2421/
341000	ggh	PowhegPythia8 EvtGen AZNLOCTEQ6L1	e3806_s2608_s2183_r6765_r6282_p2421/
341001	VBF	PowhegPythia8 EvtGen AZNLOCTEQ6L1	e3806_s2608_s2183_r6765_r6282_p2421/
341067	Wh	Pythia8EvtGen A14NNPDF23LO	e3796_s2608_s2183_r6765_r6282_p2421/
341068	Zh	Pythia8EvtGen A14NNPDF23LO	e3796_s2608_s2183_r6765_r6282_p2421/

New MC samples

DSID	Process	Generator	$\sigma \times$BR [fb]
343981	ggh	PowHEG NNLOPS	110.1
345041	VBF	PowHEG MINLO	8.578
345317	Wmh	PowHEG MINLO	1.902
345318	Wph	PowHEG MINLO	1.206
345319	qqZh	PowHEG MINLO	1.725
345061	ggZh	PowHEG MINLO	0.2782
343436	tth	MADGRAPH AMC@NLO	1.150

New samples for SM single Higgs

EFFICIENCY (%)	ggh	VBF	Wmh	Wph	qqZh	ggZh	tth
All Events	100	100	100	100	100	100	100
Duplicate	100	100	100	100	100	100	100
GRL	100	100	100	100	100	100	100
Pass Trigger	59.91	61.0	60.4	55.6	57.1	67.7	73.5
Detector Quality	59.91	61.0	60.4	55.6	57.1	67.7	73.5
Has PV	59.91	61.0	60.4	55.6	57.1	67.7	73.5
2 loose photons	49.92	51.0	48.2	43.3	46.1	56.4	59.2
Trigger Match	49.82	50.8	48.0	43.2	46.0	56.2	58.7
Tight ID	43.30	43.9	41.2	37.0	39.5	48.3	48.7
Isolation	38.66	39.7	36.2	32.6	34.8	43.4	40.3
Rel.Pt cuts	35.90	36.1	33.2	30.0	31.8	39.5	36.8
$105 < m_{\gamma\gamma} <$ 160 GeV	35.89	36.0	33.0	29.8	31.6	39.3	36.3
At least 1 lepton	0.0262	0.0348	5.66	5.25	2.31	3.10	11.4
At least two central jets	0.00454	0.00822	0.811	0.734	0.432	0.946	10.6
B-veto	0.00388	0.00727	0.768	0.702	0.391	0.866	1.97
$p_T(\gamma\gamma) > 100$ GeV	0.000873	0.00404	0.370	0.380	0.187	0.652	1.10

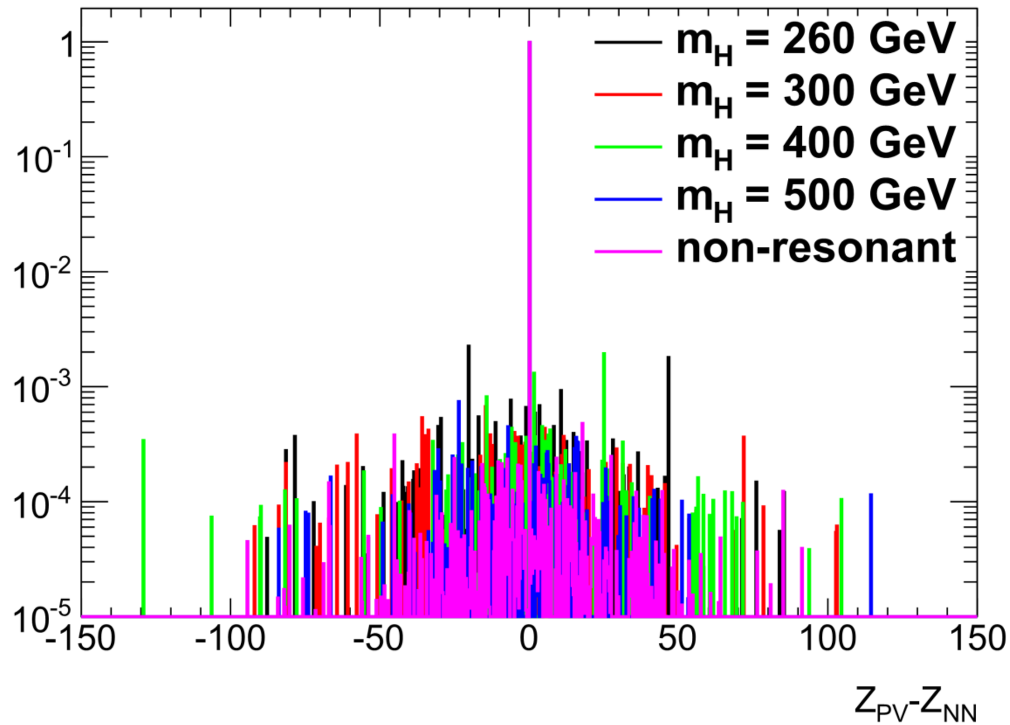
Yields for SM single Higgs

Yields	**ggh**	**VBF**	**Wmh**	**Wph**	**qqZh**	**ggZh**	**tth**
B-veto	**0.154**	**0.0225**	**0.527**	**0.306**	**0.243**	**0.0870**	**0.818**
	0.154	**0.0225**	**0.833**		**0.330**		**0.818**
$\mathbf{p_T(\gamma\gamma) >}$ **100 GeV**	**0.0347**	**0.0125**	**0.254**	**0.165**	**0.116**	**0.0654**	**0.456**
	0.0347	**0.0125**	**0.419**		**0.181**		**0.456**

Yields	ggh	VBF	Wh	Zh	tth
B-veto	0.153	0.032	0.58	0.253	0.743
$p_T(\gamma\gamma) >$ 100 GeV	0.079	0.018	0.311	0.121	0.437

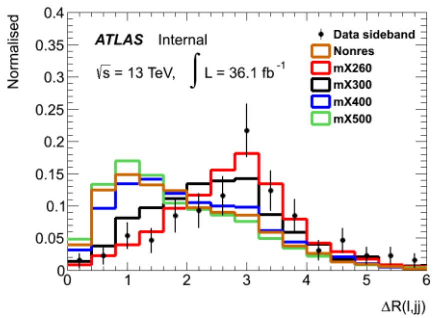
Wh: 43.6%   Zh: 30.4%

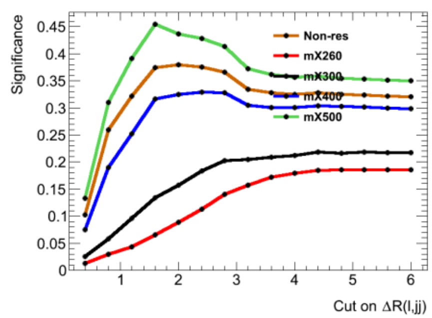
Hardest vertex vs NN vertex

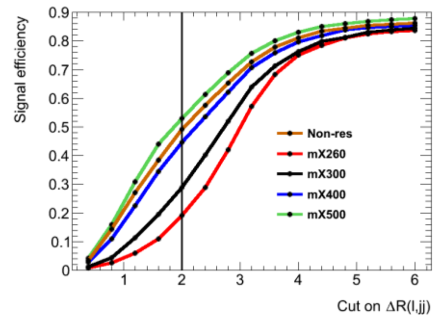


If requiring $|Z_{PV} - Z_{NN}| < 0.3$ mm, the efficiency is 97.7%, 98.4%, 98.3%, 98.8%, 99.0% for mX260, mX300, mX400, mX500 and non-resonance.

Optimization

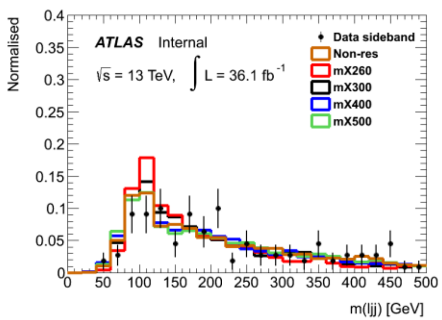


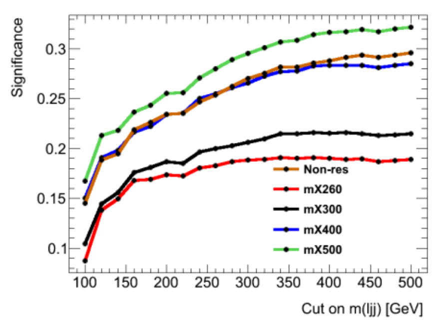


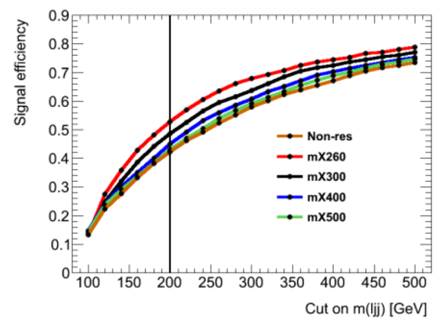


No significant improvements by applying cut on $\boldsymbol{\Delta R(l, jj)}$,

No cut

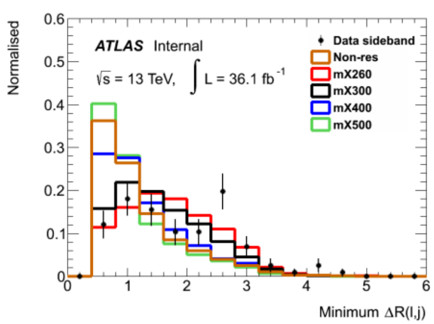






No significant improvements by applying cut on $\boldsymbol{m(ljj)}$,

No cut



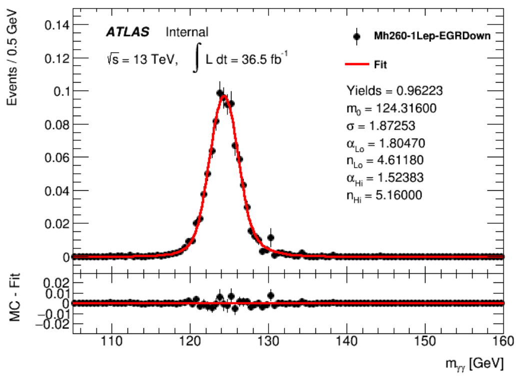
Not promising variable.

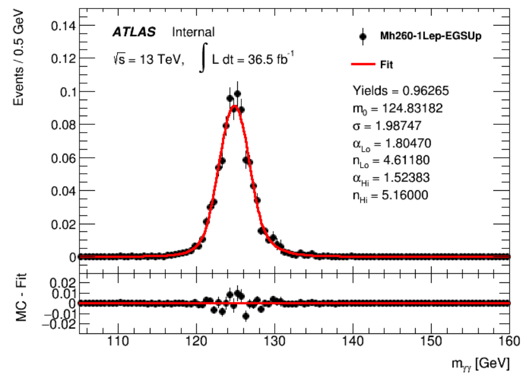
B-tagger, WP

WP	ggh	VBF	Wh	Zh	tth	Continuum bkg	SM Higgs bkg	Non-res signal	significance
60%	0	0.0010	0.042	0.016	0.093	1.60	0.152	0.128	0.09556 σ
70%	0	0.0010	0.042	0.012	0.067	1.60	0.12	0.127	0.09568 σ
77%	0	0.0010	0.042	0.012	0.050	1.60	0.10	0.126	0.09548 σ
85%	0	0.00099	0.039	0.012	0.035	1.60	0.087	0.10	0.07625 σ

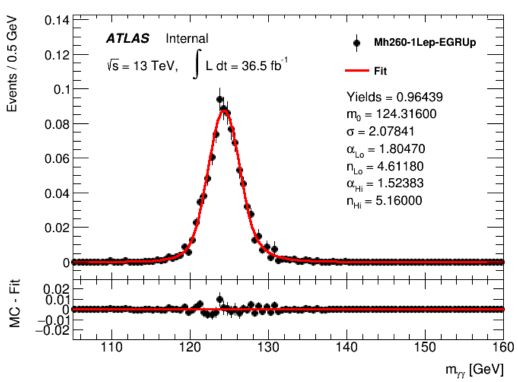
B-tagger: MV2c10
Jets: $|y| < 2.5$
With luminosity (3.2 fb-1) from 2015 data
Non-resonant signal used as a benchmark
Choose 70%

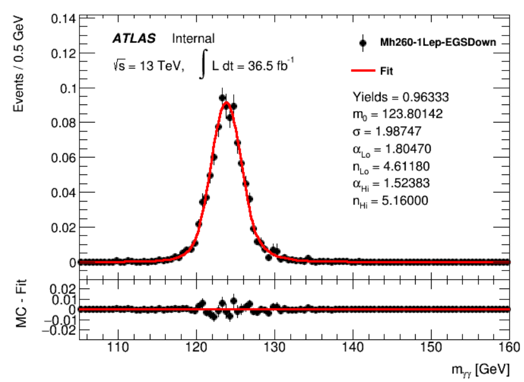
Systematic on μ and σ





Fixed the shape parameters except σ and yields when fitting to extract the systematic on σ





Fixed the shape parameters and yields except m_0 when fitting to extract the systematic on m_0

W/Zh uncertainty on generator

- MadGraph
- N_0jet: 12313./20040. = 6.14e-01
- N_1jet: 5773./20040. = 2.88e-01
- N_2jets: 1954./20040. = 9.75e-02

- Pythia8 (Required the number of lepton >=2)
- n_0jet: 0.655
- n_1jet: 0.254
- n_2jet: 0.0908 (>=2 jets)

- Error (k_Generator_zh)
  = |0.0908 – 0.0975|/ 0.0908

= 7.38%

- MadGraph
- N_0jet: 27870./44882. = 6.21e-01
- N_1jet: 12723./44882. = 2.83e-01
- N_2jets: 4289./44882. = 9.56e-02

- Pythia8 (Required the number of lepton >=1)
- n_0jet: 0.675
- n_1jet: 0.247
- n_2jet: 0.0779(>=2 jets)

- Error (k_Generator_wh)
- = |0.0779 - 0. 0956|/ 0.0779

= 22.7%