$hh \to \gamma\gamma WW$

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On behalf of the analysis team
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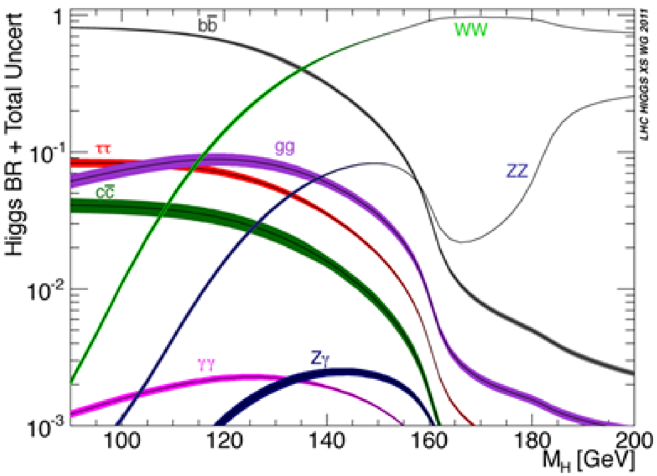
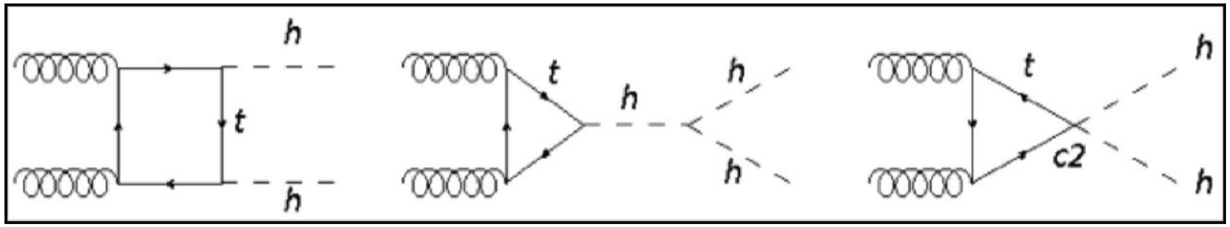
HGam micro-workshop

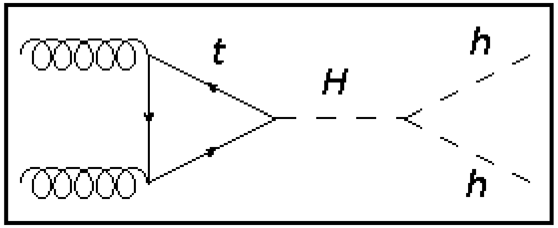
Introduction

- Higgs pair production has a small XS in SM (~33 fb @ 13 TeV)
- BSM can effectively enhance Higgs pair production.
  - non-resonance: altered Higgs self-coupling, tth coupling, tthh coupling.
  - resonance: BSM resonance decay, such as heavy Higgs and Kaluza-Klein graviton.
- [not hh search] New theoretical model:
  - arXiv:1606.01674.
  - $H \rightarrow Sh$, H (not SM Higgs) is a heavy scalar with $250 \leq m_H \leq 350$ GeV, S is a Higgs-like scalar with $125 \leq m_S \leq 225$ GeV.





(a)



(b)

Quick look

- hh (no Sh) analyses will be presented
- Three separate analyses in $\gamma\gamma WW$
  - Semi-leptonic, resolved handronic and boosted handronic ones
- All of them share the same selections at photon side as HGam
- Low mass region for resolved analyses, 260 – 500 GeV
- 260 GeV – 3 TeV for boosted analysis
- Assuming $\sigma(gg \rightarrow hh/gg \rightarrow X \rightarrow hh) = 1$ pb

Semi-leptonic - selections

Photons:

PID: Tight; Iso: FixedCutLoose;

$|\eta| \in [0,1.37] \cap [1.52, 2.37]$;

Rel. p_T cut:

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

$m(\gamma 1 \gamma 2) \in [105, 160]$ GeV

Jets:

AntiKt4EMTopoJets

$p_T > 25$ GeV; $|\eta| < 2.5$;

$JVT < 0.59$ ($p_T < 60$ GeV & $|\eta| < 2.4$)

Electrons:

$p_T > 10$ GeV;

$|\eta| \in [0,1.37] \cap [1.52, 2.47]$;

$|d_0|$ significance < 5; $|z_0| < 0.5$ mm;

PID: Medium; Iso: Loose

Muons:

$p_T > 10$ GeV; $|\eta| \in [0, 2.7]$;

$|d_0|$ significance < 3; $|z_0| < 0.5$ mm;

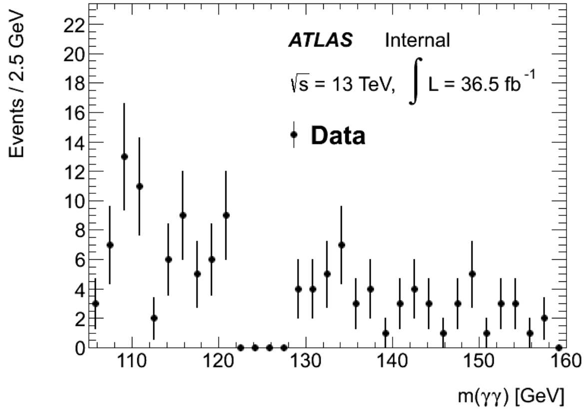
PID: Medium; Iso: GradientLoose

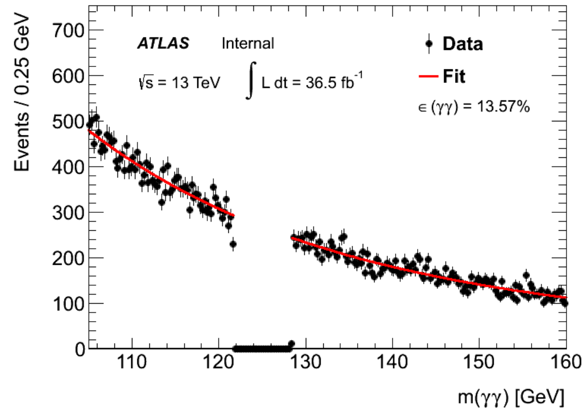
two central jets ($|\eta| < 2.5$)
B-veto (MV2c10, 70%)
Tight mass window $|m_{\gamma\gamma} - 125.09| < 2 \times 1.7\ (\sigma_{m_{\gamma\gamma}})$ GeV

Event Selection
Full $h \to \gamma\gamma$ selections
At least two central jets
At least one lepton
B-veto
Tight mass Window

BKG study 1.

- Two types of background: continuum background, SM Higgs background - VBF, ggH, WH, ZH, ttH.
  - Estimate the SM single Higgs background by MC (see next slide);
  - Using data-driven method to estimate the continuum background.
  - Now, using the method $N_{continuum}^{bkg} = N_{sb}^{continuum} \times \frac{\epsilon_{\gamma\gamma}}{1-\epsilon_{\gamma\gamma}}$
  - $N_{continuum}^{bkg} = 20.1$ events
  - Model for continuum BKG: exp2



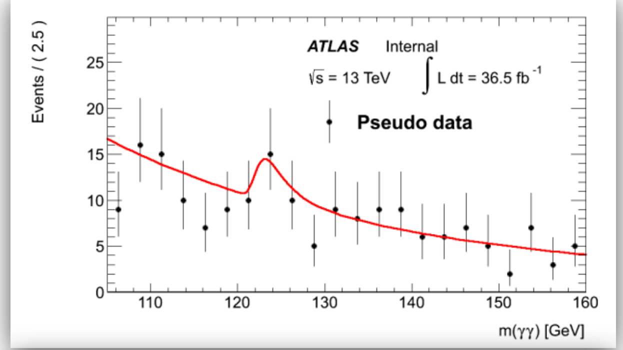


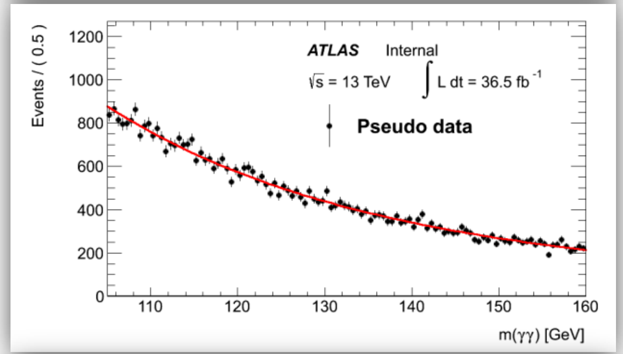
BKG study 2.

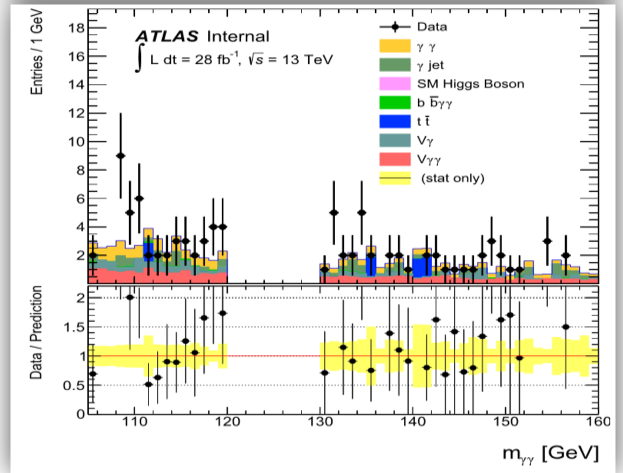
- Estimate the continuum background.
  - Fit the SB region.

- Continuum background decomposition
- Investigate the components in the continuum BKG

- Background modeling
  - Xifeng/Abdualazem have the primary result on the comtinuum background model: Exp
  - High statistics samples is running: [production]







Cutflow and Yields

	SM	Resonant			
	Higgs pair	260 GeV	300 GeV	400 GeV	500 GeV
All Events	100.0%	100.0%	100.0%	100.0%	100.0%
Duplicate	100.0%	100.0%	100.0%	100.0%	100.0%
GRL	100.0%	100.0%	100.0%	100.0%	100.0%
Pass Trigger	73.8%	68.4%	69.4%	71.8%	74.5%
Detector Quality	73.8%	68.4%	69.4%	71.8%	74.5%
has PV	73.8%	68.4%	69.4%	71.8%	74.5%
2 loose photons	59.3%	56.6%	56.1%	57.5%	59.7%
Trig Match	59.0%	56.3%	55.8%	57.2%	59.4%
Tight ID	49.3%	46.2%	45.5%	47.5%	50.2%
Isolation	44.6%	39.3%	39.3%	42.6%	45.7%
Rel.Pt cuts	41.0%	36.6%	35.6%	38.8%	42.4%
$105 < m_{\gamma\gamma} < 160$ GeV	40.9%	36.6%	35.6%	38.6%	42.2%
At least 2 central jets	29.7%	17.7%	20.1%	26.5%	32.1%
B-veto	27.8%	16.7%	19.0%	25.0%	30.2%
At least 1 lepton	11.1%	6.56%	7.60%	10.4%	12.0%
Tight mass window	9.62%	5.54%	6.48%	8.91%	10.5%

Table 5: Efficiencies for event selection

	ggh	VBF	Wh	Zh	tth
All Events	100.0%	100.0%	100.0%	100.0%	100.0%
Duplicate	100.0%	100.0%	100.0%	100.0%	100.0%
GRL	100.0%	100.0%	100.0%	100.0%	100.0%
Pass Trigger	59.6%	61.3%	56.5 %	56.0%	72.8%
Detector Quality	59.6%	61.3%	56.5 %	56.0%	72.8%
has PV	59.6%	61.3%	56.5 %	56.0%	72.8%
2 loose photons	49.8%	51.2%	44.5 %	45.2%	58.3%
Trig Match	49.7%	51.1%	44.4 %	45.1%	57.9%
Tight ID	43.4%	43.4%	38.2 %	38.9%	48.3%
Isolation	39.0%	40.2%	33.9 %	34.4%	40.0%
Rel.Pt cuts	36.1%	36.5%	31.0 %	31.4%	36.5%
$105 < m_{\gamma\gamma} < 160$ GeV	36.1%	36.4%	30.8 %	31.2%	36.0%
At least 2 central jets	5.51%	10.2%	14.9 %	15.8%	35.4%
B-veto	5.23%	9.65%	14.2 %	12.9%	6.18%
At least 1 lepton	0.00365%	0.0109%	0.533%	0.354%	1.89%
Tight mass window	0.00342%	0.00996%	0.488%	0.326%	1.76%

Table 8: Cut efficiencies and the yields for SM single Higgs processes.

	Non-res	mh260	mh300	mh400	mh500
Yields	1.50193	0.863991	1.0111	1.39069	1.64497
Stat. error	1.58%	2.06%	1.94%	1.58%	1.50%

	ggh	VBF	Wh	Zh	tth
Cross sections	48.52 pb	3.779 pb	1.369 pb	0.8824 pb	0.5065 pb
Yields	0.137	0.0312	0.554	0.238	0.737
Stat. error	16.4%	11.8%	3.27%	4.03%	3.83%

Uncertainty 1.

- The uncertainties on $\epsilon_{\gamma\gamma}$
  - From lepton multiplicity: 7.4%
  - From fitting functions: 3.8%
  - From sideband definition: 1.2%
  - Statistics on $\epsilon_{\gamma\gamma}$:1.3%
  - These uncertainties are separate NPs in the fit
- Luminosity error, 4.1%
- Theory
  - $+2.1/2.0\%$ on branching ratio of $h \to \gamma\gamma$ and $\pm$1.5% on $h \to WW$
  - Scale and PDF uncertainties, shown as tables below
  - Special 37.5% assigned to Wh for high jet multiplicity: comparing Pythia8 (parton shower jets) and MadGraph5 (matrix element jets) both with 2 jets inclusively

Processes	+QCD Scale %	-QCD Scale %	$\pm PDF$ %	$\pm\alpha_s$ %
ggh	+7.6	-8.1	± 1.8	± 2.5
VBF	+0.4	-0.3	± 2.1	± 0.5
Wh	+0.5	-0.7	± 1.7	± 0.9
Zh	+3.8	-3.0	± 1.3	± 0.9
tth	+5.8	-9.2	± 3.0	± 2.0

$\sqrt{s}$	$\sigma^{NNLO}_{gg\to hh}$	Scale	$\pm PDF$ %	$\pm\alpha_s$ %	EFT
13 TeV	33.41 fb	+4.3% -6.0%	±2.1%	±2.3%	±5%

Uncertainty 2.

Uncertainty source	Non-resonance	260 GeV	300 GeV	400 GeV	500GeV
Flavor tag (B) up	0.0652643	0.0904023	0.0761297	0.0705571	0.0574528
Flavor tag (B) down	0.0649996	0.090262	0.0755365	0.0693433	0.0574361
Flavor tag (C) up	0.466672	0.370083	0.388483	0.444137	0.474355
Flavor tag (C) down	0.46621	0.36991	0.388202	0.443792	0.473872
Flavor tag (LF) up	0.423651	0.383721	0.387303	0.409522	0.424429
Flavor tag (LF) down	0.422317	0.382755	0.386278	0.408314	0.423071
Flavor tag extrapolation up	0.00656646	0.00059068	0.00236489	0.00263544	0.00618478
Flavor tag extrapolation down	0.00653167	0.00059068	0.00236489	0.00263544	0.00618285
Pileup up	0.602061	0.137751	0.326689	0.283782	0.784207
Pileup down	0.690805	0.131408	0.803411	0.584859	0.48294
Photon up	4.34615	4.3673	4.40552	4.36301	4.34279
Photon down	4.26054	4.28156	4.31821	4.277	4.25707
Photon DD iso	0.002471	0.069094	0.0784048	0.038779	0.01602
Electron up	0.727712	0.917893	0.820141	0.738539	0.705519
Electron down	0.727712	0.917894	0.820141	0.73854	0.705519
Egamma up	2.91813	2.45743	2.58773	3.77454	2.58835
Egamma down	6.44647	5.24885	4.76768	6.21708	6.80345
Muon up	0.335954	0.48756	0.452178	0.368351	0.322988
Muon down	0.342851	0.490697	0.437081	0.367525	0.32338
JES up	4.70427	10.3741	8.08233	5.37499	3.59676
JES down	5.02407	9.81781	8.60419	5.65716	3.20561
JER	0.529567	1.97208	0.513078	0.117719	0.335593

Table 13: Experimental uncertainties on the yields in percentage for signal processes.

Uncertainty source	ggh	VBF	Wh	Zh	tth
Flavor tag (B) up	1.7477	1.05173	0.076221	0.387356	10.8571
Flavor tag (B) down	1.7477	1.05173	0.076221	0.385952	10.3946
Flavor tag (C) up	0.0231321	0.686565	0.218194	0.26209	0.481908
Flavor tag (C) down	0.0231322	0.686565	0.21787	0.261445	0.481354
Flavor tag (LF) up	0.414021	0.298243	0.380875	0.364568	0.413886
Flavor tag (LF) down	0.412888	0.29776	0.379982	0.363716	0.412388
Flavor tag extrapolation up	0	0	0.0603771	0.0866926	1.59562
Flavor tag extrapolation down	0	0	0.0601764	0.0867075	1.64182
Pileup up	5.0992	38.2552	0.128699	0.745892	1.9167
Pileup down	6.78148	18.323	0.882775	0.458142	1.73819
Photon up	4.40429	4.29194	4.49407	4.44554	4.39139
Photon down	4.31908	4.21007	4.40336	4.35658	4.30434
Photon DD iso	0	0	0.0695713	0	0
Electron up	0.174202	0.952881	0.709423	0.665133	0.731751
Electron down	0.174202	0.952882	0.709423	0.665133	0.73175
Egamma up	0	8.53131	1.2231	2.87406	1.32318
Egamma down	3.02288	0	1.89043	2.92565	1.35423
Muon up	1.31887	1.20892	0.631627	0.354505	0.334106
Muon down	1.3189	11.4129	0.549676	0.360991	0.370137
JES up	19.9013	0.095948	12.7688	11.5186	1.43675
JES down	11.5946	0.141453	9.72263	7.60885	2.72174
JER	4.31494	23.015	7.23356	2.88096	2.96028

Table 14: Experimental uncertainties on the yields in percentage for background processes.

Sensitivity 1.

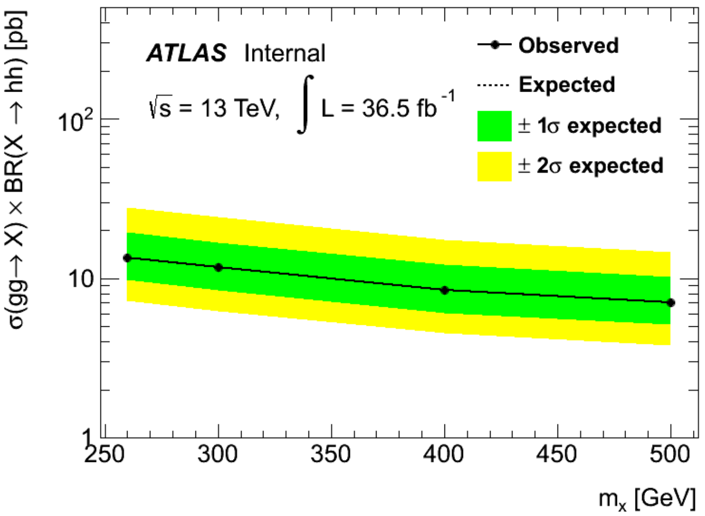
	Non-res	mh260	mh300	mh400	mh500
$+2\sigma$	16.071	27.9317	24.305	17.4098	14.5864
$+1\sigma$	11.2084	19.4905	16.8559	12.1447	10.1997
-1σ	5.60365	9.74654	8.39283	6.06772	5.10635
-2σ	4.17403	7.25999	6.25163	4.51971	3.80361
Median	7.77684	13.5264	11.6477	8.4209	7.08669
Observed	7.77491	13.5237	11.6423	8.41989	7.08776

isBlind

Sys are at 22.1 fb^{-1}

WS: HistFactory

Limits: Asymptotic

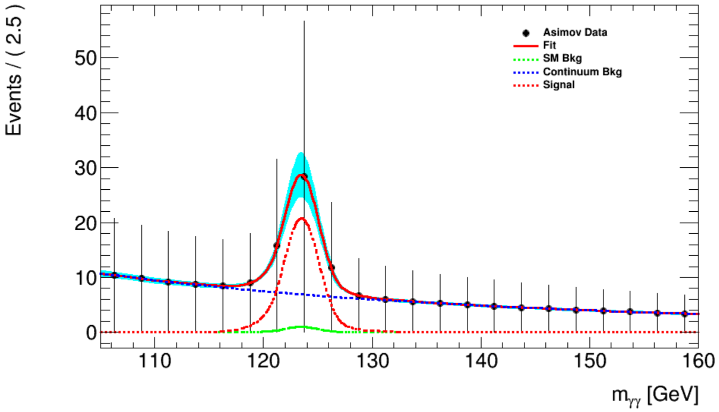


Sensitivity 2.

	Non-res	mh260	mh300	mh400	mh500
$+2\sigma$	15.4164	26.77	22.8867	16.6449	14.1244
$+1\sigma$	10.8897	18.9095	16.1665	11.7574	9.97701
-1σ	5.50492	9.55762	8.17156	5.94347	5.04366
-2σ	4.10049	7.11926	6.08682	4.42716	3.75691
Median	7.63983	13.2642	11.3406	8.24845	6.99968
Observed	7.6413	13.2688	11.344	8.25021	7.00089

isBlind
Only one sys: Photon energy resolution 5% for test
WS: created by private code, shape fitting
Limits: Asymptotic,
Limits are consistent with HistFactory, a bit more sensitive.

Signal model: DSCB
Continuum BKG model: exp2
SM higgs BKG: DSCB

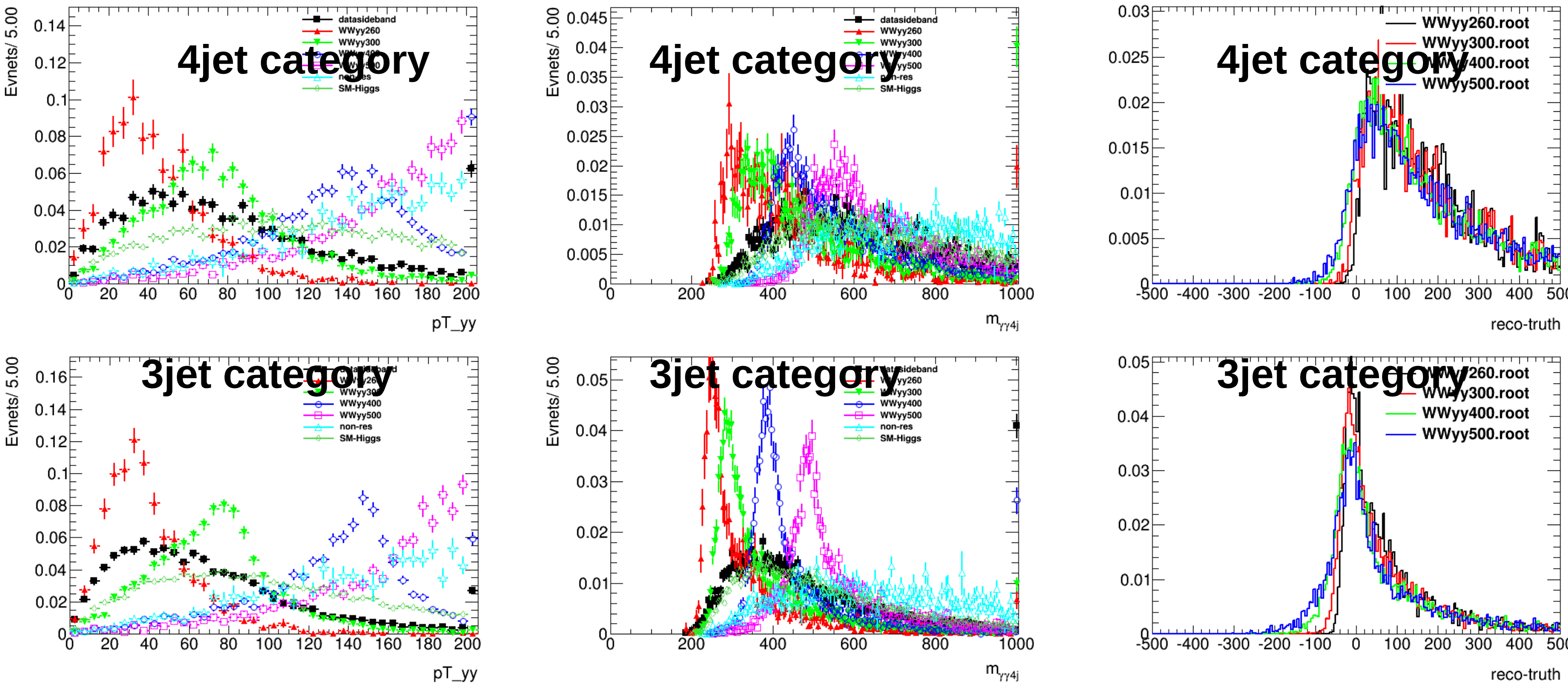


Resolved hadronic - Analysis Strategy

- Basic Selection
  - diphoton as HGam, NO LEP, b-veto (70% WP), >=3 central jets (|eta|<2.5)
  - ==3 jet category and >=4 jet category since truth signal jet has low pT
- Selection Optimization
  - define mass window of diphoton + multi-jet for resonant search
  - use one variable $pT(\gamma\gamma)$ to do optimization
  - scan the cut and fit the data sideband with Exponential to obtain continuum background, count the signal and SM Higgs yield from MC
  - calculate the significance : $\sqrt{2((N_{bsm} + N_{smHiggs} + N_{cont})ln(1 + \frac{N_{bsm}}{N_{smHiggs}+N_{cont}}) - N_{bsm}))}$
- Signal and Background Modeling
  - Signal modeling
    - signal samples : non-resonant and resonant (260 - 500 GeV)
    - shape modeling : Double-Sided Crystal Ball VS. Crystal Ball + Gauss
  - Background modeling
    - data sideband to do further optimization
    - large statistic yy+0,1,2,3 jet for spurious signal study (To do)
    - background decomposition (To do)
- Systematic (To do), especially ggH theoretical uncertainty

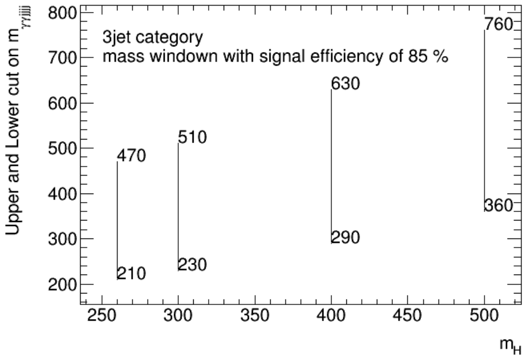
Kinematics

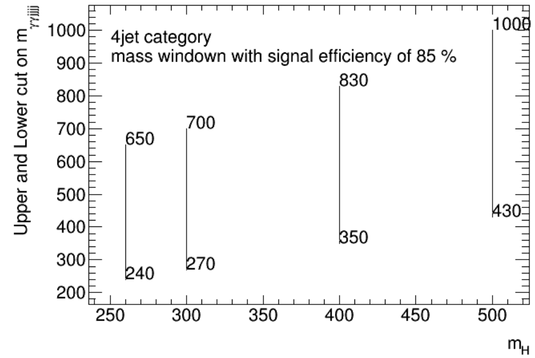
- $pT(\gamma\gamma)$, mass, mass resolution (Reco - truth)

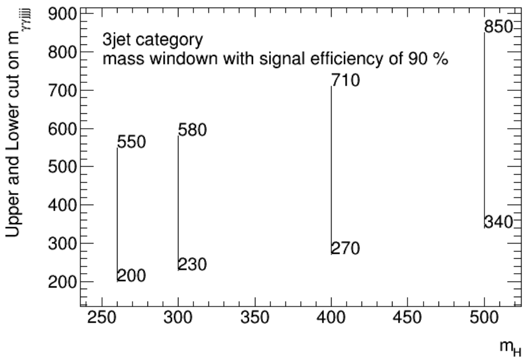


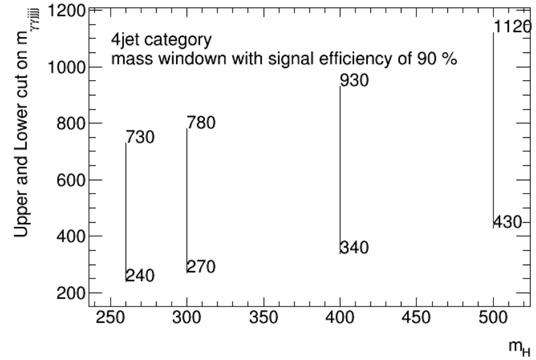
- $pT(\gamma\gamma)$ have good separation power -- mass dependent
- 3jet category has better mass resolution

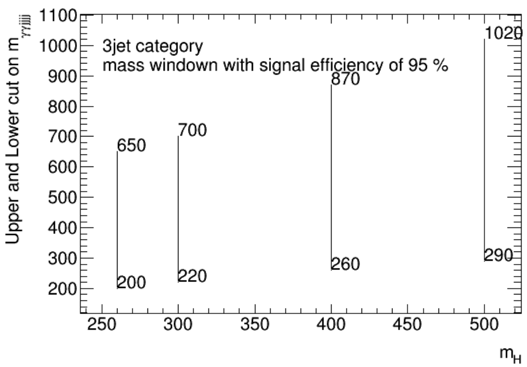
Mass window

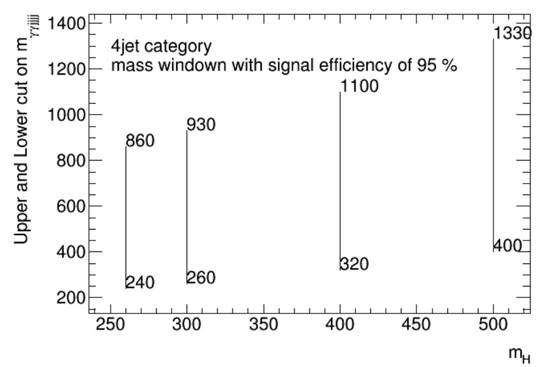








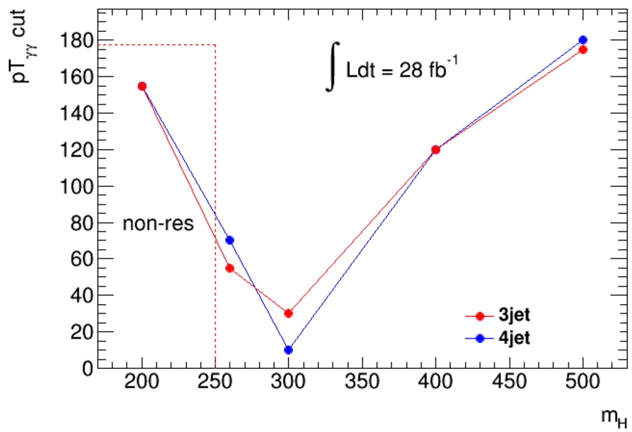


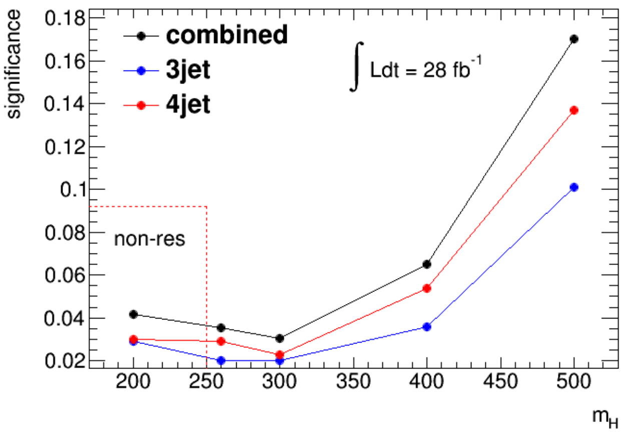


- Define a mass window which contains 85%, 90% or 95% signal events
- To decrease the width of mass window, use signal efficiency of 85% to define the mass window
- Currently the resolution is not very good

Summary of significance and cut

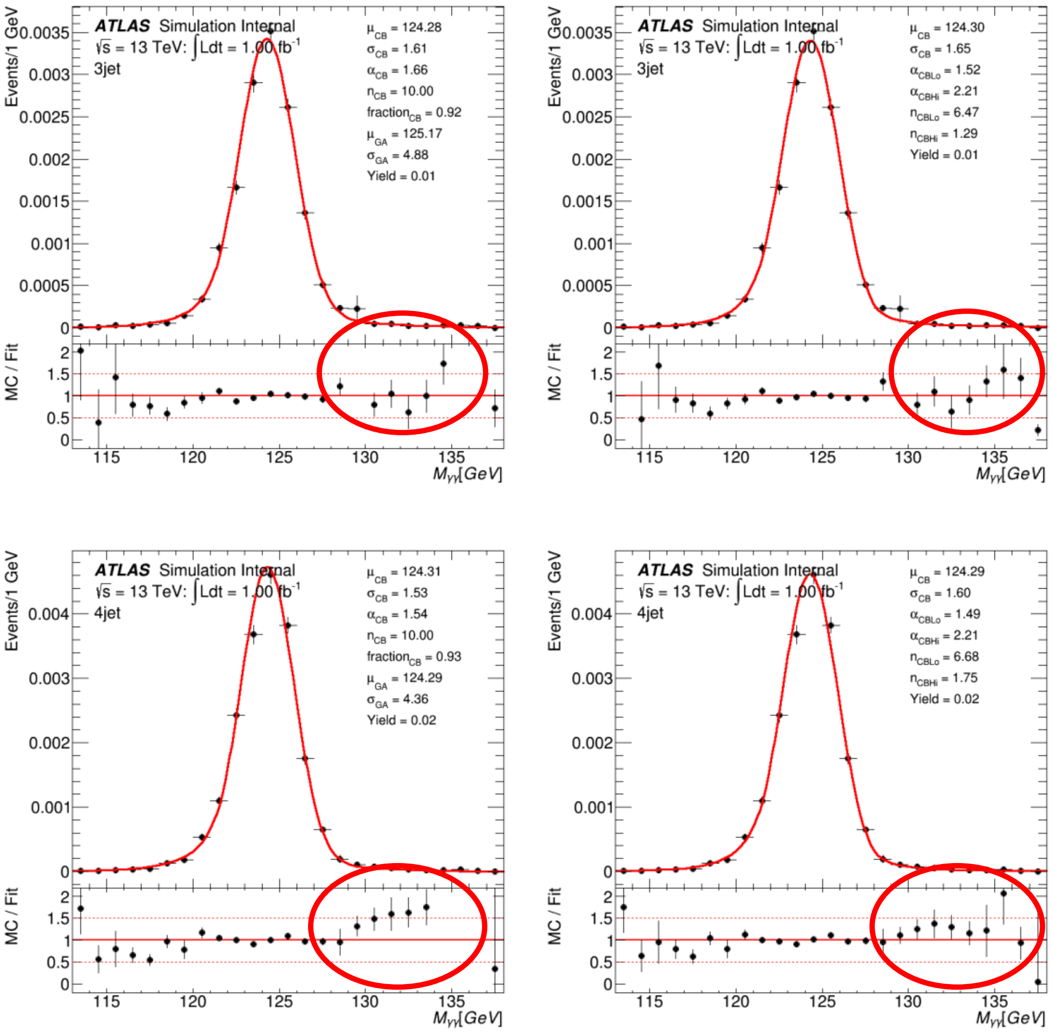
- Two plots show the cut on $pT(\gamma\gamma)$ and expected significance
- Since $pT(\gamma\gamma)$ is sensitive to high mass, 500 GeV has the highest expected significance





	non-res		260 GeV		300 GeV		400 GeV		500 GeV	
	3jet	4jet	3jet	4jet	3jet	4jet	3jet	4jet	3jet	4jet
$m_{\gamma\gamma jets}$	-	-	[210,470]	[240,650]	[230,510]	[270,700]	[290,630]	[350,830]	[360,760]	[430,1000]
$pT_{\gamma\gamma}$	>155	>155	<55	<70	>30	>10	>120	>120	>175	>180

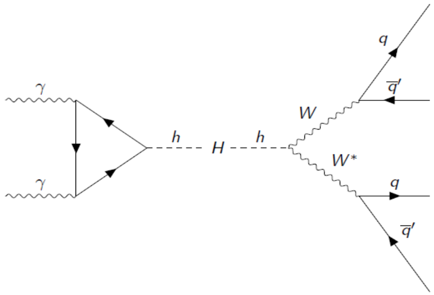
Signal modeling: non-res signal

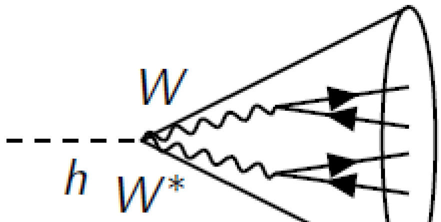


- **CB+Gau VS. DSCB**
- **The only difference between two functions is the high-mass tail**
- **Double-Sided Crystal-Ball (right hand side) able to describe the high-mass tail better in both 3jet and 4jet category (after non-res cut)**

Boosted hadronic - Analysis Strategy

- Cut based approach
- MC background (SM higgs) and data-driven (continuum) background estimation
- Boosted topology (all four quarks end up in one large R jet), use $\mathrm{AntiK_t}$ (R =1.0) jets
- Common selection
  - 2 photons in tight mass window
  - Lepton-veto (tight)
  - B-jet veto
- Optimization:
  - Use 2015 and 2016 data $\int L = 36\ \mathrm{fb}^{-1}$
  - Use the mass point $m_H = 1$ TeV (260 GeV – 3 TeV)
  - Optimize on Asimov significance: $\sqrt{2((S+B)ln\left(1+\frac{S}{B}\right)-S))}$
- Set upper limit on $\sigma \times BR$ for resonant production





Parameters to investigate - optimization

- Event level:
  - MET
  - Jet multiplicity
- Photon side:
  - $\Delta R(\gamma\gamma)$
- Jet side:
  - Substructure variables
  - nJH.$\Delta M = m_{selected\,jets} - m_h$
  - nJH.Mult = number of selected jets
- Comparing both sides:
  - $\Delta R(\gamma\gamma, qqqq)$
  - pT balance

(nJH is the subset of all given jets whose (combined) invariant mass is closest to the higgs mass)

Orthogonality study

Find orthogonality criterion to resolved analysis

- Define boosted as presence of one large radius jet ($\mathrm{AntiK_t}$ (R =1.0); $|\eta| < 2; pT >$ 200 GeV)
- Define resolved as presence of three or more jets, $\mathrm{AntiK_t}$ (R =0.4), apply a mass point and multiplicity dependent cut on the $pT_{\gamma\gamma}$
- Define four categories: resolved (R), boosted (B), resolved AND not-boosted (RnB), boosted AND not-resolved (BnR)

- Ongoing: find a suitable cut-off point (in m_H), such that below this point a combination of R and BnR yields the highest significance and above B and RnB
- Status: running on 2 fb^{-1}, reconstructing the significance results from the resolved analysis (as a cross check)

Summary

- Photons are following the selections as HGam analyses.
- Regarding the pileup jets in forward region, resolved analyses use central jets.
- No overlap between resolved analyses: lepton requirements.
- Study overlap between boosted and resolved full hadronic analyses.
- Consider applying the $mT_{l\nu jj\gamma\gamma}$ cut in semi-leptonic analysis
- Plan to combine the resolved analyses.
- Fit the $m_{\gamma\gamma}$ distribution to get sensitivity in the resolved analyses.

- Request unblinding in middle of January for resolved analyses, aim for a paper for Moriond2017

END