BSc Thesis presentation

Search for di-Higgs production in the γγWW decay channel in the boosted topology*

JOSHUA BEIRER
SUPERVISED BY S. LAI AND J. VEATCH

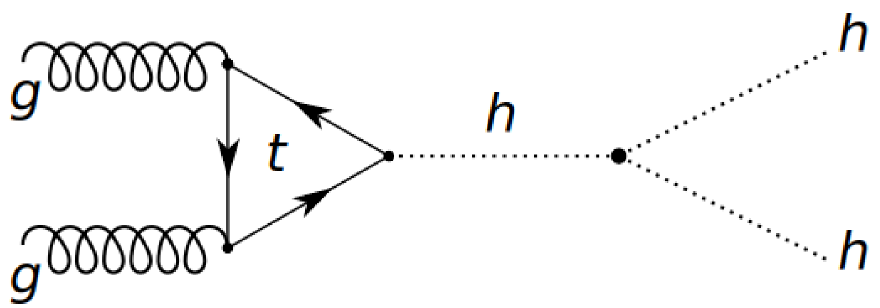
Theory and Motivation

- Higgs boson discovered in 2012
- Last missing fundamental particle predicted by the SM

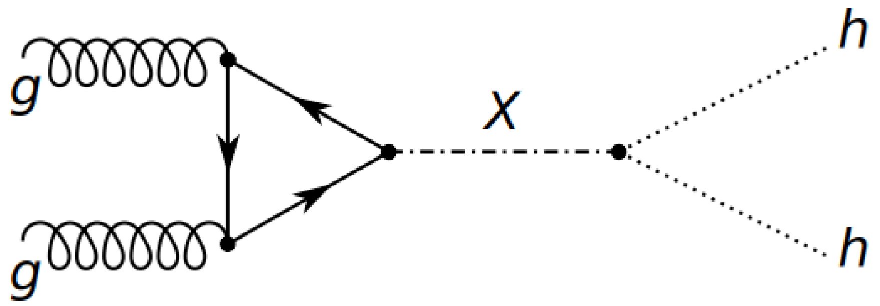
→ Many studies performed since then but important qestions remain open:

- Higgs self-coupling?
- New heavy resonanes?

No experimenetal observation yet, but could answer some questions soon, as LHC provides more and more data



(a) non-resonant



(b) resonant

Non-resonant production

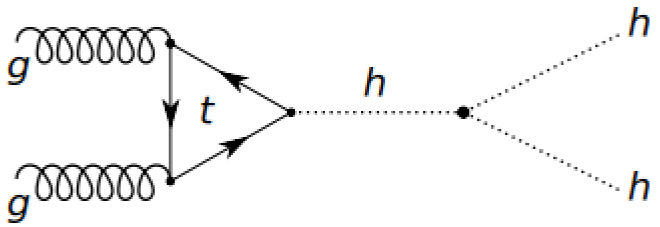
- Self coupling is predicted by the Higgs mechanism in the SM:

$$V\left(\phi\phi^{\dagger}\right) = \mu^2\left(\phi\phi^{\dagger}\right) + \lambda\left(\phi\phi^{\dagger}\right)^2$$
$$= \ldots - \lambda v h^3 - \tfrac{1}{4}\lambda h^4$$

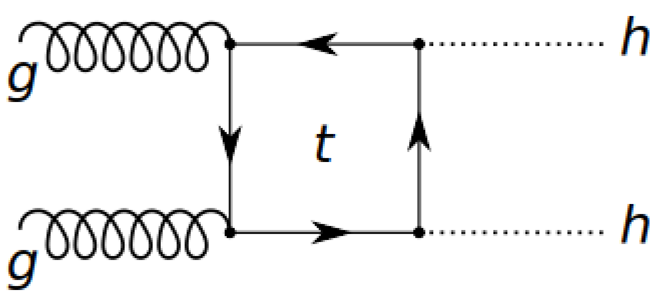
→ Trilinear and quartic couplings
→ Possibilites for double Higgs production arise

- SM predicts small cross section $(\sigma_{hh}(13\ \text{TeV}) = 33.45\ \text{fb})$

- Destructive interference with box-diagram



(a) self-coupling



(b) background

- ➢ Many observations cannot be explained by the SM, e.g.:
- Dark Matter
- Gravity
- Baryon asymmetry
- Large corrections on Higgs mass

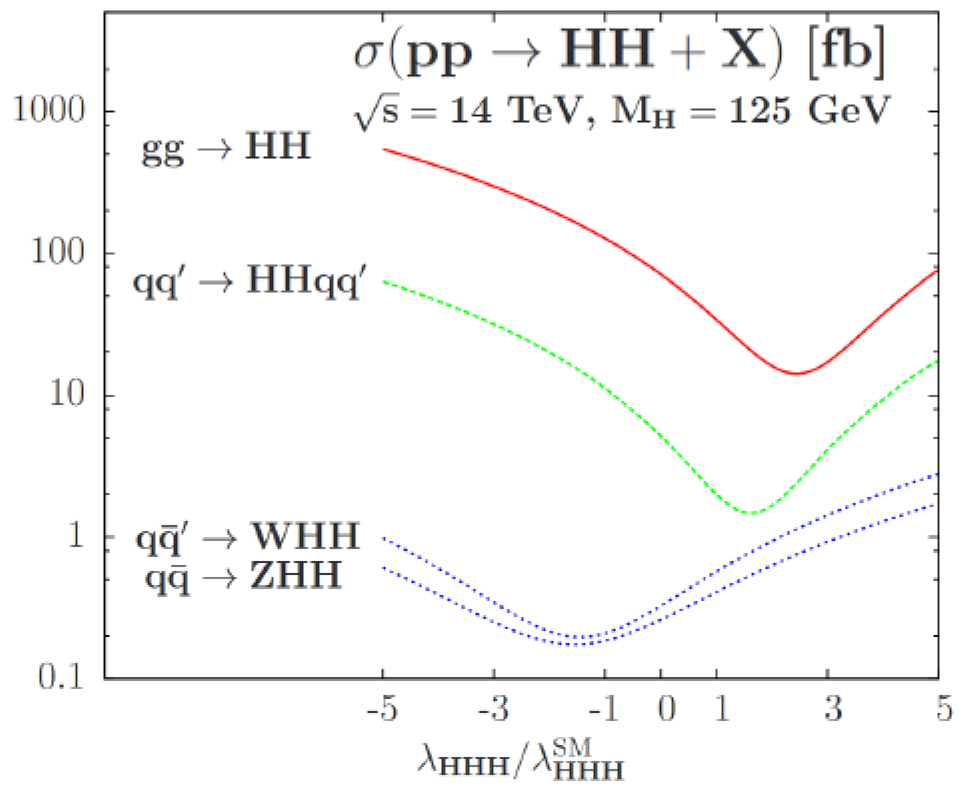
Searches for new physics plays an important role

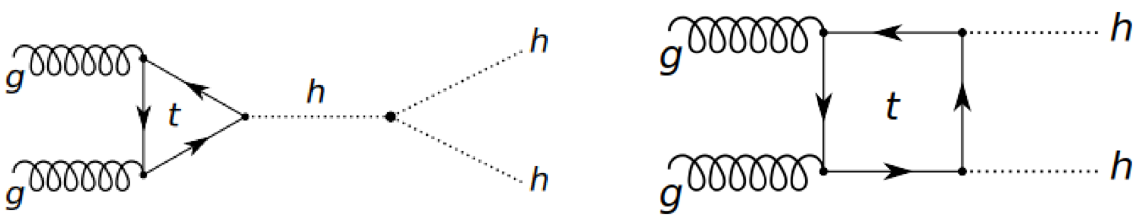
Standard model predicts trilinear coupling to be:

$$\lambda_{hhh}^{SM} = \frac{3m_h^2}{v^2}$$

Many models assume a different coupling constant
→ Alters the way both diagrams interfere
→ Changes di-Higgs production cross section

Measurement of di-Higgs cross section allows for direct inference of trilinear coupling (assuming no further contribuitions)





Resonant production

- Many models predict heavier versions of the Higgs boson
- Models introducing two Higgs doublets known as 2HDM models

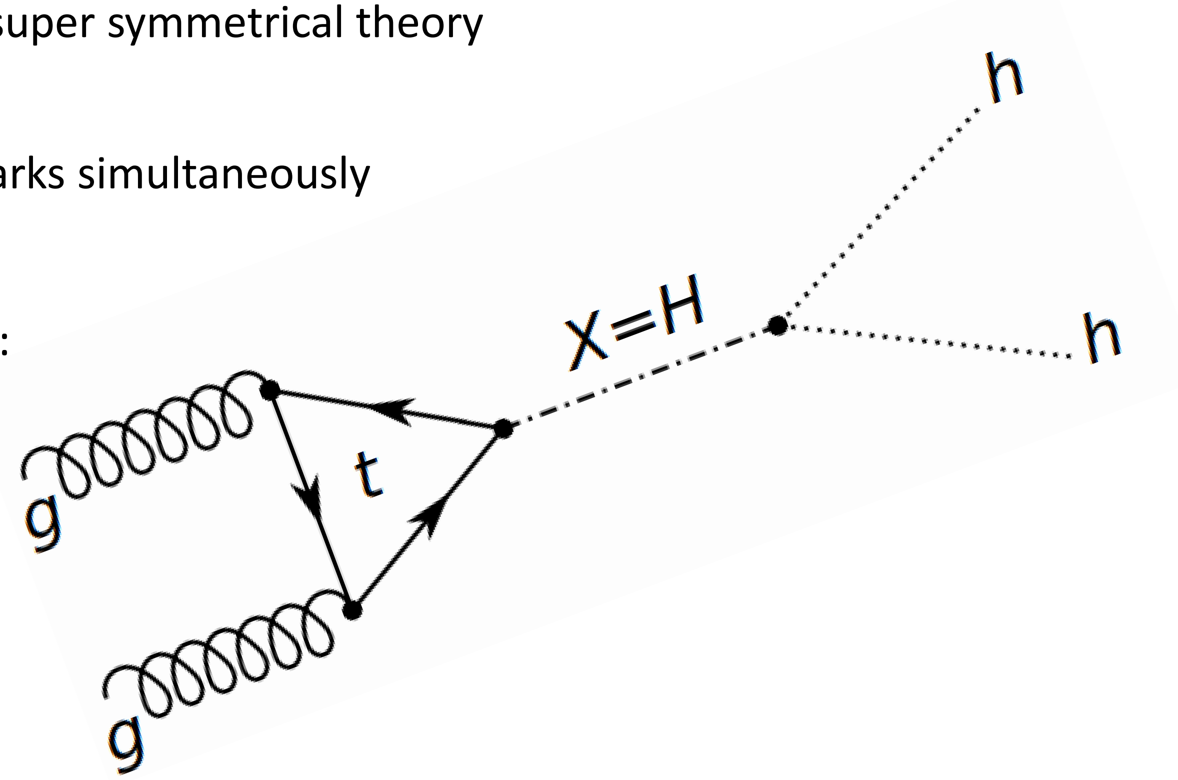
Example: Minimal Super Symmetric Model (MSSM)

- Introduces only the minimal amount of particles needed for a super symmetrical theory

Note:
- one Higgs boson cannot give masses to up- and down-type quarks simultaneously
- Two Higgs doublets necessary to cancel gauge anomalies

→ Two Higgs doublets added, leading to five physical Higgs bosons:

- known SM Higgs *h*
- heavier CP-even neutral Higgs *H*
- CP odd pseudoscalar *A*
- two charged $H^{\pm}$



Focus on heavy CP-even H decaying into two light h

- MSSM could provide additional sources of CP violation
- Provides promising candidate for Dark matter
- Solves hierarchy problem

Why the hadronic *γγWW* decay channel?*

Decay mode	Branching ratio
$h \to b\bar{b}$	57.8 %
$h \to WW^*$	21.6 %
$h \to gg$	8.6 %
$h \to \tau^+\tau^-$	6.4 %
$h \to c\bar{c}$	2.9 %
$h \to ZZ^*$	2.7 %
$h \to \gamma\gamma$	0.2 %

$$\mathrm{Br}(\mathrm{W} \to \mathrm{e}\bar{\nu}_\mathrm{e}) = 0.1046$$

$$\mathrm{Br}(\mathrm{W} \to \mu\bar{\nu}_\mu) = 0.1050$$

$$\mathrm{Br}(\mathrm{W} \to \tau\bar{\nu}_\tau) = 0.1075$$

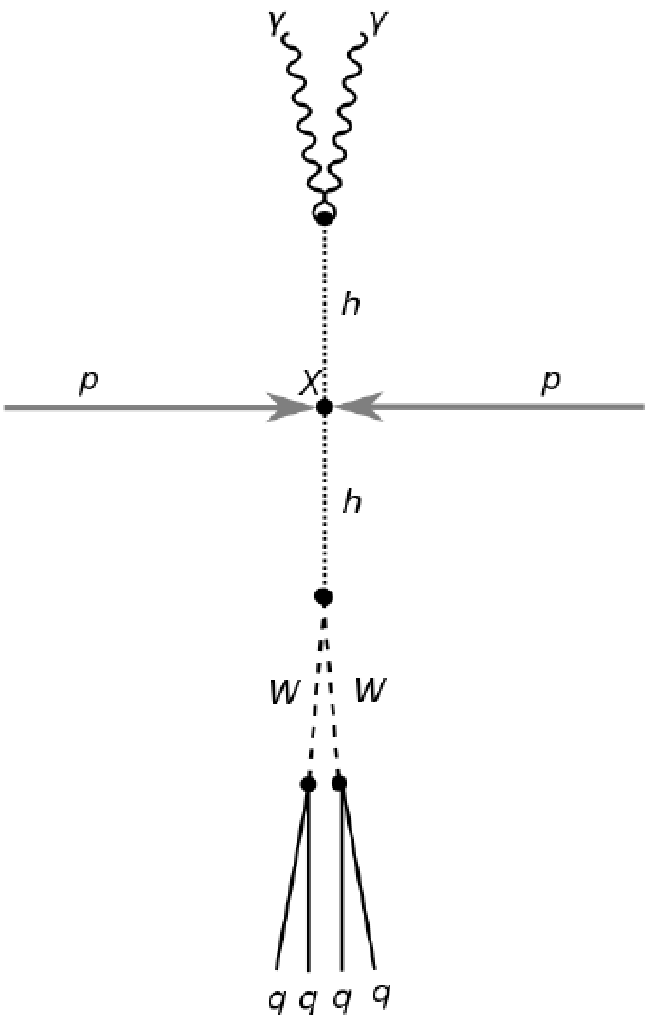
$$\mathrm{Br}(\mathrm{W} \to \mathrm{q}\bar{\mathrm{q}}) = 0.6832$$

- **γγ side**

✓ Clean signal
✓ Well-known background
X Small branching ratio

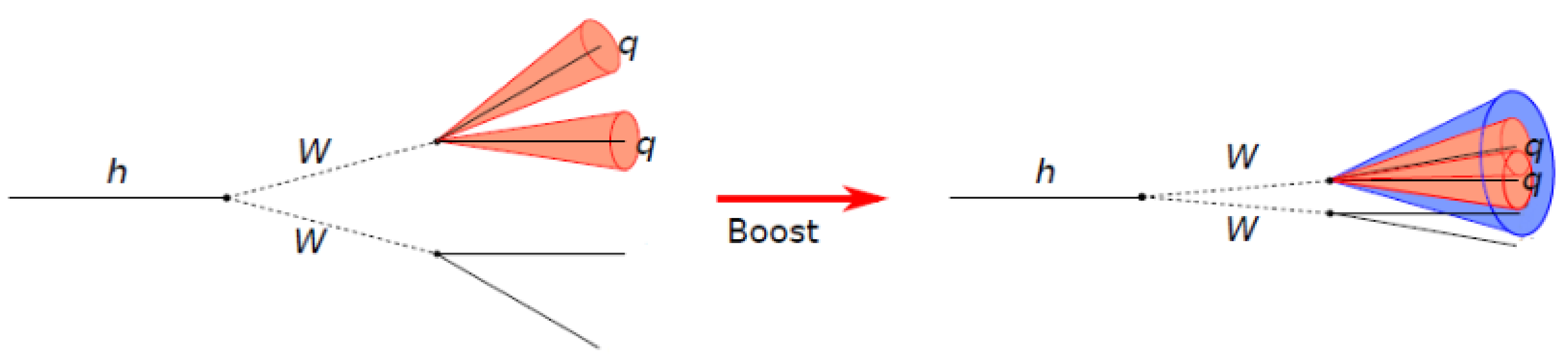
- **WW* side**

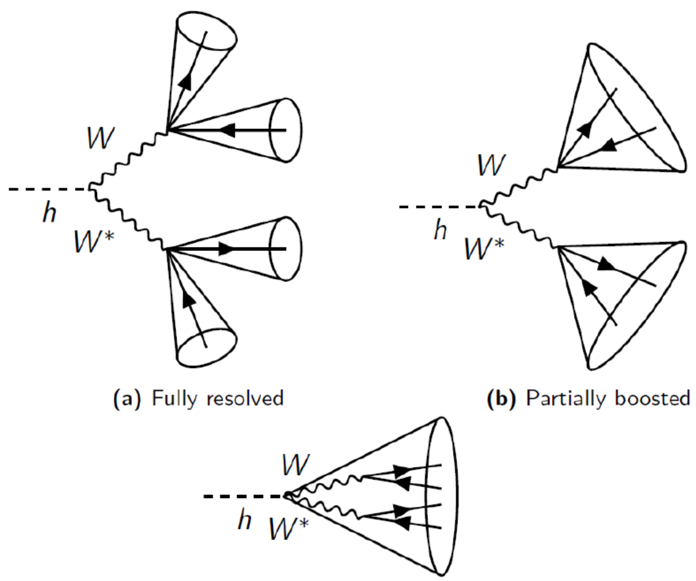
✓ High branching ratio
✓ Full reconstruction possible
X Worse identification compared to semileptonic channel



Overall branching ratio of hh → $\gamma\gamma W_{had} W^*_{had}$ is 0.044%

Boosted topology



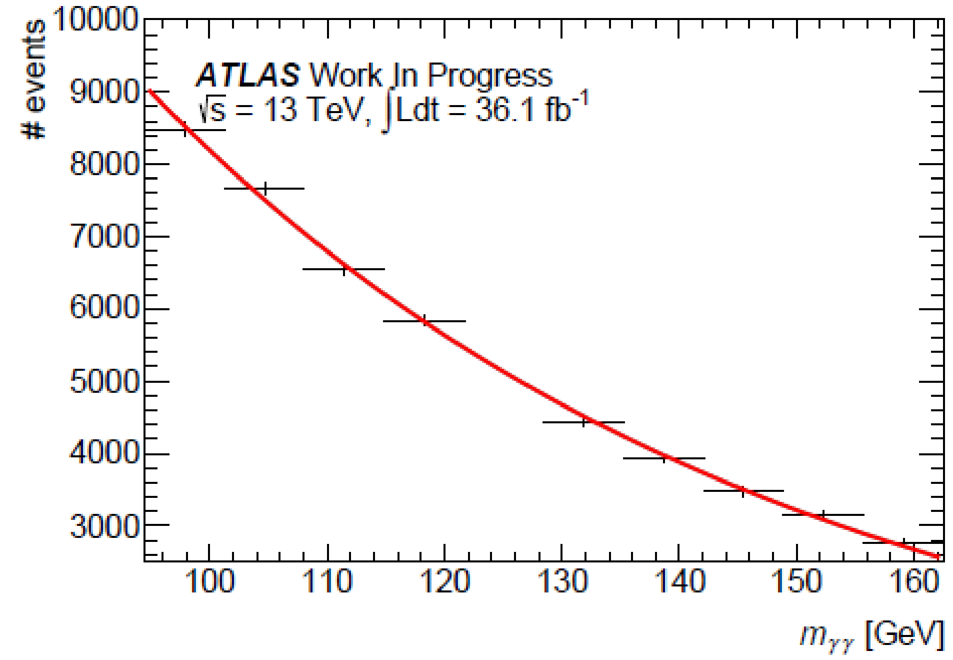


(a) Fully resolved (b) Partially boosted
(c) Fully boosted

Consider resonances above m_H =750 GeV
→ Higgs decay products get a high Lorentz boost and are closer together
→ Nominal small R-jets (Anti-k_t(R=0.4)) cannot be used anymore to resolve each parton separately

Idea: use Anti-k_t(R=1.0) jets and get information about jet structure using substructure variables, e.g. N-subjettiness and Energy Correlation Functions

Analysis strategy



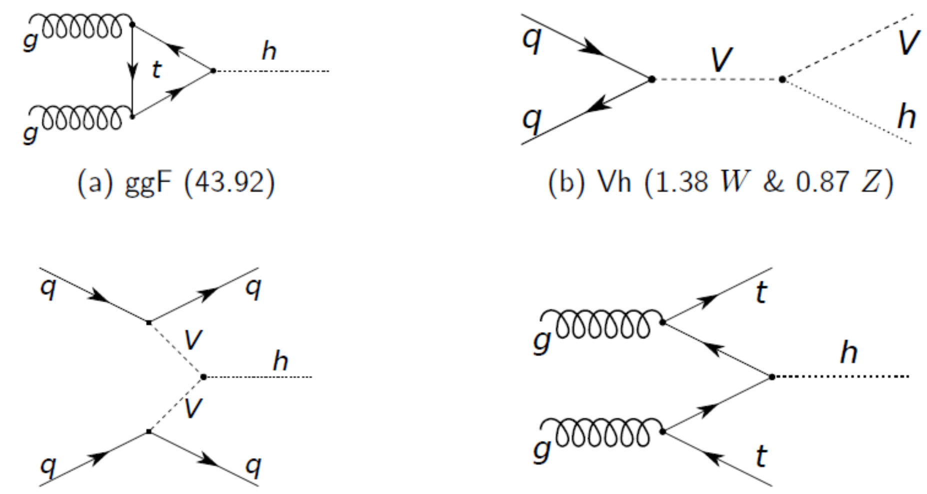
- Use complete 2015/2016 dataset recorded by ATLAS (36.1 fb^{-1})

- Signal simulation:
  - ➢ Non-resonant hh → $\gamma\gamma WW^*$ sample
  - ➢ Resonant mass points h h→ $\gamma\gamma WW^*$ ranging from 260 GeV to 3 TeV

- Background simulation:
  - ➢ Huge list of SM processes that contribute to background
  - → Continuous background hard to simulate
  - → Use data driven background:
    - ➢ Cut out signal region $m_{\gamma\gamma} \in \{125.09 \pm 3.4\ \text{GeV}\}$
    - ➢ Perform exponential fit based on sideband region

In addition use MC generated h→ $\gamma\gamma$ samples

Channel	Number of events	$\sigma \cdot BR(h \to \gamma\gamma)$ [fb]
ggF	1930000	110.1
VBF	984000	8.6
WH	246200	3.1
ZH	247800	2.0
ttH	49800	1.2



(a) ggF (43.92)
(b) Vh (1.38 W & 0.87 Z)
(c) VBF (3.75)
(d) tth (0.51)

Event selection

Jet selection

- Require at least one Anti-k_T(R=1.0) jet with $|\eta|<2.0$ and $p_T>200$ GeV

Photon selection:

- Require at least two photons that fulfill 'tight' identification criterion and $p_T>25$ GeV
- Relative p_T cut: $p_{T,\gamma 1}/m_{\gamma\gamma}>0.35$ and $p_{T,\gamma 2}/m_{\gamma\gamma}>0.25$ for $p_{T,\gamma 1}>p_{T,\gamma 2}$
- Isolation criterion "FixedCutLoose"

Vetoes

- Vetoes on b-jets and leptons

→ The optimization was redone using 'loose' ID criterion and removing the 'isolation criterion'

Optimization

Goal: maximize significance

$$\Sigma = \sqrt{2 \times \left((s+b) \ln \left(1 + \frac{s}{b} \right) - s \right)}$$

whereby s and b are the number of expected signal and background

for the 750 GeV sample by applying cuts on kinematic variables and substructure variables. We considered:

Substructure variables:

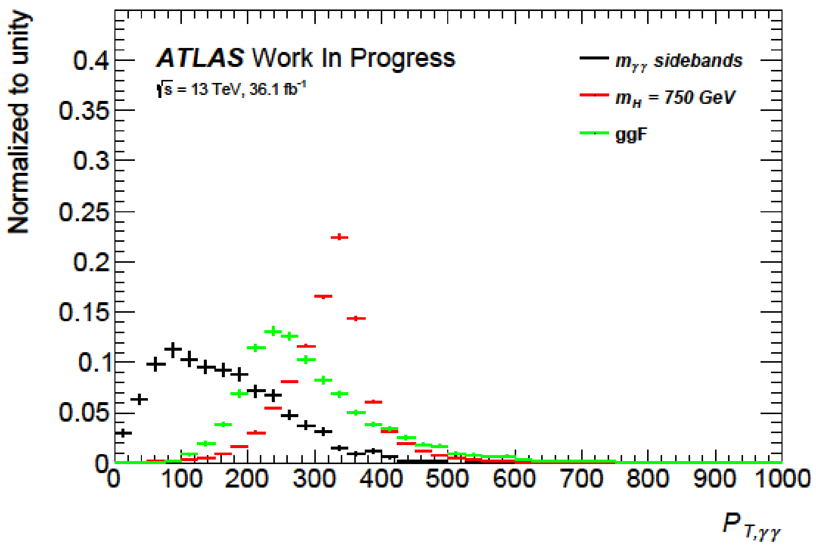
- N-Subjettiness $\tau_{21}, \tau_{31}, \tau_{32}, \tau_{41}, \tau_{42}, \tau_{43}$
- Energy correlation functions related variables C_1-C_4, D_1-D_4

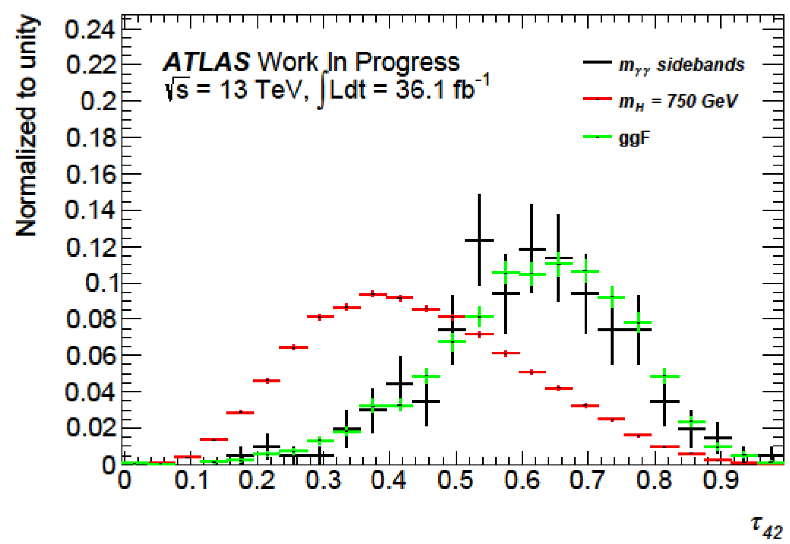
Kinematic variables:

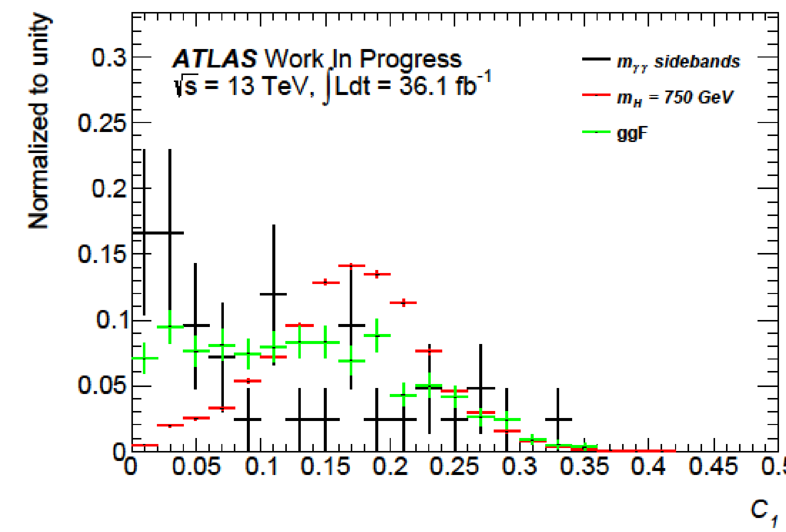
- $P_{T,\gamma\gamma}$, $P_{T,\gamma\gamma}/P_{T,J}$, $\Delta\varphi_{J,\gamma\gamma}$, $\Delta\eta_{J,\gamma\gamma}$, $\Delta R_{J,\gamma\gamma}$, $\Delta R_{\gamma\gamma}$, m_J

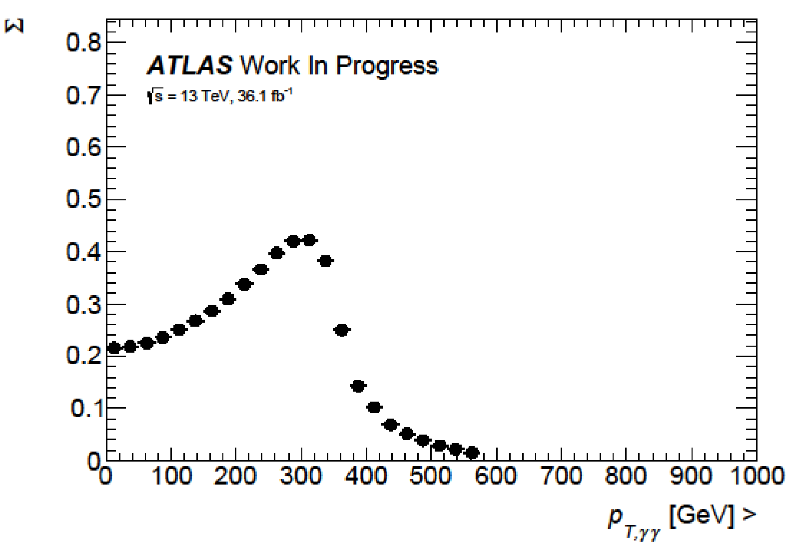
Strategy: Cut on maximum significances of variables and then re-optimize on each variable by keeping other cuts fixed.

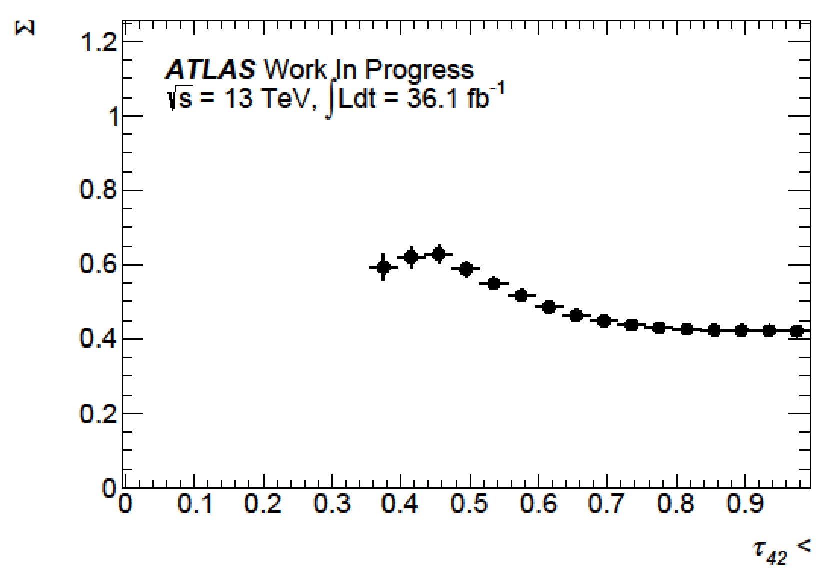
Tight photon criteria

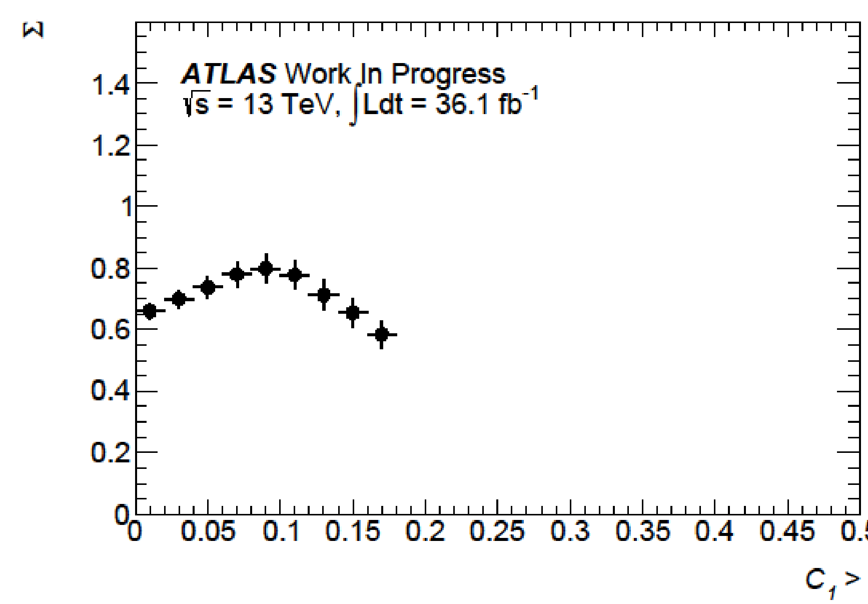












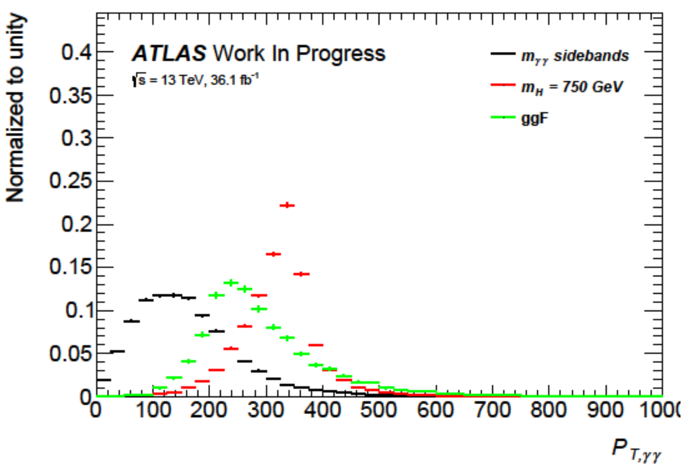
Cut $P_{T,\gamma\gamma}$ > 300 GeV leads to **Z_0=0.42**

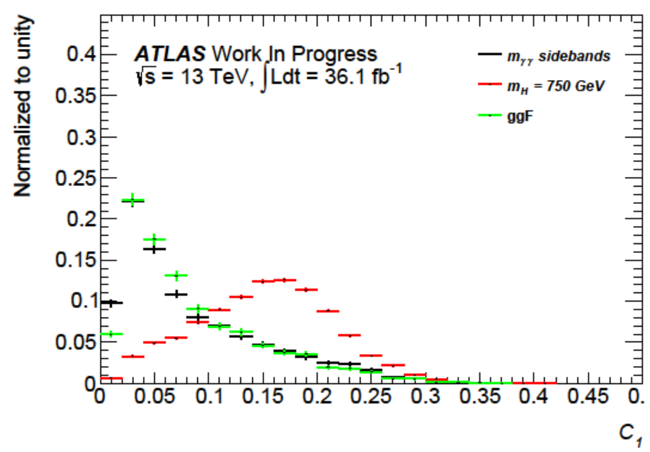
Cut τ_{42}<0.475 leads to **Z_0=0.63**

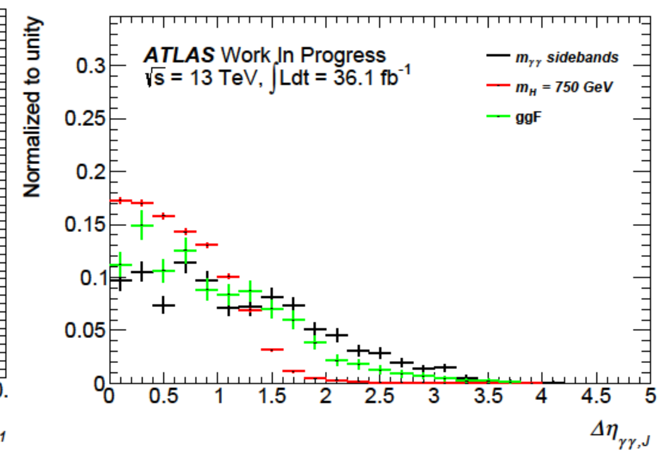
Cut C_1>0.08 leads to **Z_0=0.74**

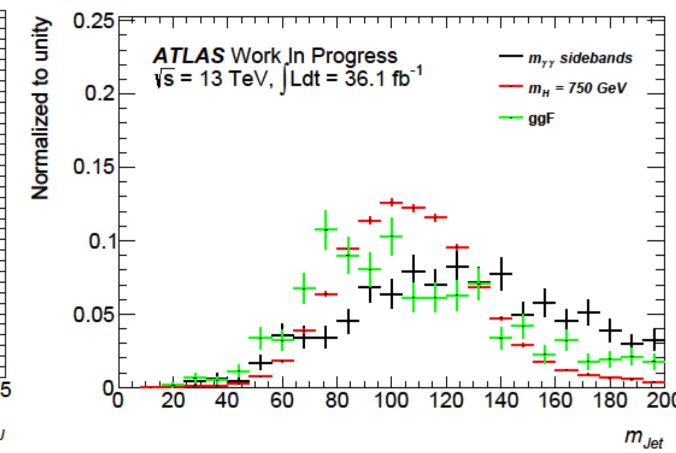
→ Re-optimization yields best significance for $P_{T,\gamma\gamma}$ > 275 GeV **Z_0=0.798597 +- 0.0446717**

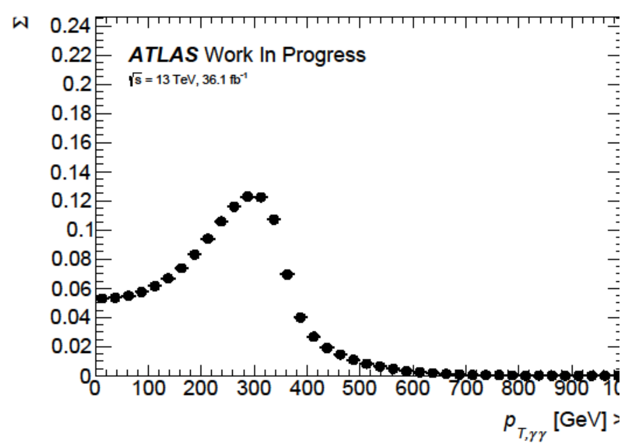
Loose photon criteria

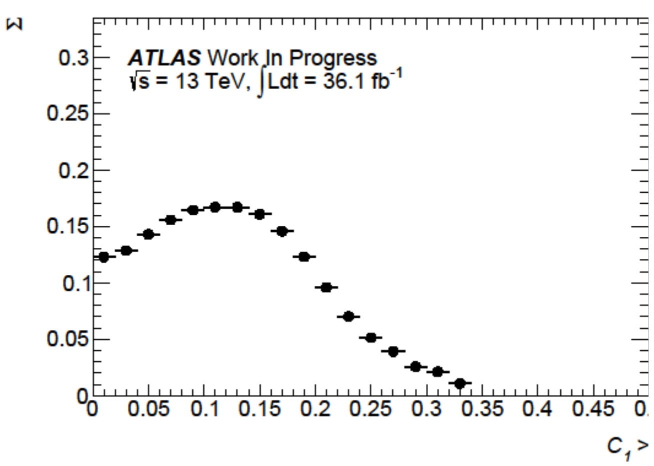


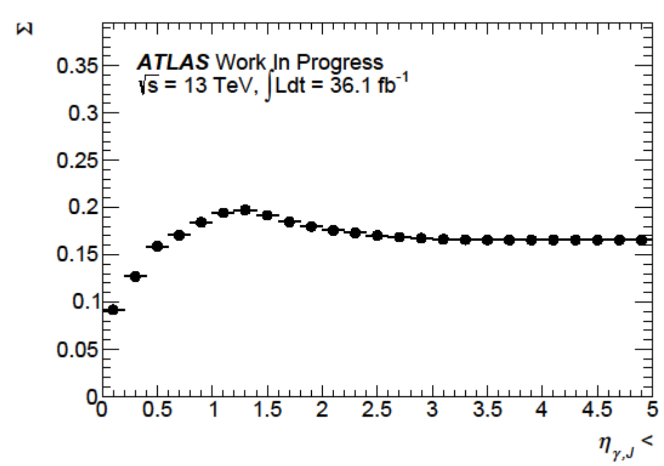


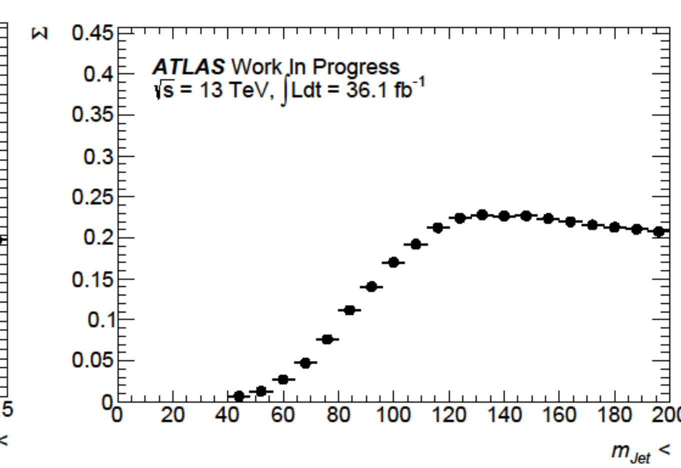












Cut $P_{T,\gamma\gamma}$ > 275 GeV leads to **Z_0=0.12**

Cut C_1 > 0.1 leads to **Z_0=0.17**

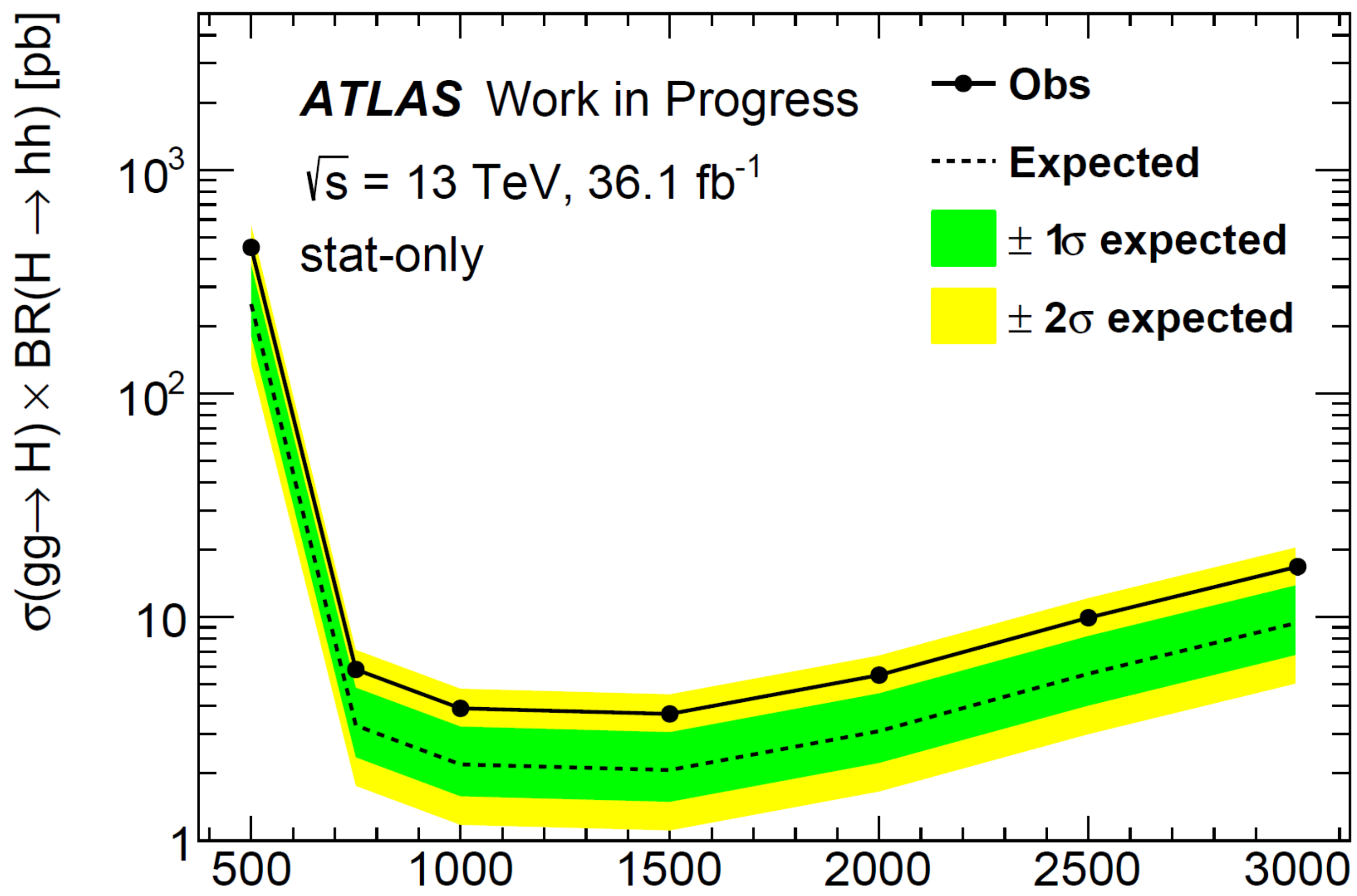
Cut $\Delta\eta_{J,\gamma\gamma}$ < 1.4 leads to **Z_0=0.20**

Cut m_{Jet} < 150 GeV leads to **Z_0=0.22**

→ Re-optimization yields best significance for $P_{T,\gamma\gamma}$ > 300 GeV, C_1 > 0.14, $\Delta\eta_{J,\gamma\gamma}$ < 1.4 and m_J <136 GeV **Z_0=0.251974 +- 0.00472369**

Limits

- As no non-resonant or resonant di-Higgs production was observed, upper limits on cross section times BR were set
- small excess for the observed limits within the 2σ band



Mass [GeV]	Non-res.	400	500	750	1000	1500	2000	2500	3000
Median [pb]	27.16	3464.32	251.22	3.27	2.19	2.07	3.09	5.58	9.44
Observed	48.37	6465.87	450.25	5.83	3.90	3.69	5.50	9.93	16.80
$+2\sigma$ [pb]	59.24	9726.23	566.71	7.14	4.78	4.51	6.73	12.16	20.58
$+1\sigma$ [pb]	40.11	5611.46	375.23	4.83	3.24	3.06	4.56	8.23	13.94
-1σ [pb]	19.57	2496.24	181.02	2.36	1.58	1.49	2.23	4.02	6.80
-2σ [pb]	14.58	1859.39	134.84	1.76	1.18	1.11	1.66	2.99	5.07

Summary and Outlook

- No di-Higgs production has been observed
- Limits on cross section times branching ratio set
- More data from the LHC in the coming years hopefully increases sensitivity for non-resonant production
- Combine limits with other channels such as with the semi leptonic topology

Thank you for your attention!

Backup slides

Final cutflow

Cut	$m_{\gamma\gamma}$ sidebands	MC-bkg	non-reso.	$m_H = 750\,\text{GeV}$
N_{DxAOD}	111112680	3485.71 ± 4.69	0.384 ± 0.002	12.44 ± 0.05
DQ	97814823	3346.16 ± 4.59	0.367 ± 0.002	12.11 ± 0.05
2 loose photons	29866531	2772.32 ± 4.17	0.296 ± 0.001	9.83 ± 0.04
trigger match	29794061	2766.72 ± 4.17	0.295 ± 0.001	9.78 ± 0.04
tight ID	4422423	2403.58 ± 3.88	0.295 ± 0.001	9.78 ± 0.04
isolation	1635695	2156.12 ± 3.66	0.262 ± 0.001	8.98 ± 0.04
rel. $p_{T,\gamma}$ cuts	1427304	1987.01 ± 3.51	0.239 ± 0.001	8.59 ± 0.04
fit range	490962	1986.29 ± 3.51	0.238 ± 0.001	8.58 ± 0.04
$m_{\gamma\gamma} = 125.09$	445828	1800.47 ± 3.34	0.204 ± 0.001	7.61 ± 0.04
> 1 large-R jet	2331	37.11 ± 0.50	0.0336 ± 0.001	4.31 ± 0.03
b-veto	2176	33.49 ± 0.48	0.0327 ± 0.0003	4.21 ± 0.03
lepton veto	2158	32.95 ± 0.48	0.0274 ± 0.0003	3.58 ± 0.03
$p_{T,\gamma\gamma} > 275\,\text{GeV}$	283	14.96 ± 3.18	0.0123 ± 0.0002	2.86 ± 0.02
$\tau_{42} < 0.475$	42	2.83 ± 0.14	0.00706 ± 0.0001	1.71 ± 0.02
$C_1 > 0.08$	21	1.61 ± 0.10	0.0063 ± 0.0001	1.57 ± 0.02

Tight

Cut	$m_{\gamma\gamma}$ sidebands	MC-bkg	non-reso.	$m_H = 750\,\text{GeV}$
N_{DxAOD}	111112680	3485.71 ± 4.69	0.384 ± 0.002	12.44 ± 0.05
DQ	97814823	3346.16 ± 4.59	0.367 ± 0.002	12.11 ± 0.05
2 loose photons	29866531	2772.32 ± 4.17	0.296 ± 0.001	9.83 ± 0.04
trigger match	29794061	2766.72 ± 4.17	0.295 ± 0.001	9.78 ± 0.04
rel. $p_{T,\gamma}$ cuts	23805404	2511.85 ± 3.97	0.266 ± 0.001	9.25 ± 0.04
fit range	8288643	2507.17 ± 3.97	0.264 ± 0.001	9.20 ± 0.04
$m_{\gamma\gamma} = 125.09$	7568261	2227.92 ± 3.73	0.223 ± 0.001	8.11 ± 0.04
> 1 large-R jet	49501	44.50 ± 0.51	$0.036 \pm 3.89 \cdot 10^{-4}$	4.59 ± 0.03
b-veto	46463	39.90 ± 0.53	$0.035 \pm 3.85 \cdot 10^{-4}$	4.48 ± 0.03
lepton veto	46262	39.20 ± 0.52	$0.030 \pm 3.61 \cdot 10^{-4}$	3.81 ± 0.03
$p_{T,\gamma\gamma} > 300\,\text{GeV}$	3792	13.72 ± 0.31	$0.010 \pm 1.27 \cdot 10^{-4}$	2.57 ± 0.02
$C_1 > 0.14$	740	2.20 ± 0.13	$0.005 \pm 9.05 \cdot 10^{-5}$	1.51 ± 0.02
$\Delta\eta_{\gamma,J} < 1.2$	423	1.44 ± 0.01	$0.004 \pm 8.67 \cdot 10^{-5}$	1.39 ± 0.02
$m_J < 136\,\text{GeV}$	183	0.89 ± 0.08	$0.003 \pm 8.05 \cdot 10^{-5}$	1.17 ± 0.01

Loose

Substructure variables

$$ECF_0(\beta) = 1$$

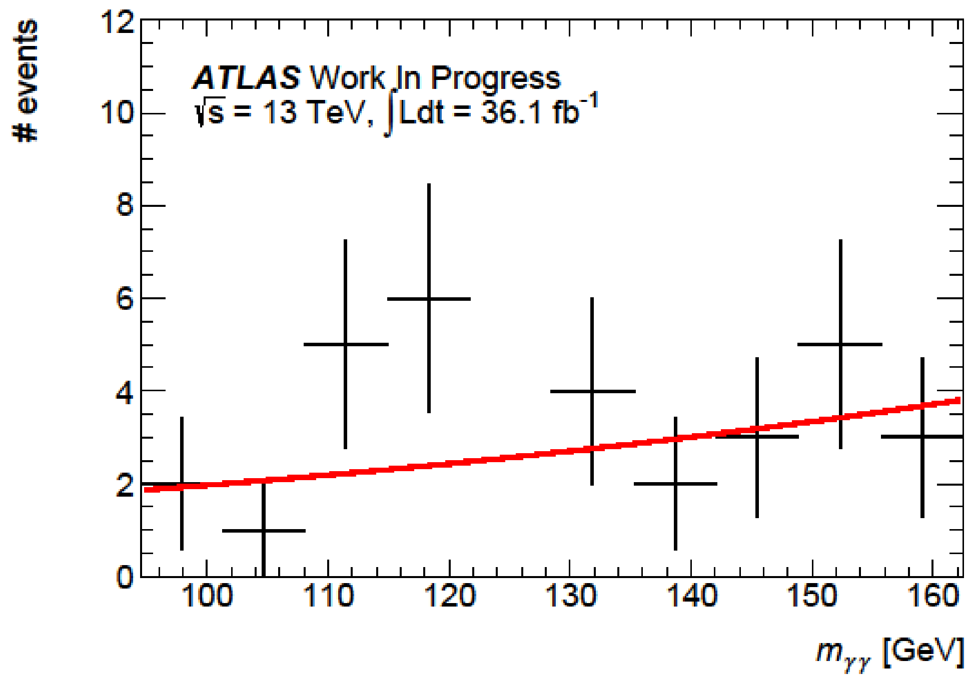
$$ECF_1(\beta) = \sum_{i \in J} p_{T,i}$$

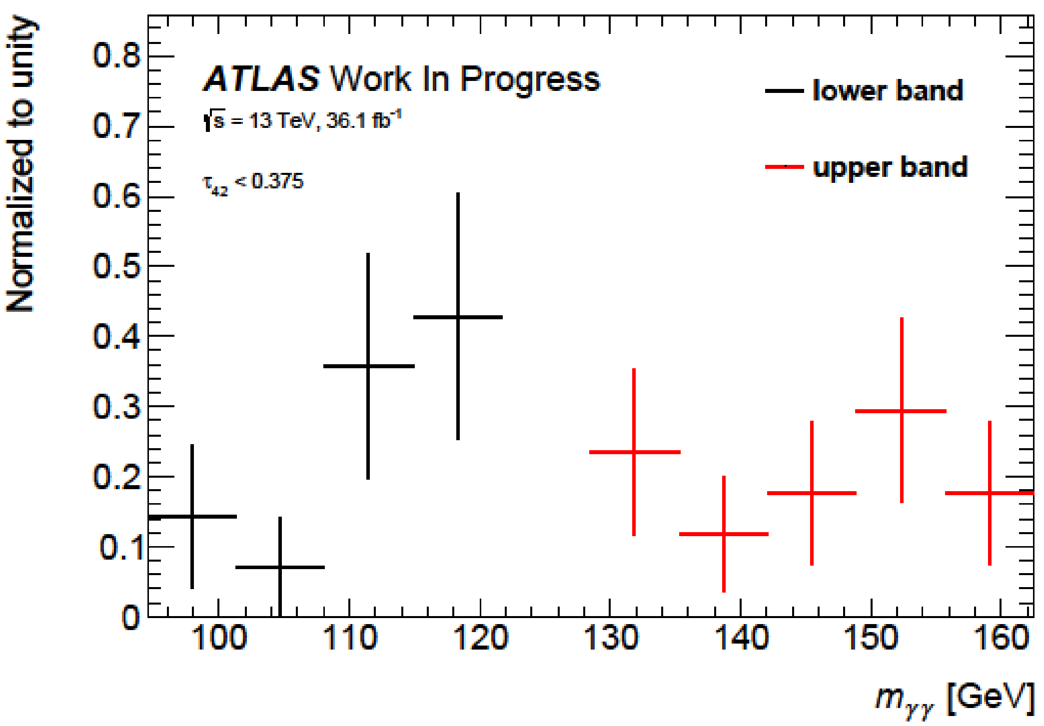
$$ECF_2(\beta) = \sum_{i<j \in J} p_{T,i} p_{T,j} \Delta R_{ij}^{\beta}$$

$$ECF_3(\beta) = \sum_{i<j<k \in J} p_{T,i} p_{T,j} p_{T,k} \left(\Delta R_{ij} \Delta R_{jk} \Delta R_{ki}\right)^{\beta}$$

$$C_N(\beta) = \frac{ECF_{N+1} \times ECF_{N-1}}{ECF_N^2}$$

$$D_N(\beta) = \frac{ECF_{N+1} \times ECF_{N-1} \times ECF_1^N}{ECF_N^3}$$


ATLAS Work In Progress
$\sqrt{s}$ = 13 TeV, $\int$Ldt = 36.1 fb^{-1}
events
$m_{\gamma\gamma}$ [GeV]


ATLAS Work In Progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
τ_{42} < 0.375
lower band
upper band
Normalized to unity
$m_{\gamma\gamma}$ [GeV]