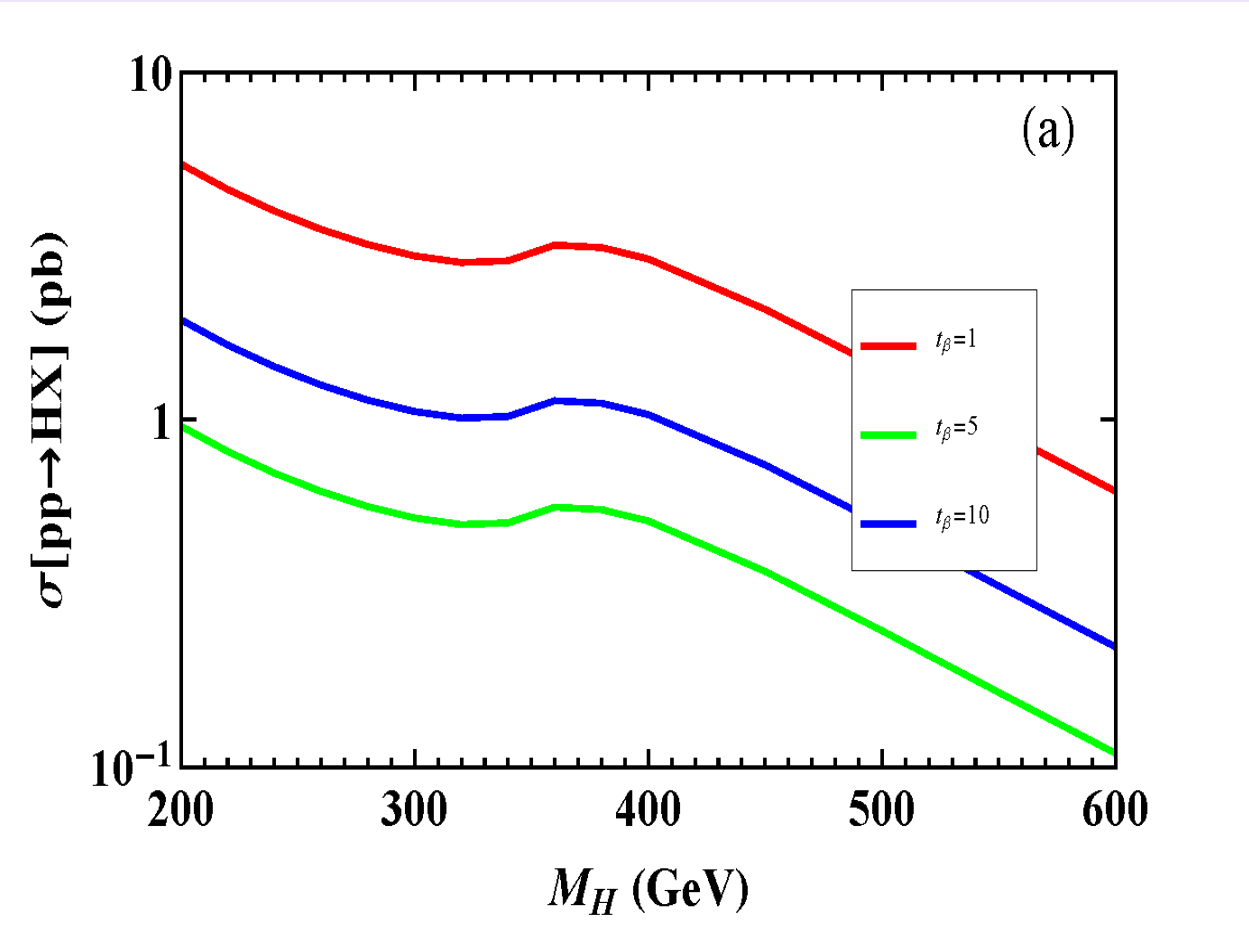
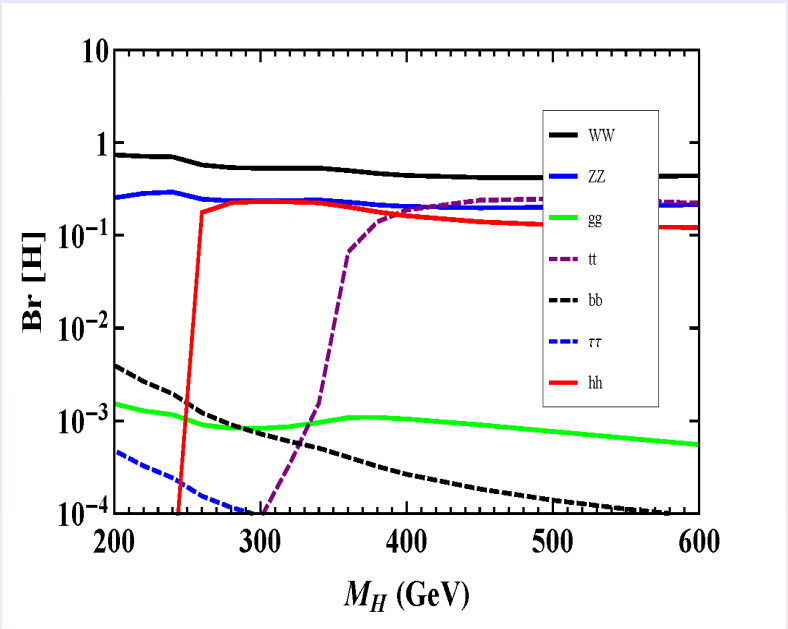
The 2HDM-I heavier CP-even Higgs production

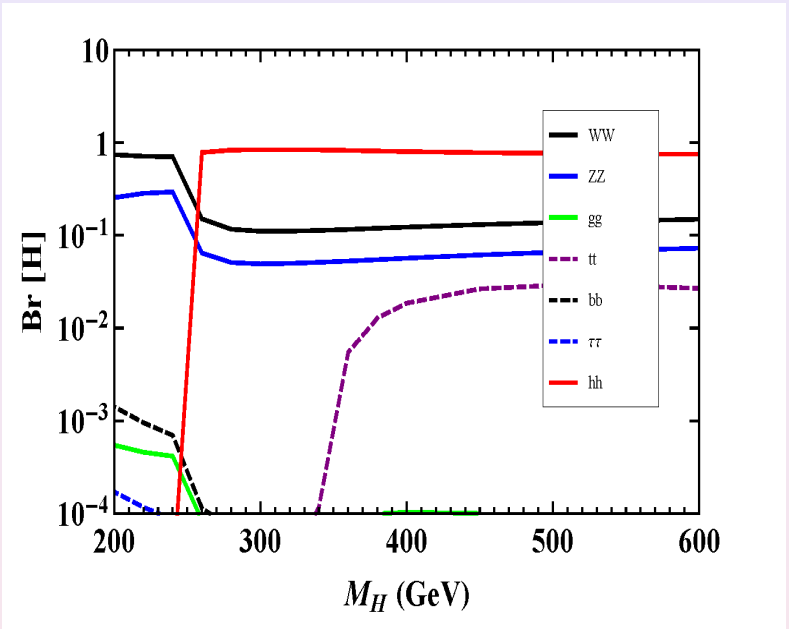
- $\sqrt{s} = 14$ TeV.
- Alinement limit: $\cos(\beta - \alpha) = 0.4$.



The 2HDM-I heavier CP-even Higgs Br



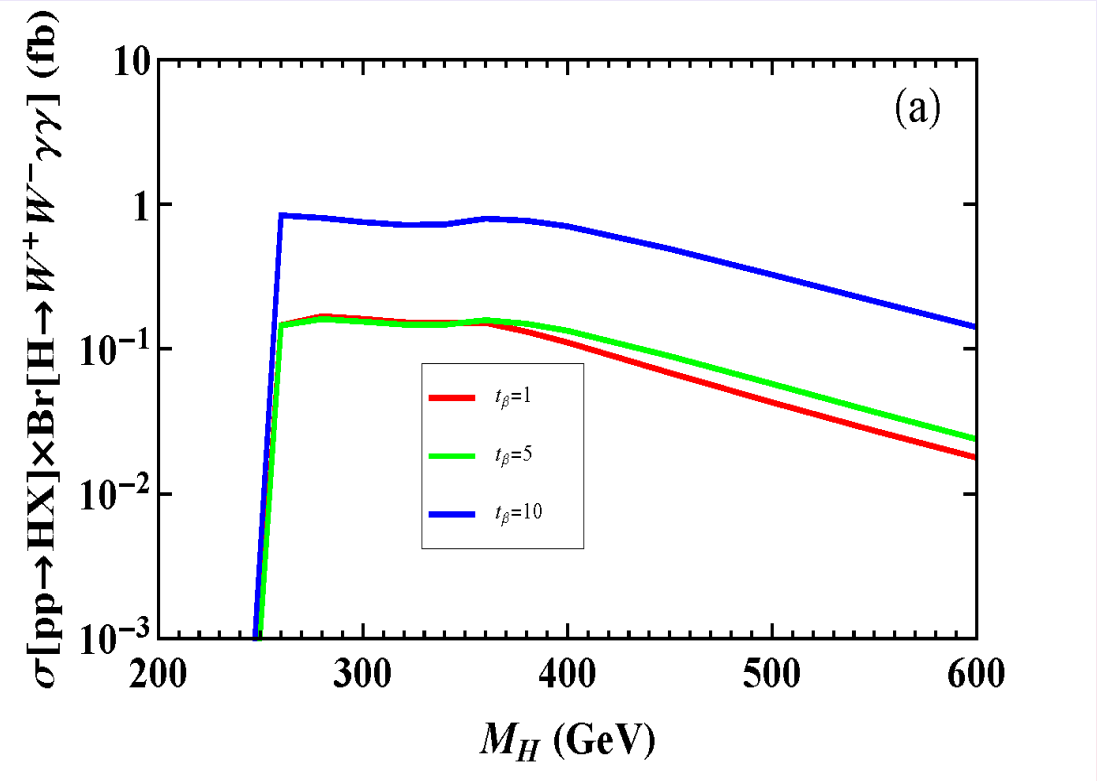
$\tan\beta = 1$



$\tan\beta = 10$

The 2HDM-I $pp \to H \to hh \to W^+W^-\gamma\gamma$ channel

$\sigma[\, pp \to HX\,] \times Br[\, H \to hh\,] \times Br[\, h \to W^+W^-\,] \times Br[\, h \to \gamma\gamma\,] \times 2$:



We take Xsection= 1 fb for $M_H = 300(400)$GeV and Xsection= 10^{-1} fb for $M_H = 600$GeV in the next analysis.

The 2HDM-I $pp \to H \to hh \to W^+W^-\gamma\gamma$ channel

- $Br\,[\ W \to \ell\ \nu\ ] \simeq 10.8\%$ $\quad$ (ℓ : e or μ or τ);
- $Br\,[\ W \to$ hadrons $\ ] \simeq 67.6\%$.
- Signal cross section with W decay:
  - hadronnic decay:

$$67.6\%^2 \times \text{Xsection} \simeq 0.457 \times \text{Xsection};$$

  - leptonic decay:

$$(3 \times 10.8\%)^2 \times \text{Xsection} \simeq 0.105 \times \text{Xsection};$$

  - semi-leptonic decay:

$$67.6\% \times 3 \times 10.8\% \times 2 \times \text{Xsection} \simeq 0.438 \times \text{Xsection}.$$

Semi-leptonic decay channel

- Fast-simulation project:

$$\text{MG5} + \text{pythia} + \text{delphes 3.0.10.}$$

- 2HDM Signal: $M_H = 300$ GeV and $M_H = 400(600)$ GeV.
- SM irreducible background:

$$p\ p \ \to \ q\ q\ \ell\ \nu\ \gamma\ \gamma \ \sim \ 31.13[\text{fb}].$$

- SM reducible background:

$$\begin{aligned}
p\ p &\to q\ q\ \ell\ \nu\ g\ g &&\sim \ \text{o}(10^{-4})[\text{fb}],\\
p\ p &\to q\ q\ \ell\ \nu\ g\ q &&\sim \ \text{o}(10^{-4})[\text{fb}],\\
p\ p &\to q\ q\ \ell\ \nu\ q\ q &&\sim \ \text{o}(10^{-4})[\text{fb}],\\
p\ p &\to q\ q\ \ell\ \nu\ q\ \gamma &&\sim \ \text{o}(10^{-1})[\text{fb}],\\
p\ p &\to q\ q\ \ell\ \nu\ g\ \gamma &&\sim \ \text{o}(10^{-1})[\text{fb}].
\end{aligned}$$

with photon identification efficiencies:

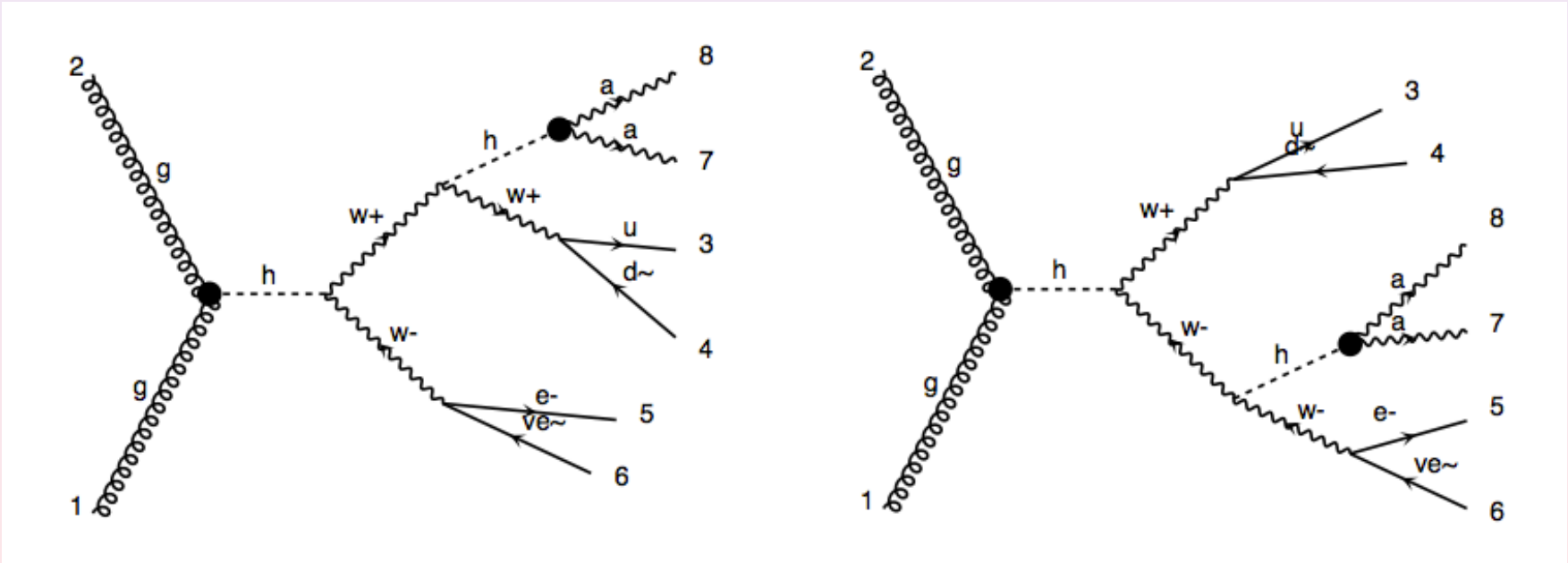
$$\epsilon_{q\to\gamma} \approx 3.6 \times 10^{-4}\,, \quad \epsilon_{g\to\gamma} \approx 3.6 \times 10^{-5}\,.$$

Semi-leptonic decay channel

- SM Higgstrahlung:

$$\text{Radiate Higgs: } p\ p \ \to\ h \ \to\ W^+\,W^- \ \to\ W^+\,W^-\,h.$$

$$p\ p \ \to\ W^+\,W^-\,h \ \to\ q\ q\ \ell\ \nu\ \gamma\ \gamma \ \sim\ 2.3\times 10^{-3}[\text{fb}].$$



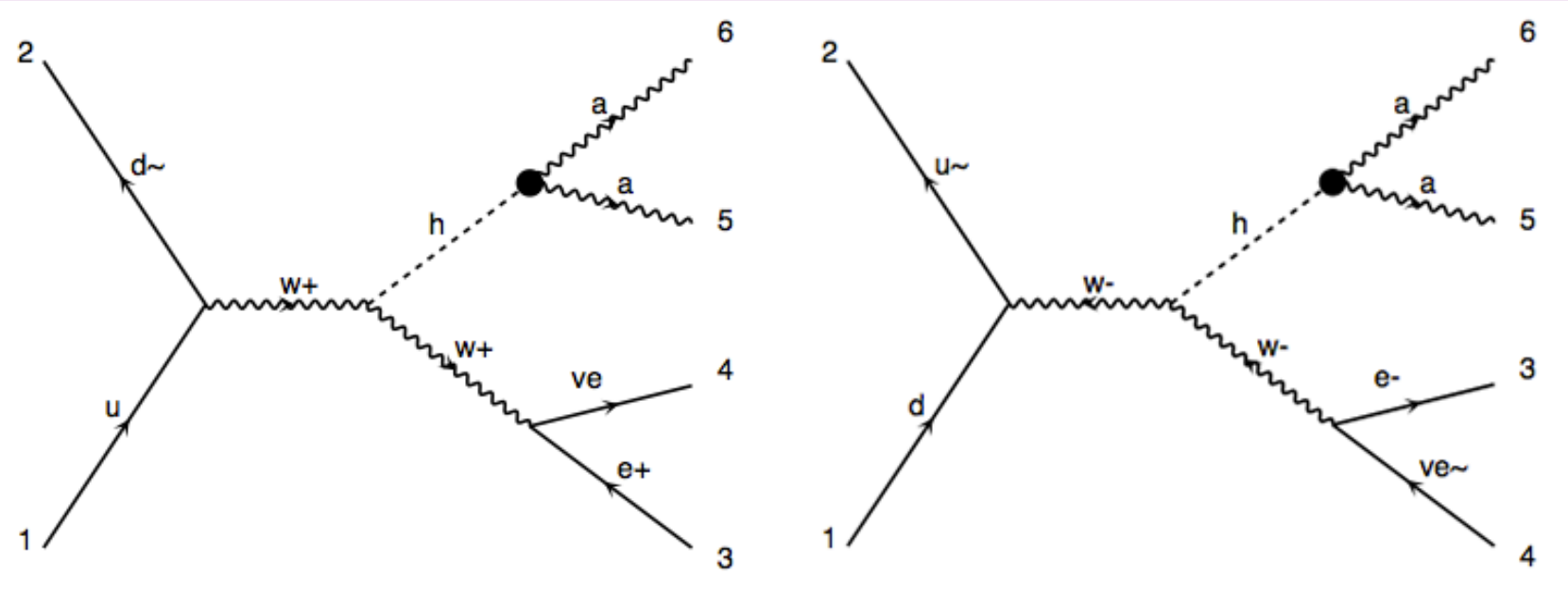
Semi-leptonic decay channel

- SM reducible background:

$$p\ p\ \rightarrow\ \ell\ \nu\ \gamma\ \gamma\ \sim\ 143.3[\text{fb}].$$

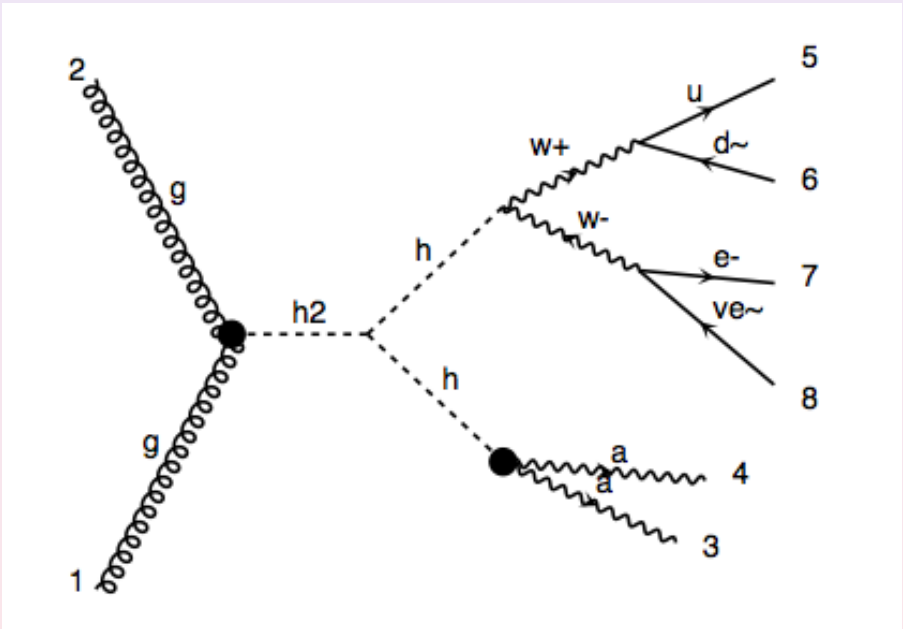
- SM Higgs reducible background:

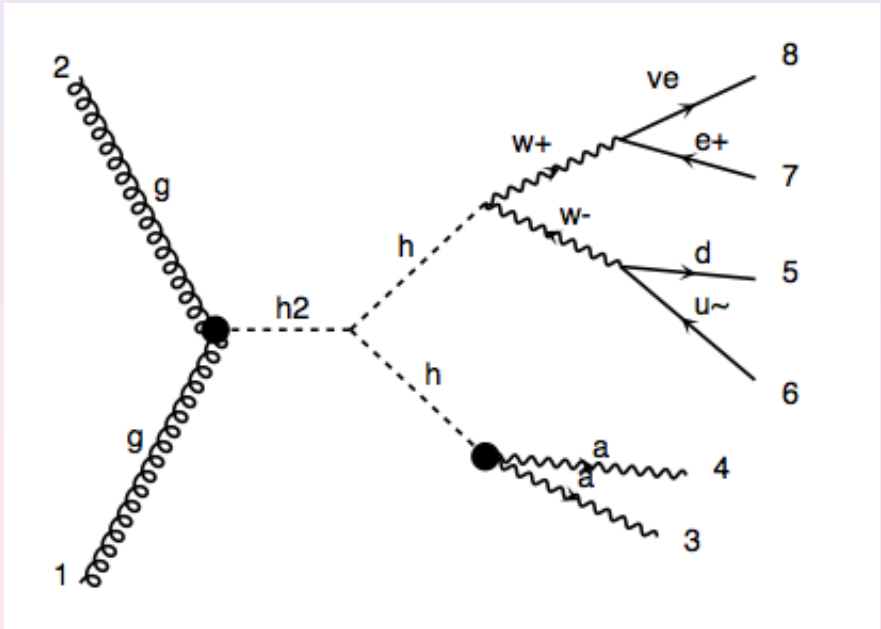
$$p\ p\ \rightarrow\ W\ h\ \rightarrow \ell\ \nu\ \gamma\ \gamma\ \sim\ 0.42[\text{fb}].$$



Signal generated by MG5

• Generating $q\ q$ on shell($\ell\ \nu$ off shell) and $q\ q$ off shell($\ell\ \nu$ on shell) separately

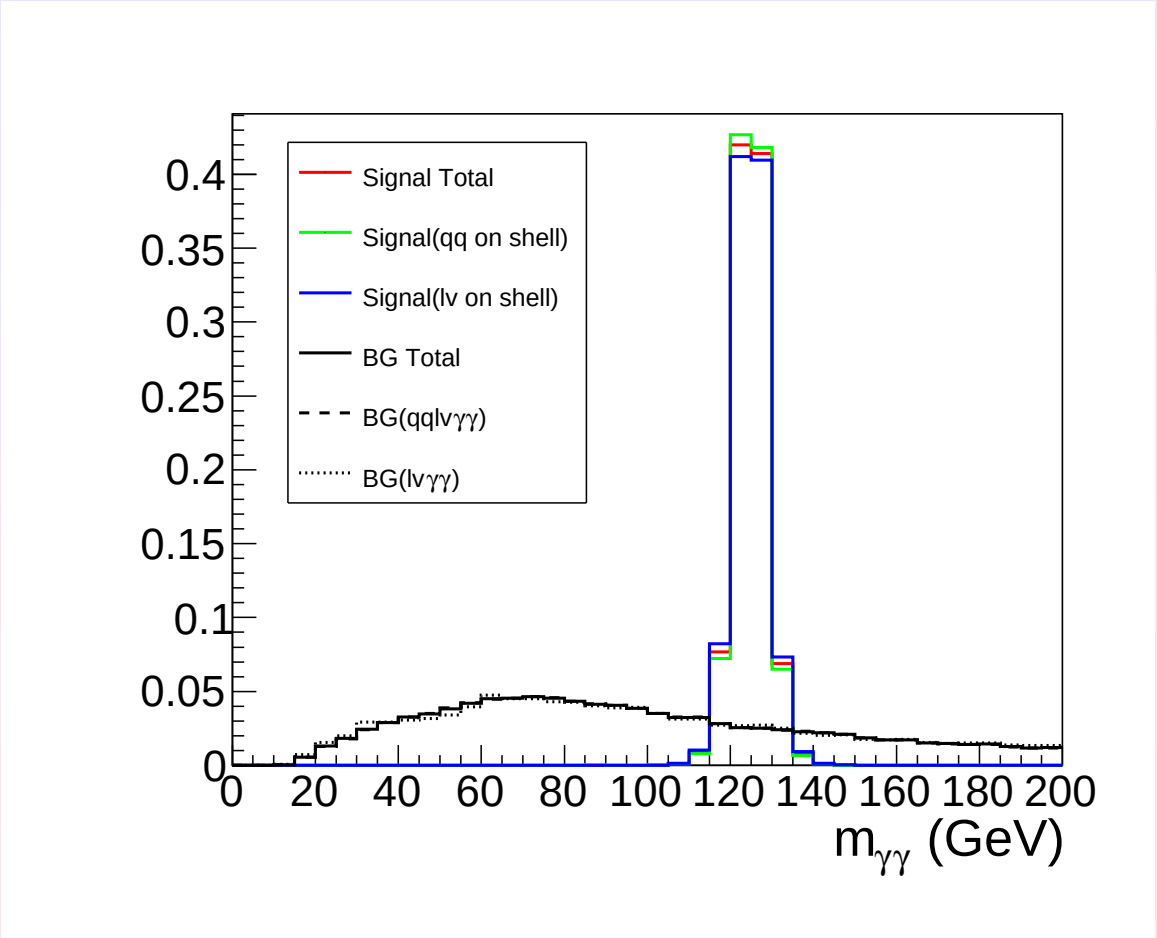




Events selection

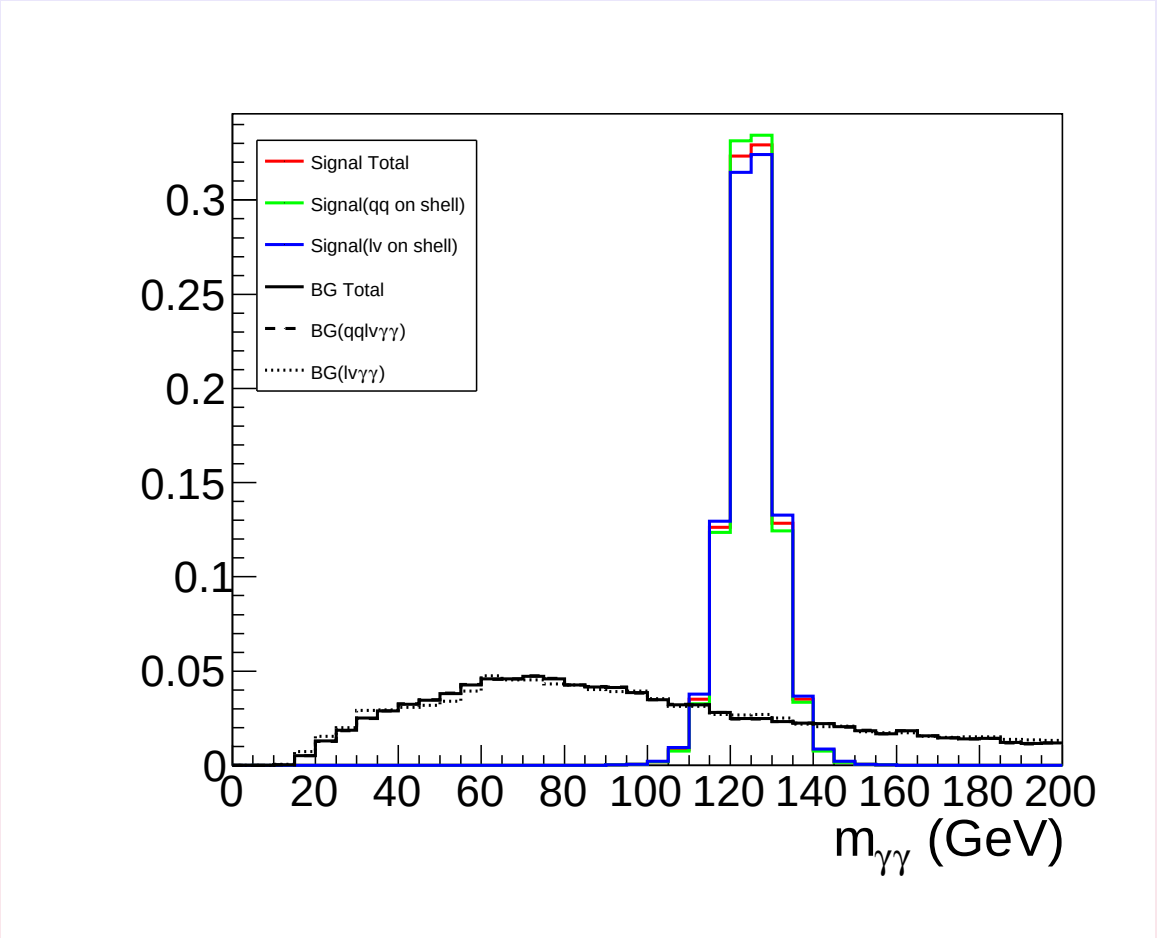
- Overlab remove:
  - Electrons with $\Delta R(e, \gamma) < 0.4$ are removed;
  - Jets(BTag,TauTag $= 0$) with $\Delta R(\text{jet}, e) < 0.2$ or $\Delta R(\text{jet}, \gamma) < 0.4$ are removed;
  - Muons with $\Delta R(\mu, \text{jet}) < 0.4$ or $\Delta R(\mu, \gamma) < 0.4$ are removed.
- Final state($q\ q\ \ell\ \nu\ \gamma\ \gamma$) selection:
  - Number of qjet ≥ 2, choosing leading and subleading qjet pair;
  - Number of photon ≥ 2, $m_{\gamma\gamma}$ of photon pair closest to m_h;
  - Number of electron or muon $= 1$.
- Basic cuts: $|\eta_{\gamma,q,\ell}| < 2.5$, $P_{T_{\gamma,q}} > 25$ GeV, $P_{T_\ell} > 15$ GeV.

Distribution of photon($M_H = 300\text{GeV}$)



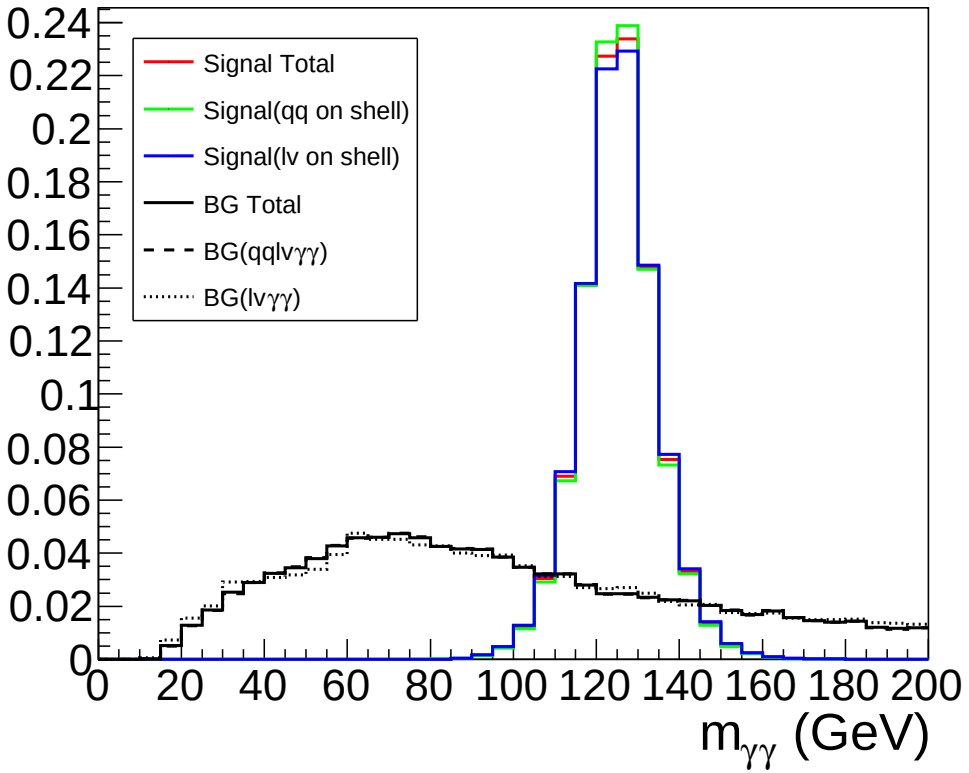
- Cut based: 120 GeV $< m_{\gamma\gamma} <$ 130 GeV.

Distribution of photon($M_H = 400\text{GeV}$)



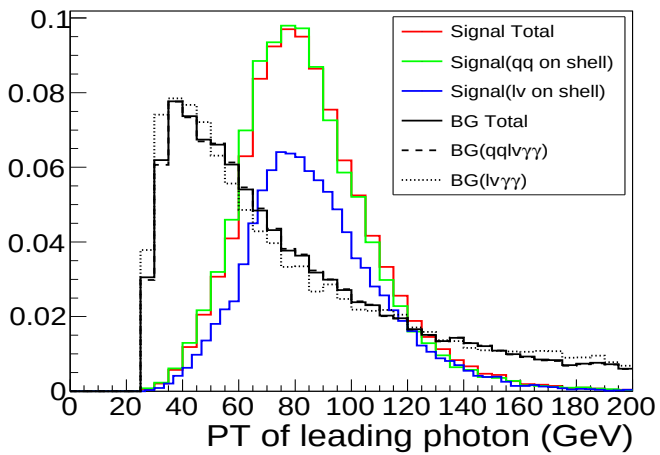
- Cut based: 120 GeV $< m_{\gamma\gamma} <$ 130 GeV.

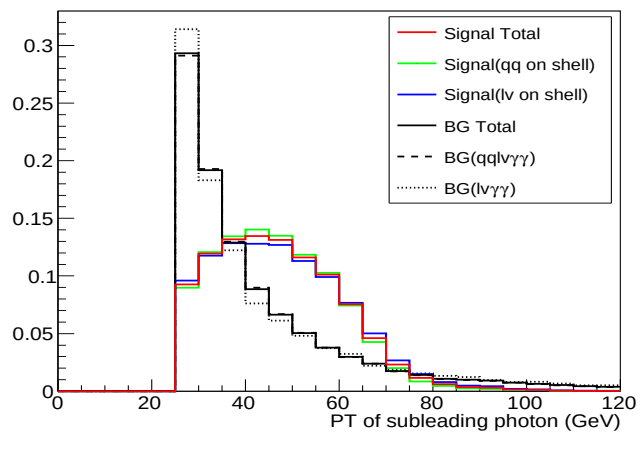
Distribution of photon($M_H = 600\text{GeV}$)

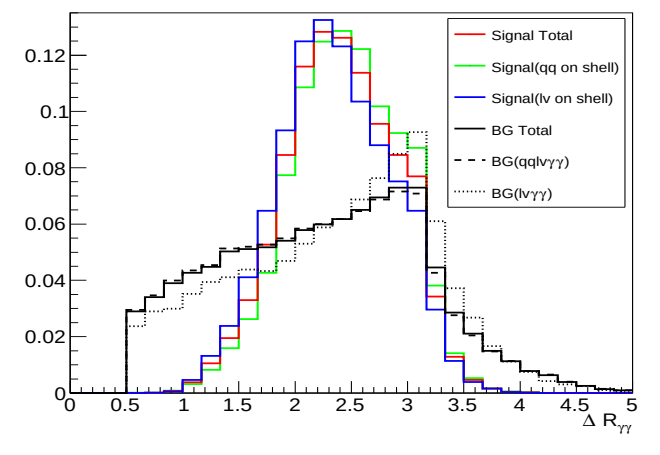


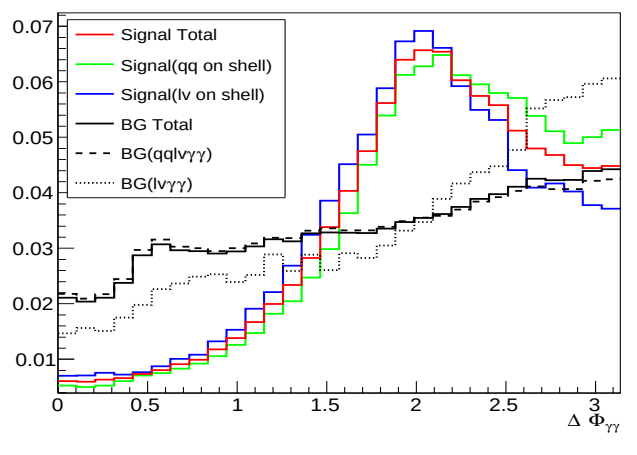
- Cut based: 115 GeV $< m_{\gamma\gamma} <$ 135 GeV.

Distribution of photon($M_H = 300\text{GeV}$)



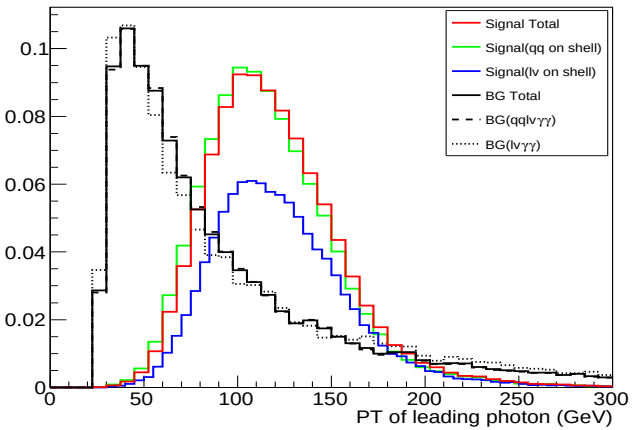


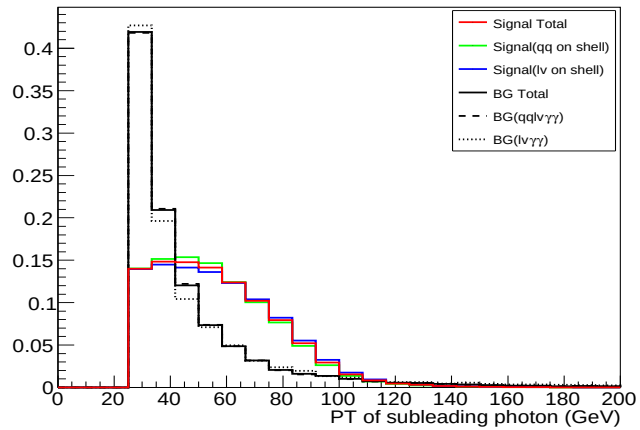


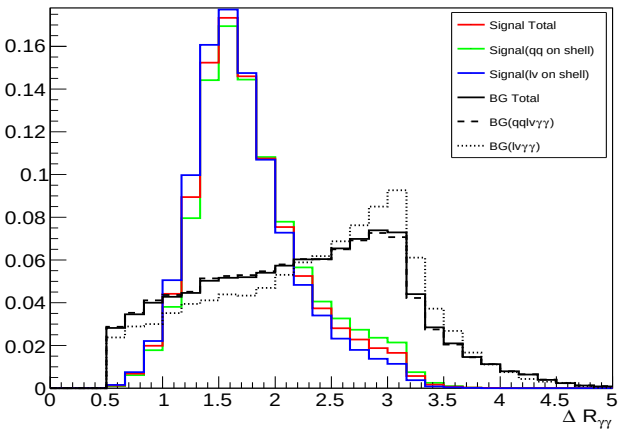


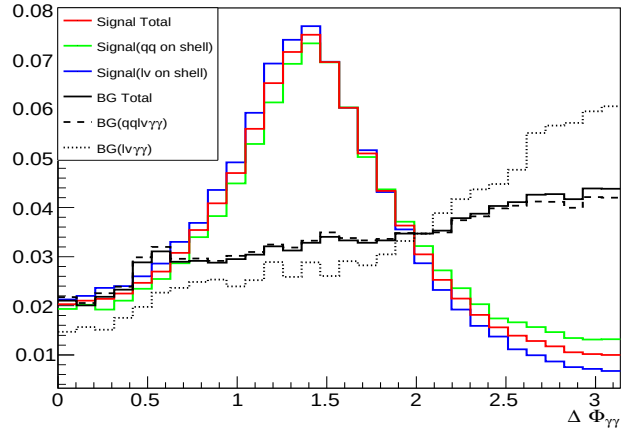
- Cut based: 60 GeV $< P_{T_{\gamma-\text{leading}}} <$ 120 GeV.

Distribution of photon($M_H = 400$GeV)



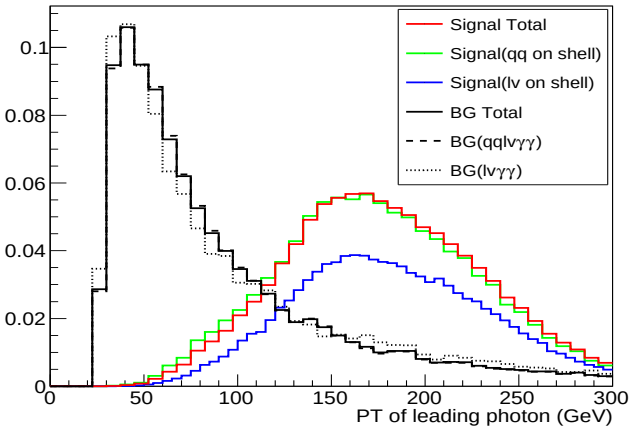


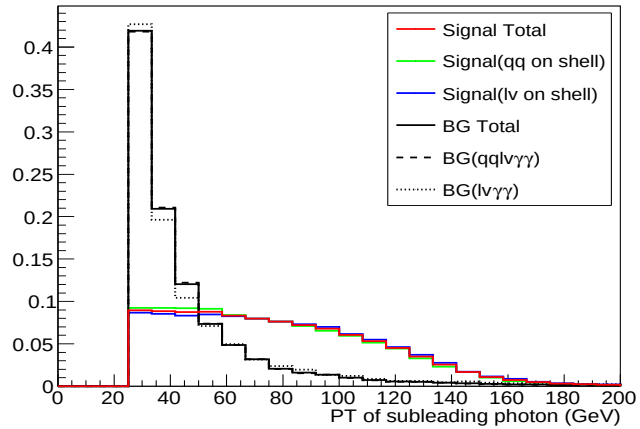


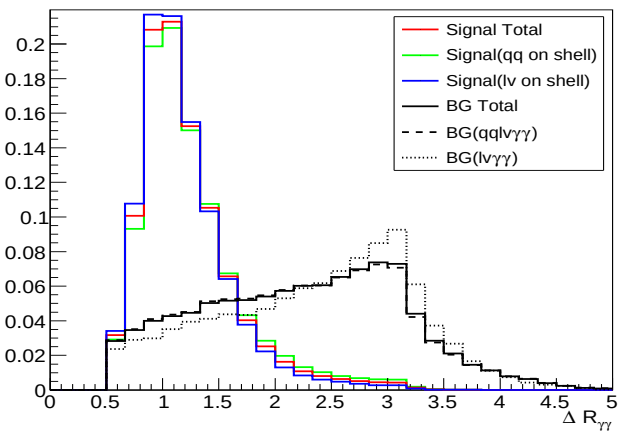


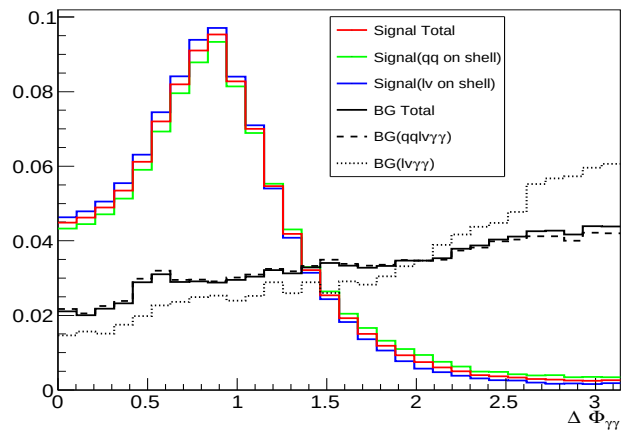
- Cut based: 80 GeV $< P_{T_{\gamma-\text{leading}}} <$ 180 GeV, $1 < \Delta R_{\gamma\gamma} < 2.1$, $\Delta\Phi_{\gamma\gamma} < 1.9$.

Distribution of photon($M_H = 600$GeV)



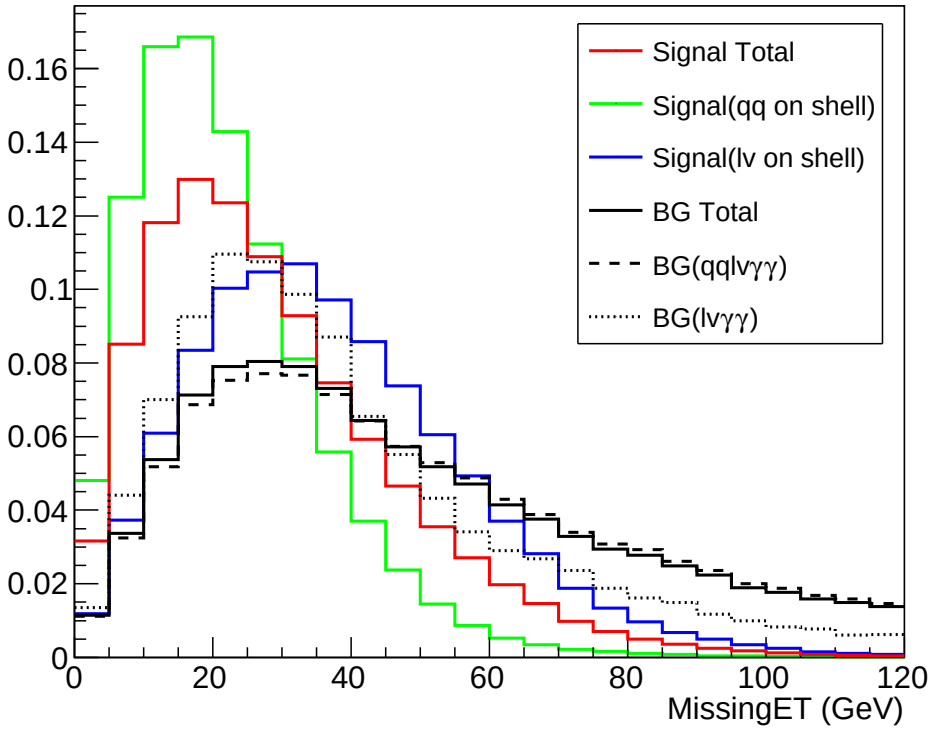






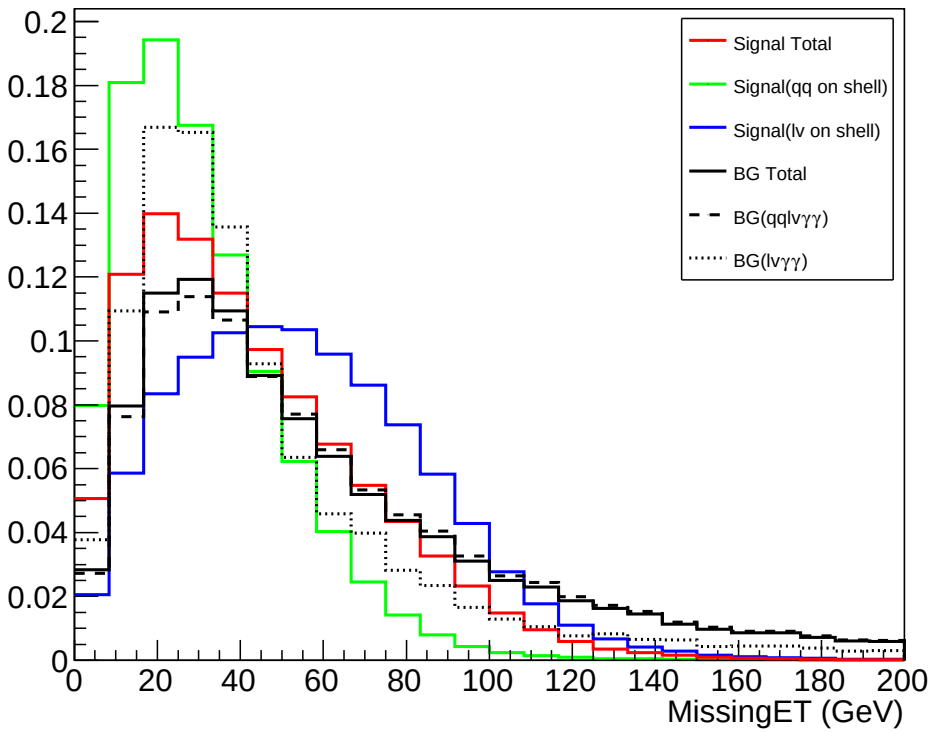
- Cut based: $P_{T_{\gamma-\text{leading}}} > 120$ GeV, $\Delta R_{\gamma\gamma} < 1.7$, $\Delta\Phi_{\gamma\gamma} < 1.4$.

Missing ET distribution($M_H = 300\text{GeV}$)

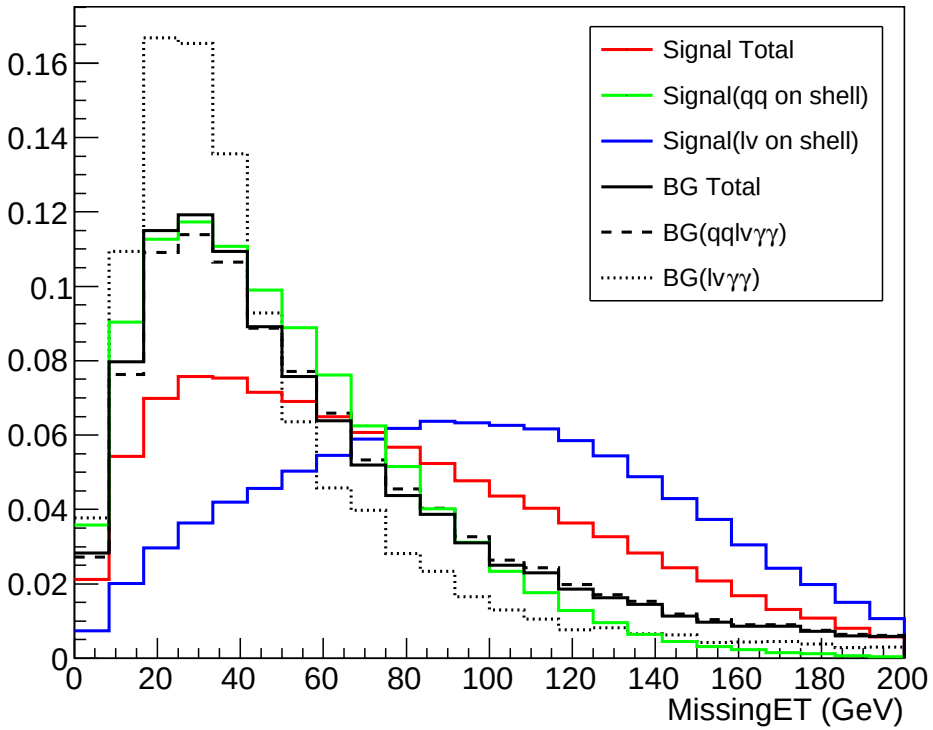


- Cut based: MET < 40 GeV.

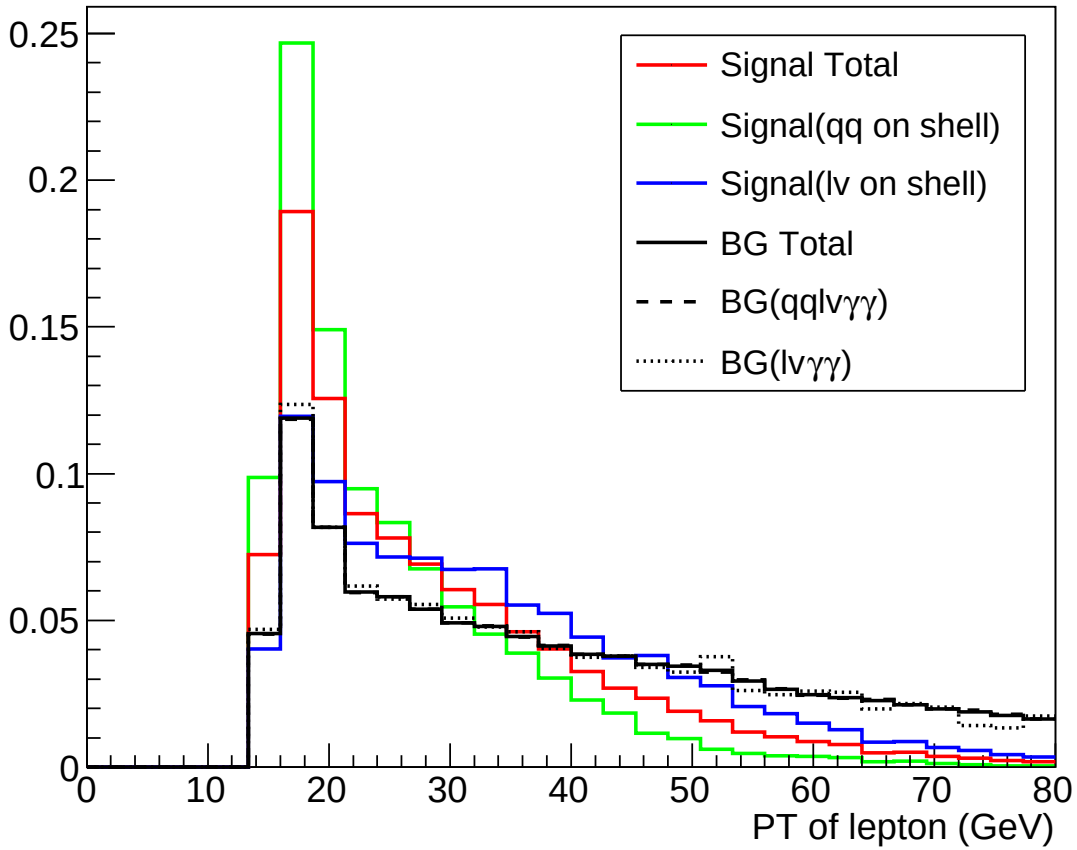
Missing ET distribution($M_H = 400\text{GeV}$)



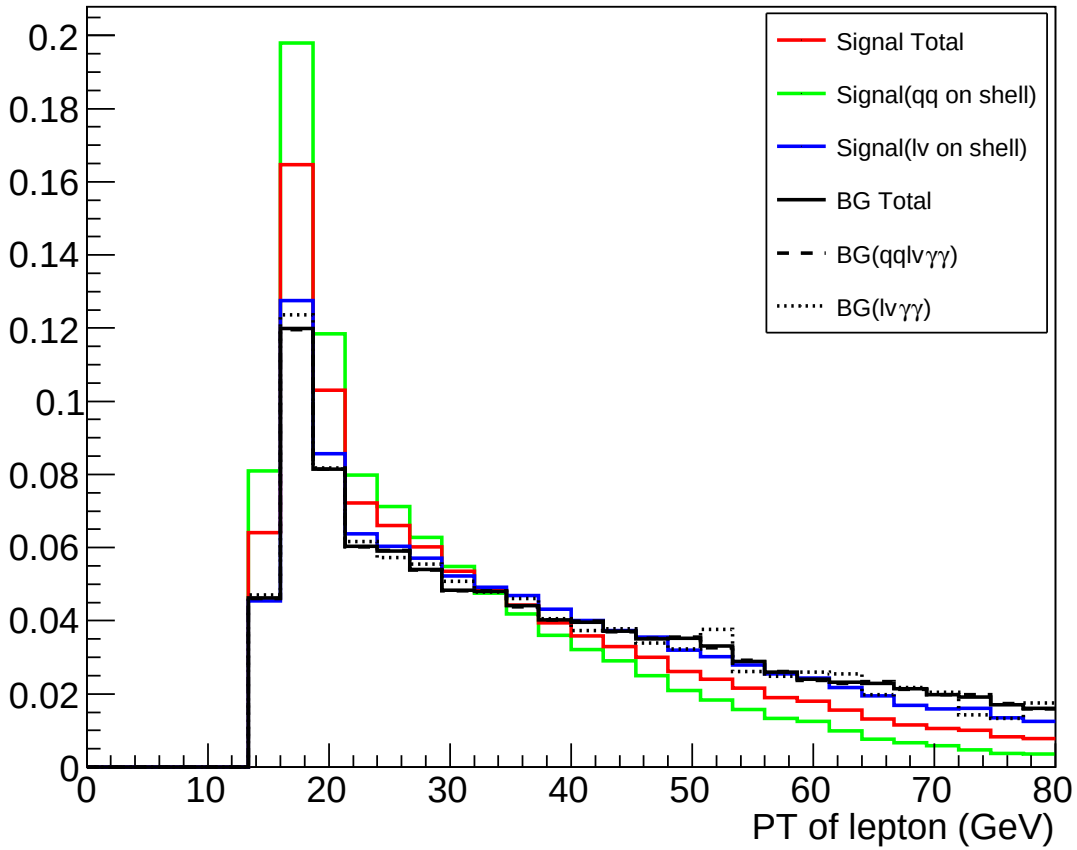
Missing ET distribution($M_H = 600\text{GeV}$)



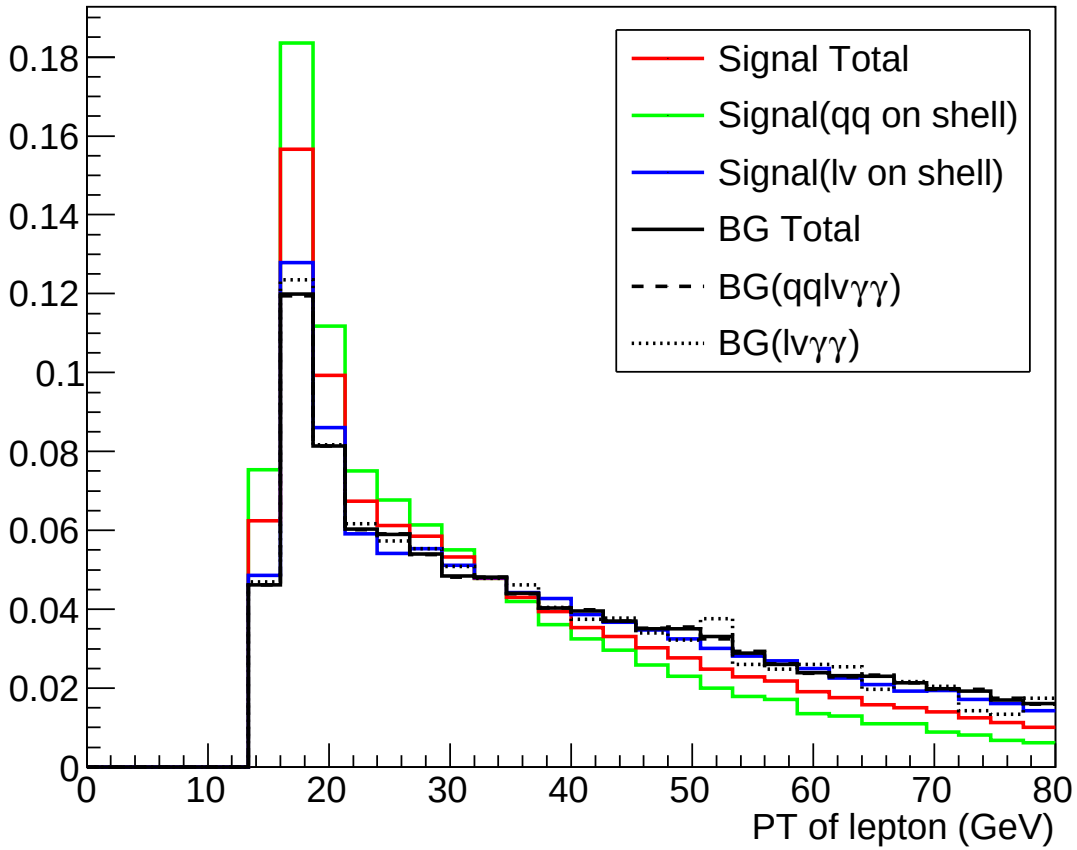
Distribution of lepton($M_H = 300\text{GeV}$)



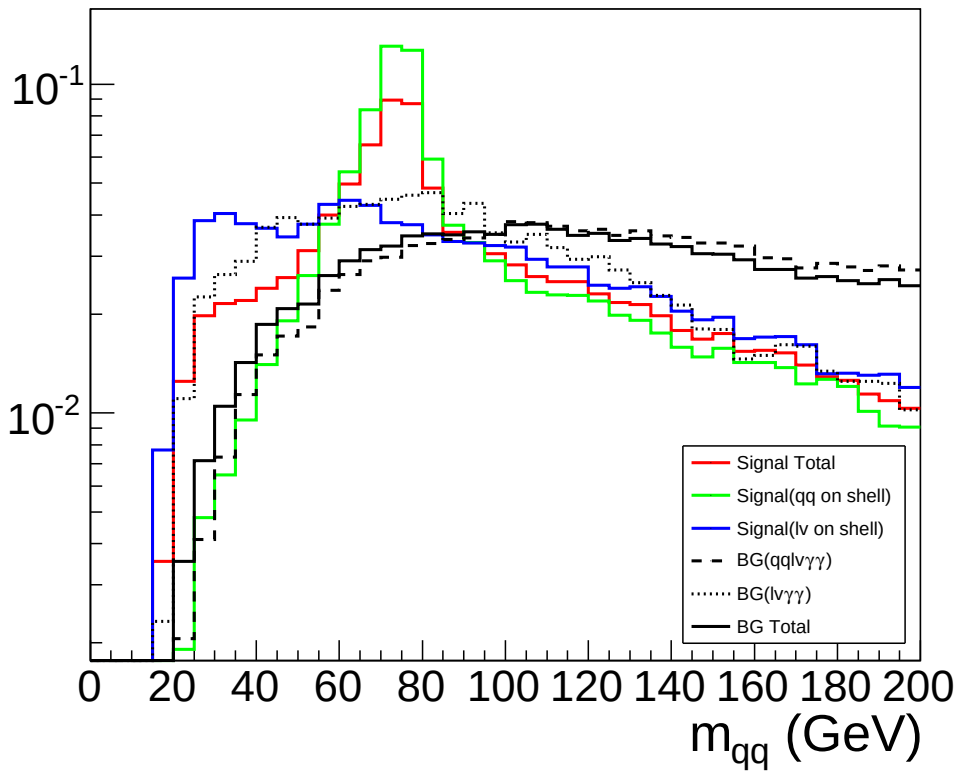
Distribution of lepton($M_H = 400\text{GeV}$)



Distribution of lepton($M_H = 600\text{GeV}$)

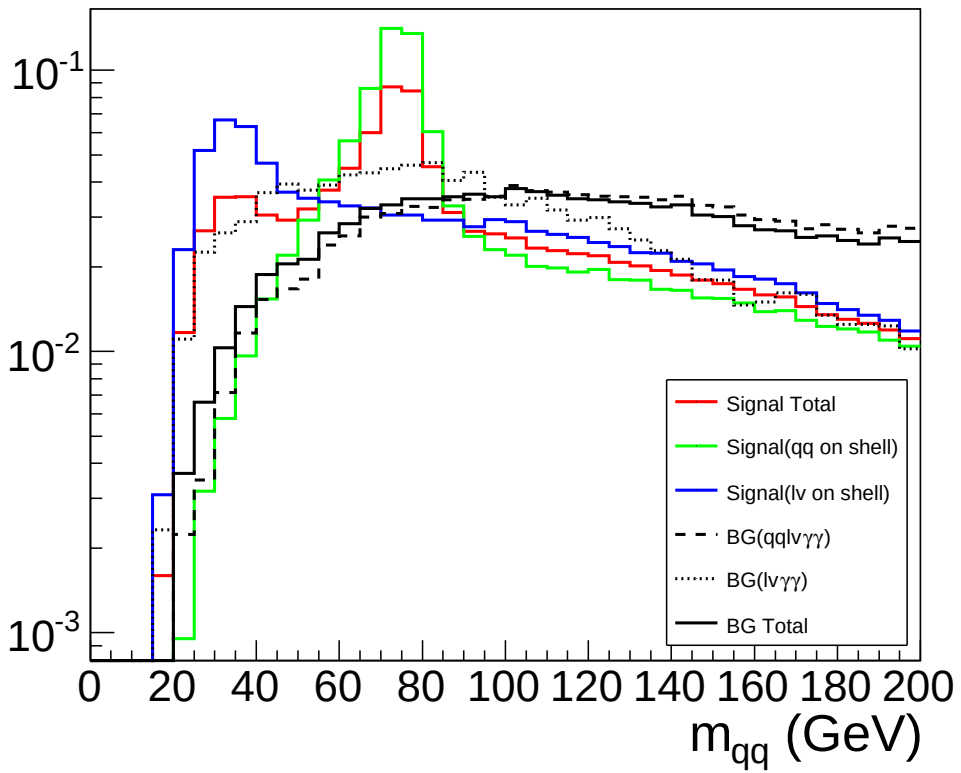


Distribution of qjet($M_H = 300\text{GeV}$)



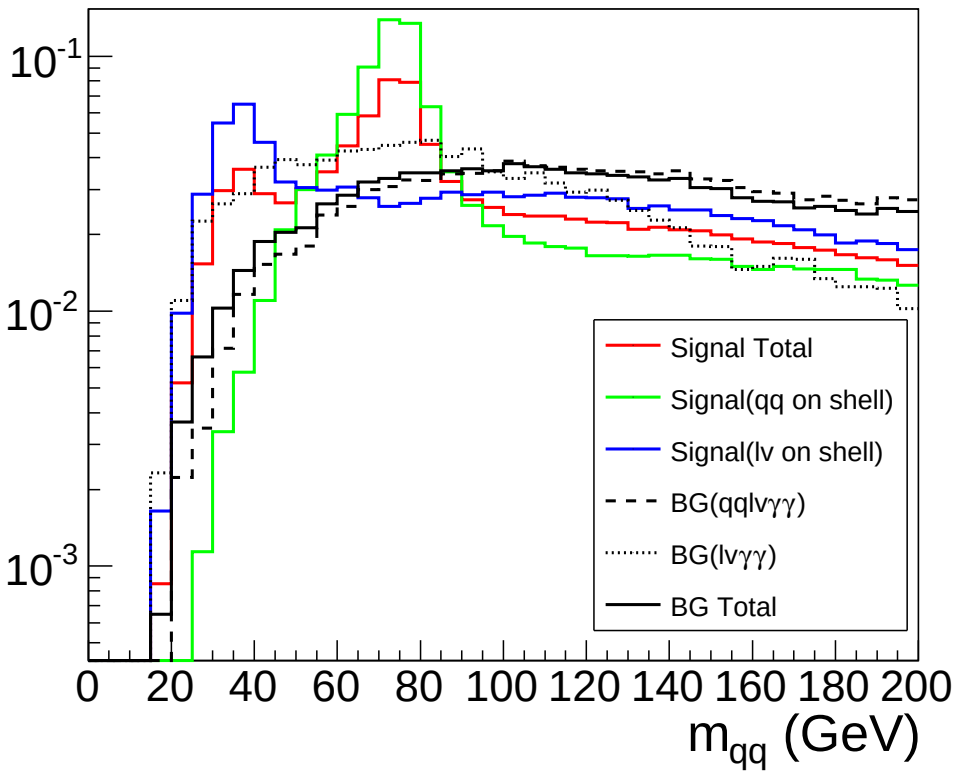
- Cut based: $m_{qq} < 90$ GeV.

Distribution of qjet($M_H = 400\text{GeV}$)



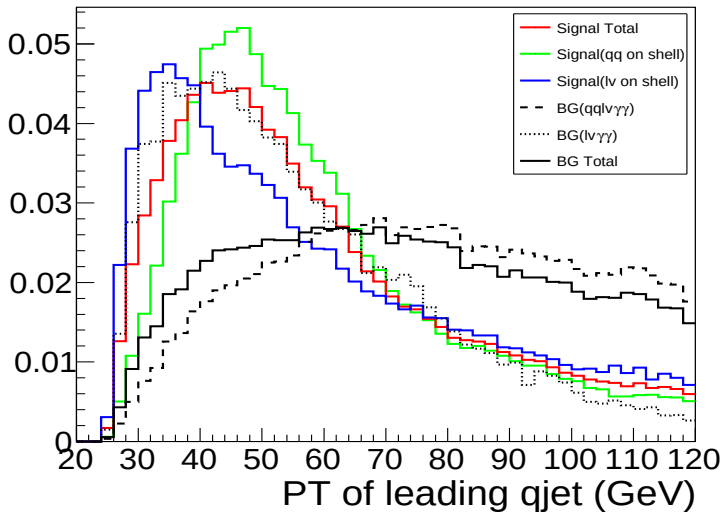
- Cut based: $m_{qq} < 90$ GeV.

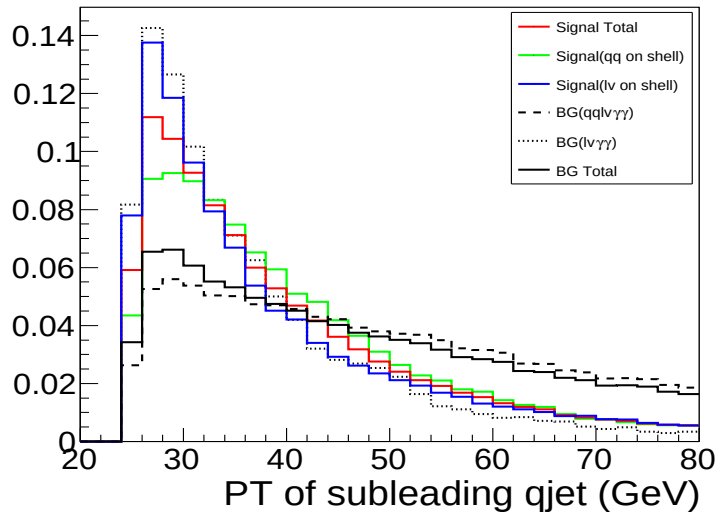
Distribution of qjet($M_H = 600\text{GeV}$)

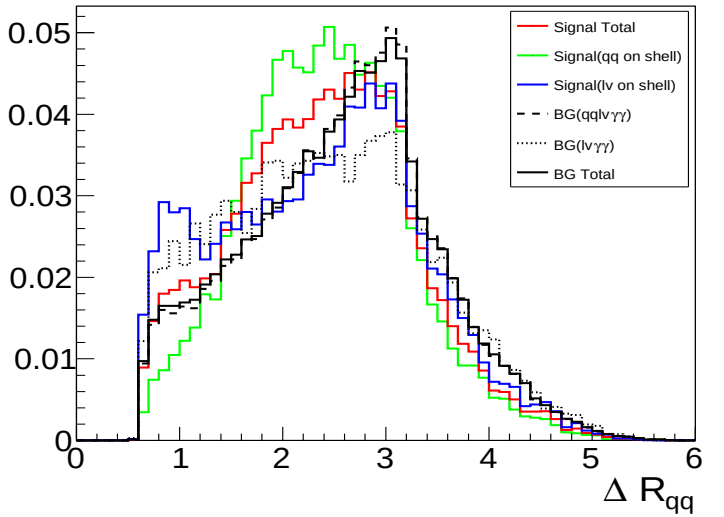


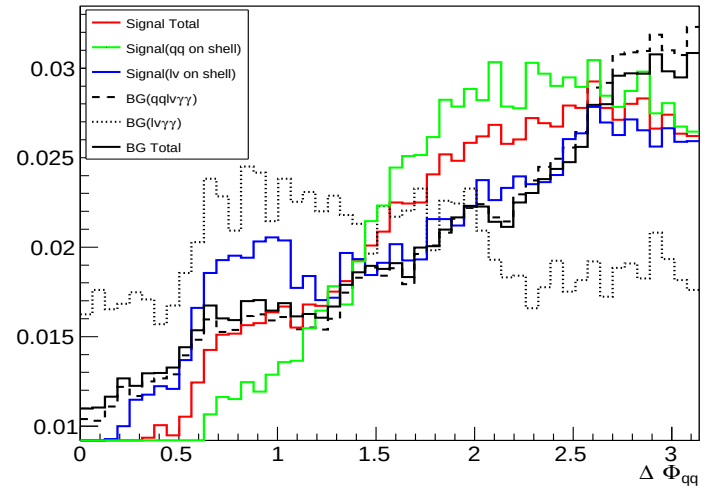
- Cut based: $m_{qq} < 90$ GeV.

Distribution of qjet($M_H = 300\text{GeV}$)

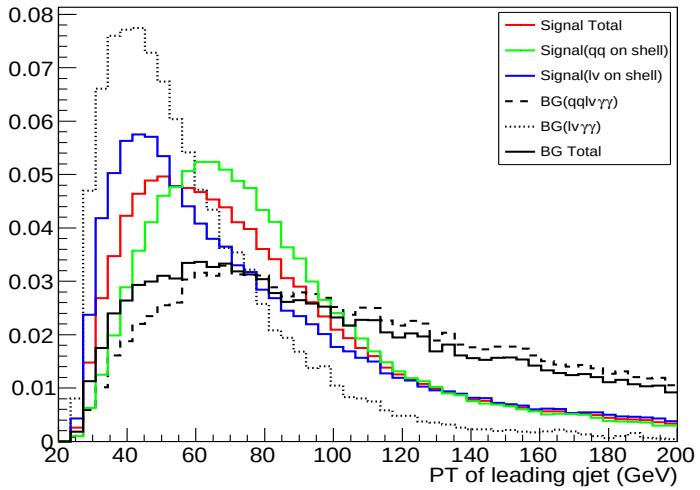


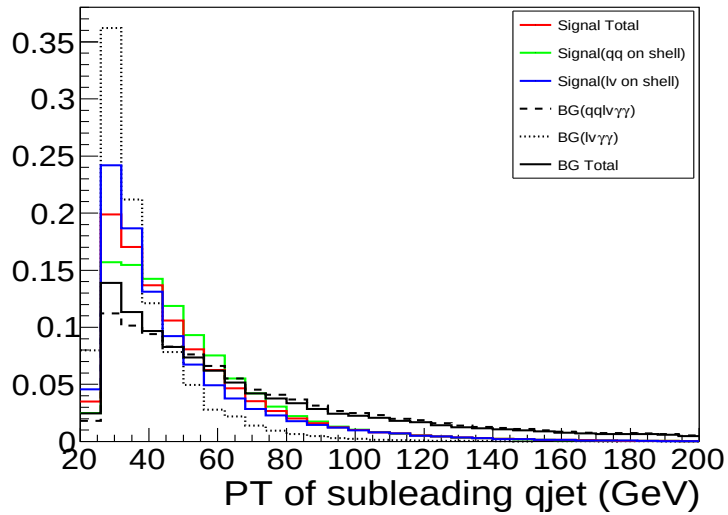


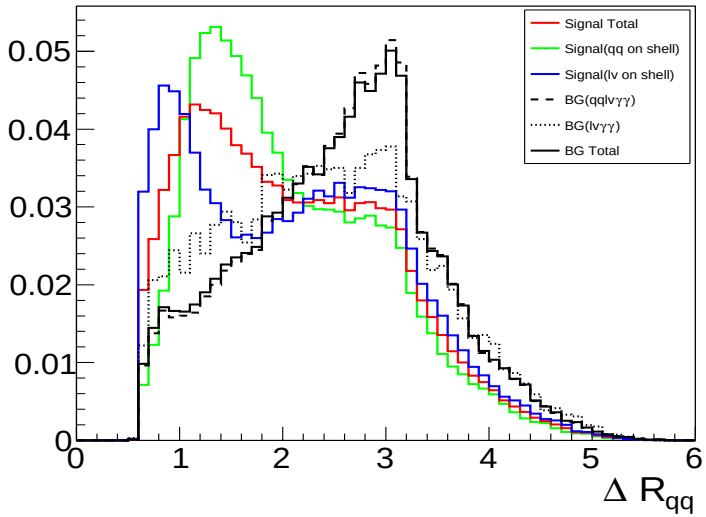


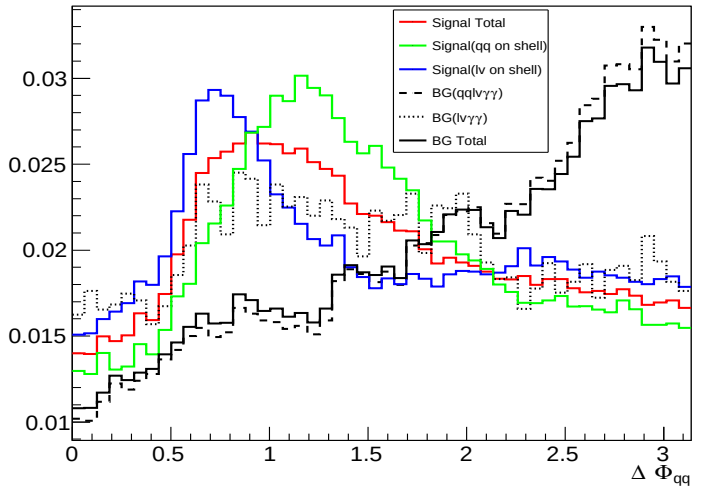


Distribution of qjet($M_H = 400$GeV)

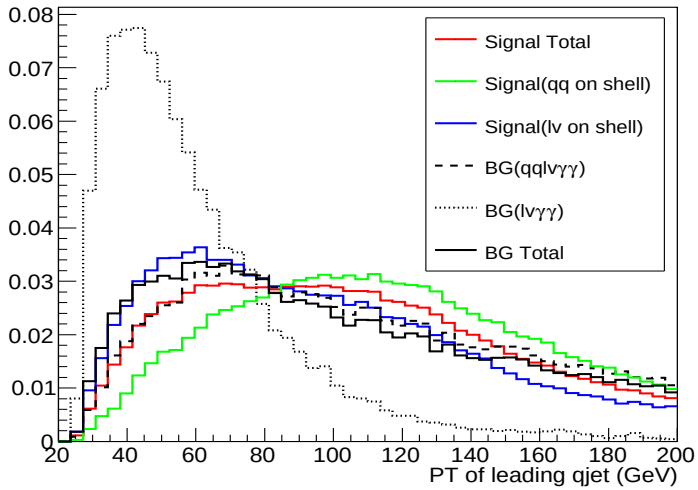


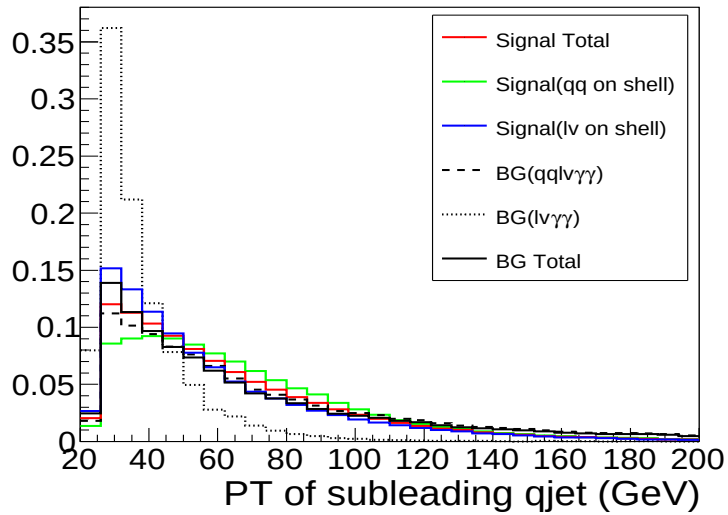


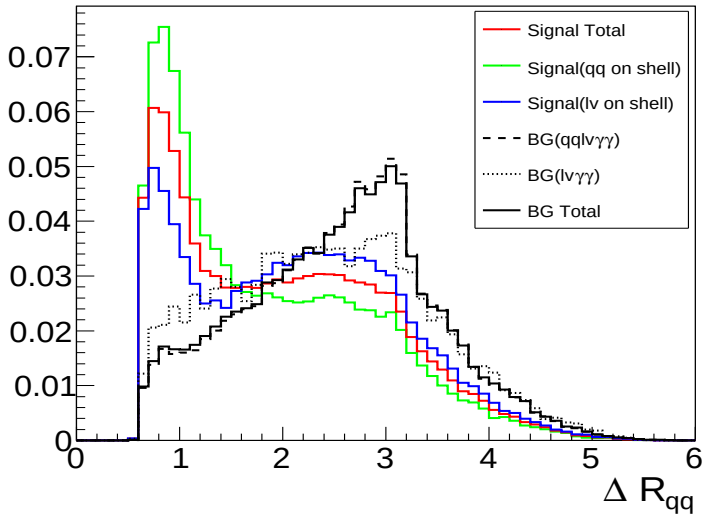


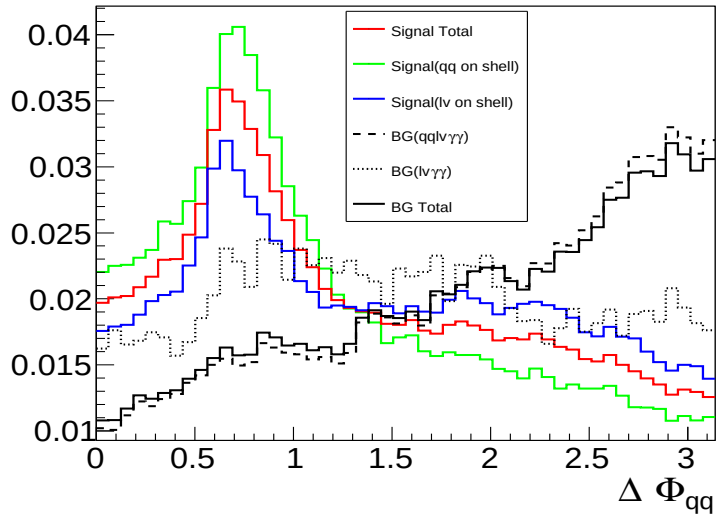


Distribution of qjet($M_H = 600\text{GeV}$)

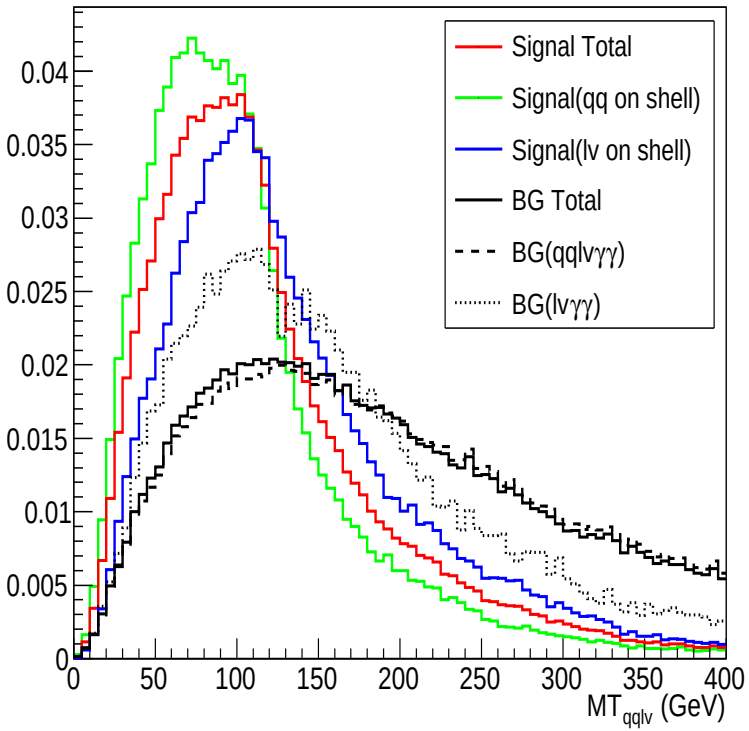


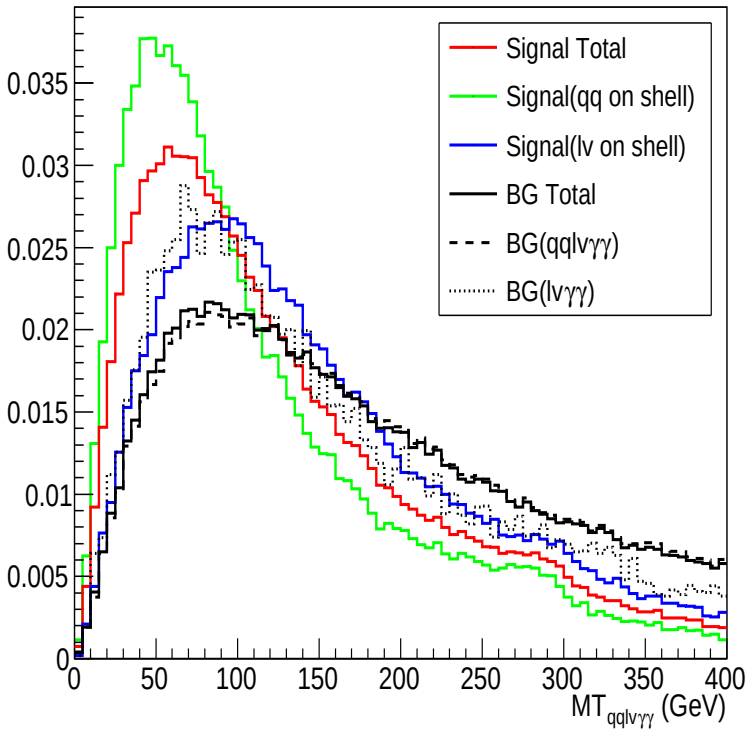






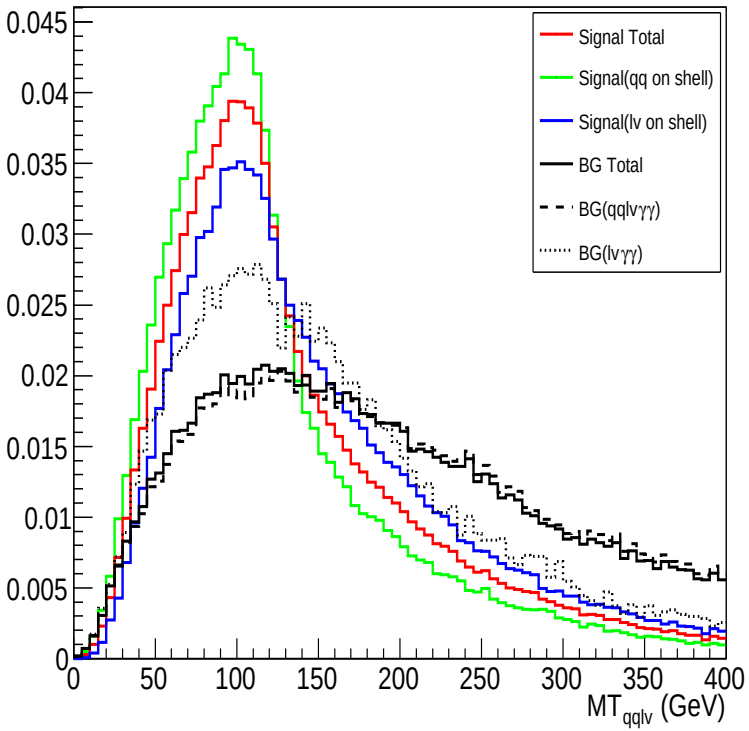
Transverse mass distribution($M_H = 300\text{GeV}$)

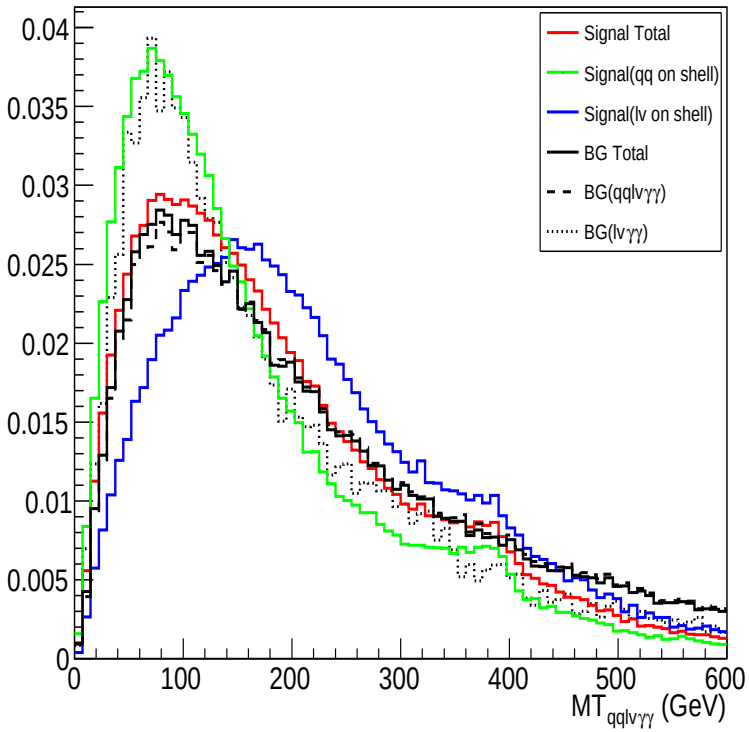




- Cut based: $M_{T_{qq\ell\nu}} < 150$ GeV.

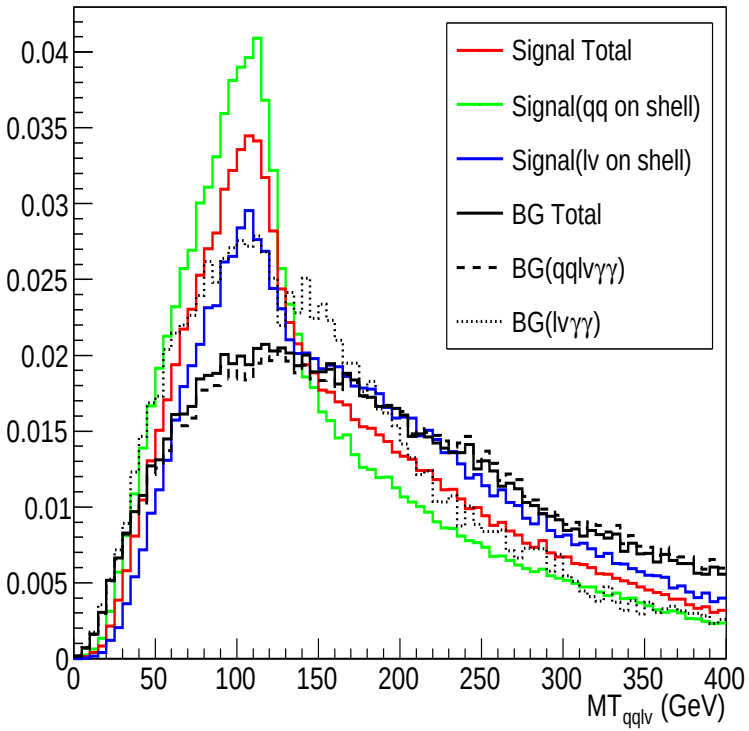
Transverse mass distribution($M_H = 400$GeV)

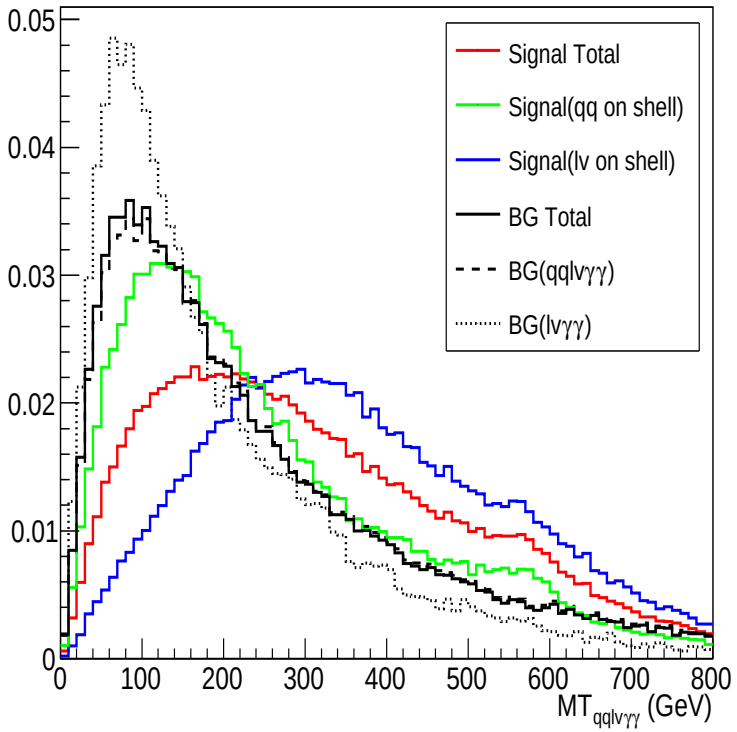




- Cut based: $M_{T_{qq\ell\nu}} < 150$ GeV.

Transverse mass distribution($M_H = 600$GeV)





- Cut based: $M_{T_{qq\ell\nu}} < 150$ GeV.

Cut efficiency(Semi-leptonic decay, $M_H = 300\text{GeV}$)

Cuts	σ_{total}	Events selection	$m_{\gamma\gamma}$ m_{qq} MET	P_{T_γ}, $M_{T_{qq\ell\nu}}$
Signal [fb]	0.44	0.025	0.0083	0.0067
$qq\ell\nu\gamma\gamma$[fb]	31.59	0.58	0.0017	0.00069
$\ell\nu\gamma\gamma$[fb]	143.3	0.064	0.00078	0.00036
Wh[fb]	0.42	0.0051	0.00026	0.00015
WWh[fb]	0.0023	0.00021	0.00002	0.00001
S/B	0.0025	0.038	3.05	5.61
$S/\sqrt{B}$	1.05	0.97	5.04	6.14
Signif-P	1.05	0.97	3.78	4.06

Signif-P: $\sqrt{2 \times \Big\{(S+B) \times \ln[(S+B)/B\,] - S\Big\}}$. Integrate luminosity is assumed to be $\int \mathcal{L} dt = 1000\ \text{fb}^{-1}$.

Cut efficiency(Semi-leptonic decay, $M_H = 400$GeV)

Cuts	σ_{total}	Events selection	$m_{\gamma\gamma}$ m_{qq} P_{T_γ}	$M_{T_{qq\ell\nu}}$ $\Delta R_{\gamma\gamma}$ $\Delta\Phi_{\gamma\gamma}$
Signal [fb]	0.44	0.030	0.0078	0.0055
$qq\ell\nu\gamma\gamma$[fb]	31.59	0.58	0.0016	0.0003
$\ell\nu\gamma\gamma$[fb]	143.3	0.064	0.00055	0.00004
Wh[fb]	0.42	0.0051	0.0004	0.0001
WWh[fb]	0.0023	0.00021	0.000028	0.000006
S/B	0.00025	0.0046	3.05	12.3
$S/\sqrt{B}$	1.05	1.16	4.89	8.20
Signif-P	1.05	1.16	3.67	4.44

Signif-P: $\sqrt{2 \times \Big\{(S+B) \times \ln[(S+B)/B\,] - S\Big\}}$. Integrate luminosity is assumed to be $\int \mathcal{L} dt = 1000$ fb^{-1}.

Cut efficiency(Semi-leptonic decay, $M_H = 600\text{GeV}$)

Cuts	σ_{total}	Events selection	$m_{\gamma\gamma}$ m_{qq} P_{T_γ}	$M_{T_{qq\ell\nu}}$ $\Delta R_{\gamma\gamma}$ $\Delta\Phi_{\gamma\gamma}$
Signal [fb]	0.044	0.0026	0.00063	0.00048
$qq\ell\nu\gamma\gamma$[fb]	31.59	0.58	0.0010	0.000069
$\ell\nu\gamma\gamma$[fb]	143.3	0.064	0.00033	0.000013
Wh[fb]	0.42	0.0051	0.00029	0.000065
WWh[fb]	0.0023	0.00021	0.000026	0.000005
S/B	0.00025	0.0040	0.38	3.17
$S/\sqrt{B}$	0.11	0.10	0.49	1.23
Signif-P	0.11	0.10	0.46	0.92

Signif-P: $\sqrt{2 \times \Big\{(S+B) \times \ln[(S+B)/B\,] - S\Big\}}$. Integrate luminosity is assumed to be $\int \mathcal{L} dt = 1000\ \text{fb}^{-1}$.

Cut efficiency(Semi-leptonic decay, $M_H = 600\text{GeV}$)

Cuts	σ_{total}	Events selection	$m_{\gamma\gamma}$ m_{qq} P_{T_γ}	$M_{T_{qq\ell\nu}}$ $\Delta R_{\gamma\gamma}$ $\Delta\Phi_{\gamma\gamma}$
Signal [fb]	0.044	0.0026	0.00063	0.00048
$qq\ell\nu\gamma\gamma$[fb]	31.59	0.58	0.0010	0.000069
$\ell\nu\gamma\gamma$[fb]	143.3	0.064	0.00033	0.000013
Wh[fb]	0.42	0.0051	0.00029	0.000065
WWh[fb]	0.0023	0.00021	0.000026	0.000005
S/B	0.00025	0.0040	0.38	3.17
$S/\sqrt{B}$	0.23	0.23	1.09	2.76
Signif-P	0.23	0.23	1.03	2.05

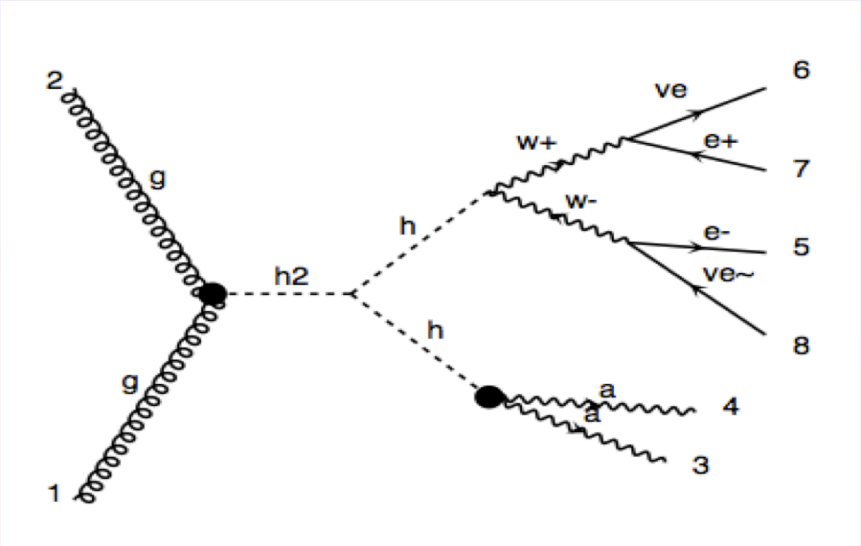
Signif-P: $\sqrt{2 \times \Big\{(S+B) \times \ln[(S+B)/B\,] - S\Big\}}$. Integrate luminosity is assumed to be $\int \mathcal{L} dt = 5000\ \text{fb}^{-1}$.

Leptonic decay channel

- Fast-simulation project:

  MG5 + pythia + delphes 3.0.10.

- 2HDM Signal: $M_H = 300$ GeV and $M_H = 600$ GeV.



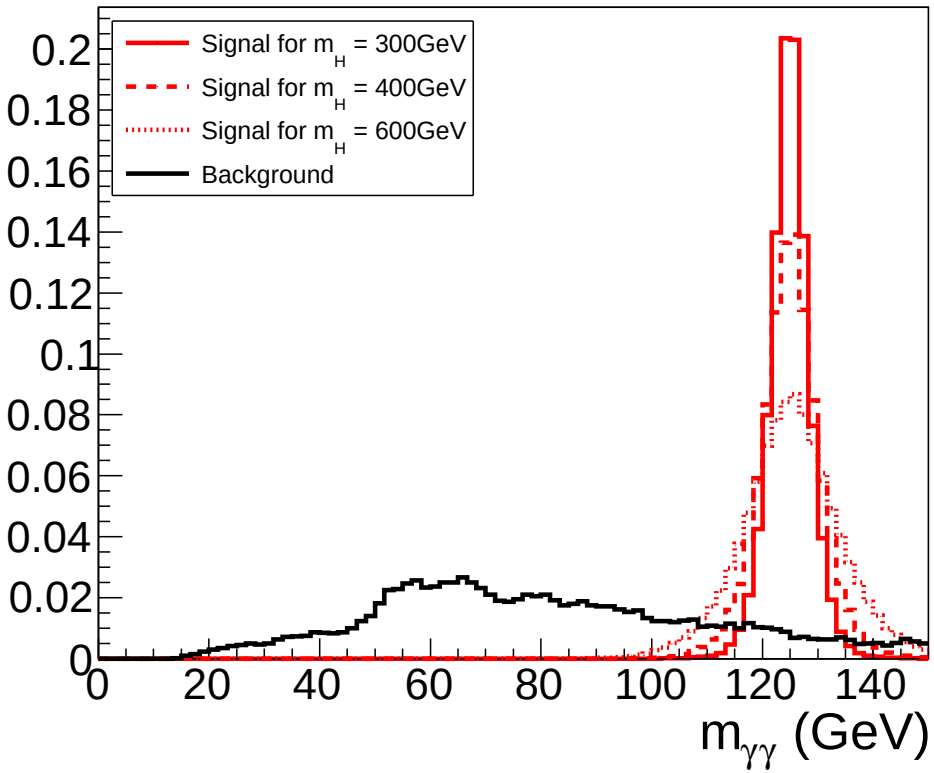
- SM irreducible background:

$$p\ p \ \to \ \ell\ \nu\ \ell\ \nu\ \gamma\ \gamma$$
$$+\ p\ p \ \to \ \ell^+\ \ell^-\ \gamma\ \gamma \sim \ 153.3[\text{fb}].$$

Events selection

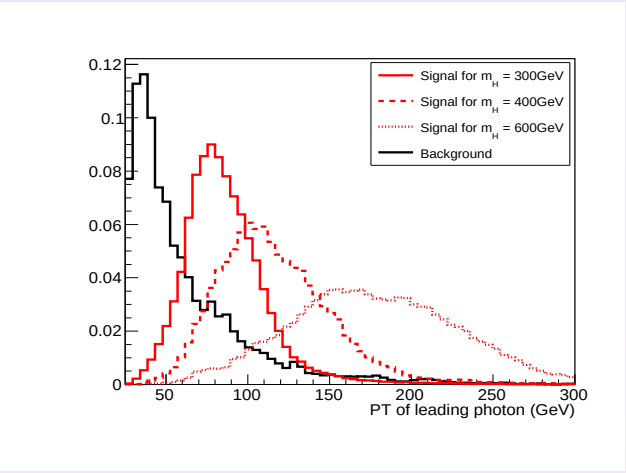
- Overlab remove:
  - Electrons with $\Delta R(e, \gamma) < 0.4$ are removed;
  - Jets(BTag,TauTag $= 0$) with $\Delta R(\text{jet}, e) < 0.2$ or $\Delta R(\text{jet}, \gamma) < 0.4$ are removed;
  - Muons with $\Delta R(\mu, \text{jet}) < 0.4$ or $\Delta R(\mu, \gamma) < 0.4$ are removed.
- Final state($\ell\ \nu\ \ell\ \nu\ \gamma\ \gamma$) selection:
  - Number of photon ≥ 2, $m_{\gamma\gamma}$ of photon pair closest to m_h;
  - Number of electron + muon $= 2$.
- Basic cuts: $|\eta_{\gamma,\ell}| < 2.5$, $P_{T_\gamma} > 25$ GeV, $P_{T_\ell} > 15$ GeV.

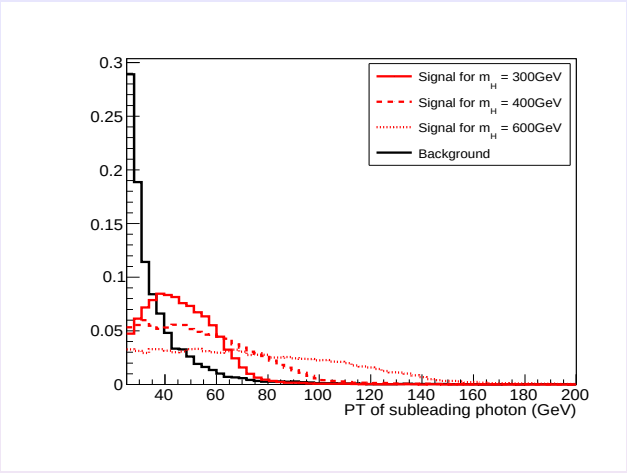
Distribution of photon

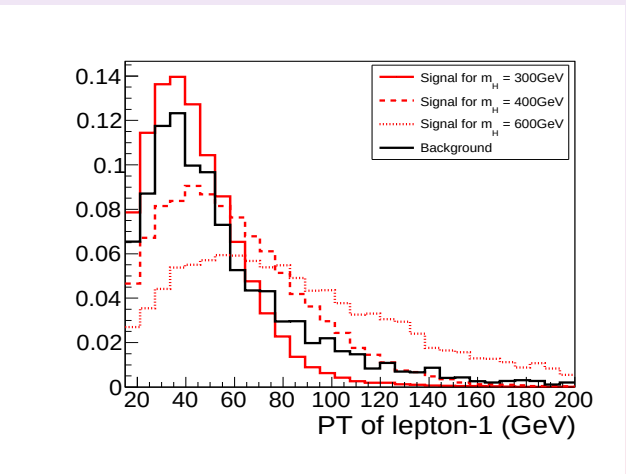


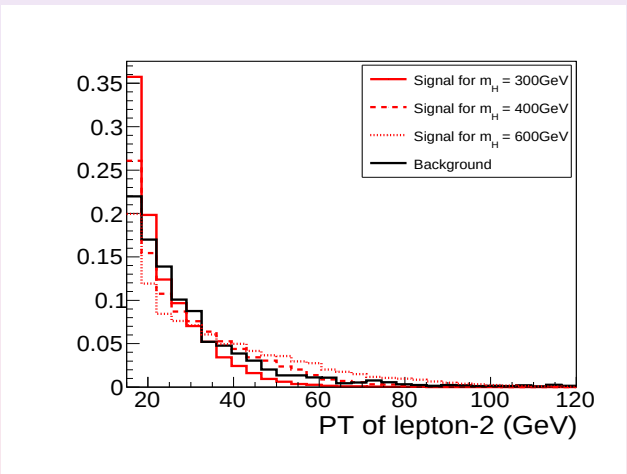
- Cut based: $120\ \text{GeV} < m_{\gamma\gamma} < 130\ \text{GeV} (m_H = 300\text{GeV})$.
- Cut based: $120\ \text{GeV} < m_{\gamma\gamma} < 130\ \text{GeV} (m_H = 400\text{GeV})$.
- Cut based: $115\ \text{GeV} < m_{\gamma\gamma} < 135\ \text{GeV} (m_H = 600\text{GeV})$.

Distribution of PT





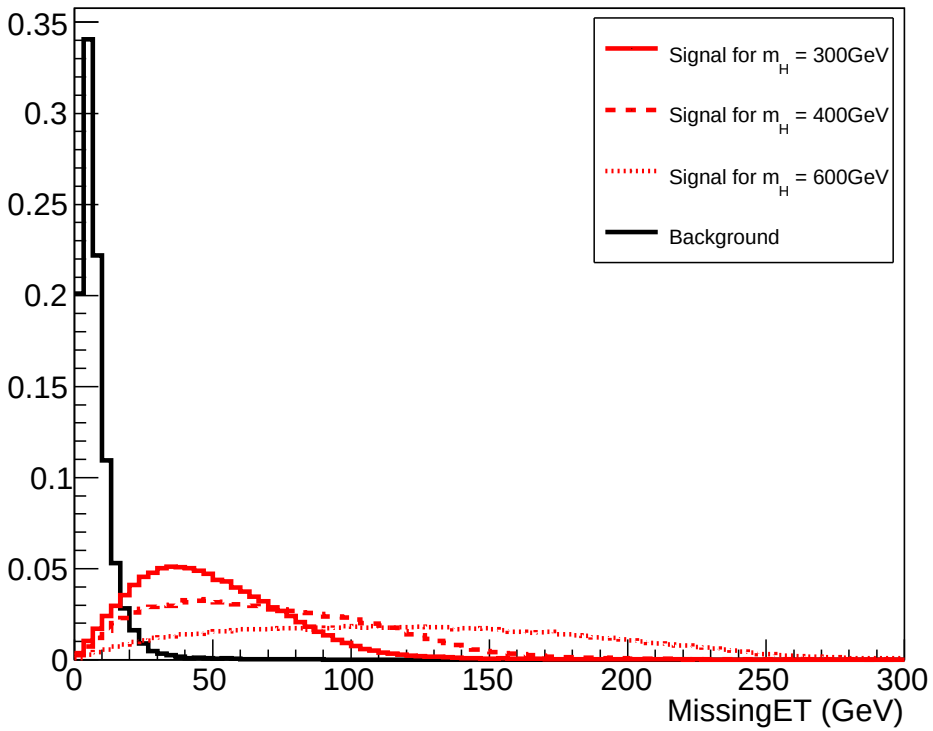




Cut based:

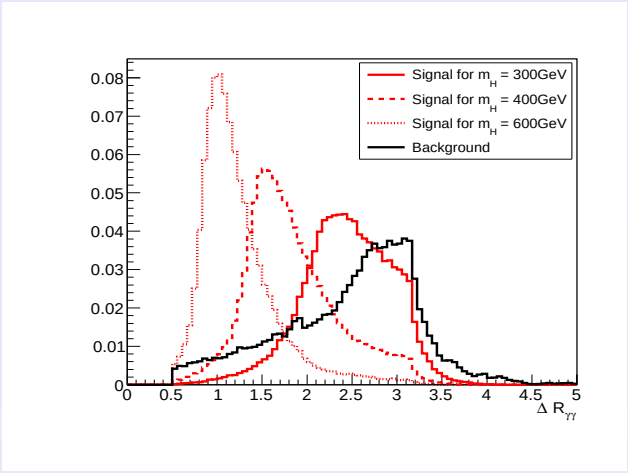
- $P_{T_{\gamma-\text{leading}}} > 70$ GeV, $P_{T_{\gamma-\text{subleading}}} > 40$ GeV$(m_H = 400\text{GeV})$.
- $P_{T_{\gamma-\text{leading}}} > 100$ GeV, $P_{T_{\gamma-\text{subleading}}} > 50$ GeV$(m_H = 600\text{GeV})$.

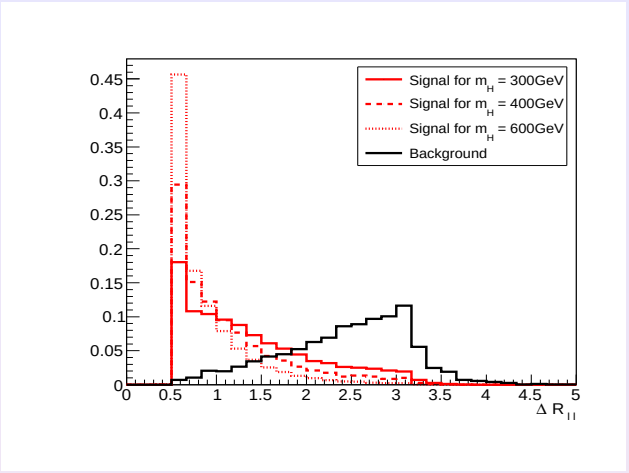
Missing ET distribution

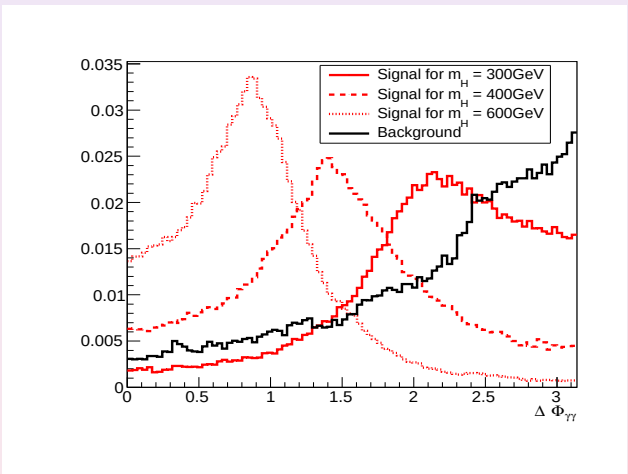


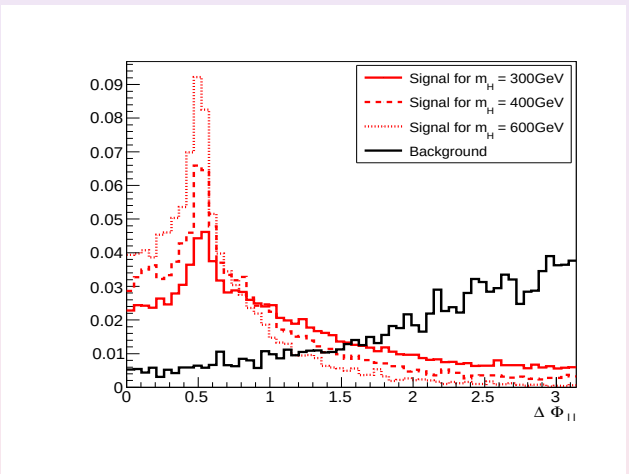
- Cut based: MET > 20 GeV$(m_H = 300\text{GeV})$.
- Cut based: MET > 20 GeV$(m_H = 400\text{GeV})$.
- Cut based: MET > 30 GeV$(m_H = 600\text{GeV})$.

Distribution of ΔR and $\Delta\Phi$





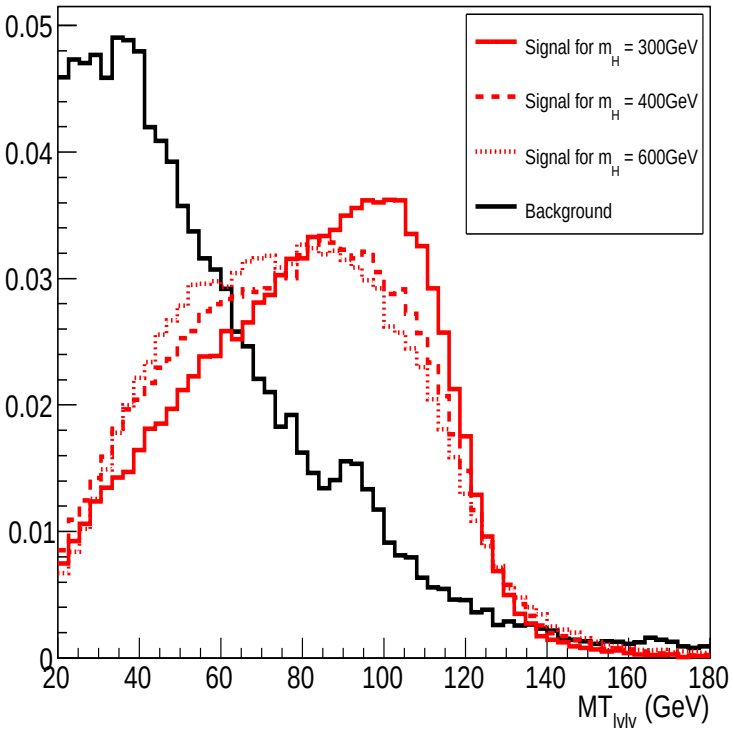


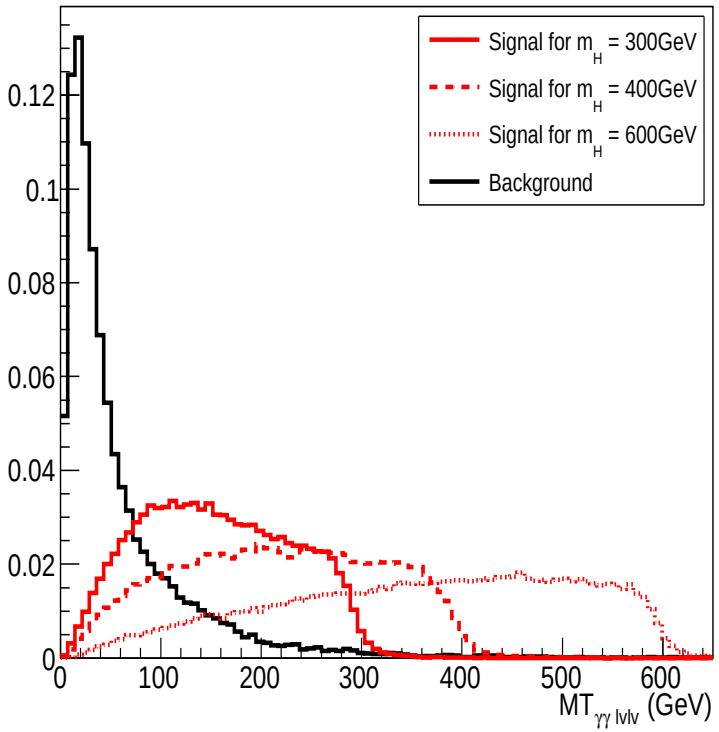


Cut based:

- $\Delta R_{\ell\ell} < 1.8$ and $\Delta\Phi_{\ell\ell} < 1.5 (m_H = 300\text{GeV})$.
- $\Delta R_{\gamma\gamma} < 2.3$, $\Delta\Phi_{\gamma\gamma} < 2.0$, $\Delta R_{\ell\ell} < 1.5$, $\Delta\Phi_{\ell\ell} < 1.5 (m_H = 400\text{GeV})$.
- $\Delta R_{\gamma\gamma} < 1.8$, $\Delta\Phi_{\gamma\gamma} < 1.6$, $\Delta R_{\ell\ell} < 1.5$, $\Delta\Phi_{\ell\ell} < 1.2 (m_H = 600\text{GeV})$.

Transverse mass distribution





- Cut based: 70 GeV $< M_{T_{\ell\nu\ell\nu\gamma\gamma}} <$ 300 GeV($m_H = 300$GeV).
- Cut based: 75 GeV $< M_{T_{\ell\nu\ell\nu\gamma\gamma}} <$ 400 GeV($m_H = 400$GeV).
- Cut based: 75 GeV $< M_{T_{\ell\nu\ell\nu\gamma\gamma}} <$ 600 GeV($m_H = 600$GeV).

Cut efficiency(Leptonic decay, $M_H = 300\text{GeV}$)

Cuts	σ_{total}	Events selection	$m_{\gamma\gamma}$, MET	$M_{T_{\ell\nu\ell\nu\gamma\gamma}}$ $\Delta R_{\ell\ell}$ $\Delta\Phi_{\ell\ell}$
Signal [fb]	0.105	0.0051	0.0038	0.0023
BG[fb]	153.3	0.94	0.0013	0.00009
S/B	0.0007	0.005	2.99	25.3
$S/\sqrt{B}$	0.27	0.17	3.37	7.69
Signif-P	0.27	0.17	2.54	3.34

Signif-P: $\sqrt{2 \times \Big\{(S+B) \times \ln[(S+B)/B\,] - S\Big\}}$. Integrate luminosity is assumed to be $\int \mathcal{L} dt = 1000\ \text{fb}^{-1}$.

Cut efficiency(Leptonic decay, $M_H = 400$GeV)

Cuts	σ_{total}	Events selection	$m_{\gamma\gamma}$ MET P_{T_γ}	$M_{T_{\ell\nu\ell\nu\gamma\gamma}}$ $\Delta R_{\ell\ell,\gamma\gamma}$ $\Delta\Phi_{\ell\ell,\gamma\gamma}$
Signal [fb]	0.105	0.0054	0.0020	0.0013
BG[fb]	153.3	0.94	0.0005	0.000015
S/B	0.00068	0.0058	4.10	84.1
$S/\sqrt{B}$	0.27	0.18	2.87	10.4
Signif-P	0.27	0.18	2.03	3.00

Signif-P: $\sqrt{2 \times \Big\{(S+B) \times \ln[(S+B)/B\,] - S\Big\}}$. Integrate luminosity is assumed to be $\int \mathcal{L} dt = 1000$ fb^{-1}.

Cut efficiency(Leptonic decay, $M_H = 600\text{GeV}$)

Cuts	σ_{total}	Events selection	$m_{\gamma\gamma}$ MET P_{T_γ}	$M_{T_{\ell\nu\ell\nu\gamma\gamma}}$ $\Delta R_{\ell\ell,\gamma\gamma}$ $\Delta\Phi_{\ell\ell,\gamma\gamma}$
Signal [fb]	0.0105	0.00057	0.00026	0.00023
BG[fb]	153.3	0.94	0.000031	0.000015
S/B	0.00007	0.0006	8.58	14.70
$S/\sqrt{B}$	0.027	0.019	1.50	1.82
Signif-P	0.027	0.019	0.90	0.94

Signif-P: $\sqrt{2 \times \Big\{(S+B) \times \ln[(S+B)/B\,] - S\Big\}}$. Integrate luminosity is assumed to be $\int \mathcal{L} dt = 1000\ \text{fb}^{-1}$.

Cut efficiency(Leptonic decay, $M_H = 600$GeV)

Cuts	σ_{total}	Events selection	$m_{\gamma\gamma}$ MET P_{T_γ}	$M_{T_{\ell\nu\ell\nu\gamma\gamma}}$ $\Delta R_{\ell\ell,\gamma\gamma}$ $\Delta\Phi_{\ell\ell,\gamma\gamma}$
Signal [fb]	0.0105	0.00057	0.00026	0.00023
BG[fb]	153.3	0.94	0.000031	0.000015
S/B	0.00007	0.0006	8.58	14.70
$S/\sqrt{B}$	0.060	0.042	3.36	4.07
Signif-P	0.060	0.042	2.00	2.09

Signif-P: $\sqrt{2 \times \Big\{(S+B) \times \ln[(S+B)/B\,] - S\Big\}}$. Integrate luminosity is assumed to be $\int \mathcal{L} dt = 5000$ fb^{-1}.