# Update in VBF Higgs CP test in $H \rightarrow \gamma\gamma$ channel

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# Previous review

In last report, we considered a 6-dimension EFT for VBF Higgs CPV.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{f_{\tilde{B}B}}{\Lambda^2}O_{\tilde{B}B} + \frac{f_{\tilde{W}W}}{\Lambda^2}O_{\tilde{W}W} + \frac{f_{\tilde{B}}}{\Lambda^2}O_{\tilde{B}}$$

$$= \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA}H\tilde{A}_{\mu\nu}A^{\mu\nu} + \tilde{g}_{HAZ}H\tilde{A}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HZZ}H\tilde{Z}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HWW}H\tilde{W}^{+}_{\mu\nu}W^{-\mu\nu}\,.$$

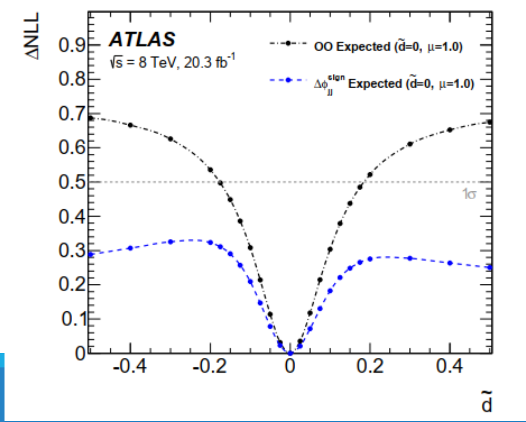
And use $\tilde{d} \sim f(\tilde{g})$ to represent the CP violation in matrix element:

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d}\cdot\mathcal{M}_{\text{CP-odd}}.$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d}\cdot 2\Re(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2\cdot|\mathcal{M}_{\text{CP-odd}}|^2\,.$$

Define Optimal Observable:

- First order: $OO_1 = \frac{2\Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$



# MC sample

Signal sample:

- SM VBF $H \rightarrow \gamma\gamma$: ATLAS official mc16, 13TeV PowhegPythia8EvtGen, NNPDF30, DxAOD file.
- BSM CP-mixing VBF: matrix element reweighting method to SM VBF sample.

Background sample:

- SM ggF $H \rightarrow \gamma\gamma$: ATLAS official h024 mc16a+d, PowhegPy8 NNLOPs ggH125, MxAOD file.
- SM di-photon: ATLAS h024 mc16a+d, Sherpa 2DP20 myy_100_160, MxAOD file.

15+16+17 sideband data as data-MC comparison.

# Validation of weight method

Use truth information in VBF sample to calculate a weight by HAWK

- $w \equiv \frac{|\mathcal{M}_{CPV}|^2}{|\mathcal{M}_{SM}|^2} = 1 + w_1\tilde{d} + w_2\tilde{d}^2$ .
- Input: incoming & outgoing VBF quarks flavor, Bjorken x, all 4-momentum of initial & final state particles.
- Output: $w_1$ and $w_2$.

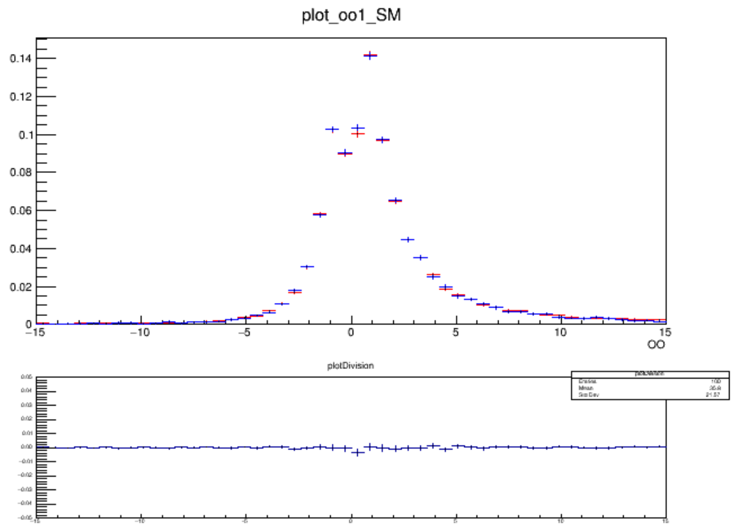
Validation: generate 2 Madgraph_aMC@NLO sample

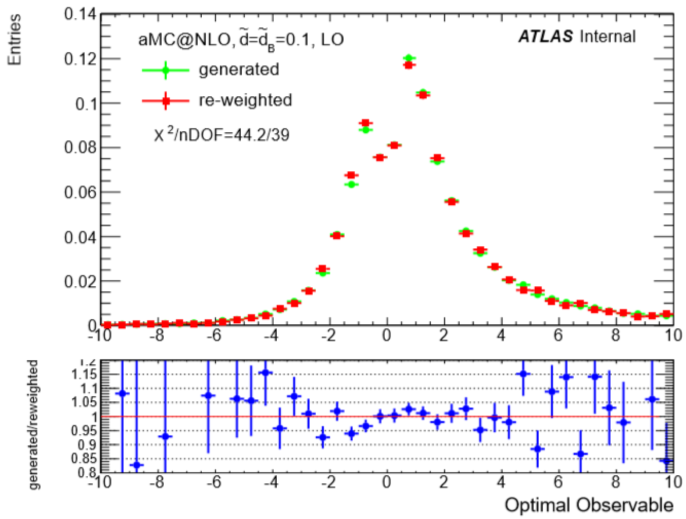
1) SM VBF: p p > h j j $$ w+ w- z a QCD=0, default pars + reweight to $\tilde{d} = 0.1$

2) CP-mixing VBF: same syntax but changed the coupling pars to $\tilde{d} = 0.1$

| MG5_aMC@NLO parameters numerical values, $\tilde{d} = \tilde{d}_B$ =0.1 |
| --- |
| $c_\alpha = 0.6$ |
| $K_{SM} = 1.\bar{6}$ |
| $k_{AWW} = -2.03$ |
| $k_{AZZ} = -2.03$ |
| $k_{A\gamma\gamma} = -155.97$ |
| $k_{AZ\gamma} = 0$ |

# Validation of weight method




Left: my result, blue is re-weight, red is generated.
Right: result cited from H->tautau supporting note.

The HAWK package has no problem, and I used correctly in my work.

# Event selection

Event selection for MC samples:

- Pre-sel: No Dalitz, PassIsolation, PassPID, passTriggerMatch, $m_{\gamma\gamma} \in [105,160]$ GeV (exclude [120, 130]GeV for sideband data)
- At least 2 photon + 2 jets
- $\frac{p_T}{m_{\gamma\gamma}} > 0.35(0.25)$
- $m_{jj} > 400GeV$
- $|\Delta\eta_{jj}| > 2$
- $|\eta^{Zepp}| < 5$

| | SM VBF | ggF | MC bkg | Sideband data |
|---|---|---|---|---|
| Sum of weight | 1506191 | 804823820 | 28449980 | |
| pre-sel | 152.93 | 642.611 | 160058.7 | 164046 |
| rel.pT | 152.93 | 642.611 | 160058.7 | 164046 |
| Mass window | 152.93 | 642.611 | 160058.7 | 164046 |
| m_jj<400 | 84.4765 | 74.2101 | 15018 | 16947 |
| deltaEta_jj>2 | 83.8883 | 70.6592 | 12727.97 | 11361 |
| Zepp<5 | 83.849 | 70.3787 | 12604.75 | 11262 |
| VBF cat. | 72.9534 | 51.8225 | 7654.16 | 7025 |

# Data-MC comparison

Background composition estimation:

- Purity 2x2DSB. Calculate $\gamma\gamma, \gamma j, j\gamma, jj$ event number and fraction

2015+2016 data, 36ifb:

```
Consistency check with sum over the bins:
Ngg    = 247648
Ngj    = 32505
Njg    = 11423
Njj    = 5505
Purity = 0.833604
```

2017 data, 44ifb:

```
Consistency check with sum over the bins:
Ngg    = 233833
Ngj    = 29814
Njg    = 9626
Njj    = 5003
Purity = 0.840292
```

Inclusive, no specific category.

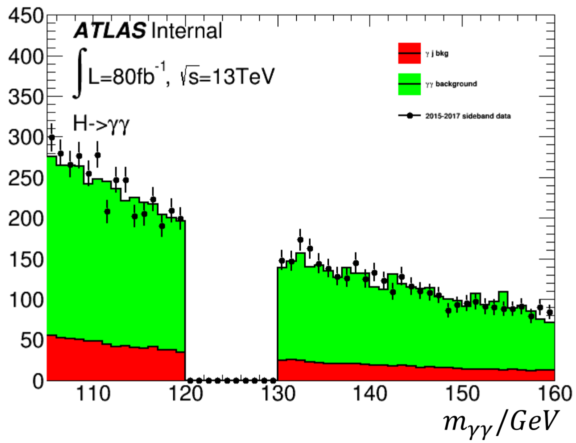
Ref from Run2 80ifb: 75.6% for yy

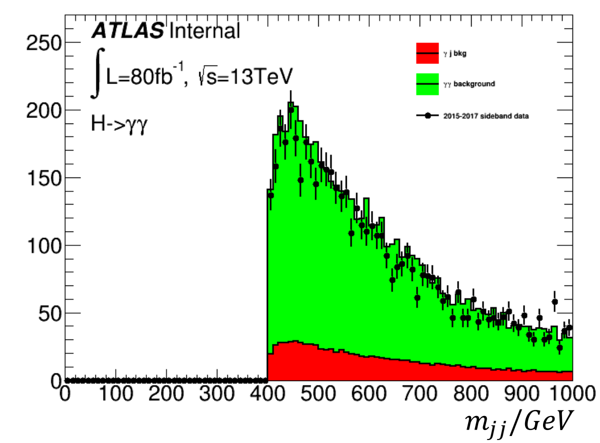
Ref from Run2 36ifb:

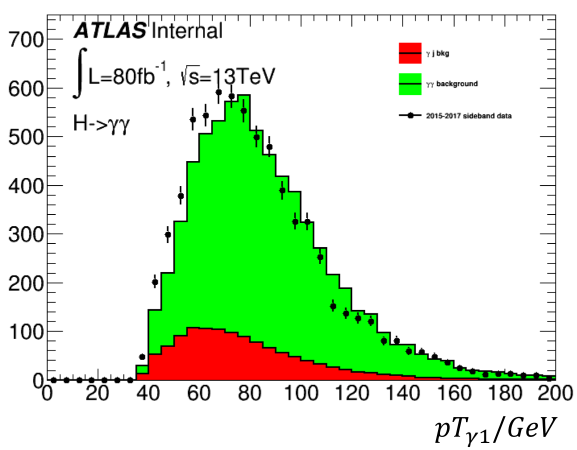
baseline 78.7% for yy

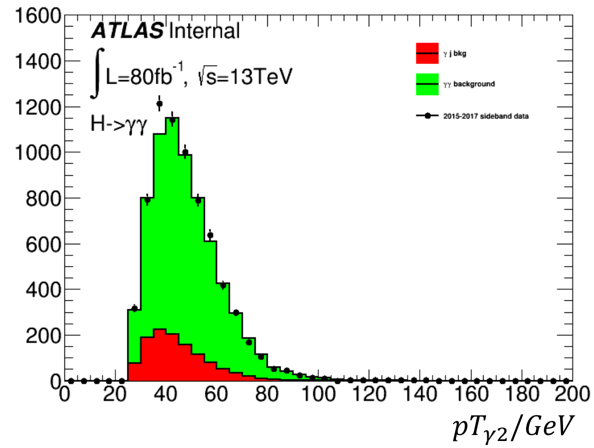
for 4 VBF cat. 80%~84%

# Data-MC comparison

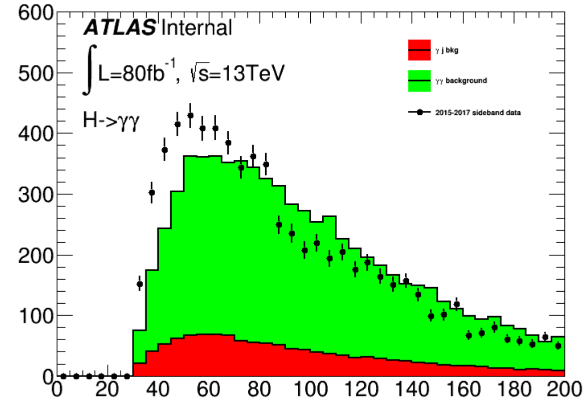


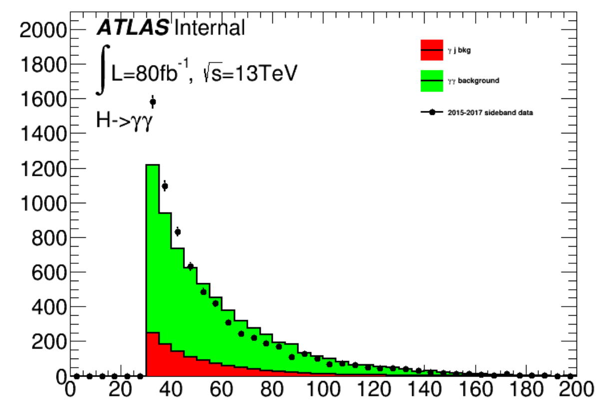



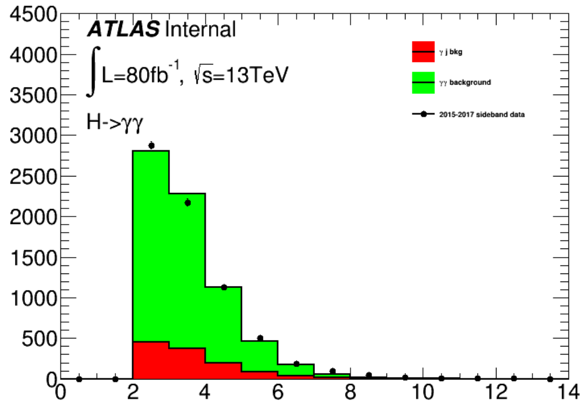



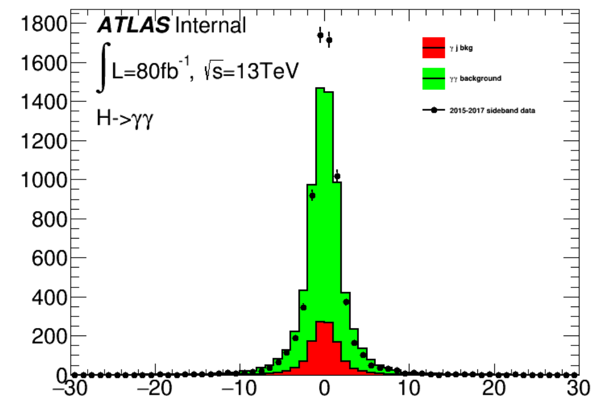



# Data-MC comparison



# Fitting with sideband data

a) Fit model with individual MC template to get PDF

b) Fix $N_{ggF}$ to $N_{ggF}^{SM}$, fit 1-D $m_{\gamma\gamma}$ distribution to get $\hat{\mu}_{VBF}$, $\widehat{N}_{bkg}$.

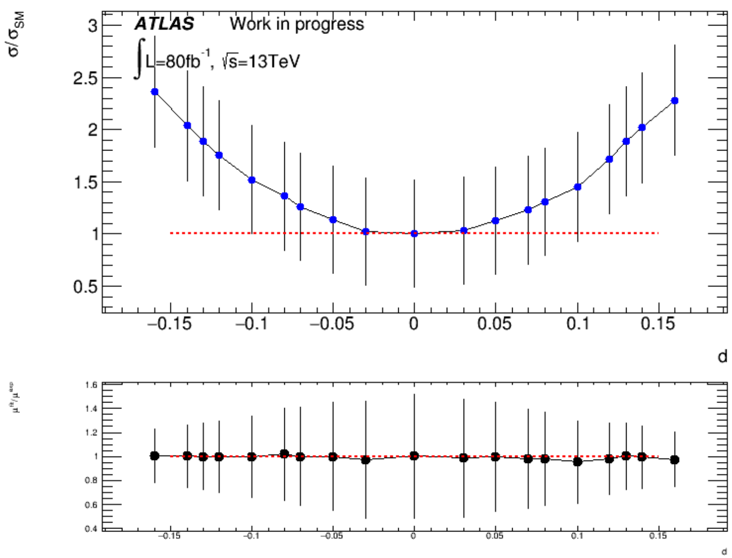
c) Construct 2-D model with:

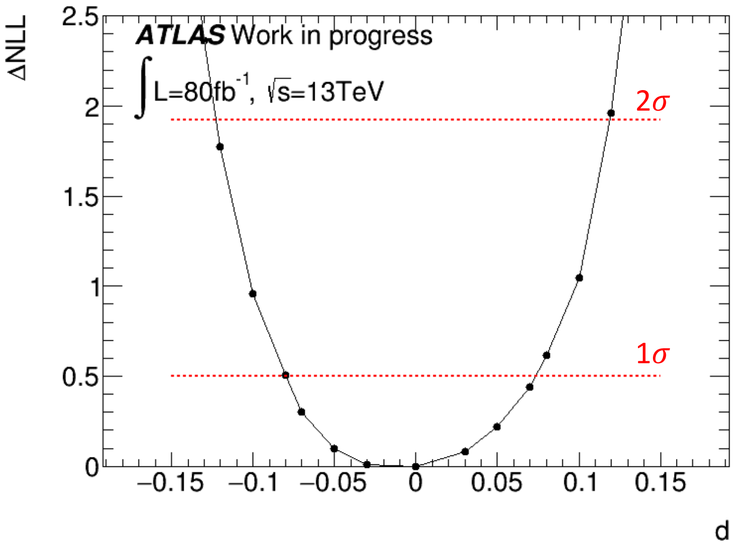
$$PDF_{total}(m_{\gamma\gamma}, OO)$$
$$= \hat{\mu}_{VBF} \times N_{VBF}^{SM} \times f_{sig}(m_{\gamma\gamma}) \times g_{VBF}(OO) + N_{ggF}^{SM} \times f_{sig}(m_{\gamma\gamma}) \times g_{ggF}(OO)$$
$$+ \widehat{N}_{bkg} \times f_{sig}(m_{\gamma\gamma}) \times g_{ggF}(OO)$$

d) Calculate Negative Log Likelihood(NLL) and $\Delta\mathrm{NLL} \equiv NLL - NLL_{min}$ with $PDF_{total}(m_{\gamma\gamma}, OO)$ and SM Asimov data for each d.

The approximate central confidence interval at 68%(95%) CL could be determined from $\Delta NLL$ curve.

# Fitting with sideband data




Left: Best fit signal strength $\mu$ and $\mu^{fit}/\mu^{\exp}$.
Right: $\Delta NLL$ for different $\tilde{d}$

# Conclusion

Statistic only expected CP mixing parameter interval:

- 68% CL: [-0.08, 0.07]
- 95% CL: [-0.12, 0.12]

Facing problem: Data and MC don't match in jet performance.

- Can I use Run2 HGam MVA categories?(HjjHigh_tight, etc. they are trained with jet-relative vars.)
- Is only using sideband data for background correct?

Next step:

- read 140ifb full Run2 data, consider systematic uncertainty.

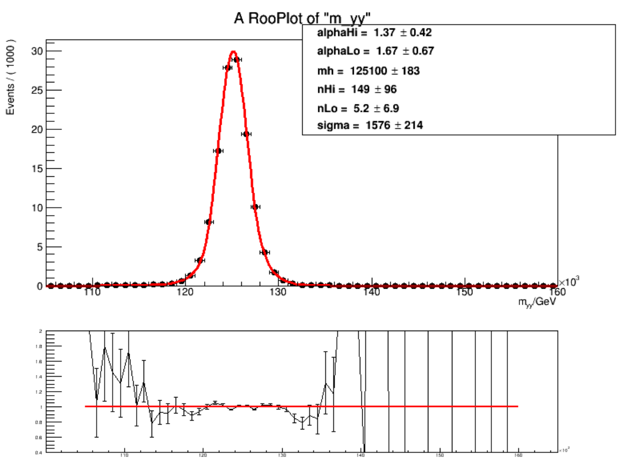
# Back up

# Fit model

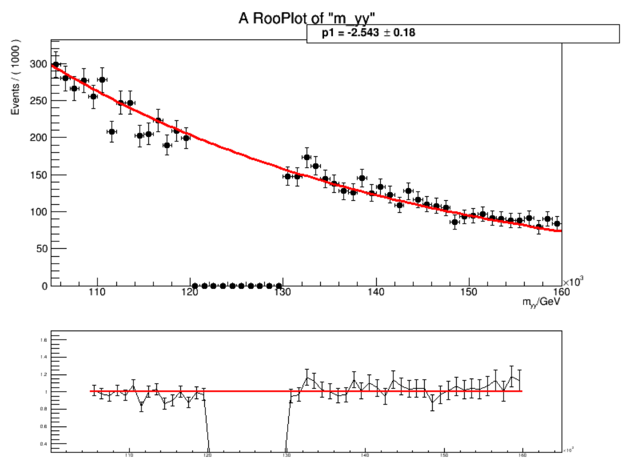
Signal: Double-side Crystal Ball

Background: exponential PDF.

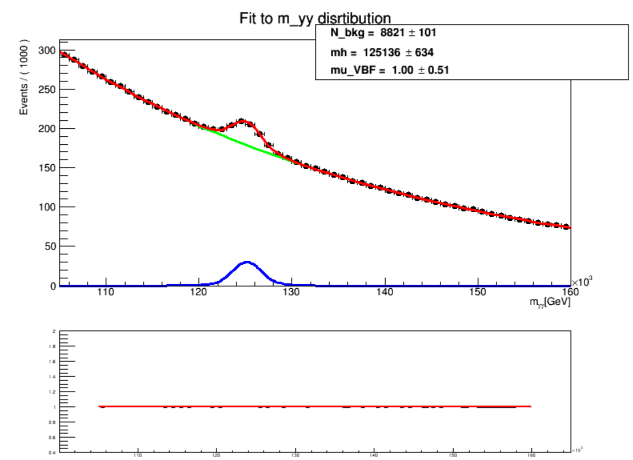
Use Asimov data to decrease statistical fluctuation.




signal



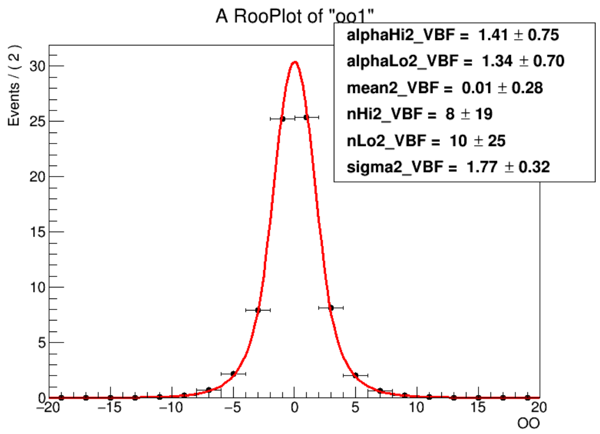

Background
(sideband data)



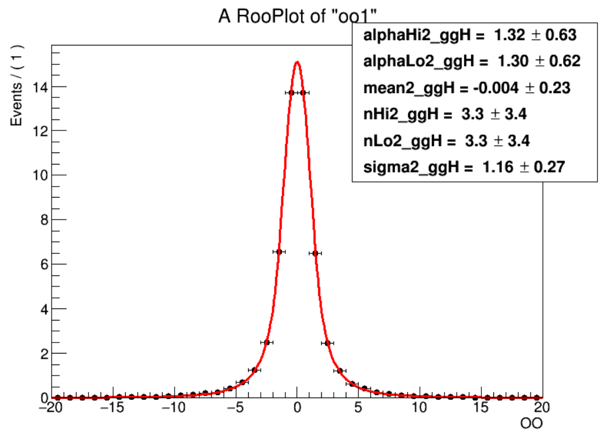

S+B comb

# Fit model

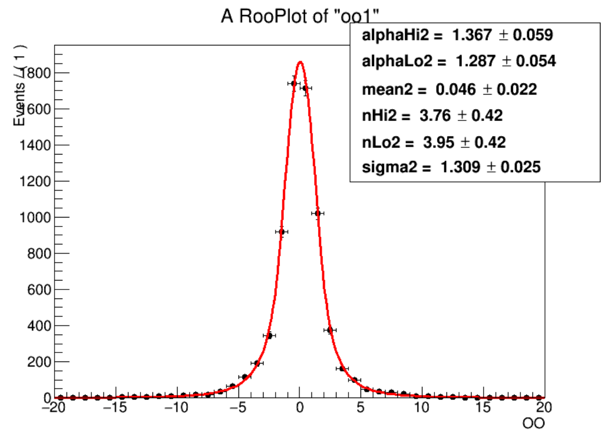
Optimal Observable: Double-side Crystal Ball




VBF

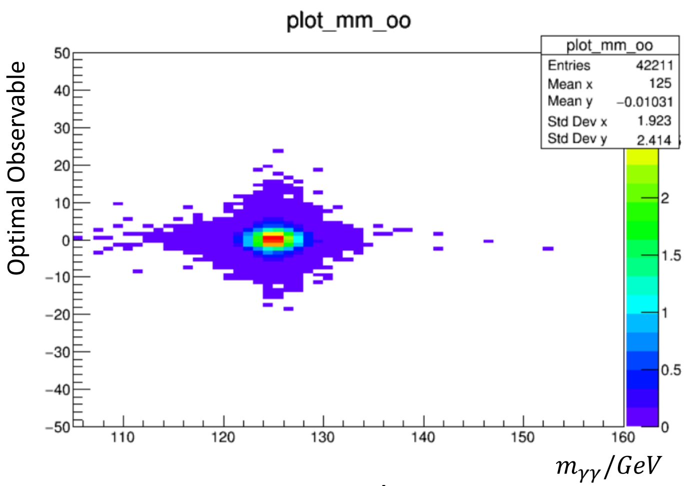



ggF

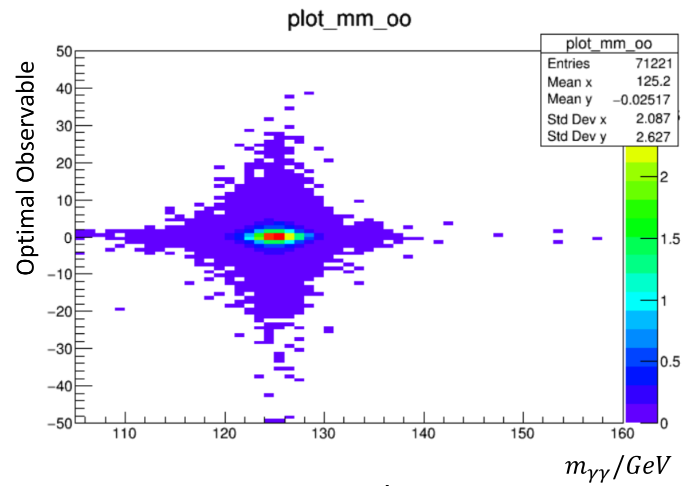



Background
(sideband data)

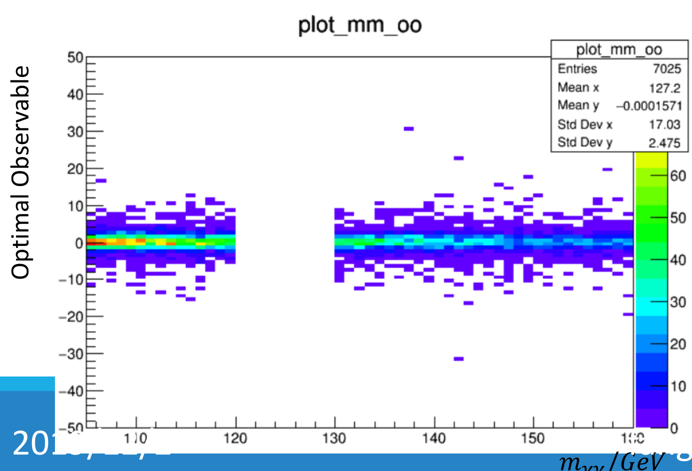
# $m_{\gamma\gamma}$ and OO correlation




VBF sample
Corr=0.004




ggF sample
Corr=0.003




Sideband data
Corr=-0.01