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.

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

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

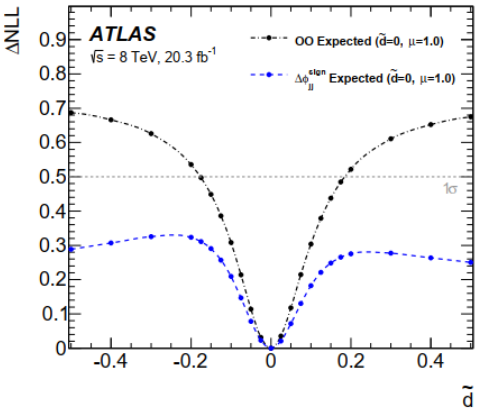
And use $\tilde{d} \sim f(\tilde{g})$ to represent the CP violation in matrix element:

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

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

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

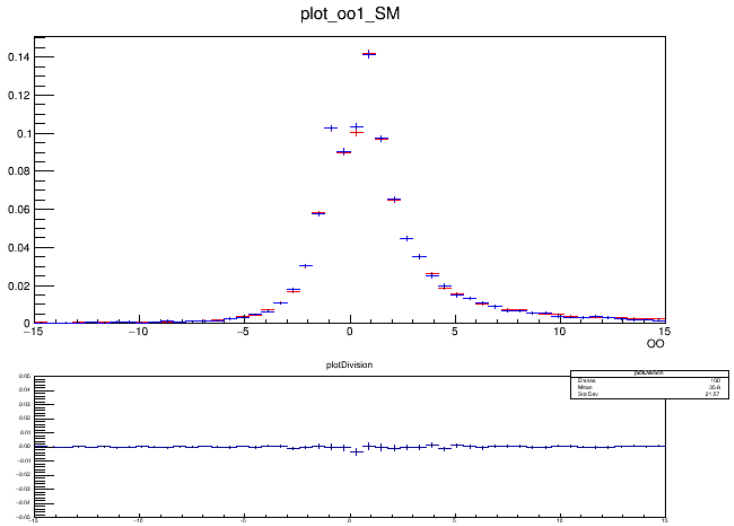
- $w \equiv \frac{|\mathcal{M}_{CPV}|^2}{|\mathcal{M}_{SM}|^2} = 1 + w_1\tilde{d} + w_2\tilde{d}^2$.
- Input: incoming & outgoing VBF quarks flavor, Bjorken x, all 4-momentum of initial & final state particles.
- Output: w_1 and w_2.

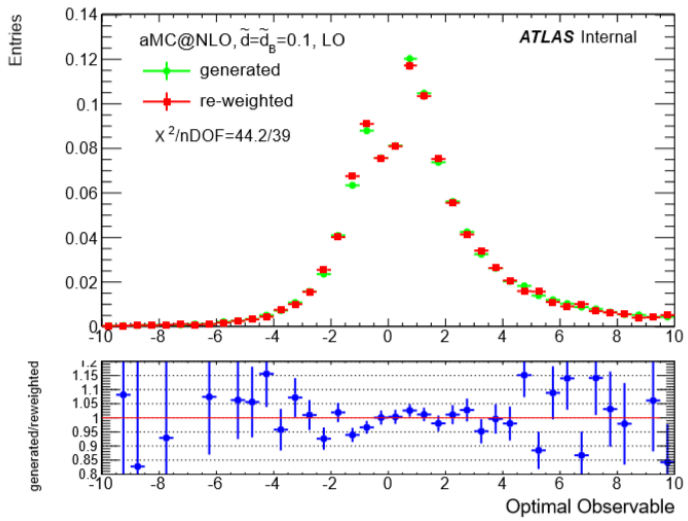
Validation: generate 2 Madgraph_aMC@NLO sample

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:

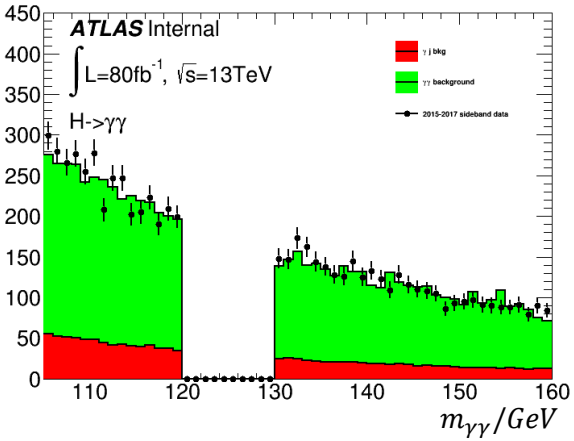
```
Consistency check with sum over the bins:
Ngg    = 247648
Ngj    = 32505
Njg    = 11423
Njj    = 5505
Purity = 0.833604
```

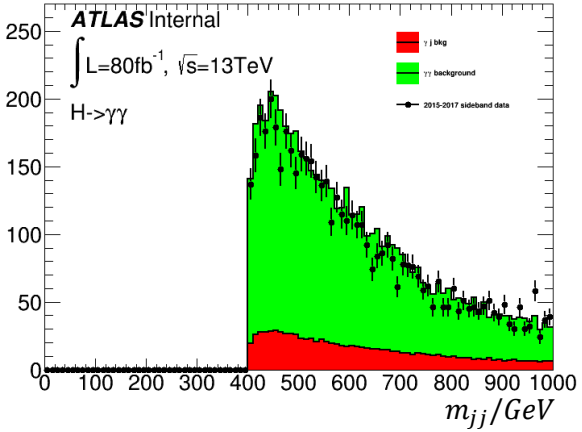
2017 data, 44ifb:

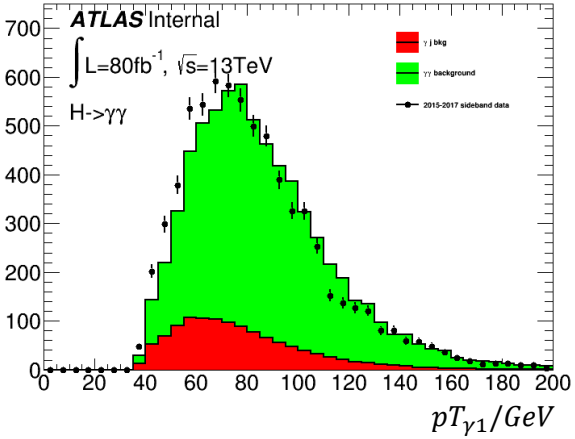
```
Consistency check with sum over the bins:
Ngg    = 233833
Ngj    = 29814
Njg    = 9626
Njj    = 5003
Purity = 0.840292
```

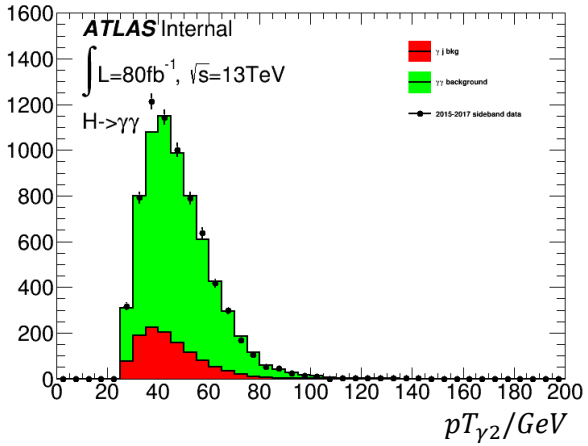
Inclusive, no specific category.
Ref from Run2 80ifb: 75.6% for yy
Ref from Run2 36ifb:
baseline 78.7% for yy
for 4 VBF cat. 80%~84%

Data-MC comparison

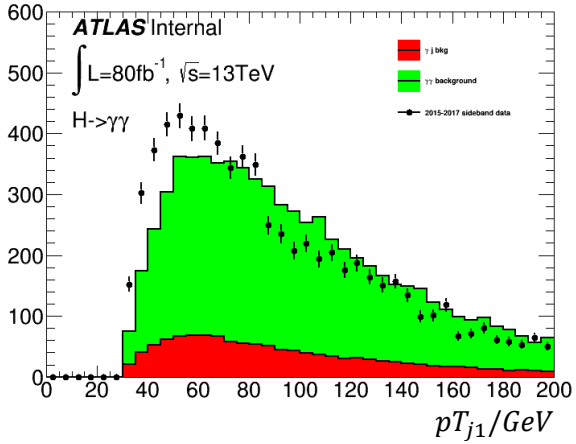


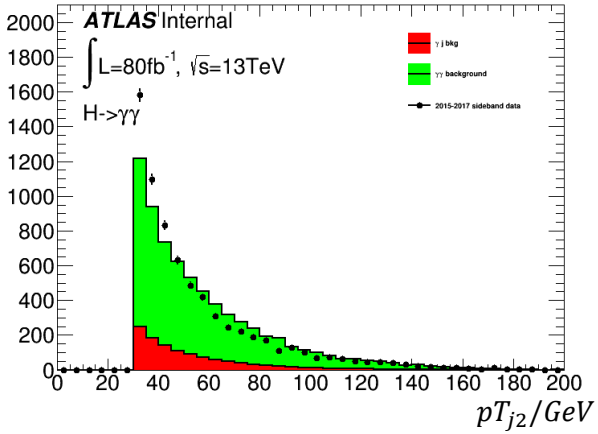


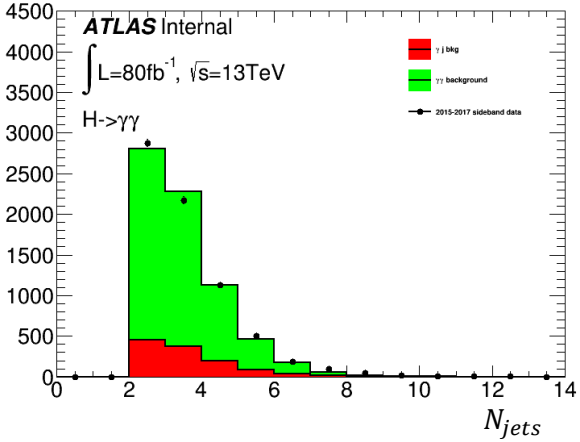


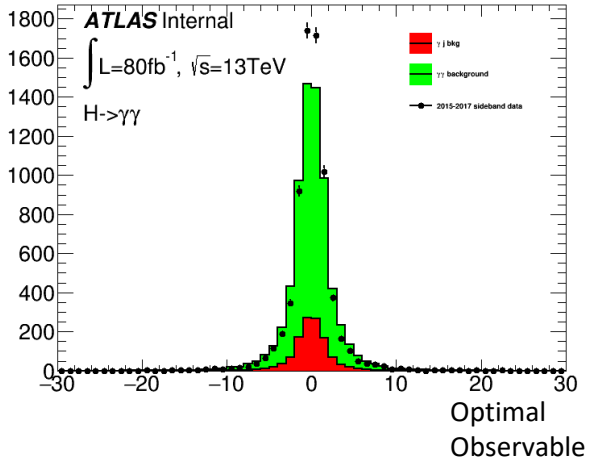


Data-MC comparison









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 $\hat{\mu}_{VBF}$, $\widehat{N}_{bkg}$.

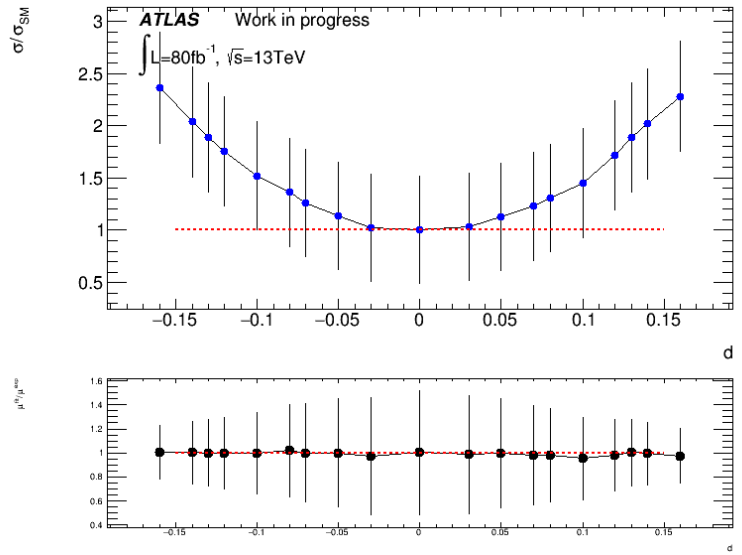
c) Construct 2-D model with:

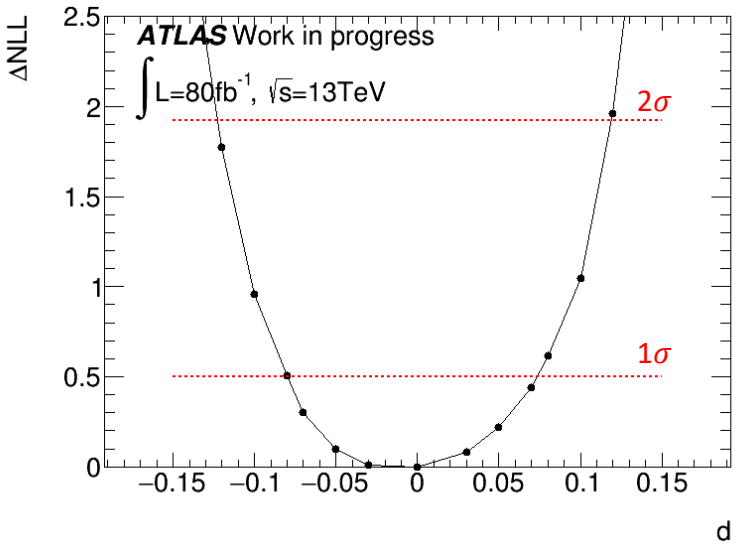
$$PDF_{total}(m_{\gamma\gamma}, OO) = \hat{\mu}_{VBF} \times N_{VBF}^{SM} \times f_{sig}(m_{\gamma\gamma}) \times g_{VBF}(OO) + N_{ggF}^{SM} \times f_{sig}(m_{\gamma\gamma}) \times g_{ggF}(OO) + \widehat{N}_{bkg} \times f_{sig}(m_{\gamma\gamma}) \times g_{ggF}(OO)$$

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 ΔNLL curve.

Fitting with sideband data





Left: Best fit signal strength μ and $\mu^{fit}/\mu^{\exp}$.
Right: ΔNLL 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

Optimal Observable

HAWK: a Monte Carlo program used for VBF/VH process

- Input: 4-momenta of Higgs and the 2 tagging jets.

$$OO = \frac{2\,\mathrm{Re}(\mathcal{M}^{*}_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}\,.$$

$$2\,\mathrm{Re}(\mathcal{M}^{*}_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}}) = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) 2\,\mathrm{Re}((\mathcal{M}^{ij\to klH}_{\mathrm{SM}})^{*}\mathcal{M}^{ij\to klH}_{\text{CP-odd}})$$

$$|\mathcal{M}_{\mathrm{SM}}|^2 = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) |\mathcal{M}^{ij\to klH}_{\mathrm{SM}}|^2\,.$$

$$x^{\mathrm{reco}}_{1/2} = \frac{m_{Hjj}}{\sqrt{s}} e^{\pm y_{Hjj}}$$

Optimal Observable

Program package: HLeptonCPRW provided by H-tautau analysis group.

3 functions:

- double getReweight()

  Input: Ecms, Higgs mass, anomalous couplings, number of partons in finel state(2 or 3), incoming&outgoing

  partons flavor, Bjoken x of incoming partons, 4-momenta for final state partons and Higgs.

  Return: a single event weight to reweight from SM to the chosen parameters.

- std::pair<double, double> getWeightsDtilde() (I used in analysis)

  Input: Ecms, Higgs mass, parton flavor, Bjorken x, 4-momenta of final state parton and Higgs.

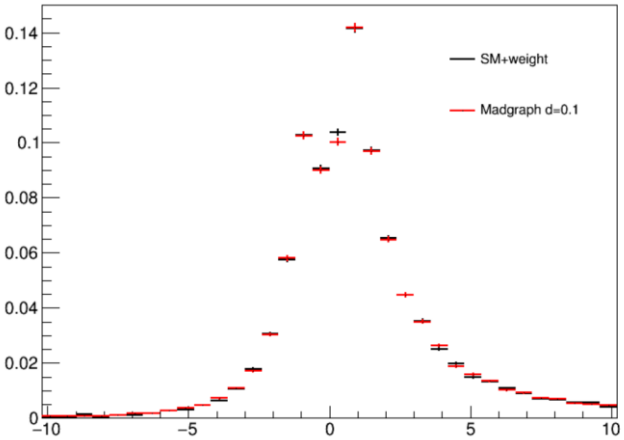
  Return: w1 and w2 in SL4.

- std::pair<double, double> getOptObs()

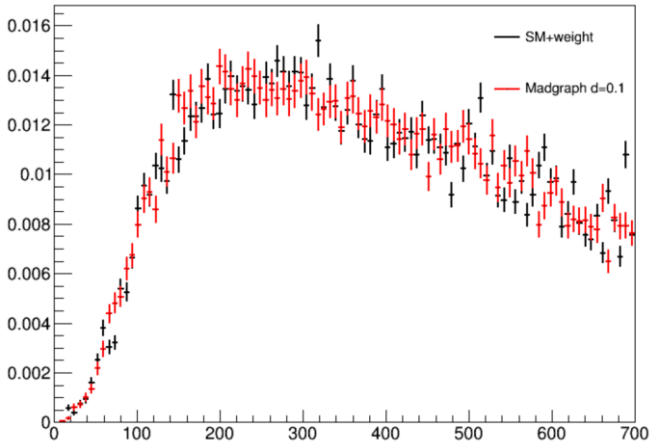
  Input: Ecms, Higgs mass, Bjorken x, pdfs for parton(or give Q + include LHAPDF), 4-momenta of 2 jets and Higgs.

  Return: 1^{st} and 2^{nd} order Optimal Observable. (Only 1^{st} order is used here)

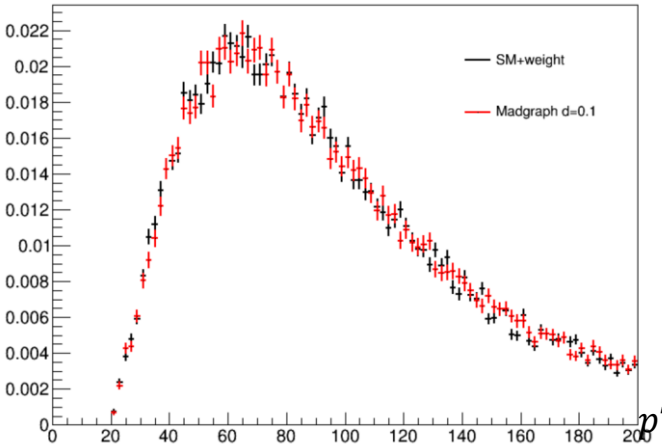
Validation of weight method



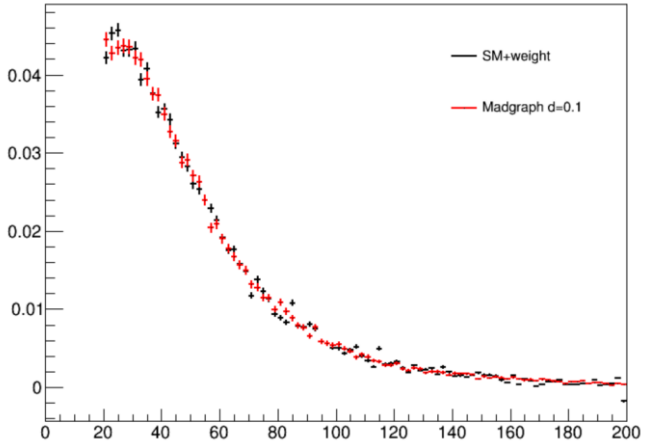
OO



m_{jj}/GeV

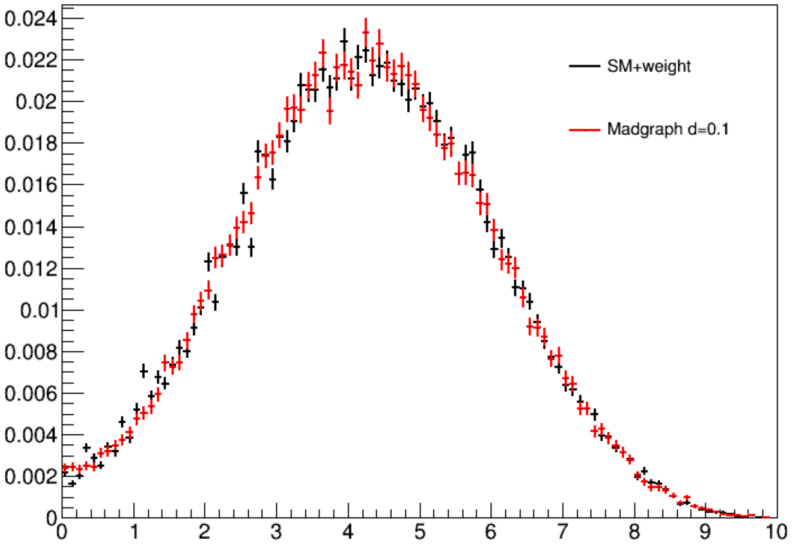


pT_{j1}/GeV

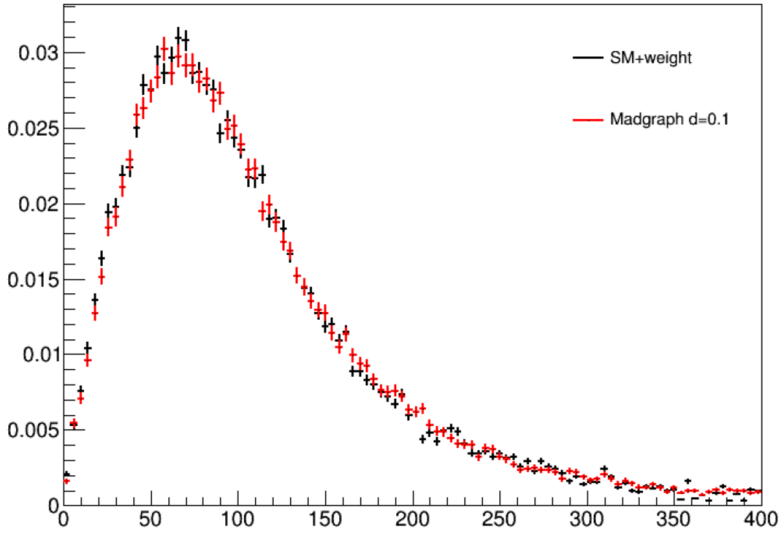


pT_{j2}/GeV

Validation of weight method



$\Delta\eta_{jj}$



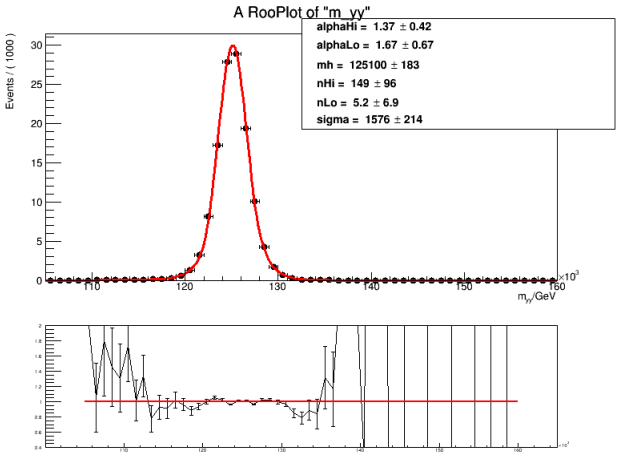
pT_{Higgs}

Fit model

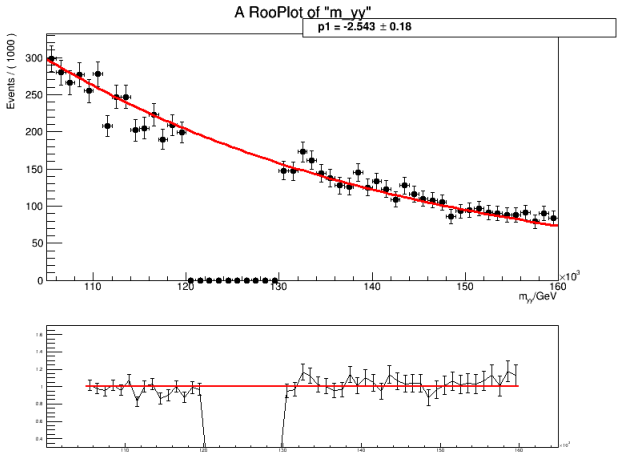
Signal: Double-side Crystal Ball

Background: exponential PDF.

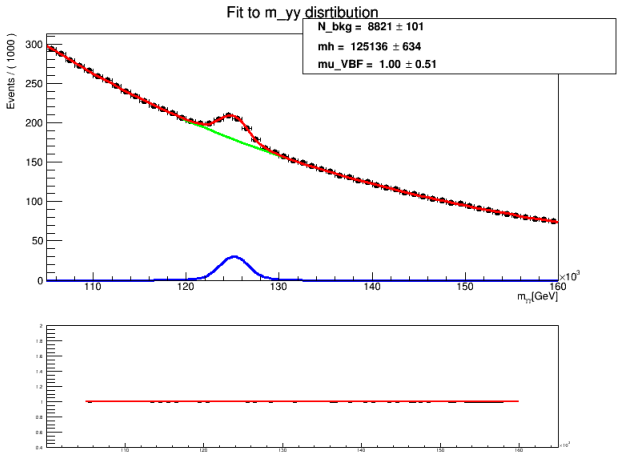
Use Asimov data to decrease statistical fluctuation.



signal



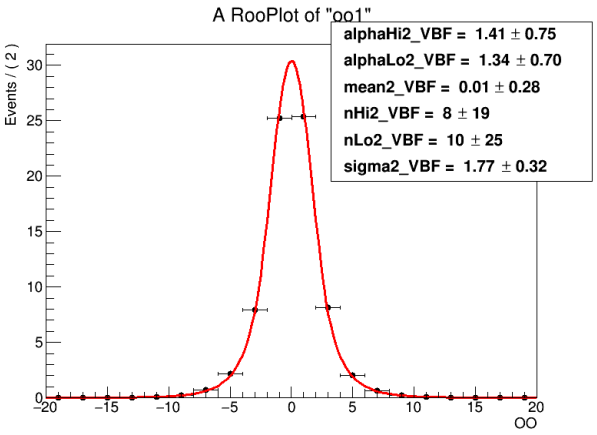
Background
(sideband data)



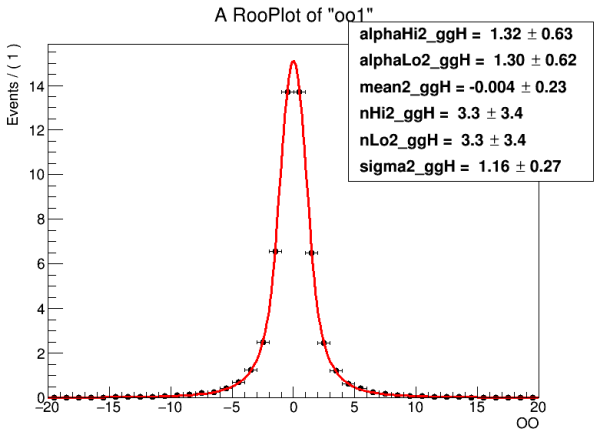
S+B comb

Fit model

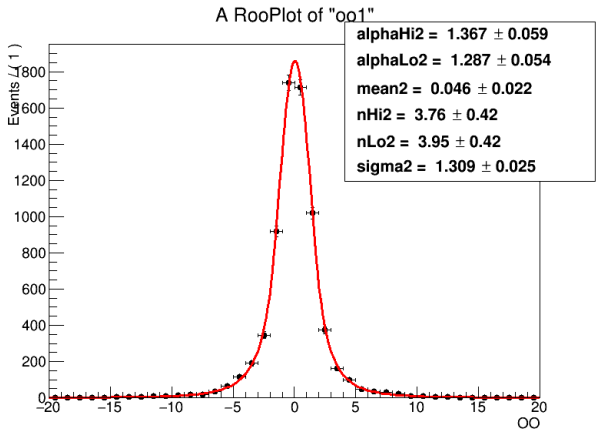
Optimal Observable: Double-side Crystal Ball



VBF

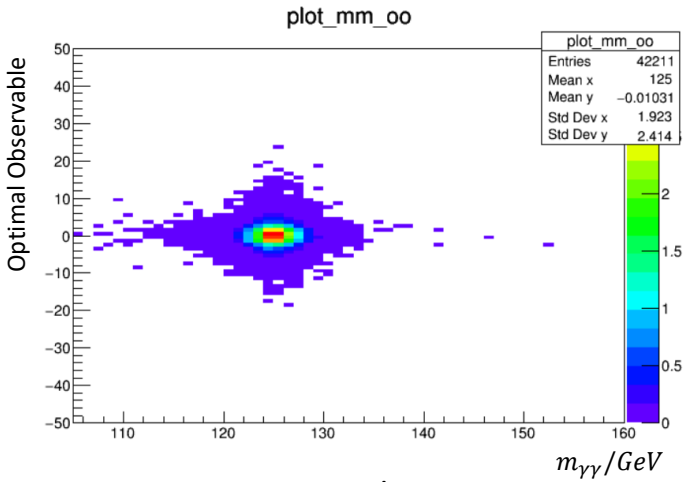


ggF

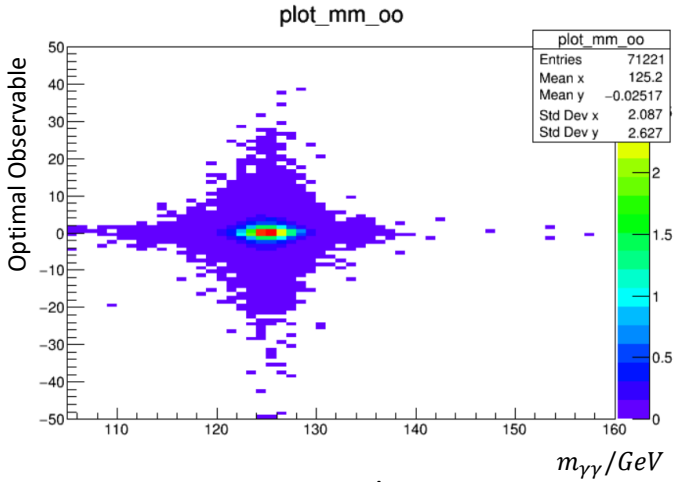


Background
(sideband data)

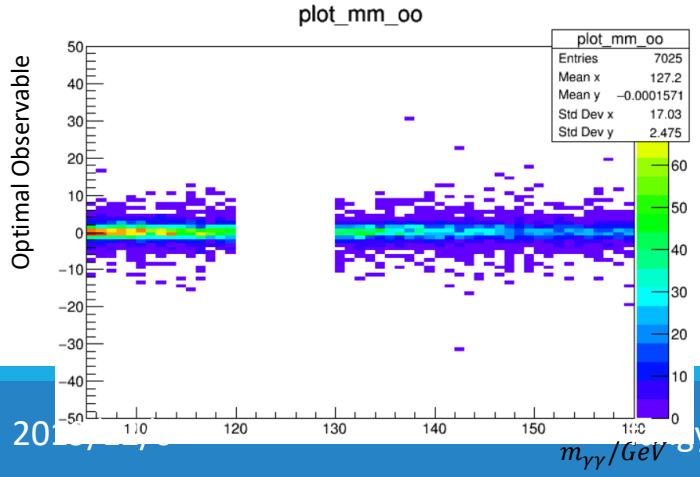
$m_{\gamma\gamma}$ and OO correlation



VBF sample
Corr=0.004



ggF sample
Corr=0.003



Sideband data
Corr=-0.01