Search for CP violation in Higgs boson interaction via VBF production at the ATLAS experiment

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Introduction

- Baryons asymmetry observed in the universe
- Sakharov : Charge-Parity (CP) symmetry has to be violated to have different reaction rates for baryons and antibaryons

$$\Gamma(N \xrightarrow{\mathcal{L}(\Delta n_{\mathrm{Bar}} \neq 0)} f) \neq \Gamma(\bar{N} \xrightarrow{\mathcal{L}(\Delta n_{\mathrm{Bar}} \neq 0)} \bar{f})$$

- In Standard Model (SM), CP violation is encoded in the CKM matrix for the quarks
  - Source of CP violation only appears in the charged current couplings
  - Effect too small to generate the observed matter-antimatter asymmetry

- Higgs boson predicted to be a scalar ($J^{CP} = 0^{++}$) in SM with no CP-violating interactions
  - The measurement of a CP-odd contribution in the Higgs boson couplings would be a sign of physics beyond the SM (BSM)
  - This motivates searches in the Higgs sector for additional sources of CP violation

Higgs boson couplings

- The SM Higgs boson couplings can be summarized in the Lagrangian

$$\mathcal{L} = -\frac{m_f}{v} f\bar{f}H + \frac{m_H^2}{2v}H^3 + \frac{m_H^2}{8v^2}H^4 + \delta_V V_\mu V^\mu \left(\frac{2m_V^2}{v}H + \frac{m_V^2}{v^2}H^2\right)$$

- Main couplings with W, Z, and/or third generation quarks and leptons

- CP violation search in :
  - Yukawa couplings: consider dimension 4 with SM-like couplings which are CP-mixed
  - **Bosonic couplings: consider dimension 6 BSM couplings which are CP-mixed**
    - VBF $H \rightarrow \tau\tau$ analysis (Phys.Lett.B805(2020)135426)
    - VBF $H \rightarrow \gamma\gamma$ analysis (work in progress)

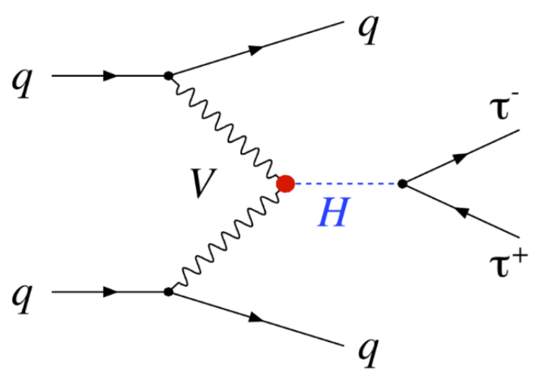
VBF Higgs CP analysis

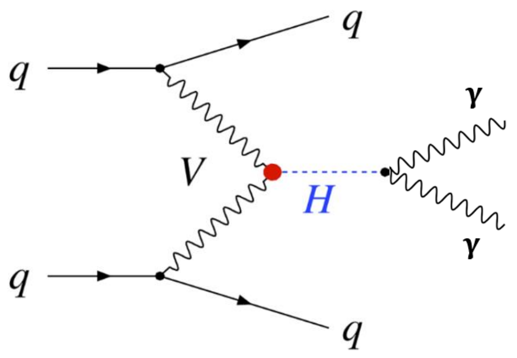
- Strong VBF signal and good resolution of reconstructed Higgs boson 4-momentum
- Consider only HVV couplings
- EFT Lagrangian :

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{f_{\tilde{B}B}}{\Lambda^2} H^\dagger \hat{\tilde{B}}_{\mu\nu} \tilde{B}_{\mu\nu} H + \frac{f_{\tilde{W}W}}{\Lambda^2} H^\dagger \hat{\tilde{W}}_{\mu\nu} \tilde{W}_{\mu\nu} H$$

- Simplify using only one CP-violating parameter (HIGZ basis)

$$\tilde{d} = -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W} = -\frac{m_W^2}{\Lambda^2} \tan^2(\theta_W) f_{\tilde{B}B}$$





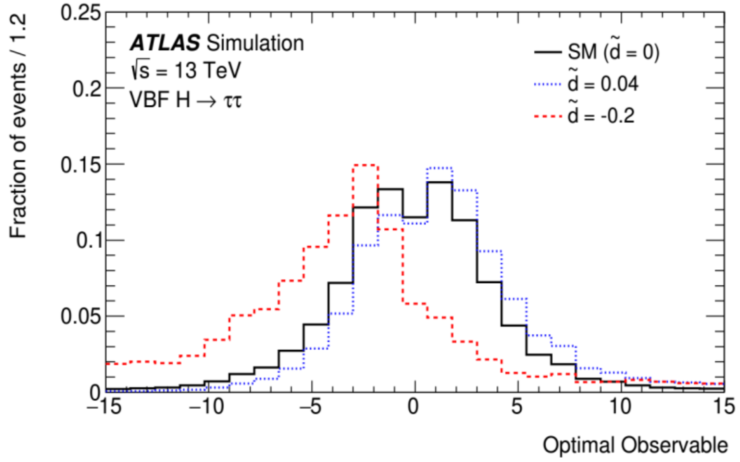
Optimal Observable

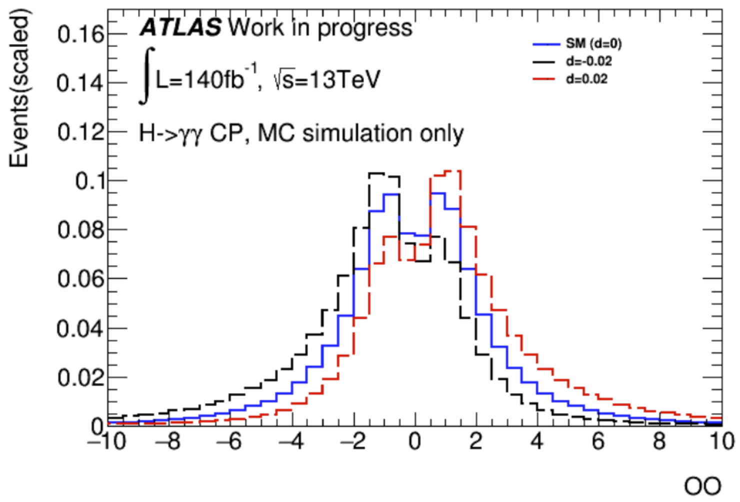
- Use *Optimal Observable* to measure $\tilde{d}$

$$OO = \frac{Re(M_{SM}^{*} M_{CP-Odd})}{|M_{SM}^{2}|}$$

- Combine full phase space information of Higgs + 2 jets final state in 1-dim. observable for small $\tilde{d}$

- $<OO> \neq 0 \rightarrow$ CP violation neglecting re-scattering effects by new light particles in loops

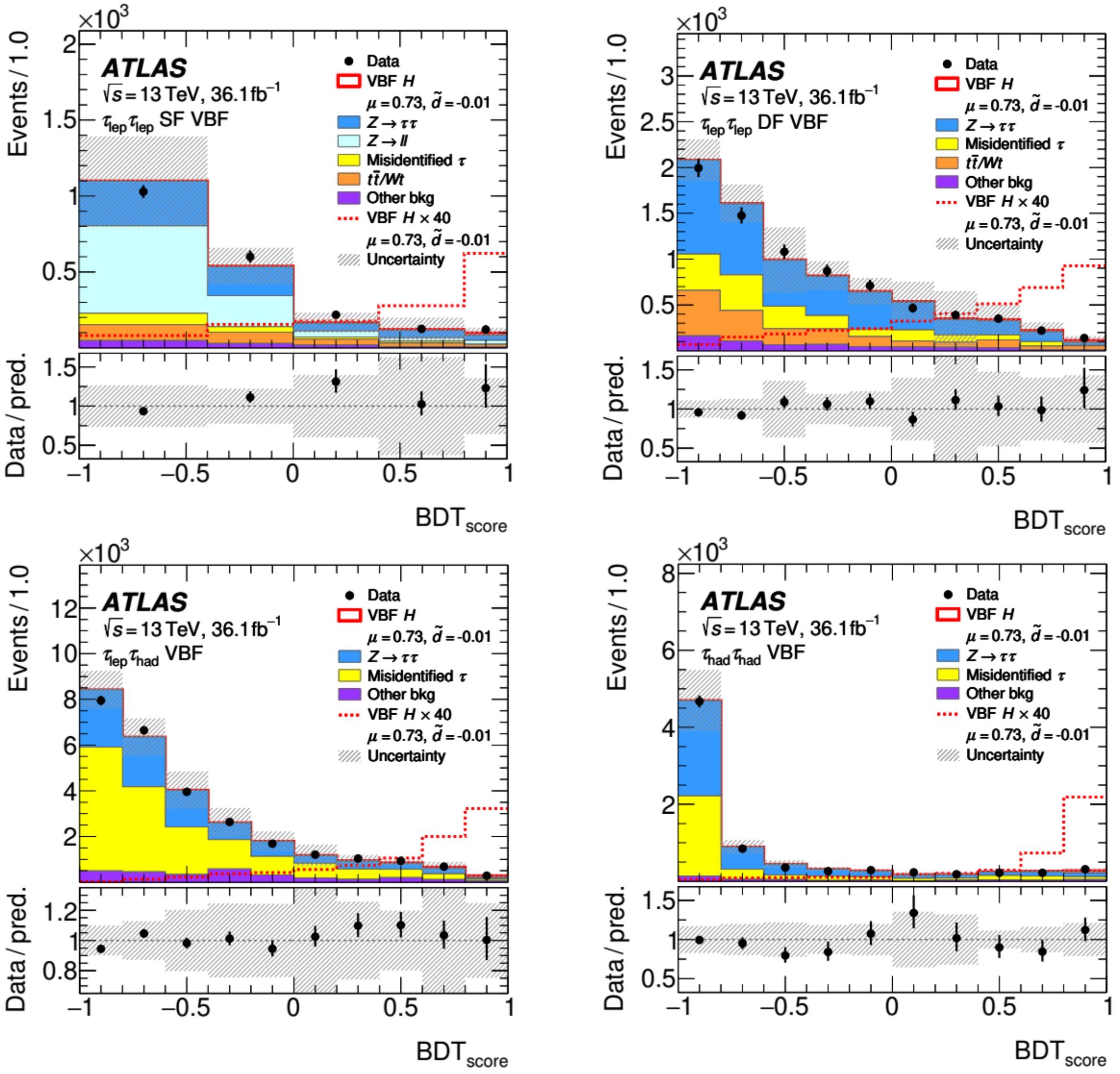




VBF $H \rightarrow \tau\tau$ analysis

Phys.Lett.B805(2020)135426

- Four analysis channels according to all combinations of tau decay : $\tau_{lep}\tau_{lep}$ SF, $\tau_{lep}\tau_{lep}$ DF, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- Main backgrounds : $Z \rightarrow \tau\tau$ and misidentified τ decay (for all channels), $t\bar{t}/Wt$ and Z →ll (for the $\tau_{lep}\tau_{lep}$ SF channel)
- Use BDTs to separate VBF signal from backgrounds



VBF $H \to \tau\tau$ analysis

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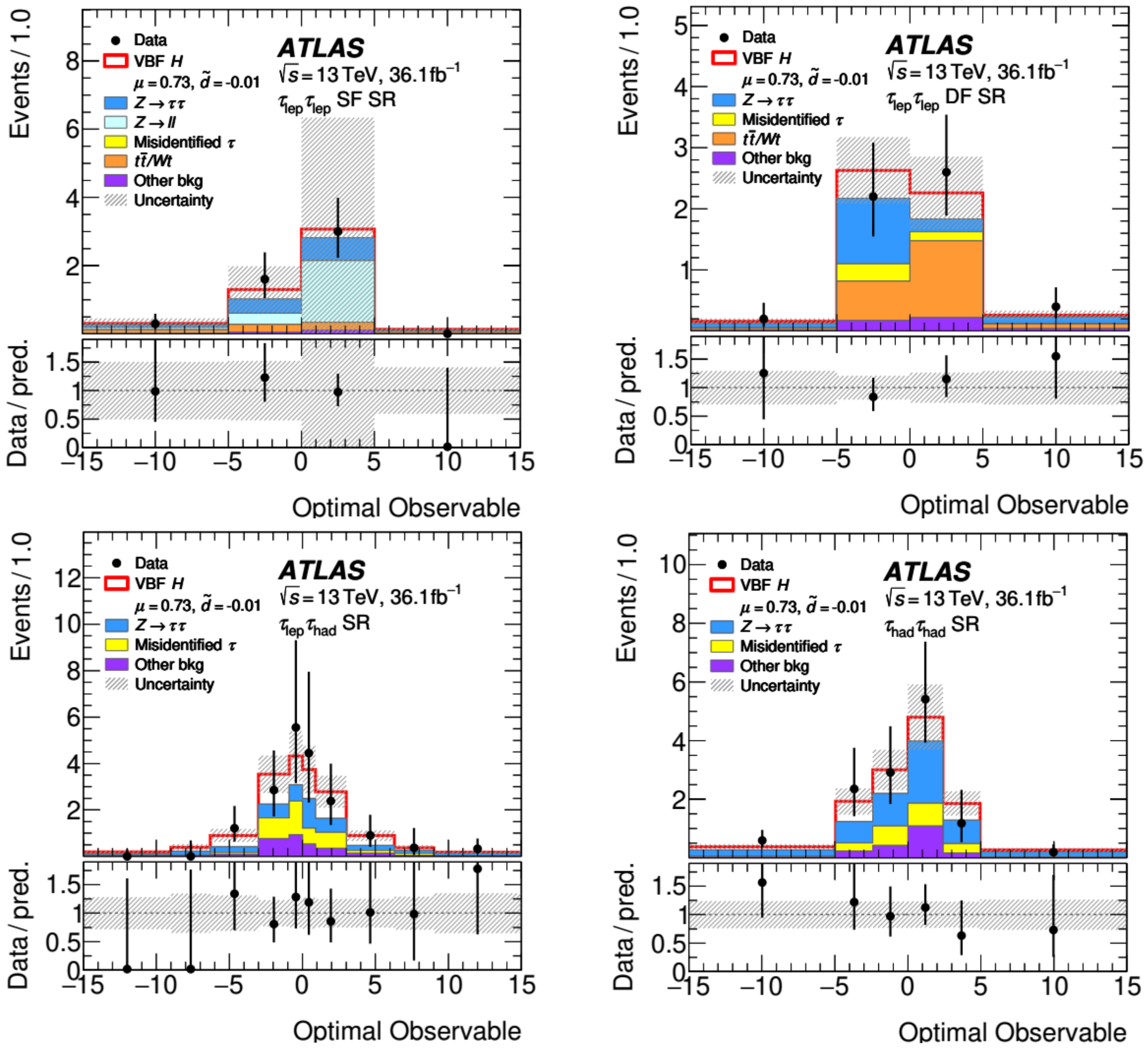
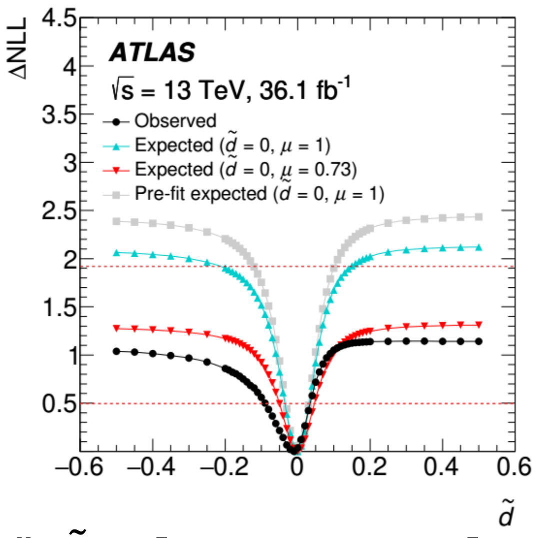


- Measured mean value in data consistent with SM expectation (<*OO*>=0)
- Confidence intervals on $\tilde{d}$ determined through fit for various signal hypotheses
  - No rate information used in fit to have less model-dependent CP test

Channel	⟨Optimal Observable⟩
$\tau_{lep}\tau_{lep}$ SF	-0.54 ± 0.72
$\tau_{lep}\tau_{lep}$ DF	0.71 ± 0.81
$\tau_{lep}\tau_{had}$	0.74 ± 0.78
$\tau_{had}\tau_{had}$	-1.13 ± 0.65
Combined	-0.19 ± 0.37

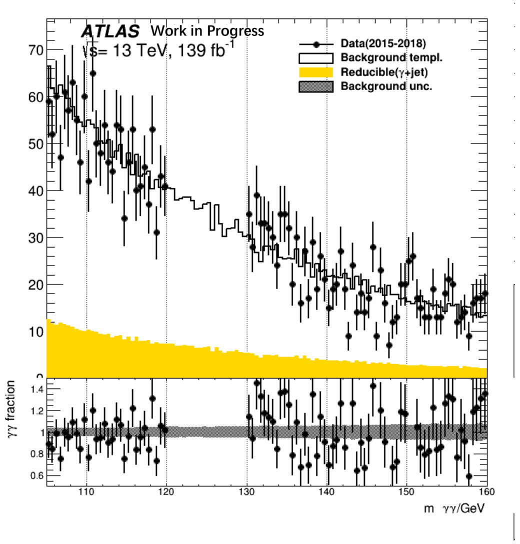


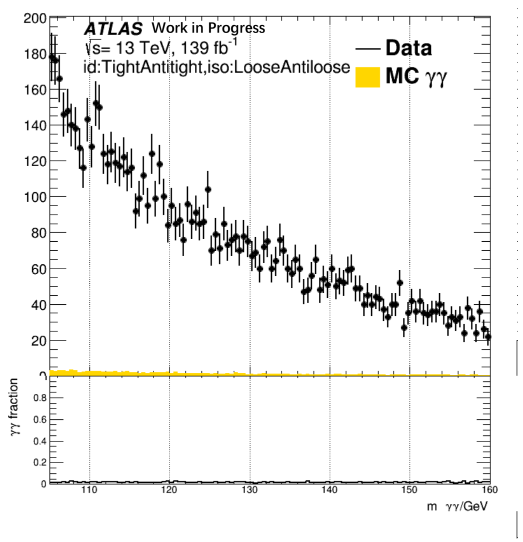
- Expected (Observed) $\tilde{d} \in$ [-0.035.0.033] ([-0.090,0.035]) at 68% confidence level

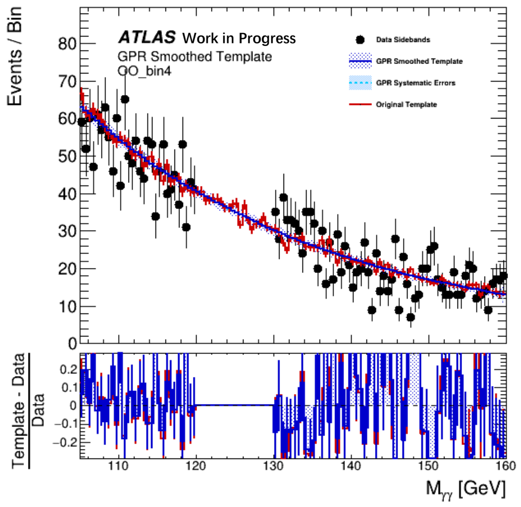
VBF $H \rightarrow \gamma\gamma$ analysis

- Lower br. respect to $\tau\tau$ channel yet excellent Higgs mass reconstruction

- Signal selection : 2 tight photons, 2 jets
- 4 BDT-based categories enriched in VBF
- Backgrounds :
  - ggF $H \rightarrow \gamma\gamma$
  - continuum background ($\gamma\gamma,\ \gamma jet,\ jetjet$)
- Continuum templates :
  - $\gamma\gamma$ shape (MC) + γjet shape (CR data)
  - fractions measured with 2x2D decomposition
  - Gaussian Process Regression : smooth out fluctuation to reduce sys.
- Spurious signal test using the templates

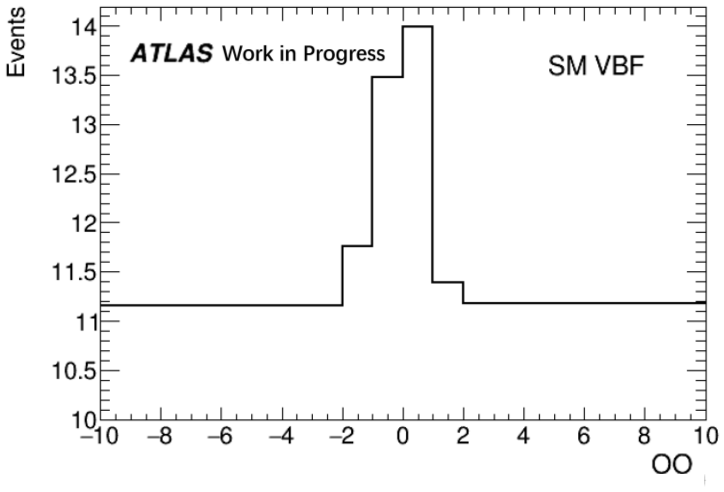


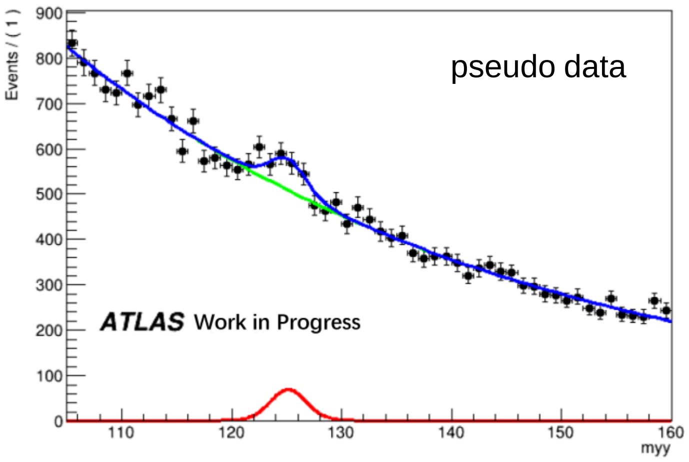




VBF $H \to \gamma\gamma$ analysis

- OO distribution divided into several bins optimized to achieve best significance while ensuring enough statistics
- A simultaneous fit to diphoton invariant mass performed in all OO bins
  - Signal parameterized using Crystal Ball function
  - Background parameterized using function suggested by spurious signal test





Conclusion

- Baryons asymmetry observed in the universe cannot be explained only with CP-violation predicted by Standard Model

- Higgs boson predicted to be a scalar with no CP-violating interactions
  - Additional sources of CP violation in the Higgs sector would bring to new physics

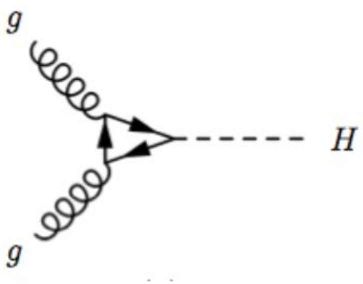
- HVV only coupling probed in VBF$H \rightarrow \tau\tau$ and $H \rightarrow \gamma\gamma$ channels but so far no sign of CP violation

- Looking forward to new searches while waiting for Run 3 data-taking and HL-LHC

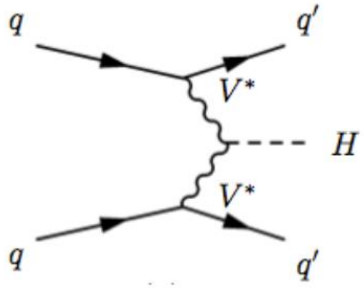
Thanks for Your Attention

backups

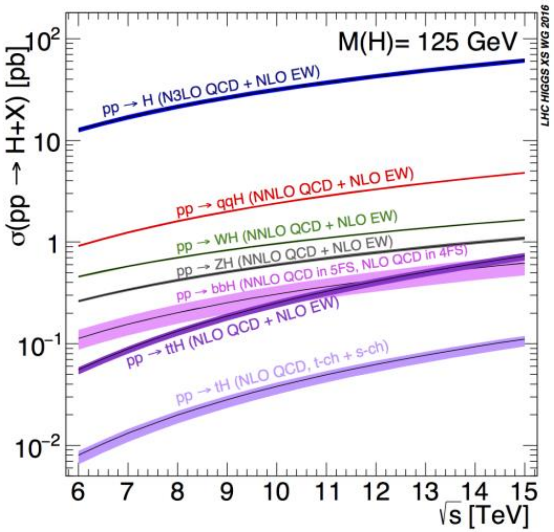
Higgs boson production modes



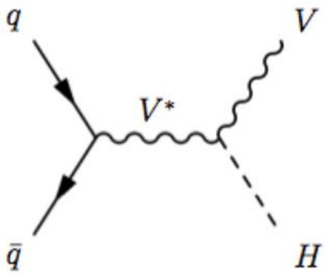
gluon fusion (ggF)



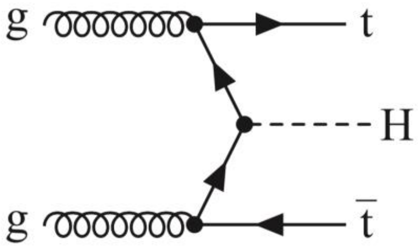
vector boson fusion (VBF)



Higgs boson production cross section



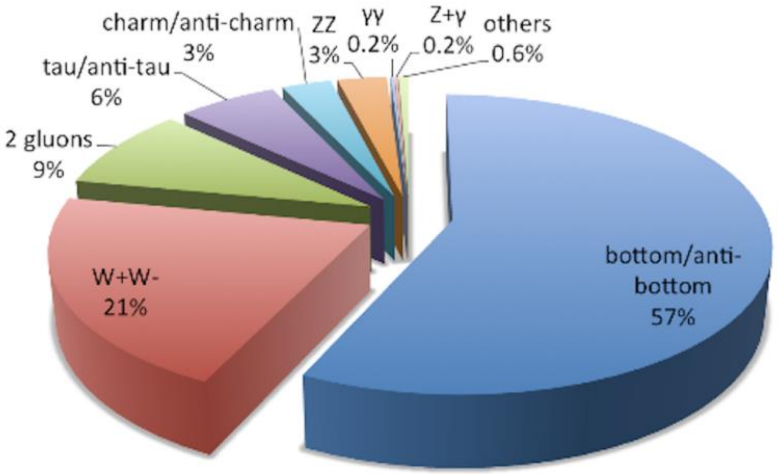
associated production with a gauge boson (VH)



associated production with a $t\bar{t}$ pair (ttH)

- Largest cross section for gluon fusion and vector boson fusion production modes

Higgs boson decay branching ratios

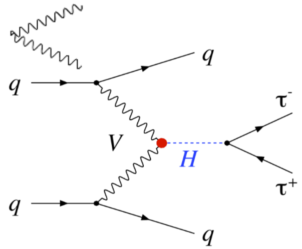


Higgs decay branching ratios

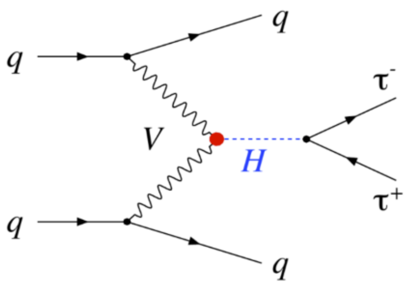
- Larger branching ratio (BR) for $H \to b\bar{b}$, $H \to WW^*$ and $H \to \tau\tau$, however poor mass resolution and large background contamination

- $H \to \gamma\gamma$ and $H \to ZZ^*(\to 4l)$ have lower BR, but high mass resolution; can be used for precision measurements

γ



γ



$\tau_{lep}\tau_{lep}$ same-flavor

$\tau_{lep}\tau_{lep}$ DF $\tau_{lep}\tau_{had}$ $\tau_{had}\tau_{had}$

tion

Higgs boson

Higgs boson

Baryon asymmetry observed in the universe

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$$\tilde{d} = -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W} = -\frac{m_W^2}{\Lambda^2} \tan^2(\theta_W) f_{\tilde{B}B}$$

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{f_{\tilde{B}B}}{\Lambda^2} H^\dagger \hat{B}_{\mu\nu} \tilde{B}_{\mu\nu} H + \frac{f_{\tilde{W}W}}{\Lambda^2} H^\dagger \hat{W}_{\mu\nu} \tilde{W}_{\mu\nu} H$$

$$OO = \frac{Re(M^*_{SM} M_{CP-Odd})}{|M^2_{SM}|}$$