Resonance-Continuum Interference effect in $\gamma\gamma$ and ZZ channels
(with discussion about 750 GeV diphoton excess)

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based on
1505.00291, 1510.03450, 1601.00006, 160x,xxxxx
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Highlights in Resonance-Continuum Interference for $h(125)$

1. Mass shift

Interference distribution

S. Martin 1208.1533
2. Quantitative Effect (to constrain total decay width)

Caola, Melnikov 1307.4935

On-resonance (NWA)

\[
\sigma_{i \rightarrow H \rightarrow f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}.
\]

\[
\frac{d\sigma_{pp \rightarrow H \rightarrow ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_{H}^2)^2 + m_{H}^2 \Gamma_{H}^2}.
\]

Off-resonance

\[
N_{4l}^{\text{off}} = 3.72 \times \frac{\Gamma_{H}}{\Gamma_{H}^{\text{SM}}} - 9.91 \times \sqrt{\frac{\Gamma_{H}}{\Gamma_{H}^{\text{SM}}}}.
\]

\[
\Gamma_{H} \leq 38.8 \Gamma_{H}^{\text{SM}} \approx 163 \text{ MeV}
\]
Resonance-Continuum Interference formalism

Resonance-Continuum Interference is inevitable.

Interference can change
1. total signal rate
2. resonance shape

“The interference effect for any resonance signal must be seriously taken into account.”
Resonance-Continuum Interference formalism

\[ \hat{\sigma} = \sigma_{\text{cont}} + \sigma_{\text{res}} \frac{M^4}{(\hat{s} - M^2)^2 + M^4w^2} \left[ 1 + \frac{2\Gamma}{RM} \sin \phi + \frac{2(\hat{s} - M^2)}{M^2} \frac{\cos \phi}{R} \right] \]

3 Key Parameters

- \( w = \frac{\Gamma}{M} \)
- \( R \approx \frac{A_{\text{res}}}{A_{\text{cont}}} \)
- \( \phi \approx \text{Arg}(A_{\text{res}}/A_{\text{cont}}) \)

Im-Intf.

\[ \phi = \pm \frac{\pi}{2} \]

Change total signal rate

Re-Intf.

\[ \phi = 0, \pi \]

Change resonance shape

Song, Jung, YWY, 1505.00291, 1510.03450
Resonance-Continuum Interference formalism

Multiplication factor that quantifies Interference effect

\[ C \cdot = \frac{\sigma_{\text{mNWA}}}{\sigma_{\text{prod}} \cdot B_{\gamma\gamma}} \]

\[ = \left( 1 + \frac{2\Gamma}{R M_{s\phi}} \right) \]

For narrow width

\[ K_{\text{intf}} = \frac{\sigma_{\text{mNWA}}}{\sigma_{\text{prod}} \cdot B_{\gamma\gamma}} \]

\[ \sigma_{\text{mNWA}} = \int_{M-\Delta}^{M+\Delta} d m_{\gamma\gamma} \left[ \frac{d\sigma_{\text{sig}}}{d m_{\gamma\gamma}} \right] \]

For broad width
1. Resonance-Continuum Interference in ttbar

\( t\bar{t} \) channel

\( R \) is one-loop suppressed \( \rightarrow \) Large Interference

\( \phi \approx -90^\circ \rightarrow \) Destructive Interference

\[
C = \left( 1 + \frac{2\Gamma}{RM}s_\phi \right) < 0
\]
1. Resonance-Continuum Interference in t\bar{t}bar

Mostly Dip-like
2. Resonance-Continuum Interference in ZZ

ZZ channel

\[ R \text{ is roughly order 1 } \rightarrow \text{Small Interference} \]
\[ \phi \approx 0^\circ \rightarrow \text{Real Interference} \]

\[ C = \left( 1 + \frac{2\Gamma}{RM} s_\phi \right) \approx 1 \]
2. Resonance-Continuum Interference in $ZZ$

$O(10\%)$ intf. effect
2. Resonance-Continuum Interference in $ZZ$

Hatched: w/o intf.
Colored: w/ intf.

→ 20~30 GeV difference
2. Resonance-Continuum Interference in ZZ

Role of width:
By changing

$5 \times \Gamma_\phi$
3. Resonance-Continuum Interference in $\gamma\gamma$

$\gamma\gamma$ channel

$R$ is one-loop suppressed $\Rightarrow$ Large Interference

$\phi$ is non-trivial, model dependent
3. Resonance-Continuum Interference in $\gamma\gamma$

Relative strength of Photon PDF:

$$\frac{L_{\gamma\gamma}}{L_{gg}} \cdot 10^4$$

By using NNPDF2.3QED

NNPDF Collaboration 1308.0598

$$L_{gg(\gamma\gamma)}(x) = \int_x^1 \frac{dy}{y} f_{g(\gamma)/p}(y) f_{g(\gamma)/p}\left(\frac{x}{y}\right)$$
3. Resonance-Continuum Interference in $\gamma\gamma$

We assume scalar diphoton resonances which can be discovered at $5\sigma$ with 300/fb at 13TeV.

Model independent approach:

Coefficients $c_{gg}, c_{\gamma\gamma}$ can be complex numbers (ex: loop-induced Wilson Coefficients)

$\phi_{\text{res}}$: complex phase of resonance amplitude
3. Resonance-Continuum Interference in $\gamma\gamma$

We assume ggF dominance

Even for Narrow width, the interference effect is quite significant

For $\gamma\gamma$F dominant case, its interference effect is working in progress
3. Resonance-Continuum Interference in $\gamma\gamma$

(focusing on Im-part interference effect)

For the 2HDM, MSSM

→ Various interference patterns depending on $\phi$

$C$ is a correction factor due to the interference effect.

$C = 0$ means that the interference term cancels the BW resonance.

→ $O(100\%)$ intf. effect
Now we consider 750GeV diphoton excess

$\Gamma_\Phi = 45\text{GeV}$

$\sigma(pp \rightarrow \Phi \rightarrow \gamma\gamma) = \begin{cases} 
6.5 \pm 2.5 \text{ fb} & (68\% \text{ CL}) \\
6.5^{+4.5}_{-3.5} \text{ fb} & (95\% \text{ CL})
\end{cases}$
Real Interference ($\phi = 0, \pi$) - Peak Shift

Model 1: Singlet + VLQ/VLL

$\phi \simeq \begin{cases} 8.3^\circ & \text{for } s_L > 0; \\ 188.3^\circ & \text{for } s_L < 0, \end{cases}$

$\cos \phi \simeq \pm 1$, $\sin \phi \simeq 0 \rightarrow$ Real Interference

$M_Q = 1 \text{ TeV}, N_Q = 2, s_Q = 0.2.$
$M_L = 400 \text{ GeV}, N_L = 6, s_L \text{ is varied}$
$\Gamma_\phi = 5 \text{ GeV}$
Real Interference ($\phi = 0, \pi$) - Peak Shift

Model 1: Singlet + VLQ/VLL

- $M_\Phi=750$ GeV
- $\sigma_{NWA}=4$ fb

$s_L<0$, peak–dip intf
$s_L>0$, dip–peak intf

Almost real–part intf
singlet A
Model 1: Singlet + VLQ/VLL

The Peak Shift can be 1~4 GeV
2. Imaginary Interference \( (\phi = \pm \frac{\pi}{2}) \) (Signal Enhancement)

Model 2: 2HDM+VLL

VLL contribution in \( \Phi \to \gamma\gamma \):

\[
A_{\gamma\gamma, \text{VLL}}^\Phi = \sum_{\text{VLL}} \sum_{i=1,2} \left( Q_{E_i}^2 \frac{\hat{y}_t^\Phi y_{E_i} v}{M_{E_i}} A_{1/2}(\tau_{E_i}) + Q_{D_i}^2 \frac{\hat{y}_b^\Phi y_{D_i} v}{M_{D_i}} A_{1/2}(\tau_{D_i}) \right)
\]

We fix \( y_D \) as follows to avoid the SM Higgs precision:

\[
y_D = -\frac{Q_E^2}{Q_D^2} y_E = -0.25 y_E
\]

We set \( t_\beta = 0.7 \) to raise up the pseudo-scalar Higgs contribution.

Total decay rate is determined by dominant ttbar decays:

\[
\Gamma_{H(A)} = 46(58) \text{ GeV}
\]
2. Imaginary Interference ($\phi = \pm \frac{\pi}{2}$) (Signal Enhancement)

Model 2: 2HDM+VLL

\[ \begin{align*}
\phi &\sim \begin{cases} 
90^\circ & \text{for } y_E > 0; \\
-90^\circ & \text{for } y_E < 0.
\end{cases} \\
\cos \phi &\approx 0, \\
\sin \phi &\approx \pm 1
\end{align*} \]

⇒ Imaginary Interference
Model 2: 2HDM+VLL

Total cross section w/ interference

\[ \sigma_{\text{mNWA}} = \int_{M-\Delta}^{M+\Delta} \frac{d\sigma_{\text{sig}}}{dm_{\gamma\gamma}} \text{peak} \]

\[ K_{\text{intf}} = \frac{\sigma_{\text{mNWA}}}{\sigma_{\text{prod}} \cdot \text{Br}_{\gamma\gamma}} \]

Ratio of total cross Section w/ intf. to w/o intf.

\[ K_{\text{intf}} = 1.6 \text{ for 6fb} \]
\[ 2 \text{ for 3 fb} \]
\[ 4 \text{ for 1 fb} \]
Summary

- Resonance-Continuum Interference effect is inevitable and can be significant for any resonance.

- Not only $\Gamma/M$, but also $R$ (resonance to continuum ratio) and $\phi$ (relative phase) plays the roles to quantify and characterize the interference effect.

- Interference effect can be $O(10\%)$ for $ZZ$ and $O(100\%)$ for $\gamma\gamma$.

- For 750GeV diphoton excess, we find two distinct interference effects:
  1. Signal Enhancement from imaginary interference ($2HDM+VLL$)
     - factor 1.6, 2, 4, for the signal rate 6fb, 3fb, 1fb.
  2. Peak Shift from real interference ($Singlet+VLF$)
     - 1~4 GeV