750 GeV Diphoton Excess: Resonance Shape and Enhancement

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mainly 1601.00006, but also 1505.00291, 1510.03450

with Jeonghyeon Song, Yeo Woong Yoon
Resonances in history

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Excitement on new excess

ATLAS Preliminary

Data

Background-only fit

Spin-0 Selection

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

Events / 20 GeV

Data - fitted background

$m_{\nu}$ [GeV]

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Resonance shapes

- Good reasons why not seen in elementary particle physics. Also why will be more generic phenomena.

- Not just a mere mathematical possibility.
What my talk is about

1. Origin of various resonance shapes.

2. Best-fit analysis of two representative example models:
   (1) maximum shape distortion/peak-shift
   (2) maximum signal enhancement/suppression

3. Prospects
1. Origin: Resonance-continuum interference
Resonance-continuum interference

- Continuum SM background and resonant processes with same initial-final states can interfere:

\[
\frac{d\hat{\sigma}}{dz} = \frac{1}{32\pi\hat{s}} \sum \left| M_{bg} + \frac{M^2}{\hat{s} - M^2 + iM\Gamma} \cdot M_{res} \right|^2
\]

- Amplitudes M can, in general, be complex (besides complex BW): complex couplings or loops with Cutkosky cuts.
Purely real interference

- Continuum SM background and resonant processes with same initial-final states can interfere:

\[
\frac{d\hat{\sigma}}{dz} = \frac{1}{32\pi \hat{s}} \sum \left| \mathcal{M}_{\text{bg}} + \frac{M^2}{\hat{s} - M^2 + iM\Gamma} \cdot \mathcal{M}_{\text{res}} \right|^2
\]

- If the interference is purely real,

\[
\hat{\sigma} = \hat{\sigma}_{\text{bg}} + \frac{1}{(\hat{s} - M^2) + M^4w^2} \times \left[ M^2(\hat{s} - M^2)\hat{\sigma}_{\text{int}} + M^4\hat{\sigma}_{\text{res}} \right]
\]

odd in \( \hat{s} \)-hat
Purely real interference

- The real-part induces a peak and dip together.
- Shifting the location of a peak (affecting the pole mass measurement).

~70 MeV shift to the 125 GeV Higgs mass, but can be much bigger for new resonances.

L.Dixon et al.

S. Martin
The resonance-continuum interference with a relative phase.

\[
\frac{d\hat{\sigma}}{dz} = \frac{1}{32\pi \hat{s}} \sum \left| A_{bg} e^{i\phi_{bg}} + \frac{M^2}{\hat{s} - M^2 + iM\Gamma} \cdot A_{res} e^{i\phi_{res}} \right|^2
\]

NB: Complex phases can arise from either loops with Cutkosky cuts or from CPV.
The resonance-continuum interference with a relative phase.

\[ \frac{d\hat{\sigma}}{dz} = \frac{1}{32\pi\hat{s}} \sum \left| A_{bg}e^{i\phi_{bg}} + \frac{M^2}{\hat{s} - M^2 + iM\Gamma} \cdot A_{res}e^{i\phi_{res}} \right|^2 \]

\[ \hat{\sigma} = \hat{\sigma}_{bg} + \frac{1}{(\hat{s} - M^2) + M^4\omega^2} \]

\[ w = \Gamma/M \]

\[ R = \frac{\hat{\sigma}_{res}}{\hat{\sigma}_{int}} \approx \frac{A_{res}}{A_{bg}} \]

\[ \phi \approx \phi_{res} - \phi_{bg} \]

usual real-part interference

resonance square

imaginary interference
Purely imaginary intf

- Pure dip, nothingness, and rescaled pure peak can be newly produced.

\[ \hat{\sigma} = \hat{\sigma}_{bg} + \frac{1}{(\hat{s} - M^2) + M^4w^2} \left[ 0 + M^4\hat{\sigma}_{res}\left(1 \pm \frac{2w}{R}\right)\right] \]

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Narrow width approximation (NWA)

- The **total resonance rate** is the area below the BW peak, and is estimated approximately/easily by NWA.

\[
\frac{1}{(\hat{s} - M^2)^2 + M^2\Gamma^2} \quad \rightarrow \quad \frac{\pi}{M\Gamma} \delta(\hat{s} - M^2)
\]

\[
\sigma(H/A) \cdot BR(H/A \rightarrow t\bar{t})
\]
Modified NWA

- The imaginary-part now does contribute to the total rate; usual NWA is not valid with the imaginary-part.

- We can modify the NWA by a multiplicative C-factor.

\[ \sigma(H/A) \cdot BR(H/A \rightarrow t\bar{t}) \cdot \left(1 + 2\frac{w}{R}s_\phi\right) \]
MSSM Heavy Higgs in most channels can be dips!

SJ, Song, Yoon
Phases from top-loop

Phase when $m_H > 2m_t$
2. Implications:

750 GeV Diphoton Excess from a Scalar Resonance
Two representative models

- (1) **Purely real**: Maximum shape distortion/peak-shift

- (2) **Purely imaginary**: Maximum signal enhancement/suppression
(1) shape distortion

- **750 GeV scalar resonance**: singlet, gg->diphoton.

- **400 GeV VL leptons + TeV VL quarks.** (fitting rate, no phases)

- **Width=5 GeV.** (by some hidden decay modes)
(1) shape distortion
(1) shape distortion

SJ, Song, Yoon
(2) resonance enhancement

- 2HDM + VL leptons: 750 GeV heavy Higgses in $gg\rightarrow$ diphoton.
- Almost purely complex with the top-loop.
- Width $\sim 50$ GeV.
(2) resonance enhancement

\[ R = \frac{\hat{\sigma}_{\text{res}}}{\hat{\sigma}_{\text{int}}} \approx \frac{A_{\text{res}}}{A_{\text{bg}}} \]

\[ w = \frac{\Gamma}{M} \]

SJ, Song, Yoon
Summary & prospect

• The 750 GeV gg->diphoton scalar resonance can be complicated by resonance-continuum interference.

• For the current O(1) fb excess rate,
  - resonance shape is likely to be pure BW peak (shifting the peak by O(1) GeV),
  - signal rate can be enhanced/suppressed by ~1.5.

• For smaller excess rate in the future, intf effects will be larger, providing non-trivial test of a spin-0 resonance.
Backup
Why not seen so far?

• 1. Narrow resonances
• 2. Small complex phases