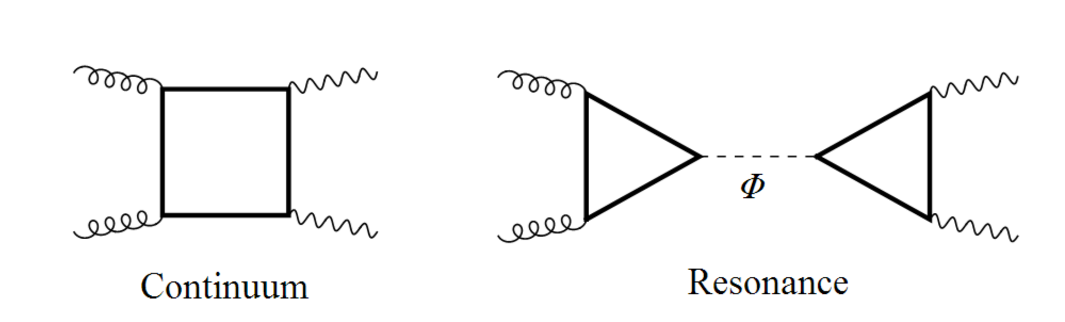


Resonance-Continuum Interference effect in $\gamma\gamma$ and ZZ channels

(with discussion about 750 GeV diphoton excess)

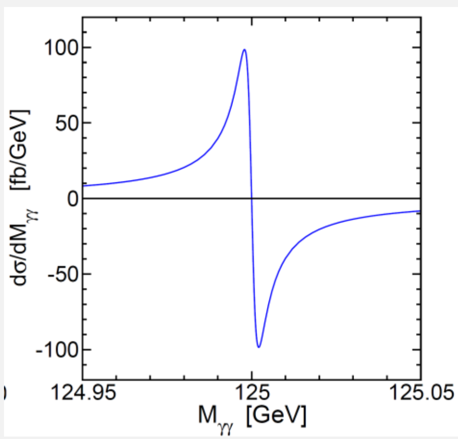
Yeo Woong Yoon (KU)

High1-2016 KIAS-NCTS joint workshop
on Particle Physics, String theory and Cosmology

based on
1505.00291, 1510.03450,
1601.00006, 160x,xxxxx
in collaboration with
Jeonghyeon Song, Sunghoon Jung

Highlights in Resonance-Continuum Interference for $h(125)$

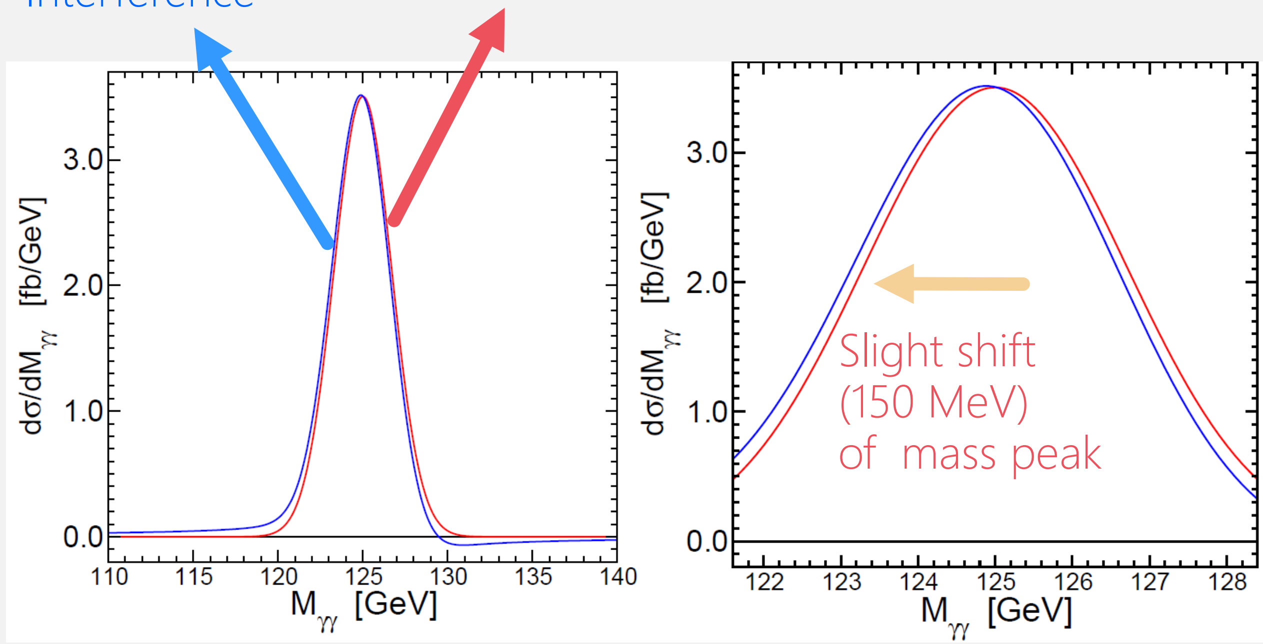
1. Mass shift



Interference distribution

Res. signal + Interference

Res. signal only



S. Martin 1208.1533

Highlights in Resonance-Continuum Interference for $h(125)$

2. Quantitative Effect (to constrain total decay width)

Caola, Melnikov 1307.4935

$$\sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H};$$

On-resonance (NWA)

$$\frac{\mathrm{d}\sigma_{pp\to H\to ZZ}}{\mathrm{d}M_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}.$$

Off-resonance

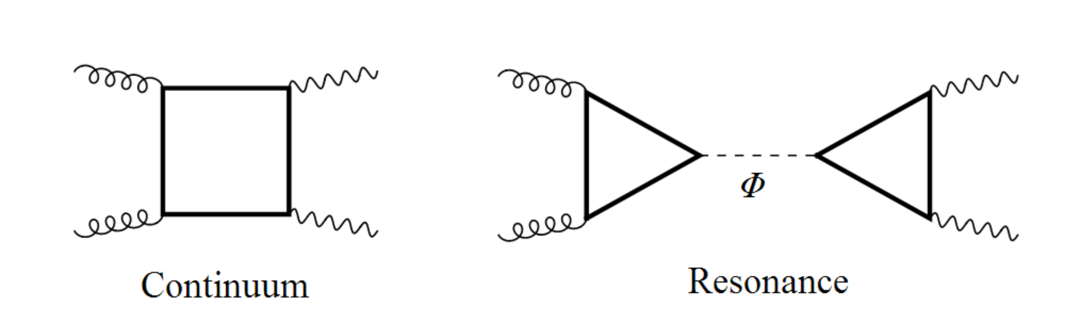
$$N_{4l}^{\mathrm{off}} = \underbrace{3.72 \times \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}}}_{\text{Off-res.}} - \underbrace{9.91 \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}}}}_{\text{Interference}}.$$

Peak		Off-res.		Interference
21.1	:	3.72	:	-9.92

$$\Gamma_H \leq 38.8\,\Gamma_H^{\mathrm{SM}} \approx 163\ \mathrm{MeV}$$

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

Song, Jung, YWY, 1505.00291, 1510.03450

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

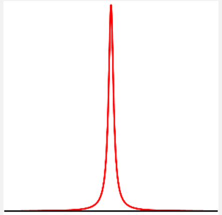
- 3 Key Parameters

$\mathbf{w} = \Gamma/M$

$\mathbf{R} \approx \mathcal{A}_{\text{res}}/\mathcal{A}_{\text{cont}}$

$\boldsymbol{\phi} \approx \text{Arg}(\mathcal{A}_{\text{res}}/\mathcal{A}_{\text{cont}})$

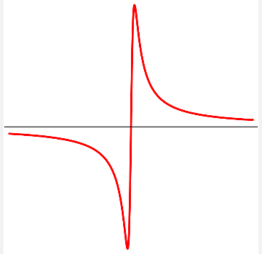
Im-Intf.



$\phi = \pm\frac{\pi}{2}$

Change total signal rate

Re-Intf.



$\phi = 0, \pi$

Change resonance shape

Resonance-Continuum Interference formalism

Multiplication factor that quantifies Interference effect

$$C = \frac{\sigma_{\mathrm{mNWA}}}{\sigma_{\mathrm{prod}} \cdot \mathrm{Br}_{\gamma\gamma}}$$

$$= \left(1 + \frac{2\Gamma}{RM} s_{\phi}\right)$$

For narrow width

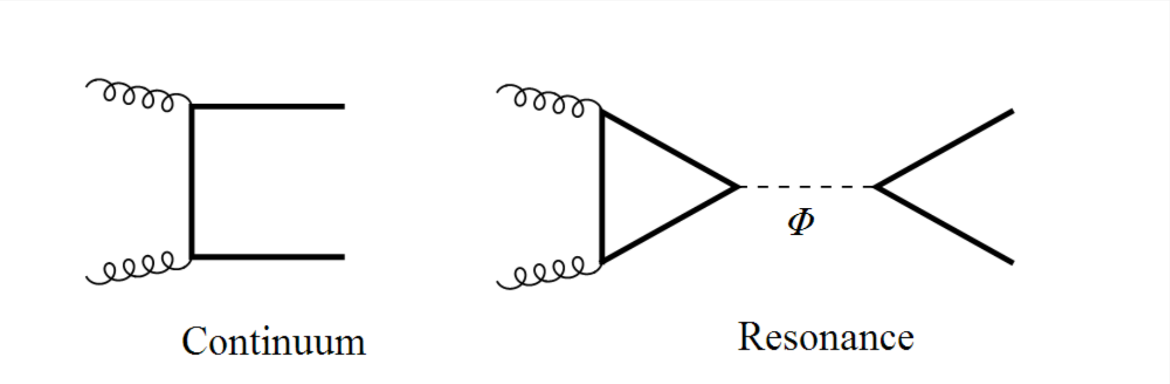
$$K_{\mathrm{intf}} = \frac{\sigma_{\mathrm{mNWA}}}{\sigma_{\mathrm{prod}} \cdot \mathrm{Br}_{\gamma\gamma}}$$

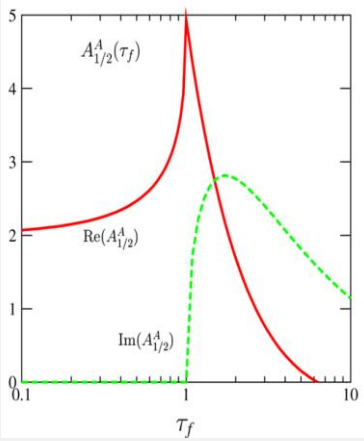
$$\sigma_{\mathrm{mNWA}} = \int_{M-\Delta}^{M+\Delta} dm_{\gamma\gamma} \left[\frac{d\sigma_{\mathrm{sig}}}{dm_{\gamma\gamma}}\right]$$

For broad width

1. Resonance-Continuum Interference in ttbar

$t\bar{t}$ channel



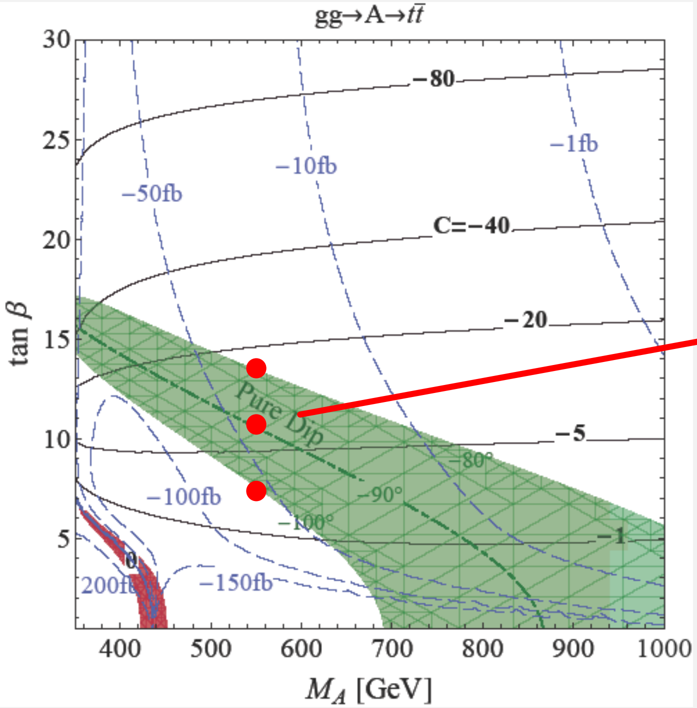


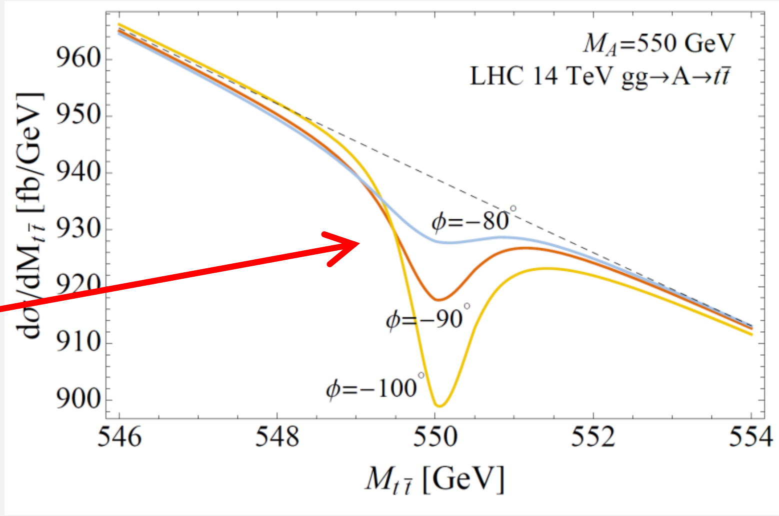
R is one-loop suppressed → Large Interference

$\phi \approx -90°$ → Destructive Inteterference

$$C = \left(1 + \frac{2\Gamma}{RM} s_\phi\right) < 0$$

1. Resonance-Continuum Interference in ttbar

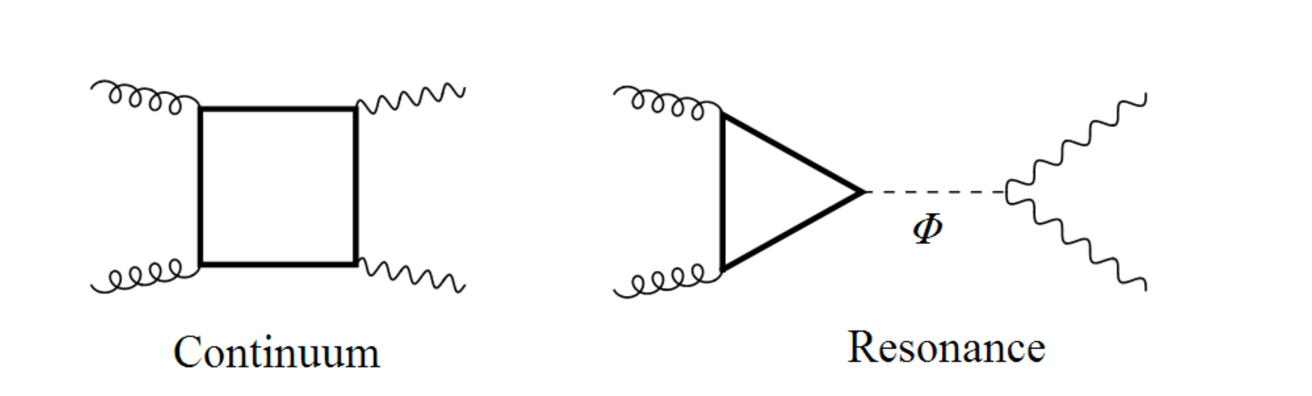




Mostly Dip-like

2. Resonance-Continuum Interference in ZZ

ZZ channel

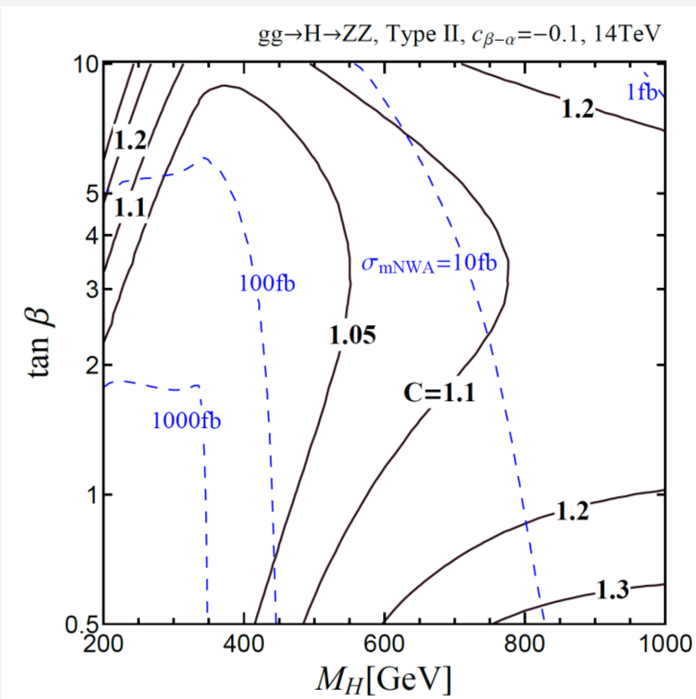


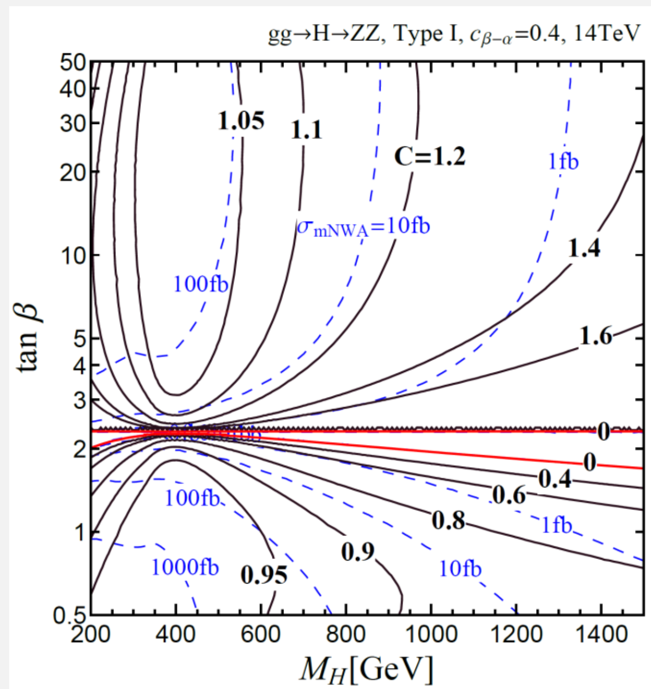
R is roughly order 1 → Small Interference

$\phi \approx 0^\circ$ → Real Interference

$$C = \left(1 + \frac{2\Gamma}{RM} s_\phi\right) \approx 1$$

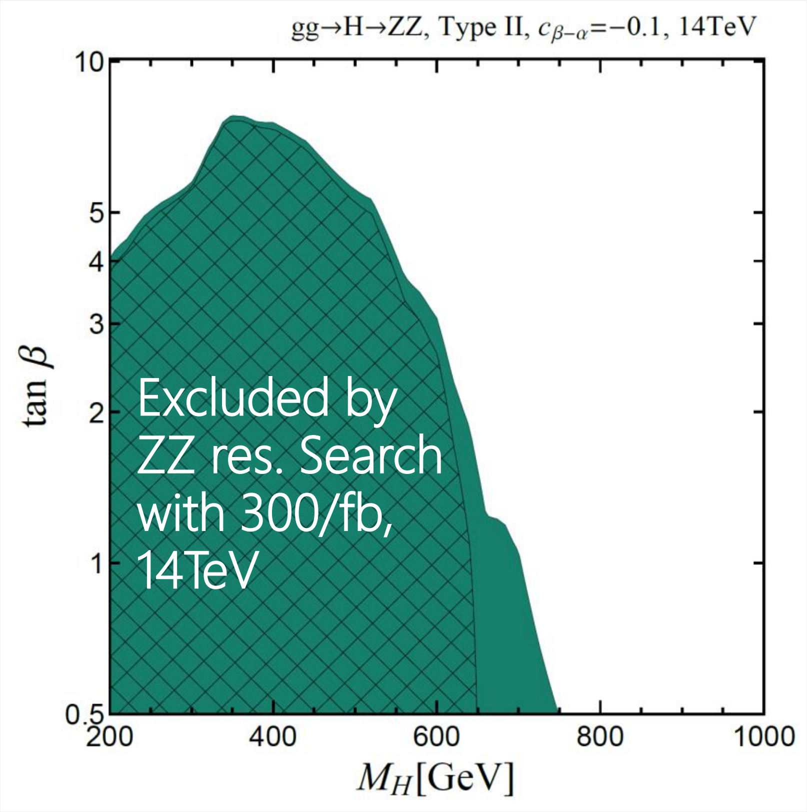
2. Resonance-Continuum Interference in ZZ





O(10%) intf. effect

2. Resonance-Continuum Interference in ZZ

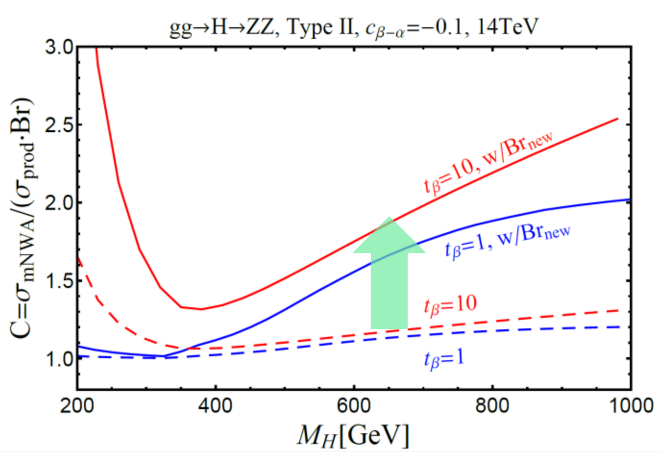


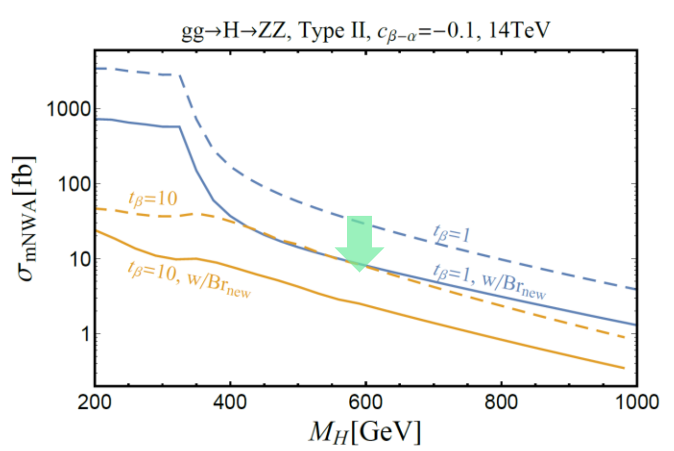
Hatched : w/o intf.

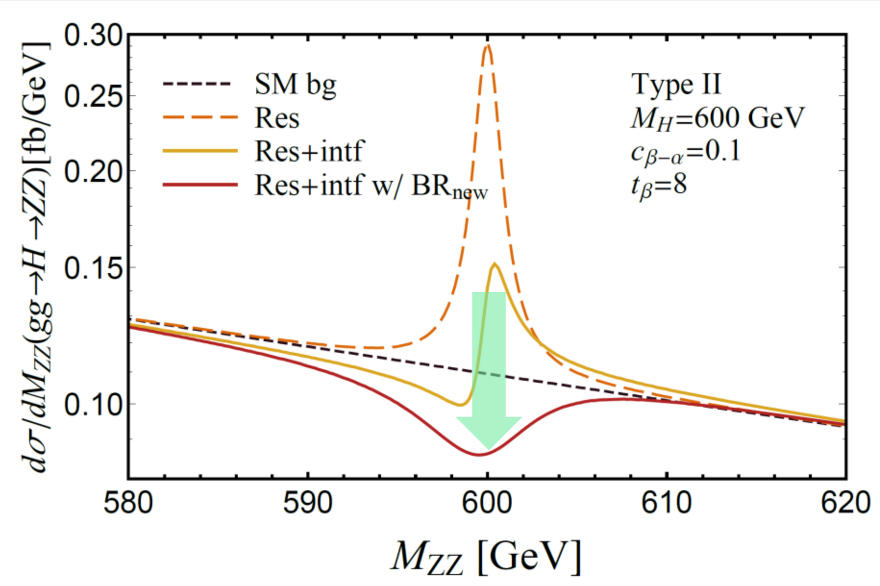
Colored : w/ intf.

→ 20~30 GeV difference

2. Resonance-Continuum Interference in ZZ





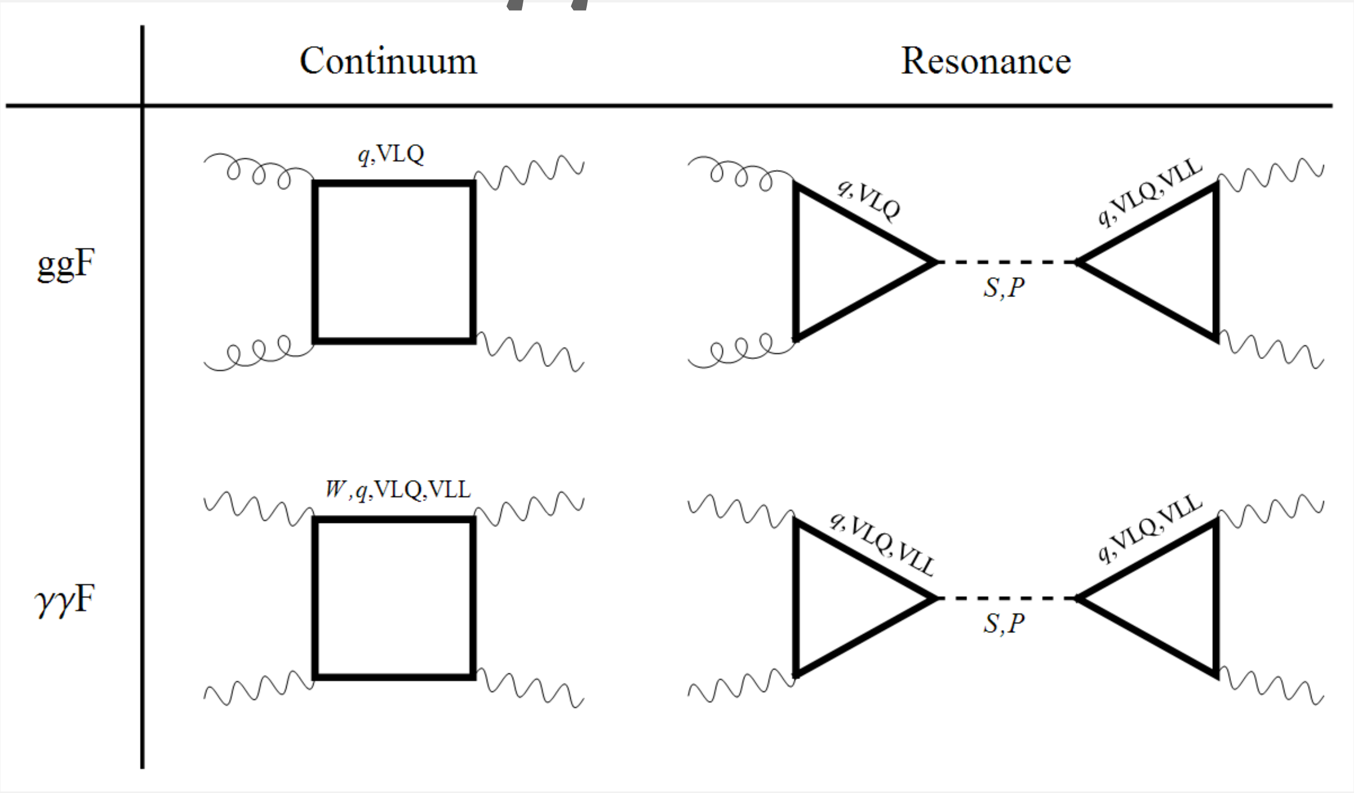


Role of width:
By changing

$$5\times\Gamma_\phi$$

3. Resonance-Continuum Interference in $\gamma\gamma$

$\gamma\gamma$ channel

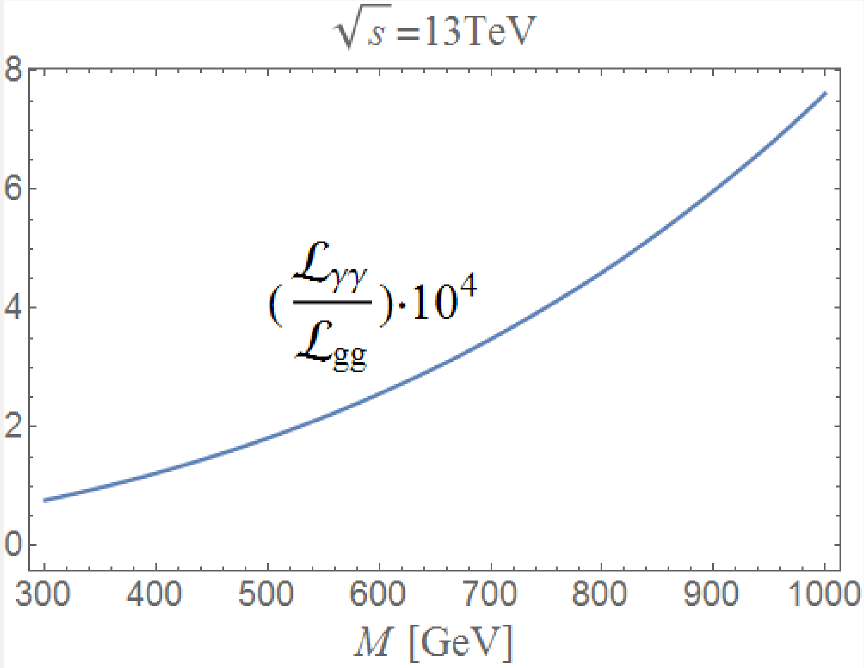


R is one-loop suppressed
→ Large Interference

ϕ is non-trivial, model dependent

3. Resonance-Continuum Interference in $\gamma\gamma$

Relative strength of Photon PDF:



By using NNPDF2.3QED

NNPDF Collaboration 1308.0598

$$\mathcal{L}_{gg(\gamma\gamma)}(x) = \int_x^1 x\frac{dy}{y} f_{g(\gamma)/p}(y) f_{g(\gamma)/p}\left(\frac{x}{y}\right)$$

3. Resonance-Continuum Interference in $\gamma\gamma$

We assume scalar diphoton resonances

M [GeV]	200	300	400	500	600	700	800	900	1000
$\sigma(pp \to S \to \gamma\gamma)$ [fb] $\left(\frac{\Gamma_S}{M} = 0.01\right)$	1.7	0.78	0.48	0.34	0.24	0.18	0.15	0.11	0.11
$\sigma(pp \to S \to \gamma\gamma)$ [fb] $\left(\frac{\Gamma_S}{M} = 0.1\right)$	5.2	2.5	1.5	1.1	0.77	0.58	0.47	0.36	0.33

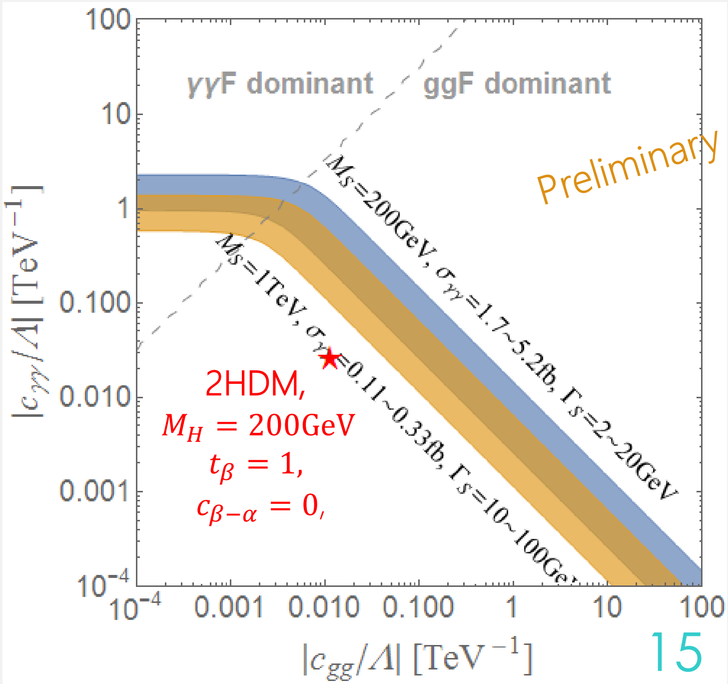
which can be discovered at 5σ with 300/fb at 13TeV

Model independent approach:

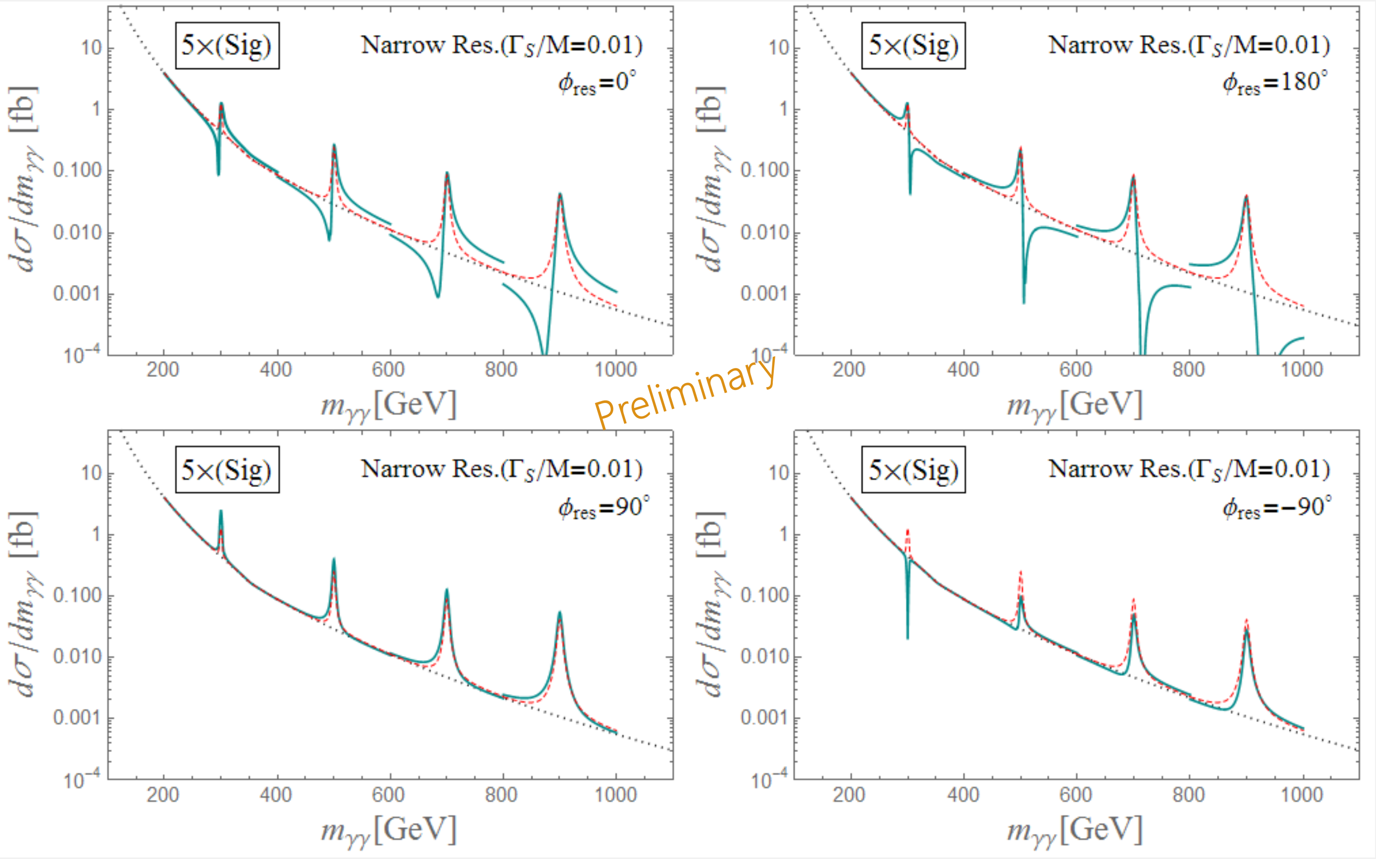
$$\mathcal{L}_{\rm eff} = \frac{c_{gg}}{\Lambda} g_3^2 S\, G^a_{\mu\nu} G^{\mu\nu\, a} + \frac{c_{\gamma\gamma}}{\Lambda} e^2 S\, F_{\mu\nu} F^{\mu\nu} + \frac{\tilde{c}_{gg}}{\Lambda} g_3^2 P\, G^a_{\mu\nu} \tilde{G}^{\mu\nu\, a} + \frac{\tilde{c}_{\gamma\gamma}}{\Lambda} e^2 P\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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

ϕ_{res}: complex phase of resonance amplitude



3. Resonance-Continuum Interference in $\gamma\gamma$



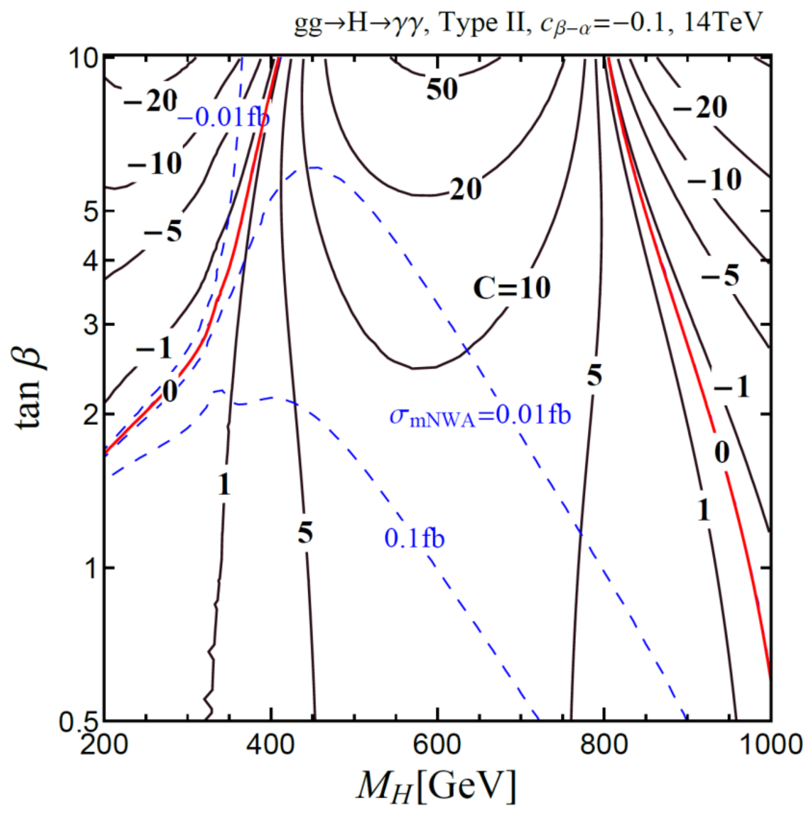
We assume ggF dominance

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 ϕ

C is a correction factor due to the interference effect.

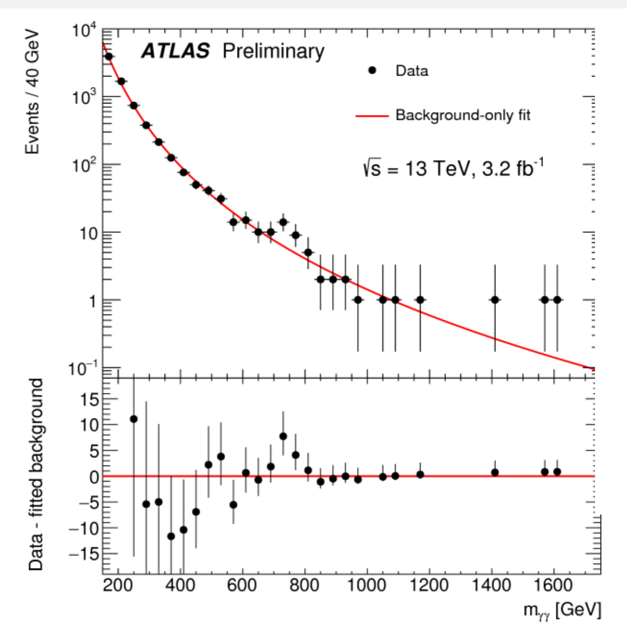
C=0 means that the interference term cancels the BW resonance.

→ O(100%) intf. effect

3. Resonance-Continuum Interference in $\gamma\gamma$

Now we consider 750GeV diphoton excess

ATLAS-CONF-2015-081



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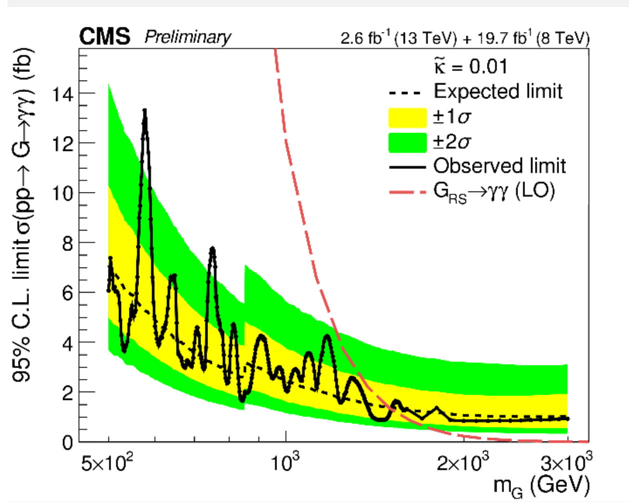
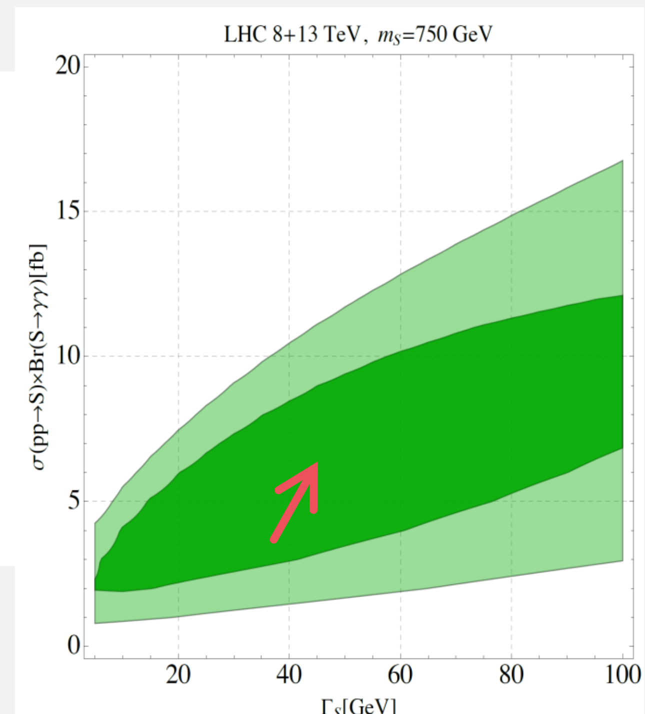


Falkowski, Slone, Volansky 1512.05777



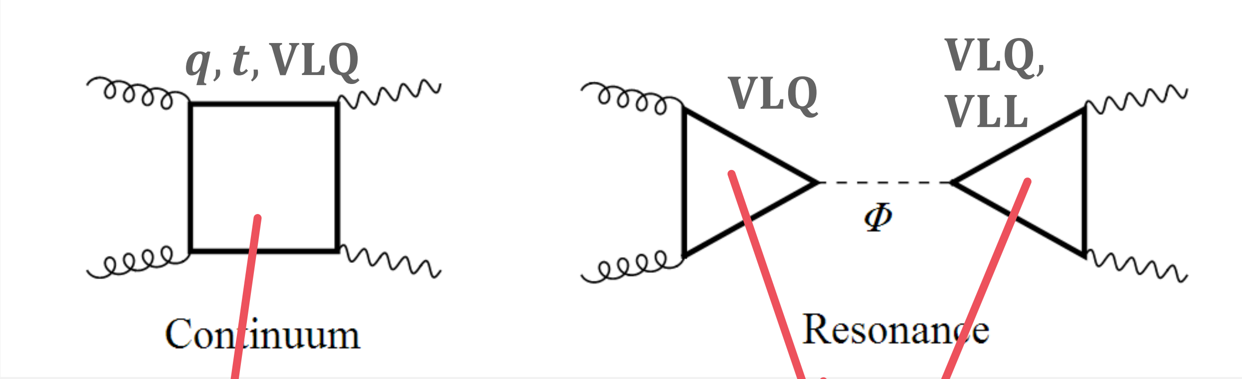
$\Gamma_\phi = 45\text{GeV}$

$$\sigma(pp \to \Phi \to \gamma\gamma) = \begin{cases} 6.5 \pm 2.5\,\text{fb} & (68\%\text{CL}) \\ 6.5^{+4.5}_{-3.5}\,\text{fb} & (95\%\text{CL}) \end{cases}$$

Real Interference ($\phi = 0, \pi$) - Peak Shift

Model 1 : Singlet + VLQ/VLL

$M_Q = 1\,\mathrm{TeV},\ N_Q = 2,\ s_Q = 0.2.$
$M_L = 400\,\mathrm{GeV},\ N_L = 6,\ s_L$ is varied
$\Gamma_\Phi = 5\,\mathrm{GeV}$



Small phase
from top loop

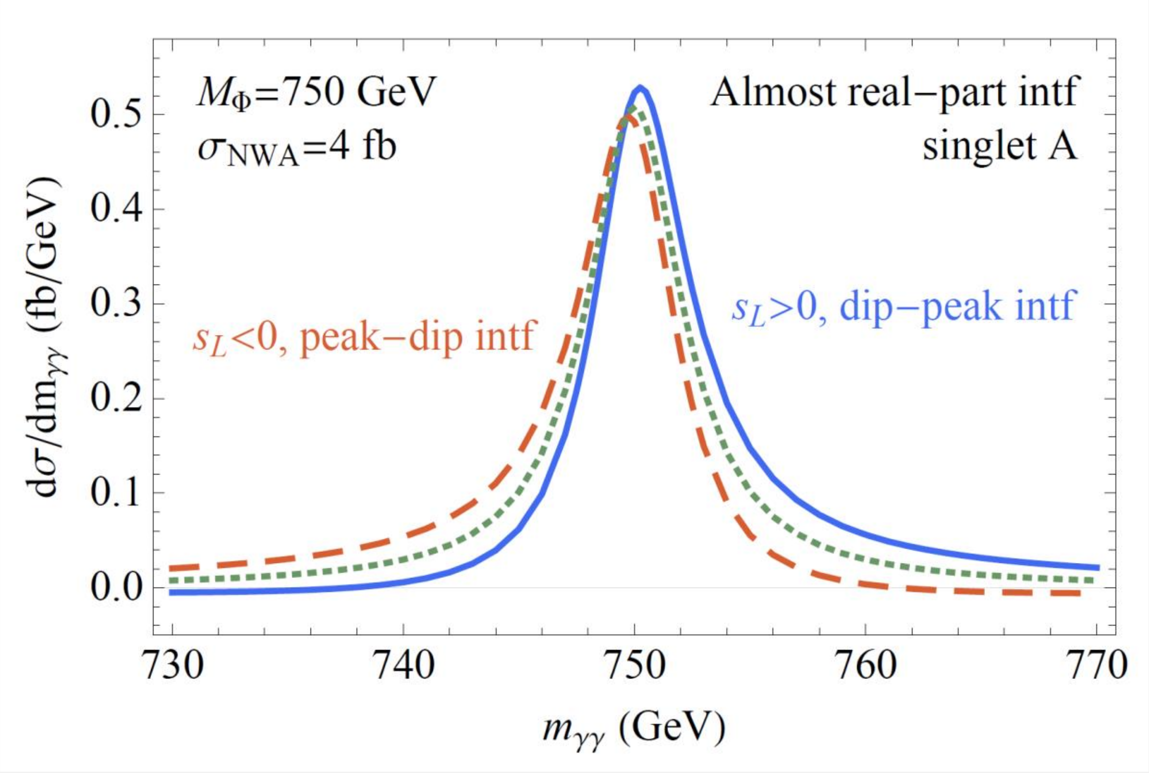
No phase since $M_\phi < 2M_{\mathrm{VLF}}$

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

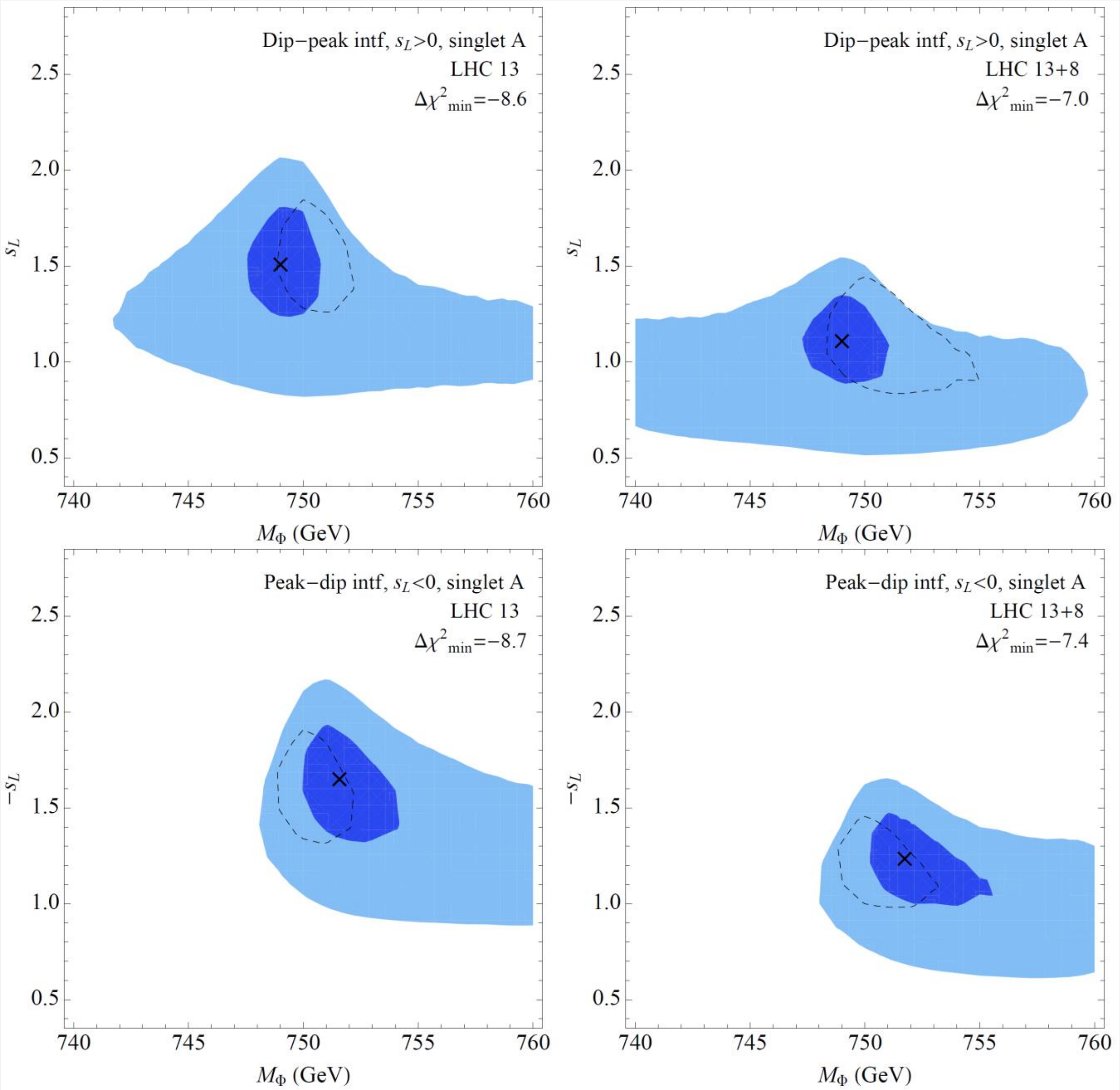
$\cos\phi \simeq \pm 1,$
$\sin\phi \simeq 0$ → Real Interference

Real Interference ($\phi = 0, \pi$) - Peak Shift

Model 1 : Singlet + VLQ/VLL



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 $\boldsymbol{\Phi} \to \boldsymbol{\gamma\gamma}$:

$$\mathcal{A}^{\Phi}_{\gamma\gamma,\mathrm{VLL}} = \sum_{\mathrm{VLL}}\sum_{i=1,2}\left[Q^2_{E_i}\frac{\hat{y}^{\Phi}_t y_E v}{M_{E_i}}A^{\Phi}_{1/2}(\tau_{E_i}) + Q^2_{D_i}\frac{\hat{y}^{\Phi}_b y_D v}{M_{D_i}}A^{\Phi}_{1/2}(\tau_{D_i})\right]$$

We fix $\mathbf{y_D}$ as follows to avoid the SM Higgs precision

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

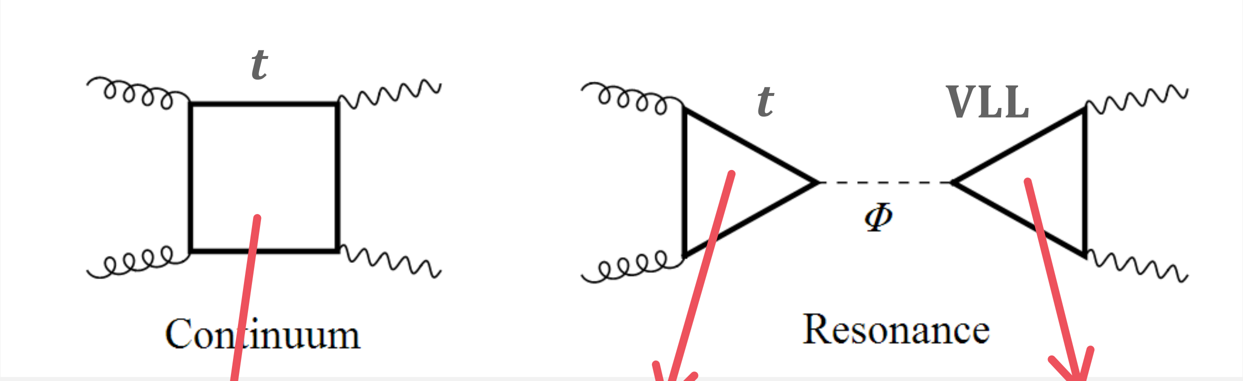
We set $t_\beta = 0.7$ to raise up the pseudo-scalar Higgs contribution

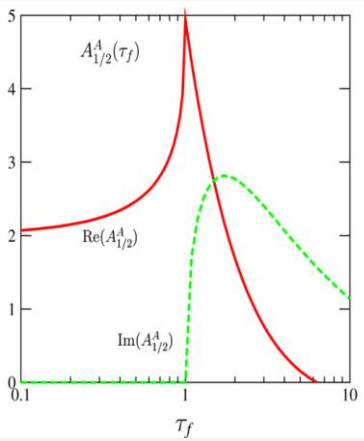
Total decay rate is determined by dominant ttbar decays:

$$\Gamma_{H(A)} = 46(58)\ \mathrm{GeV}$$

2.Imaginary Interference ($\phi = \pm\frac{\pi}{2}$) (Signal Enhancement)

Model 2 : 2HDM+VLL





Small phase from top loop

Phase $90°$

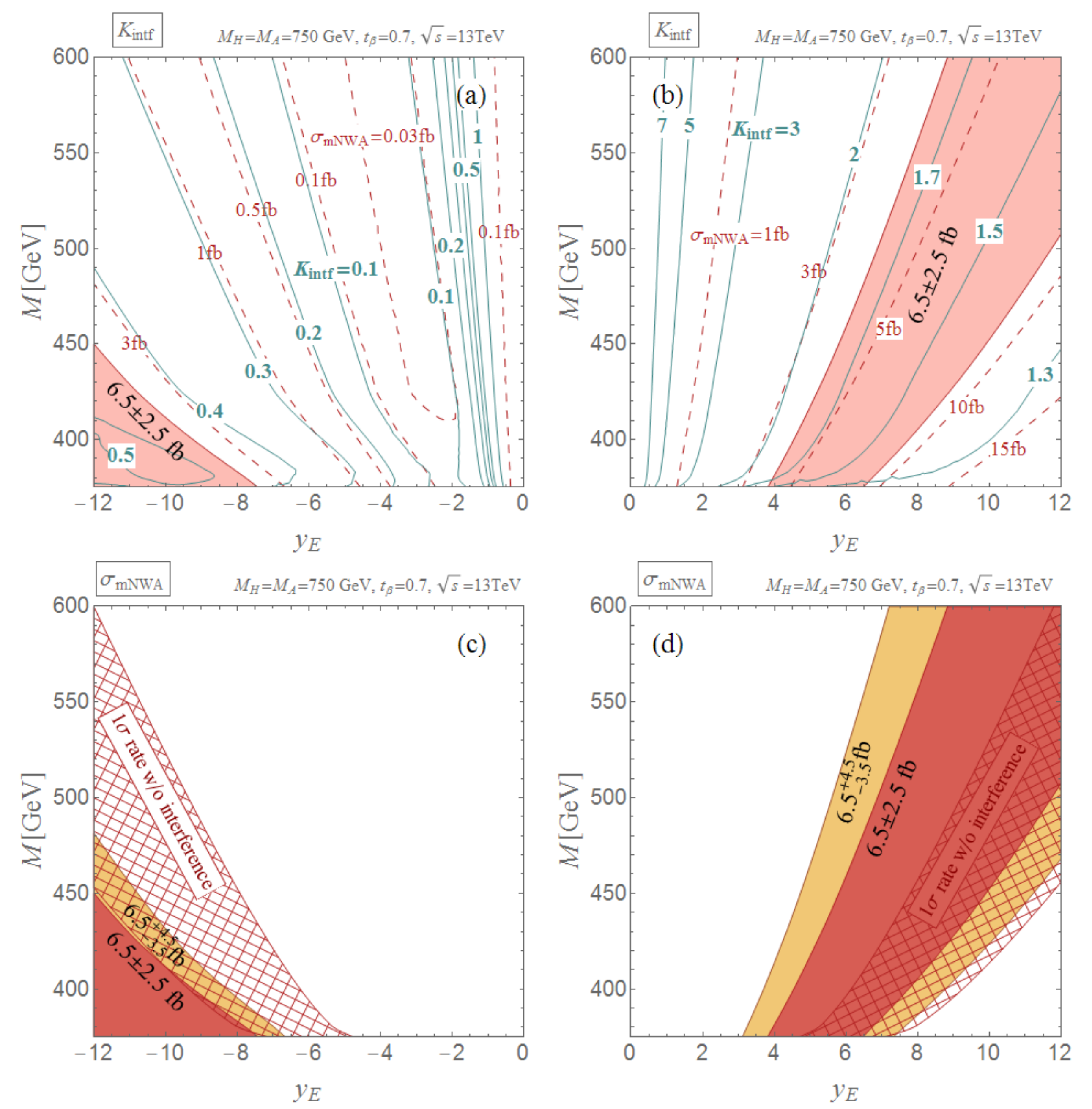
Small phase $20°\sim30°$

$$\phi \sim \begin{cases} 90° & \text{for } y_E > 0; \\ -90° & \text{for } y_E < 0. \end{cases}$$

$\cos\phi \simeq 0$, $\sin\phi \simeq \pm 1$

→ Imaginary Interference

Model 2 : 2HDM+VLL



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

→ Total cross section w/ interference

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

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

K_{intf} = 1.6 for 6fb
2 for 3 fb
4 for 1 fb

Summary

- Resonance-Continuum Interference effect Is inevitable and can be significant for any resonance.
- Not only Γ/M, but also R (resonance to continuum ratio) and ϕ (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