2016 Spring KPS Pioneer Symposium Program
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Resonance-continuum interference in the 750 GeV diphoton excess

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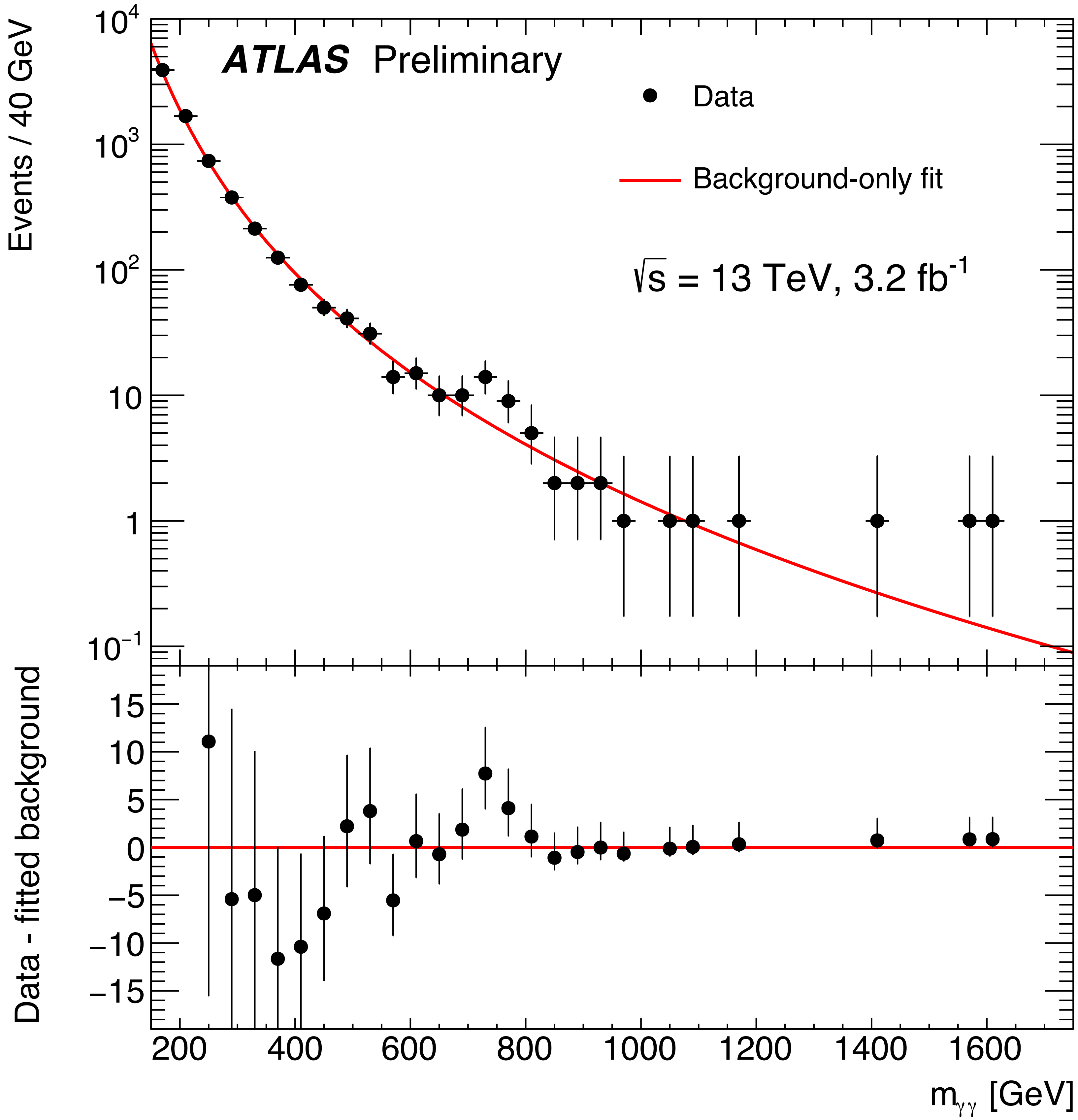
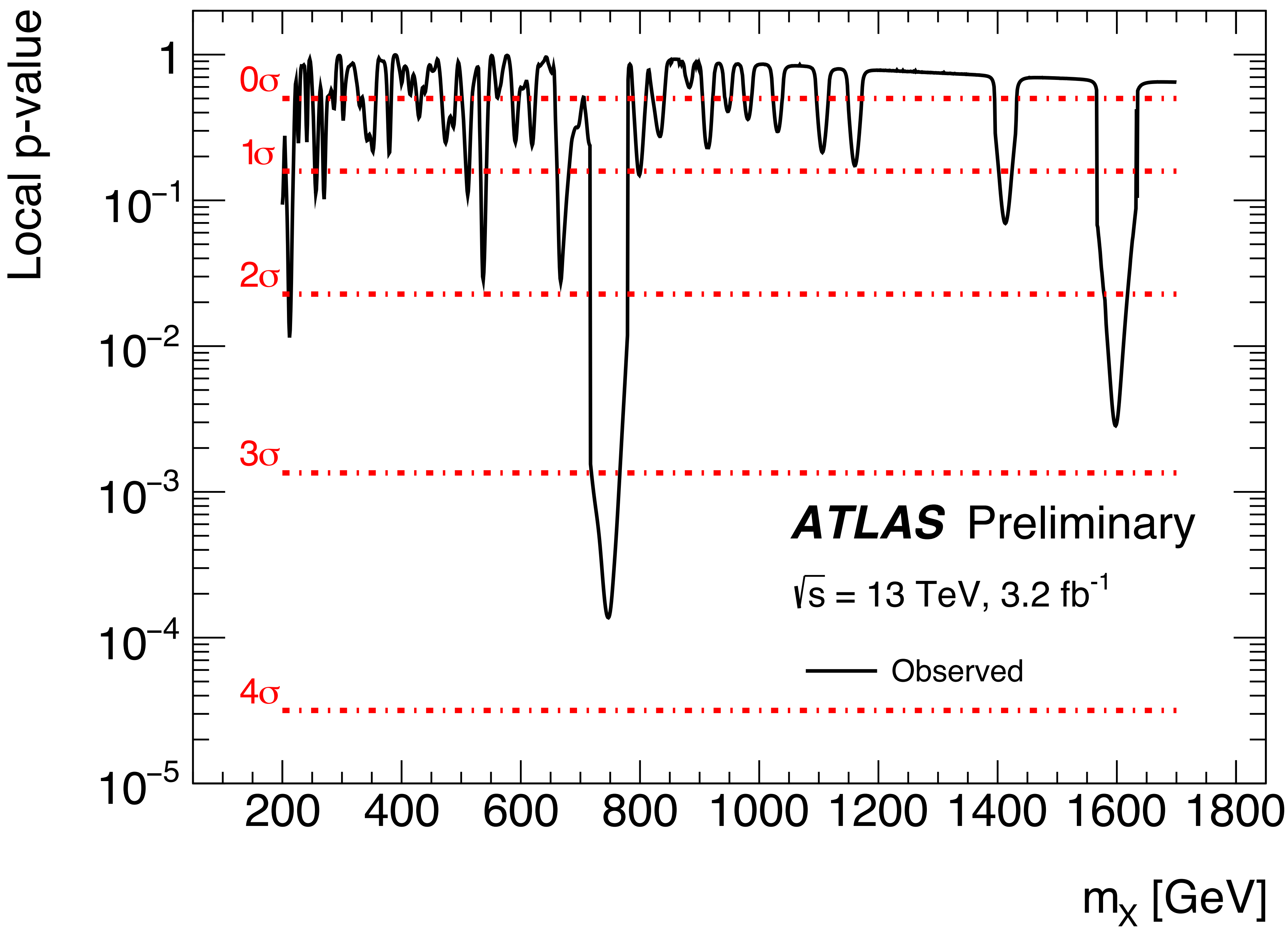
to appear in JHEP

1. Diphoton excess at 750 GeV

ATLAS-CONF-2015-081



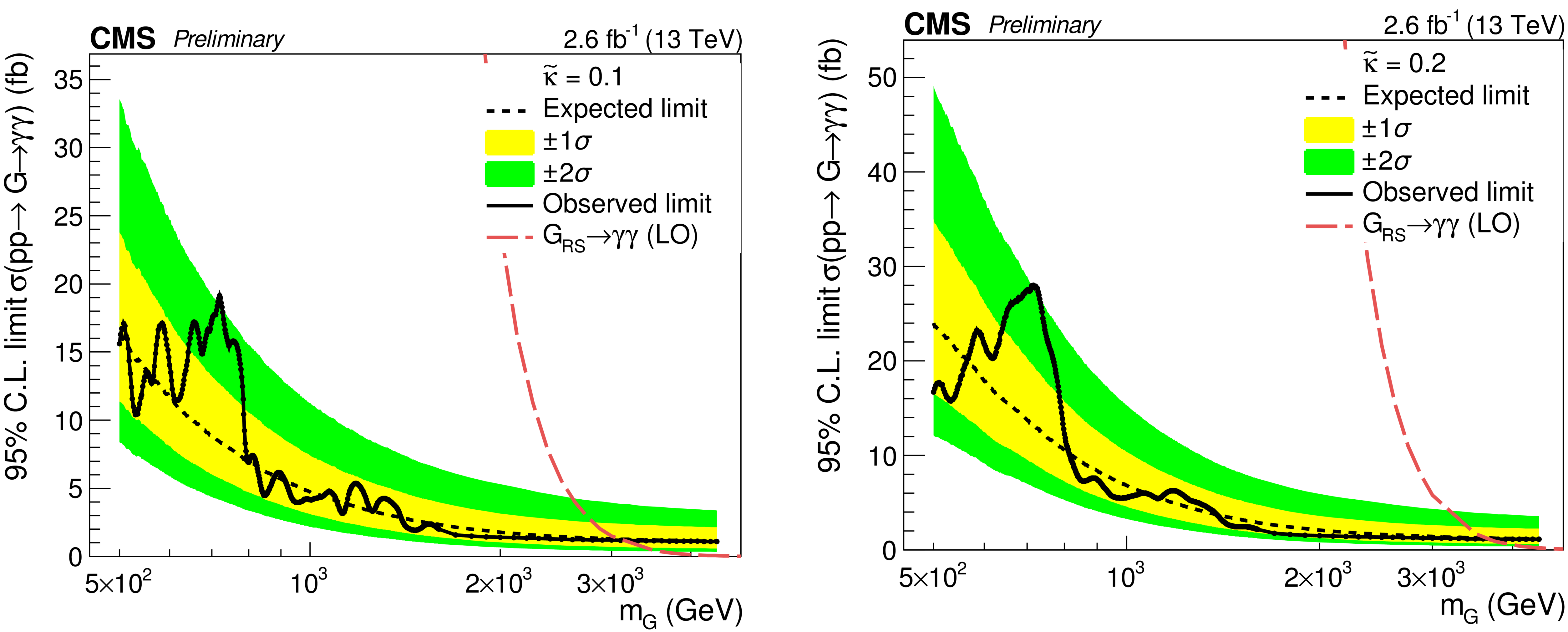
ATLAS-CONF-2015-081



local significance: 3.6 σ

global significance: 2.3 σ

CMS PAS EXO-15-004



local significance: 2.6 σ

global significance: 1.2 σ

Mass? Width?

to be answered by the χ^2 analysis

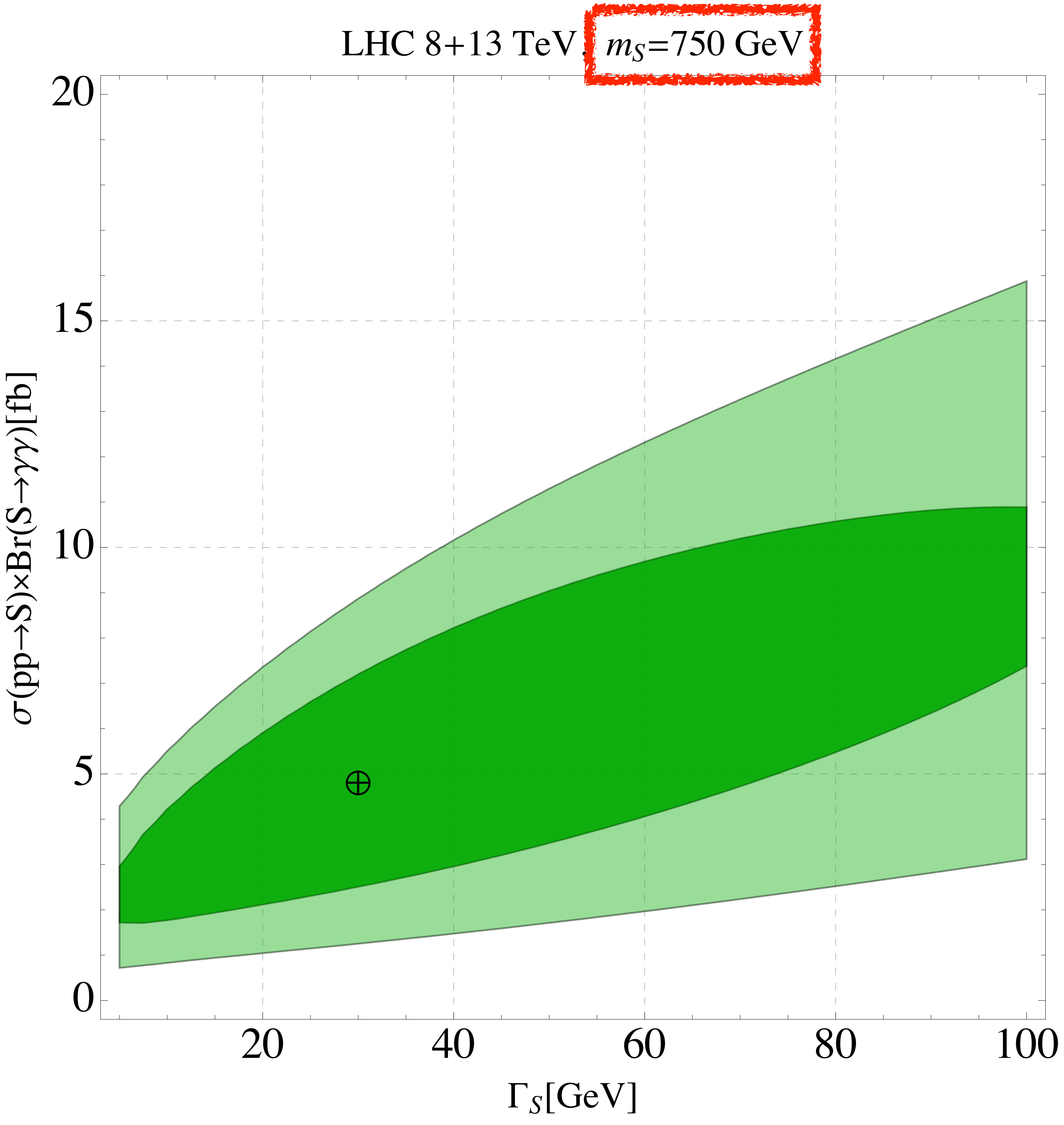
ATLAS

Bin[GeV]	650	690	730	770	810	850
$N_{\rm events}$	10	10	14	9	5	2
$N_{\rm background}$	11.0	8.2	6.3	5.0	3.9	3.1

CMS

Bin[GeV]	700	720	740	760	780	800
$N_{\rm events}$ (EBEB)	3	3	4	5	1	1
$N_{\rm background}$ (EBEB)	2.7	2.5	2.1	1.9	1.6	1.5
$N_{\rm events}$ (EBEE)	16	4	1	6	2	3
$N_{\rm background}$ (EBEE)	5.2	4.6	4.0	3.5	3.1	2.8

Falkowski arXiv:1512.05777



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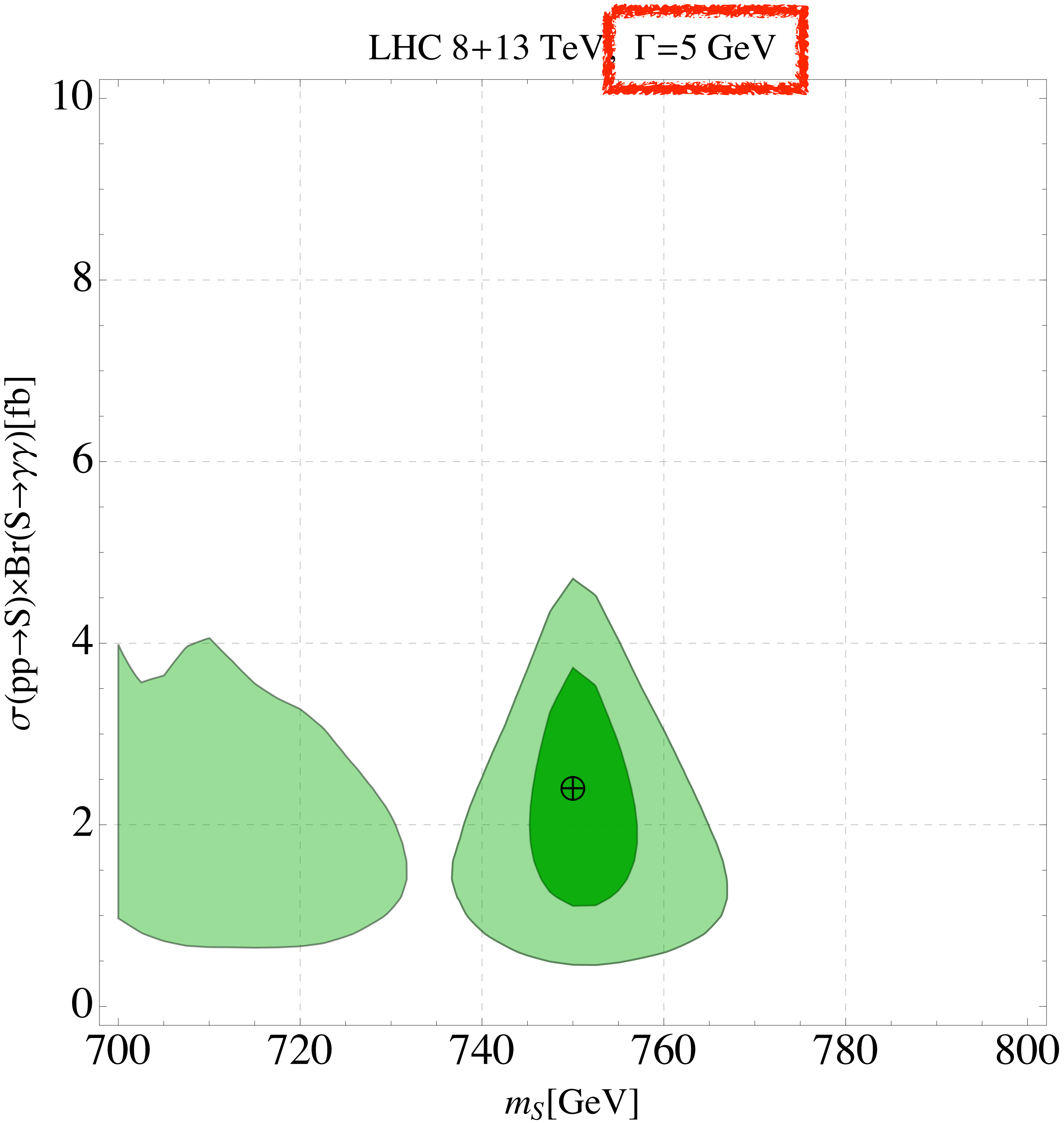


$$2.4^{+1.35}_{-1.30}\ \text{fb}$$

How do we explain this 2.4 fb?

How do we explain this 2.4 fb?

- NP particle with m=750 GeV
- Production cross section
- BR of the diphoton channel

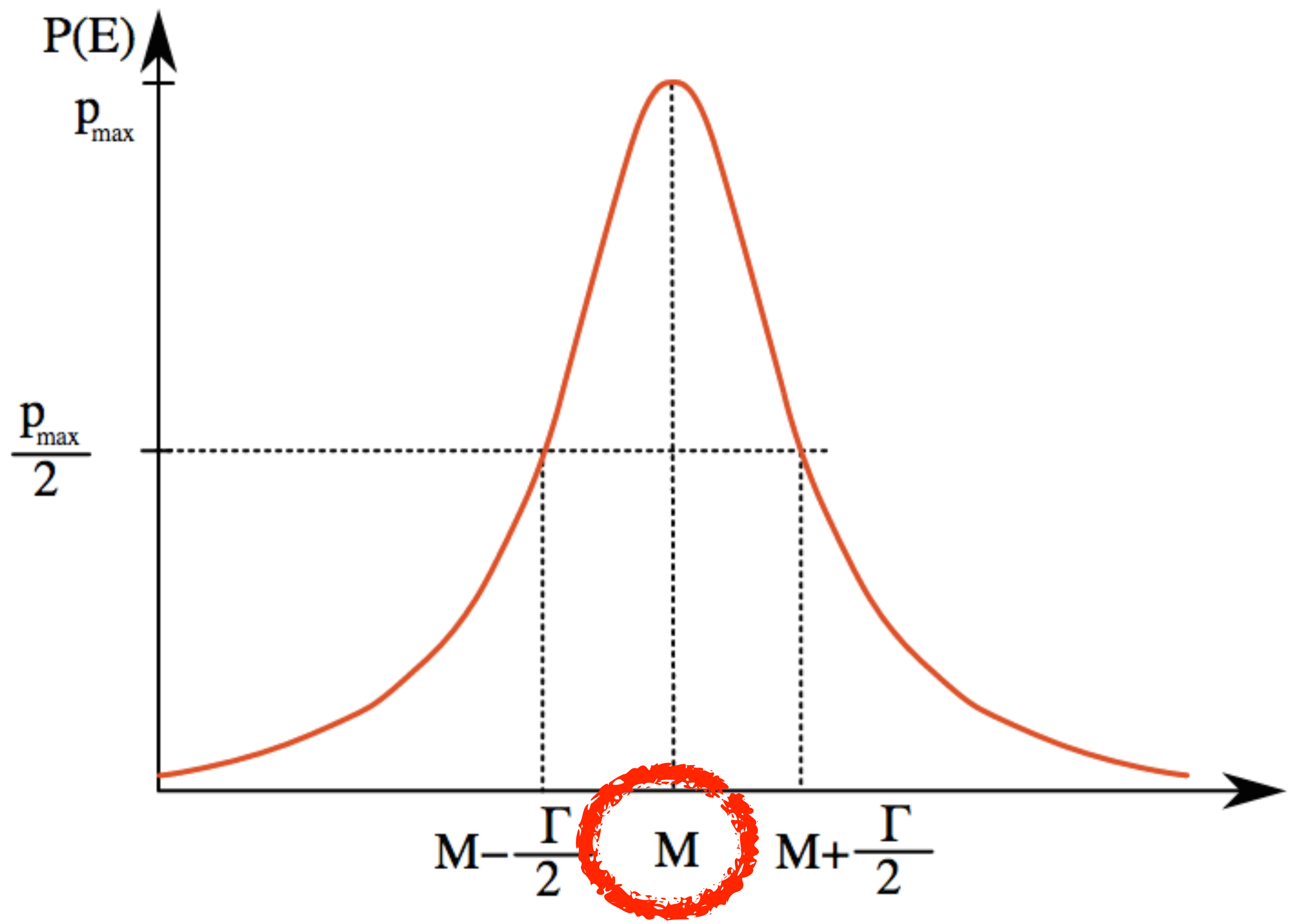
$$\sigma_{\rm prod} \cdot B = 2.4\,{\rm fb}$$


Interference

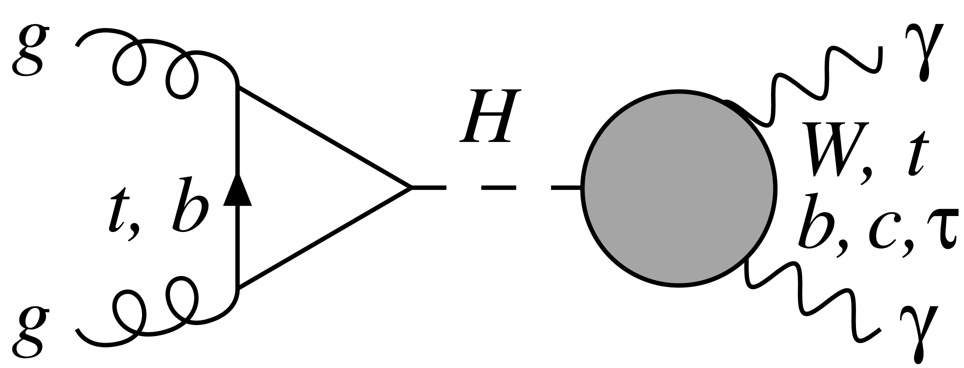
2. Interference Effects

New Particle search for Breit-Wigner resonance

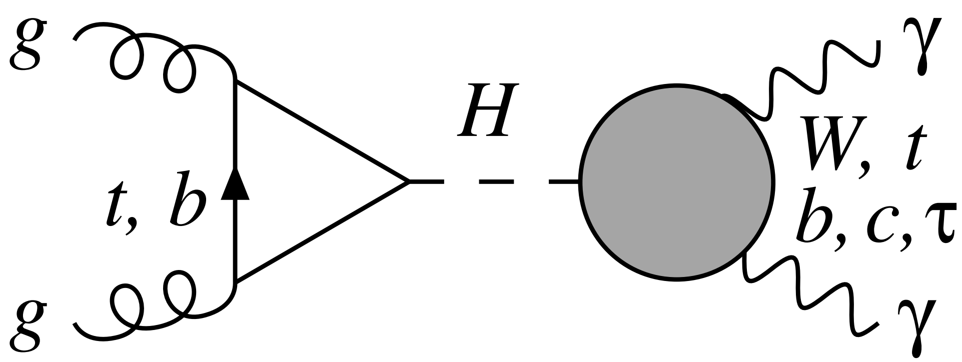
$$f(E) \sim \frac{1}{(E^2 - M^2)^2 + M^2\Gamma^2}.$$

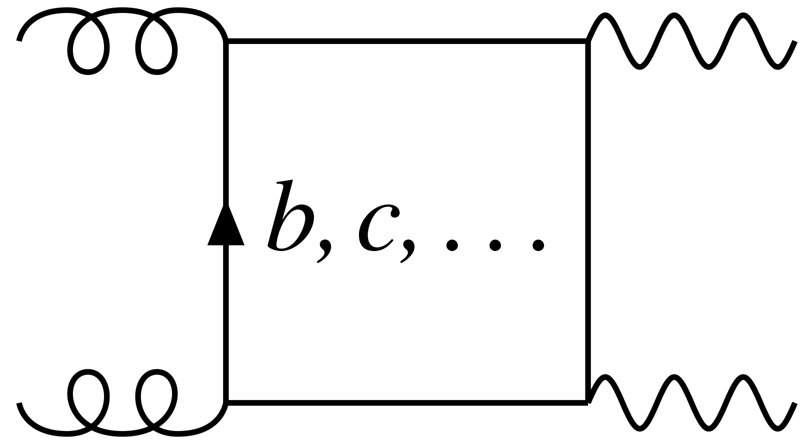


Diphoton channel of a Higgs boson

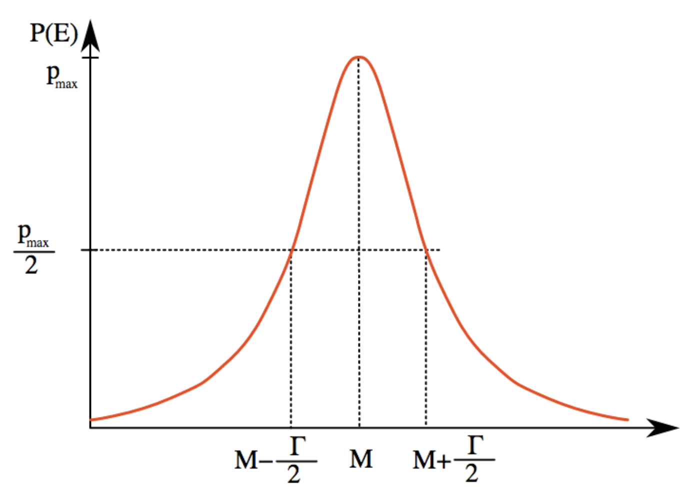


Diphoton channel of a Higgs boson





interference effects



Parton cross section

$$\frac{d\hat{\sigma}}{dz} = \frac{1}{32\pi\hat{s}} \sum \left| \mathcal{A}_{\rm bg} e^{i\phi_{\rm bg}} + \frac{M^2}{\hat{s} - M^2 + iM\Gamma} \cdot \mathcal{A}_{\rm res} e^{i\phi_{\rm res}} \right|^2$$

$$\text{where } z = \cos\theta^*$$

$$\frac{d\hat{\sigma}}{dz} = \frac{1}{32\pi\hat{s}} \sum \left| \mathcal{A}_{\rm bg} e^{i\phi_{\rm bg}} + \frac{M^2}{\hat{s} - M^2 + iM\Gamma} \mathcal{A}_{\rm res} e^{i\phi_{\rm res}} \right|^2$$

where $z = \cos\theta^*$

Propagator factor

$$\hat{\sigma} = \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res} \frac{M^4}{(\hat{s}-M^2)^2 + M^4 w^2} \left[1 + \frac{2w}{R} s_\phi + \frac{2(\hat{s}-M^2)}{M^2} \frac{c_\phi}{R} \right]$$

Exact definition

$$\hat{\sigma}_{\rm bg,res} = \frac{1}{32\pi\hat{s}} \int dz \sum \mathcal{A}^2_{\rm bg,res},$$

$$\hat{\sigma}_{\rm int} e^{i\phi} = \frac{1}{32\pi\hat{s}} \int dz \sum \mathcal{A}_{\rm bg} \mathcal{A}_{\rm res} e^{i(\phi_{\rm res}-\phi_{\rm bg})},$$

$$R = \frac{\hat{\sigma}_{\rm res}}{\hat{\sigma}_{\rm int}}, \quad w \equiv \frac{\Gamma}{M},$$

$$\hat{\sigma} \ = \ \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res} \frac{M^4}{(\hat{s} - M^2)^2 + M^4 w^2} \left[1 + \frac{2w}{R} s_\phi + \frac{2(\hat{s} - M^2)}{M^2} \frac{c_\phi}{R} \right]$$

If there is one dominant amplitude

$$R \simeq \frac{\mathcal{A}_{\rm res}}{\mathcal{A}_{\rm bg}}, \qquad \phi \simeq \phi_{\rm res} - \phi_{\rm bg}$$

$$\hat{\sigma} \;=\; \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res} \frac{M^4}{(\hat{s} - M^2)^2 + M^4 w^2} \left[1 + \frac{2w}{R} s_\phi + \frac{2(\hat{s} - M^2)}{M^2} \frac{c_\phi}{R} \right]$$

BW resonance

$$\hat{\sigma} = \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res} \frac{M^4}{(\hat{s}-M^2)^2 + M^4 w^2} \left[1 + \frac{2w}{R} s_\phi + \frac{2(\hat{s}-M^2)}{M^2} \frac{c_\phi}{R} \right]$$

BW resonance

imaginary-part interference

$$\hat{\sigma} = \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res} \frac{M^4}{(\hat{s}-M^2)^2 + M^4 w^2} \left[1 + \frac{2w}{R} s_\phi + \frac{2(\hat{s}-M^2)}{M^2} \frac{c_\phi}{R} \right]$$

BW resonance

imaginary-part interference

real-part interference

if w is small, only resonance region is important

$$\hat{\sigma} \;=\; \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res}\frac{M^4}{(\hat{s}-M^2)^2 + M^4 w^2}\left[1 + \frac{2w}{R}s_\phi + \frac{2(\hat{s}-M^2)}{M^2}\frac{c_\phi}{R}\right]$$

if w is small, only resonance region is important

$$\hat{\sigma} = \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res} \frac{M^4}{(\hat{s}-M^2)^2 + M^4 w^2} \left[1 + \frac{2w}{R} s_\phi + \frac{2(\hat{s}-M^2)}{M^2} \frac{c_\phi}{R} \right]$$

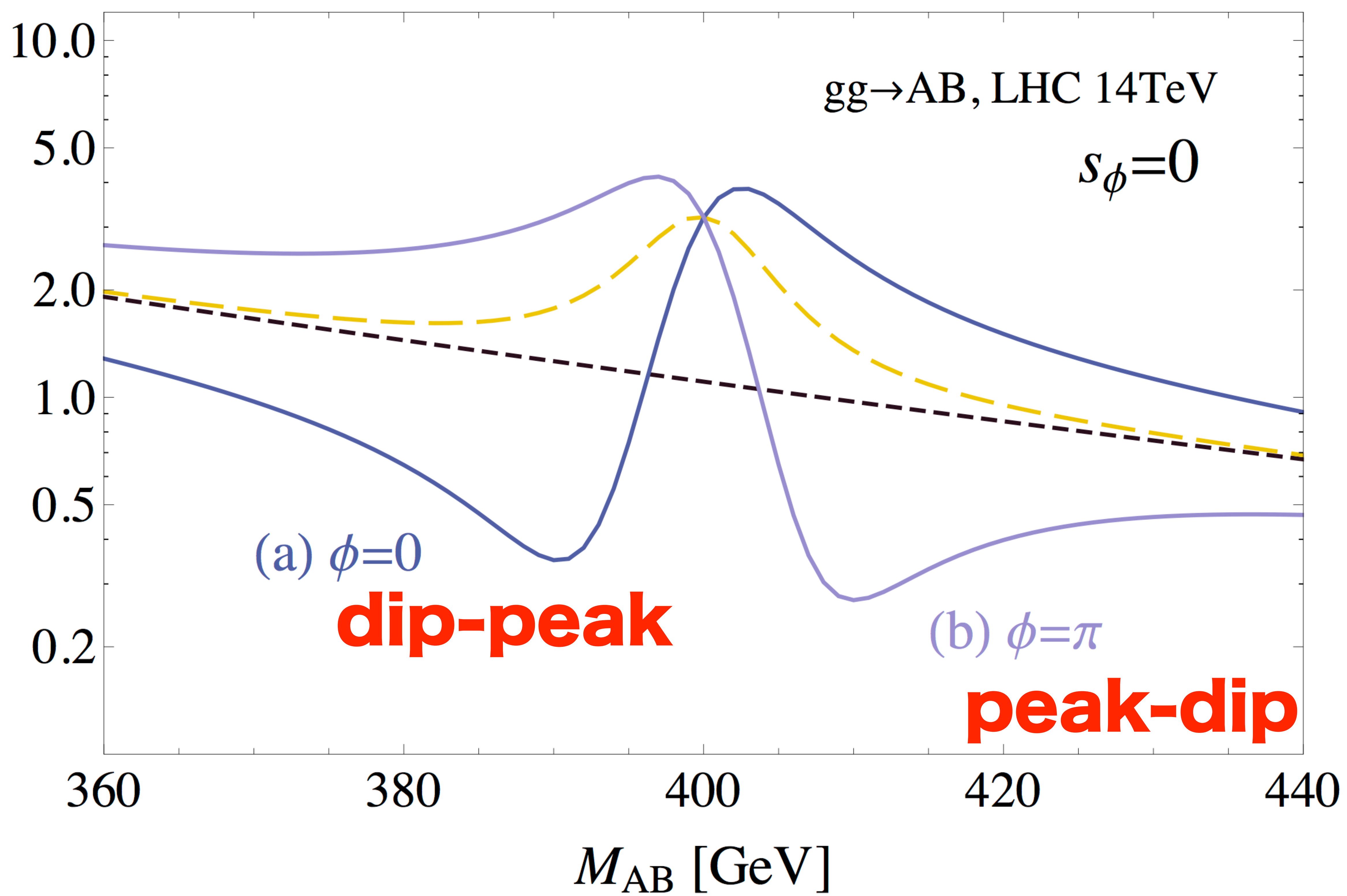
* slowly varying near s=M^2
* treated as constants

Real part interference

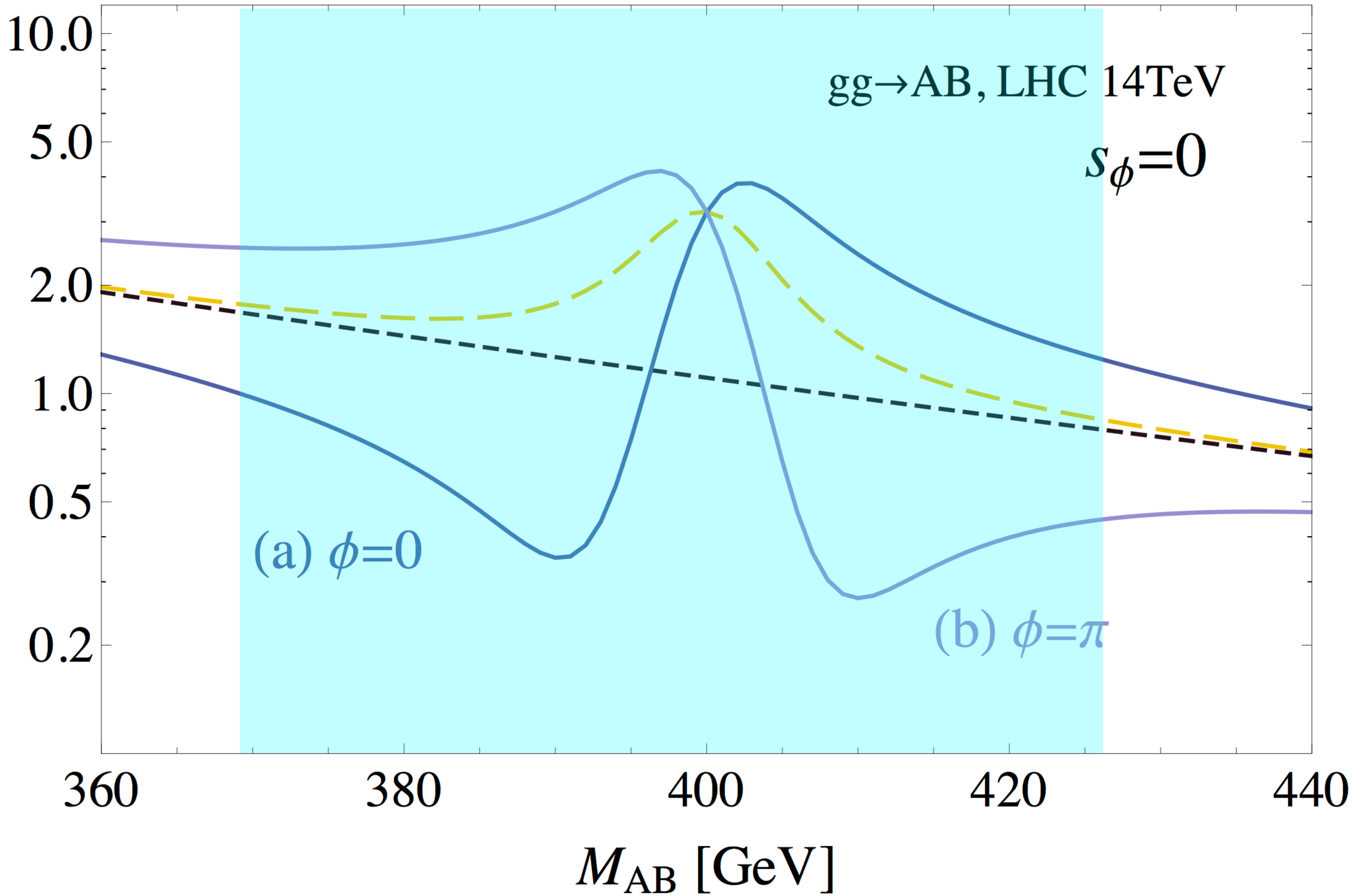
$$\hat{\sigma} = \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res} \frac{M^4}{(\hat{s} - M^2)^2 + M^4 w^2} \left[1 + \frac{2w}{R} s_\phi + \frac{2(\hat{s} - M^2)}{M^2} \frac{c_\phi}{R} \right]$$

- Odd function about the invariant mass
- Cancelled by the integration over a finite bin

Real part interference



Large enough bin



Cancelled out!

Real part: integrated out

$$\hat{\sigma} \;=\; \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res}\frac{M^4}{(\hat{s}-M^2)^2 + M^4 w^2}\left[1 + \frac{2w}{R} s_\phi \qquad \right]$$

Integrated out

Imaginary part interference & BW

$$\hat{\sigma} \;=\; \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res}\frac{M^4}{(\hat{s}-M^2)^2+M^4w^2}\left[1+\frac{2w}{R}s_\phi \cdots\right]$$

- Even function about $\sqrt{\hat{s}} = M$
- survived from the integration over a finite bin.

Correction factor to the NWA

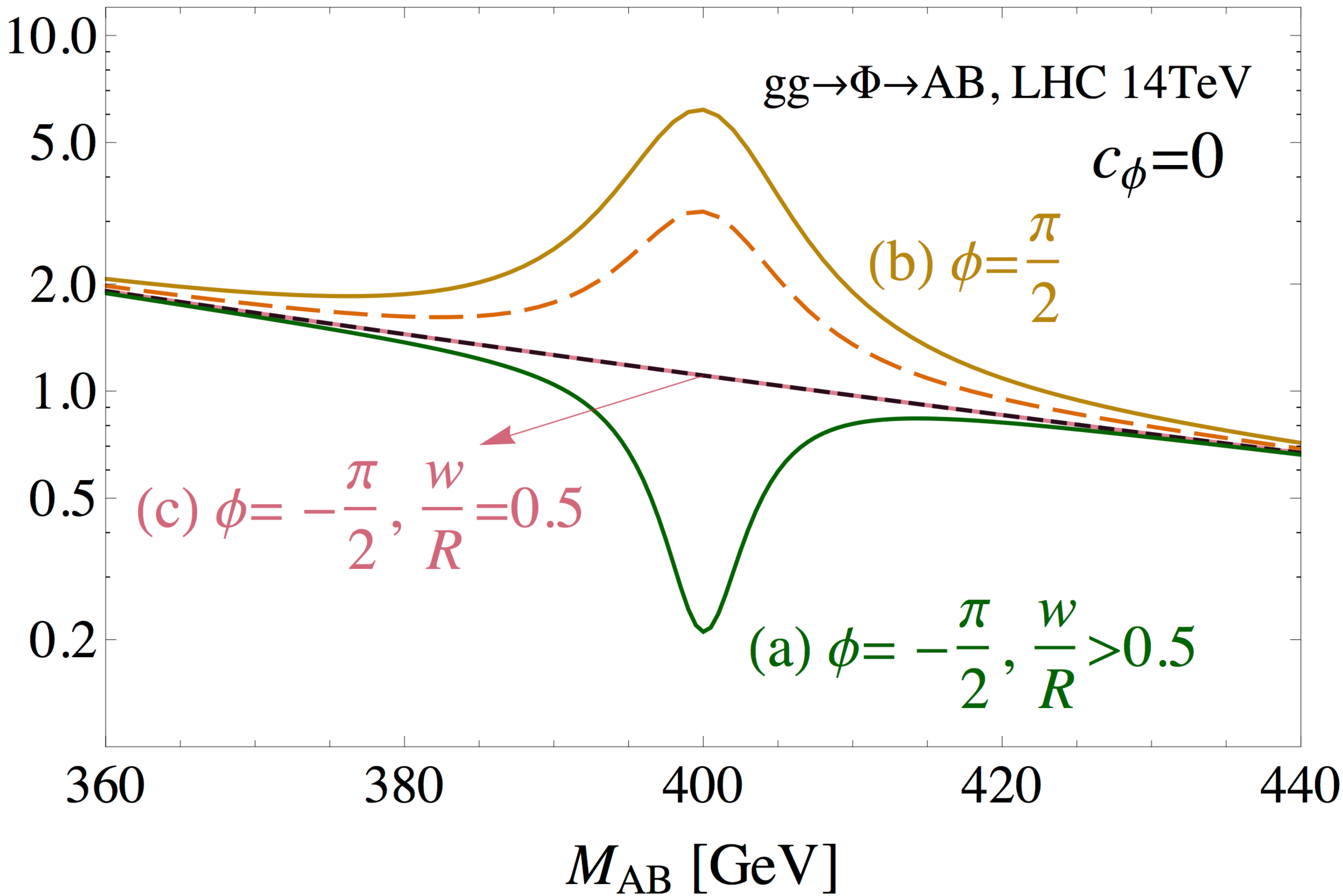
$$\hat{\sigma} \;=\; \hat{\sigma}_{\rm bg} + \hat{\sigma}_{\rm res}\frac{M^4}{(\hat{s}-M^2)^2+M^4w^2}\left[1+\frac{2w}{R}s_\phi \quad\quad\quad\right]$$

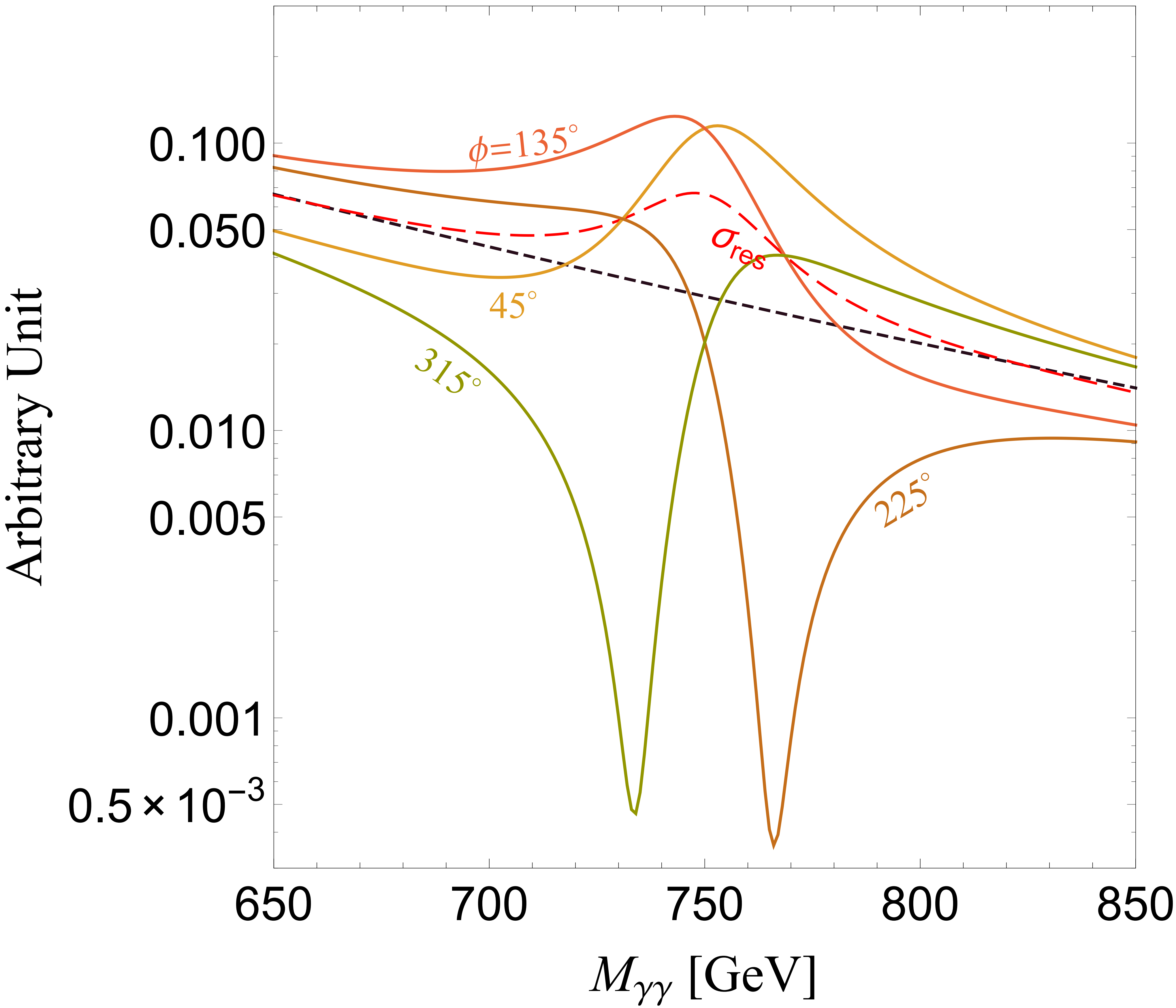
Integrated out

C

$$\sigma(ab\to\Phi\to cd)_{\texttt{w/ intf}} = \sigma(ab\to\Phi)\cdot{\rm Br}(\Phi\to cd)\cdot C$$

Imaginary part interference





Arbitrary Unit
0.100
0.050
0.010
0.005
0.001
0.5 × 10^−3
650
700
750
800
850
M_γγ [GeV]
ϕ=135°
45°
315°
225°
σ_res

How does the interference effect change the 750 GeV diphoton excess?

3. Singlet Model:
Real-Part Interference

Contents

- a CP-odd SM-singlet scalar $\Phi = A$
- vector-like quarks $Q \equiv Q^{7/6} = (\mathbf{3}, \mathbf{2}, 7/6)$
- vector-like leptons $L \equiv L^{3/2} = (\mathbf{1}, \mathbf{2}, 3/2)$

Lagrangian

$$-\mathcal{L} \ni \frac{1}{2} M_\Phi^2 \Phi^2 + \sum_Q (s_Q \Phi + M_Q) \overline{Q} \gamma_5 Q + \sum_L (s_L \Phi + M_L) \overline{L} \gamma_5 L$$

$$\Gamma(\Phi \to gg) = \frac{\alpha_S^2}{128\pi^3} \frac{M_\Phi^3}{M_Q^2} \left| \sum_Q s_Q A_{1/2}^\Phi \left(\frac{M_\Phi^2}{4M_Q^2} \right) \right|^2 ,$$

$$\Gamma(\Phi \to \gamma\gamma) = \frac{\alpha^2}{256\pi^3} M_\Phi^3 \left| \sum_{f=Q,L} N_C \, q_f^2 \frac{s_f}{M_f} A_{1/2}^\Phi \left(\frac{M_\Phi^2}{4M_f^2} \right) \right|^2 ,$$

Quark sector

$$M_Q = 1\,\mathrm{TeV},\; N_Q = 2,\; s_Q = 0.2.$$

Lepton sector

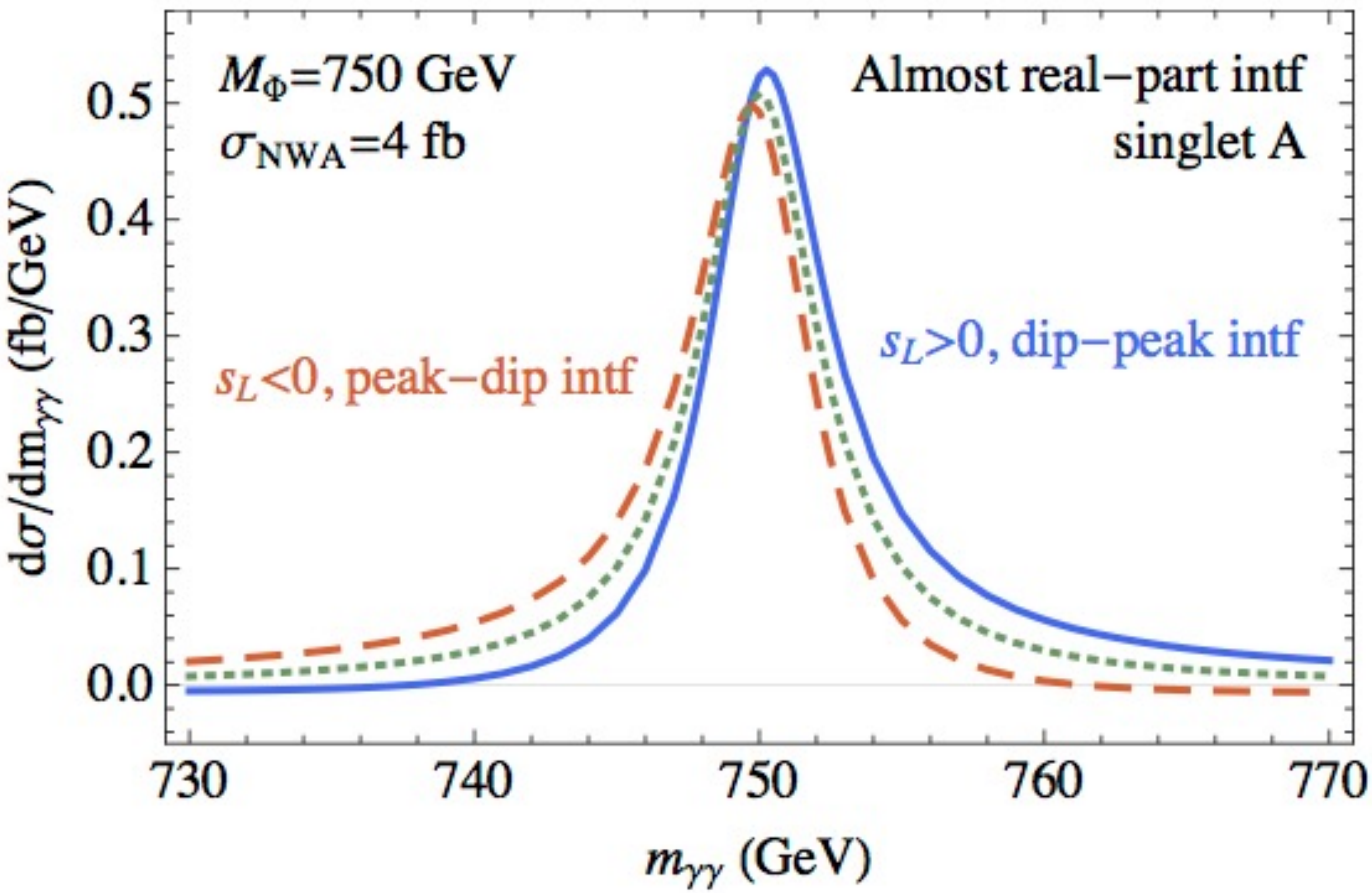
$$M_L = 400\,\mathrm{GeV},\; N_L = 6,\; s_L \text{ is varied.}$$

Relative phase?

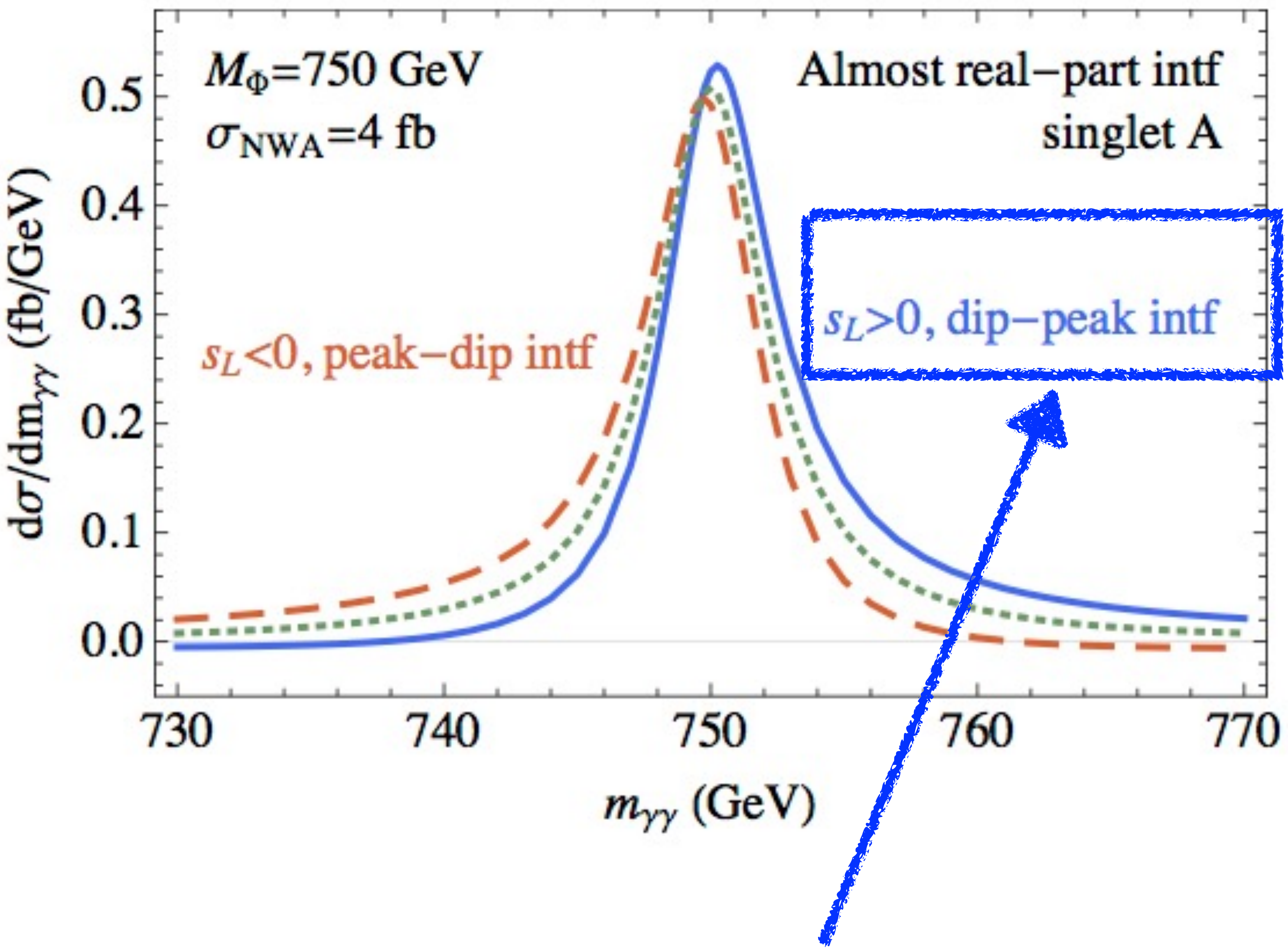
Relative phase?

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

Real interference

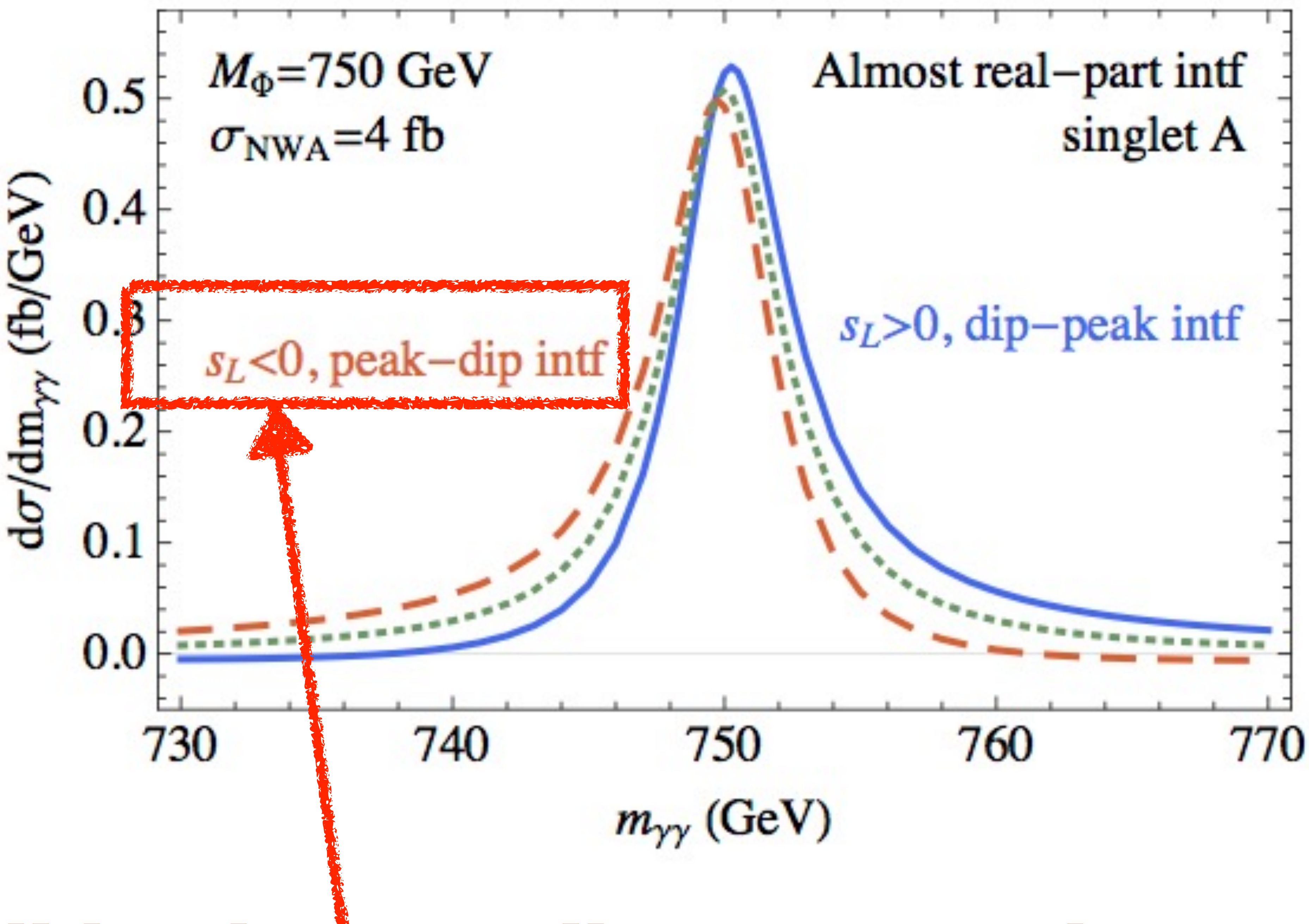


M_Φ=750 GeV
σ_NWA=4 fb
Almost real−part intf
singlet A
s_L<0, peak−dip intf
s_L>0, dip−peak intf
dσ/dm_γγ (fb/GeV)
m_γγ (GeV)
0.0
0.1
0.2
0.3
0.4
0.5
730
740
750
760
770



*** Long tail in high mass region**

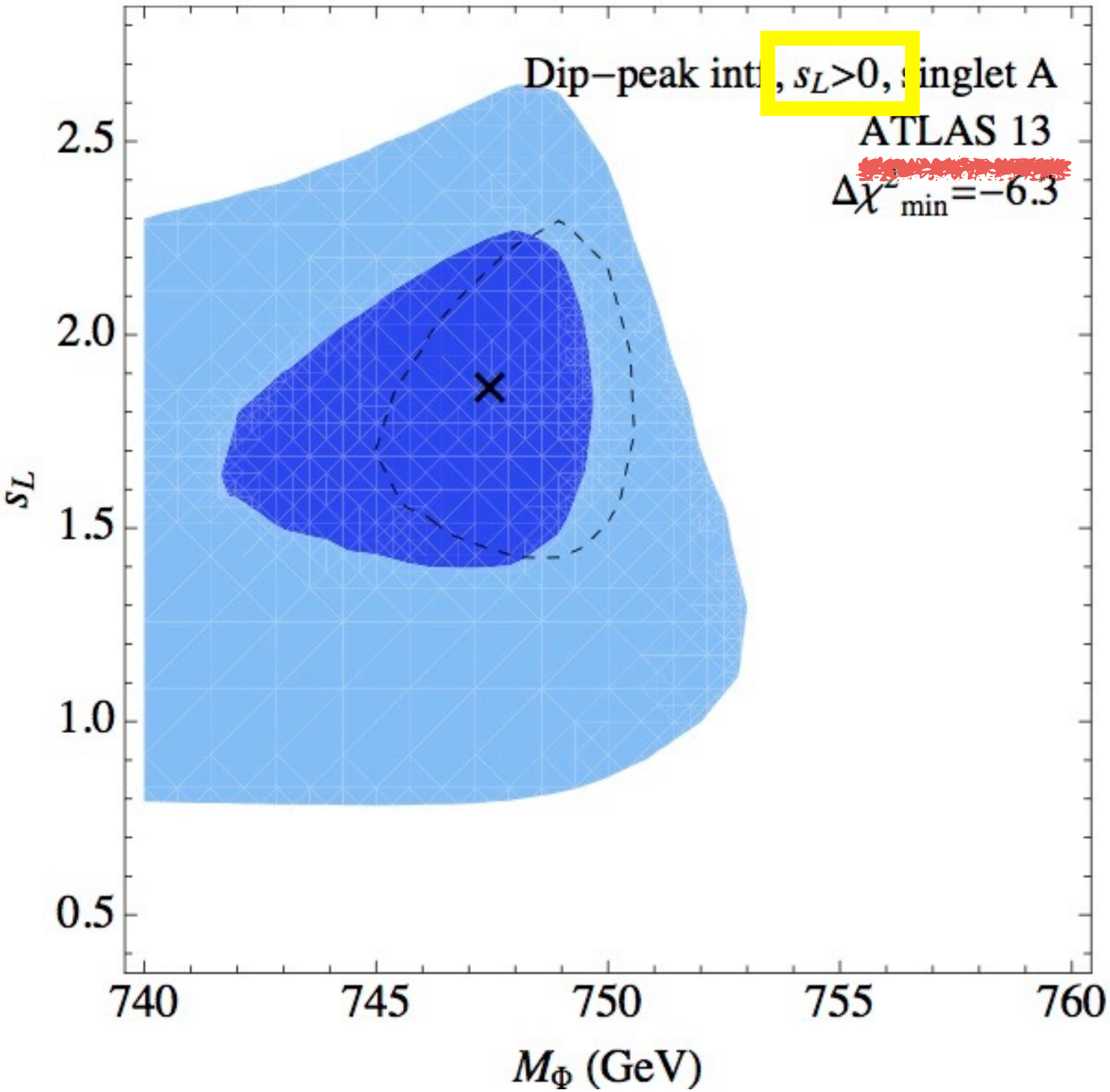
*** Peak shift into larger mass**



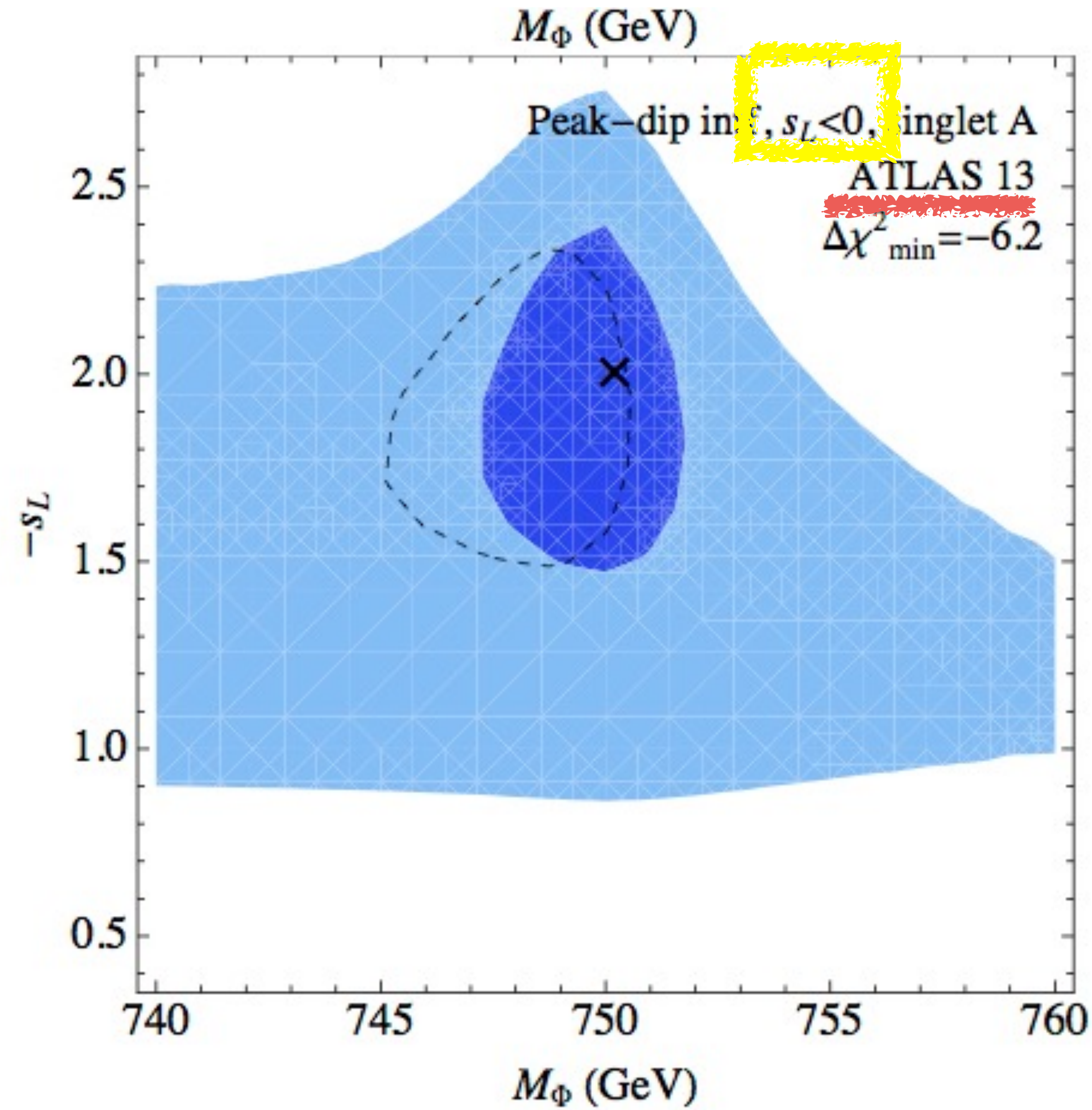
* **Tail in the small mass region**
* **Peak shift into small mass**

Quantitatively?

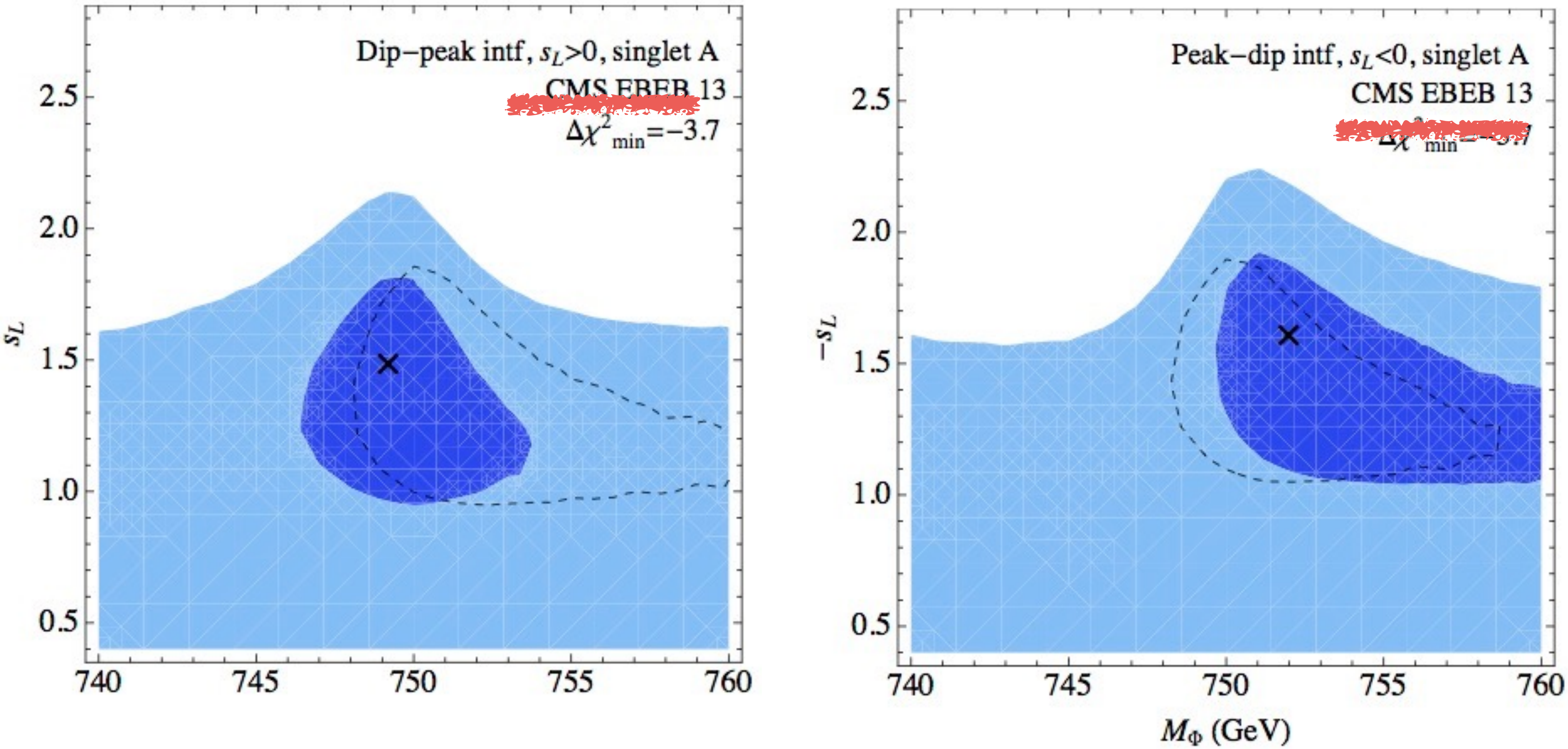
Only through the χ^2 analysis



- Dashed: 1σ allow region w/o interference
- Blue: w/ interference ⇒ lower mass region



- Dashed: w/o interference
- Blue: w/ interference ⇒ higher mass region



- positive sL ⇒ the tail region shrinks
- negative sL ⇒ the tail region expands

3. Doublet Model: Imaginary-Part Interference

Two Higgs doublets

$$\Phi_1 \text{ and } \Phi_2 \; .$$

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \dfrac{v_a + \rho_a + i\eta_a}{\sqrt{2}} \end{pmatrix}, \quad a = 1, 2.$$

Two Higgs doublets

In order to suppress FCNC at tree level, we impose Z2 symmetry

$$\Phi_1 \to \Phi_1 \quad \text{and} \quad \Phi_2 \to -\Phi_2$$

Z2 parity of other fermions

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II	+	−	−	+	+	+
Type X	+	−	−	−	+	+
Type Y	+	−	−	+	−	+

Five physical Higgs bosons

$$h^0, H^0, A^0, H^\pm$$

Alignment limit

0

$$H^{\rm SM} = s_{\beta-\alpha} h^0 + c_{\beta-\alpha} H^0$$

750 GeV state

$$M_\phi = M_H = M_A = 750\,\mathrm{GeV}$$

2HDM with VLL

		$SU(3) \times SU(2) \times U(1)_Y$
$L_L = \begin{pmatrix} E_L \\ D_L \end{pmatrix}$	$L_R = \begin{pmatrix} E'_R \\ D'_R \end{pmatrix}$	$(\mathbf{1},\ \mathbf{2},\ -\frac{3}{2})$
E_R	E'_L	$(\mathbf{1},\ \mathbf{1},\ -1)$
D_R	D'_L	$(\mathbf{1},\ \mathbf{1},\ -2)$

Lagrangian

$$
\begin{aligned}
-\mathcal{L} \;\; = \;\; & Y_D \overline{L}_L H_1 D_R + Y'_D \overline{L}_R H_1 D'_L + Y_E \overline{L}_L \tilde{H}_2 E_R + Y'_E \overline{L}_R \tilde{H}_2 E'_L \\
& + M_L \overline{L}_L L_R + M_E \overline{E}'_L E_R + M_D \overline{D}'_L D_R + \mathrm{h.c.}
\end{aligned}
$$

Mass matrix in the basis of (E, E')

$$\mathcal{M}_E = \begin{pmatrix} M_L & \frac{1}{\sqrt{2}} Y_E v_2 \\ \frac{1}{\sqrt{2}} Y'_E v_2 & M_E \end{pmatrix}$$

Lagrangian in mass basis

$$
\begin{aligned}
-\mathcal{L} \supset\ & y_E h(\overline{E}_1 E_1 - \overline{E}_2 E_2) + y_D h(\overline{D}_1 D_1 - \overline{D}_2 D_2) \\
& - \frac{1}{t_\beta} y_E H(\overline{E}_1 E_1 - \overline{E}_2 E_2) + t_\beta y_D H(\overline{D}_1 D_1 - \overline{D}_2 D_2) \\
& - i \frac{1}{t_\beta} y_E A(\overline{E}_1 \gamma_5 E_1 - \overline{E}_2 \gamma_5 E_2) \\
& - i\, t_\beta y_D A(\overline{D}_1 \gamma_5 D_1 - \overline{D}_2 \gamma_5 D_2)
\end{aligned}
$$

where $y_E = -s_\beta s_{2\theta_E} Y_E/\sqrt{2}$, $y_D = -c_\beta s_{2\theta_D} Y_D/\sqrt{2}$

The partial decay widths of $\Phi = h, H, A$

$$\Gamma(\Phi \to \gamma\gamma) = \frac{G_F \alpha_e^2 M_\Phi^3}{128\sqrt{2}\pi^3} \left| \sum_q \hat{y}_q^\Phi N_c Q_q^2 A_{1/2}^\Phi(\tau_q) + \sum_\ell \hat{y}_\ell^\Phi Q_\ell^2 A_{1/2}^\Phi(\tau_\ell) + \mathcal{A}^\Phi_{\gamma\gamma,\mathrm{VLL}} \right|^2$$

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

h $\to \gamma\gamma$ OK?

YES!

If we allow some fine tuning

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

Width?

Large like 50 GeV

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

$M[\mathrm{GeV}]$	y_E	ϕ^H	ϕ^A	C
457	2	99°	123°	3.5
413	4	93°	108°	2.0
400	6	91°	104°	1.6
385	-5	-96°	-88°	0.32
395	-8	-95°	-86°	0.43

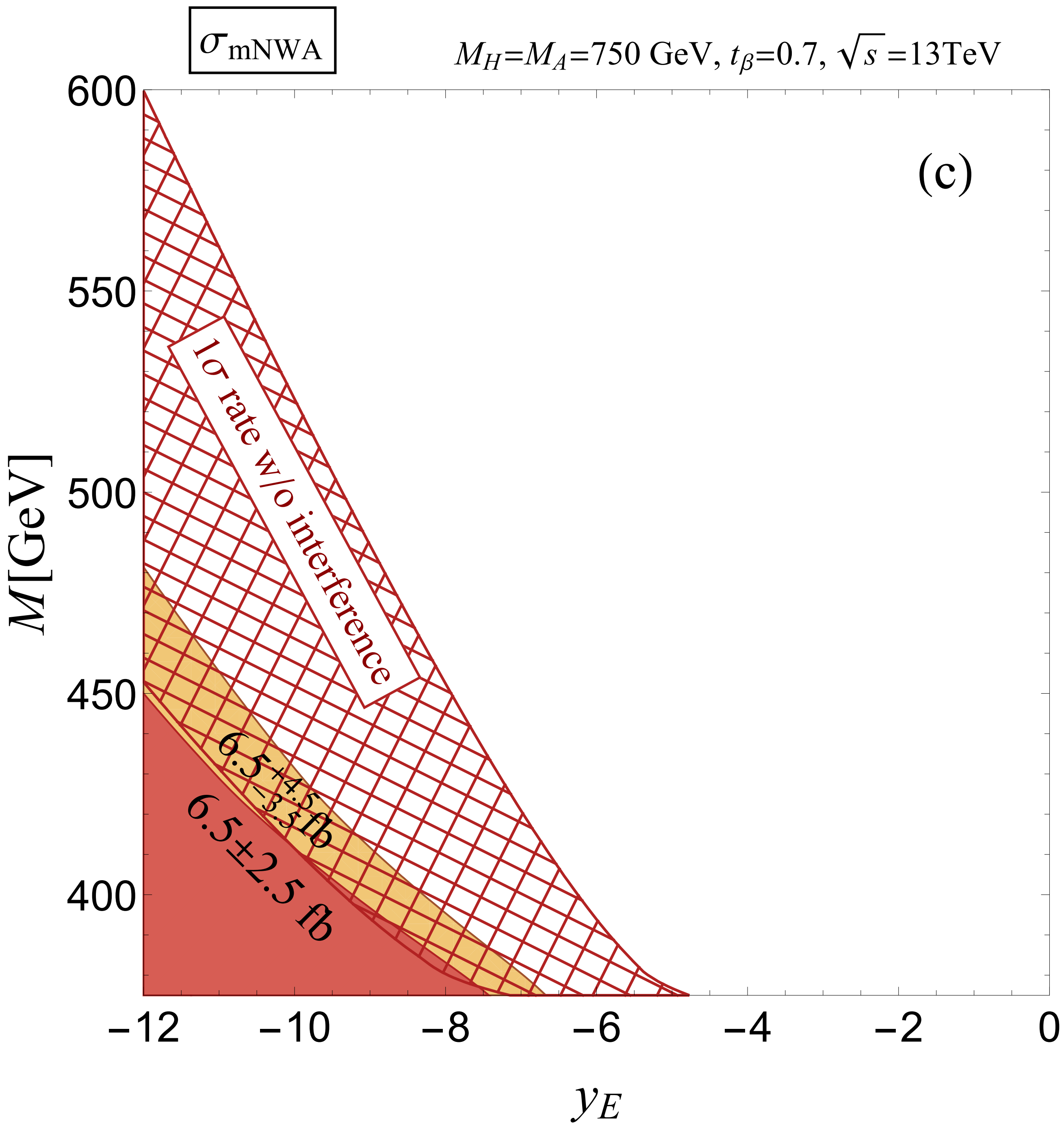
Imaginary interference

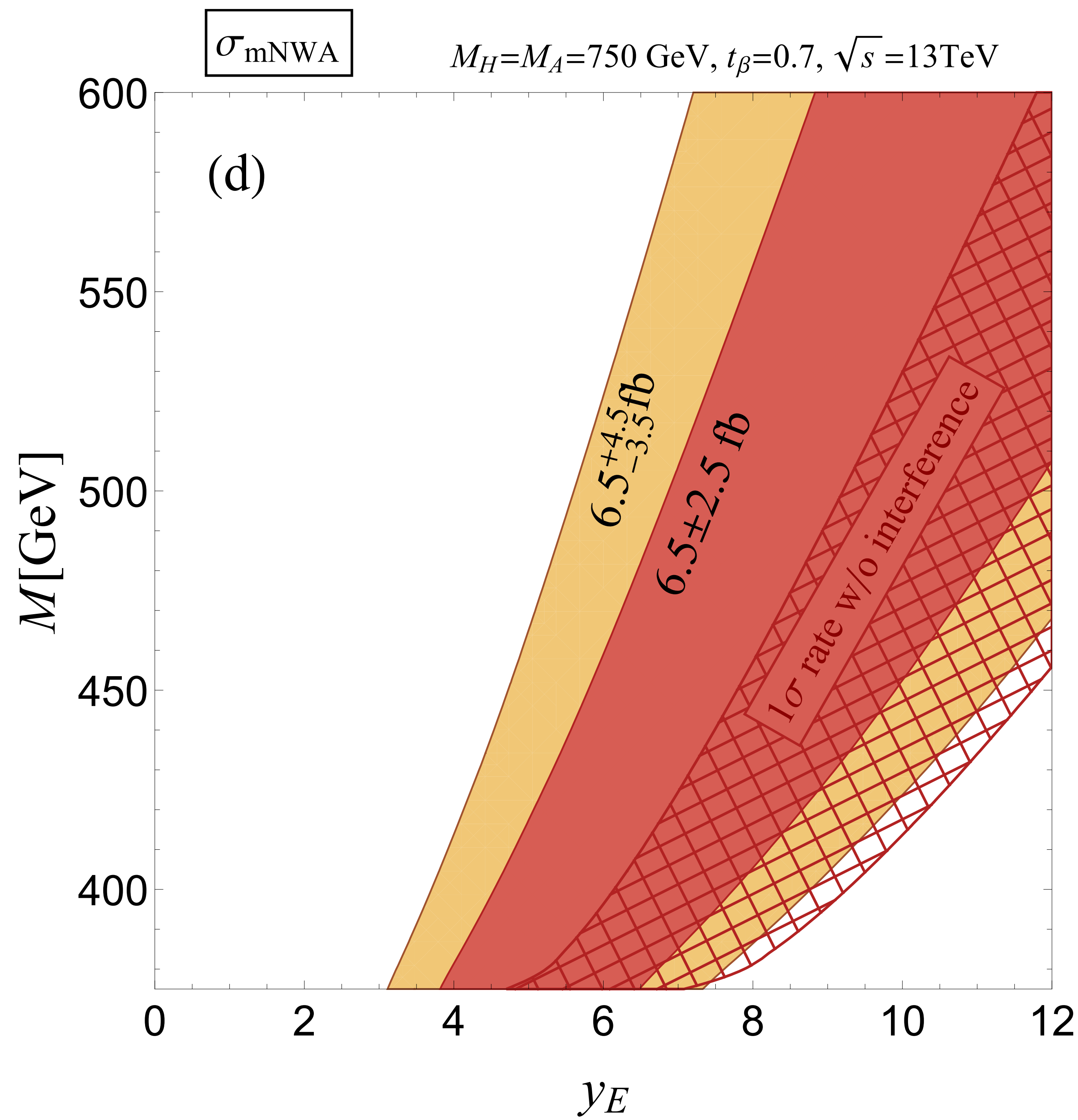
$M[\mathrm{GeV}]$	y_E	ϕ^H	ϕ^A	C
457	2	99°	123°	3.5
413	4	93°	108°	2.0
400	6	91°	104°	1.6
385	-5	-96°	-88°	0.32
395	-8	-95°	-86°	0.43

- **Enhanced signal!**
- **Constructive interference**

$M[\mathrm{GeV}]$	y_E	ϕ^H	ϕ^A	C
457	2	99°	123°	3.5
413	4	93°	108°	2.0
400	6	91°	104°	1.6
385	-5	-96°	-88°	0.32
395	-8	-95°	-86°	0.43

Destructive interference





For $y_E < 0$

- Destructive interference
- Larger y_E is required

For $y_E > 0$

- Constructive interference
- Smaller y_E is required

5. Conclusions

- The 750 GeV diphoton excess can be a new scalar boson, through the gluon fusion production.
- Interference with the continuum background can be significant.
- Real interference shifts the mass pole position, and imaginary interference enhances or reduces the signal rate.