Quantum Interference in the NMSSM Higgs Sector

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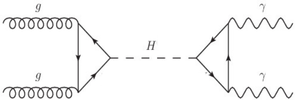
- To analyse the quantum interference effects, both in the CPC and CPV-NMSSM, considering the full propagator matrix for $pp \to H_{\rm obs} \to \gamma\gamma$ when
  - Two or more mass states exist near $M_{H_{\rm obs}} \sim 125$ GeV
  - Mass difference is comparable to decay widths
  - Quantum interference effects become sizable, invalidating the narrow width approximation (NWA)
- To investigate how such mutually interfering states can be distinguished from a single resonance at the LHC.
- **Our analyses go beyond the state of the art, as current penomenological analyses normally neglect off-diagonal effects.**

Light Higgs: Di-photon Production through Gluon Fusion in the NWA

The amplitude-square for $gg \to H_i \to \gamma\gamma$

$$| \mathcal{M} |^2 = \sum_{\lambda,\sigma=\pm 1} \sum_{i=1,5} \mathcal{M}_{P_i\lambda} \mathcal{M}^*_{P_i\lambda} \left| D_{H_i}(\hat{s}) \right|^2 \mathcal{M}_{D_i\sigma} \mathcal{M}^*_{D_i\sigma}$$



λ, σ: gluon, photon helicities, $D_{H_i}(\hat{s})$: propagator matrix

Larger splitting between the Higgs boson masses $\implies$ NWA in the $i-$th Higgs boson propagator

$$|D_i(\hat{s})|^2 = \left| \frac{1}{\hat{s} - m^2_{H_i} + i m_{H_i} \Gamma_{H_i}} \right|^2 \to \frac{\pi}{m_{H_i} \Gamma_{H_i}} \delta(\hat{s} - m^2_{H_i})$$

The total cross-section for $pp \to H_i \to \gamma\gamma$ in the NWA:

$$\sigma(pp \to H_i \to \gamma\gamma) = \int_{\frac{m^2_{H_i}}{s}}^{1} dx_1 \, \frac{1}{1024 s m^3_{H_i} \Gamma_{H_i}} \sum_{i=1-5} \left(\sum_{\lambda=\pm} \left| \mathcal{M}_{P_i\lambda} \right|^2 \sum_{\sigma=\pm} \left| \mathcal{M}_{D_i\sigma} \right|^2 \right) \frac{g(x_1) g(\frac{m^2_{H_i}}{s}/x_1)}{x_1}$$

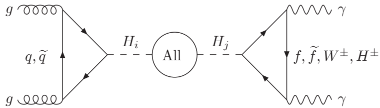
$g(x)$ are the pdfs for the two gluons.

- **Beyond the NWA:** two (or more) Higgses are almost mass degenerate at a given $\sqrt{\hat{s}}$:

$$D_H(\hat{s}) = \hat{s}\begin{pmatrix} \mathrm{m}_{11} & i\Im\mathrm{m}\hat{\Pi}_{12}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{13}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{14}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{15}(\hat{s}) \\ i\Im\mathrm{m}\hat{\Pi}_{21}(\hat{s}) & \mathrm{m}_{22} & i\Im\mathrm{m}\hat{\Pi}_{23}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{24}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{25}(\hat{s}) \\ i\Im\mathrm{m}\hat{\Pi}_{31}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{32}(\hat{s}) & \mathrm{m}_{33} + i\Im\mathrm{m}\hat{\Pi}_{33}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{34}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{35}(\hat{s}) \\ i\Im\mathrm{m}\hat{\Pi}_{41}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{42}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{43}(\hat{s}) & \mathrm{m}_{44} & i\Im\mathrm{m}\hat{\Pi}_{45}(\hat{s}) \\ i\Im\mathrm{m}\hat{\Pi}_{51}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{52}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{53}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{54}(\hat{s}) & \mathrm{m}_{55} \end{pmatrix}^{-1}$$

$\mathrm{m}_{ii} \equiv \hat{s} - m^2_{H_i} + i\Im\mathrm{m}\hat{\Pi}_{ii}(\hat{s})$, $\Im\mathrm{m}\hat{\Pi}_{ij}(\hat{s})$: the absorptive parts of the Higgs self-energies

- $i-$th Higgs state can undergo resonant transition to the $j-$th state, invalidating the NWA.



- **The total cross section beyond the NWA:**

$$\sigma(pp \to H_i \to H_j \to \gamma\gamma) = \int_0^1 d\tau \int_\tau^1 \frac{dx_1}{x_1}\frac{g(x_1)g(\tau/x_1)}{1024\pi\hat{s}^3}\sum_{i,j=1-5}\left\{\sum_{\lambda=\pm}\left|\mathcal{M}_{P_i\lambda}\right|^2 \left|D_{ij}(\hat{s})\right|^2 \sum_{\sigma=\pm}\left|\mathcal{M}_{D_j\sigma}\right|^2\right\}$$

The differential cross section wrt $\sqrt{\hat{s}}$ $(\tau = \frac{\hat{s}}{s})$

$$\frac{d\sigma}{d\sqrt{\hat{s}}} = \int_\tau^1 \frac{2\sqrt{\hat{s}}}{s}\frac{dx_1}{x_1}\frac{g(x_1)g(\hat{s}/sx_1)}{1024\pi\hat{s}^3}\sum_{i,j=1-5}\left\{\sum_{\lambda=\pm}\left|\mathcal{M}_{P_i\lambda}\right|^2 \left|D_{ij}(\hat{s})\right|^2 \sum_{\sigma=\pm}\left|\mathcal{M}_{D_j\sigma}\right|^2\right\}$$

- **Model parameters:** Dimensionful parameters are in GeV

$$M_0 \equiv M_{Q_{1,2,3}} = M_{U_{1,2,3}} = M_{D_{1,2,3}} = M_{L_{1,2,3}} = M_{E_{1,2,3}} : 800 - 2000,$$
$$M_{\frac{1}{2}} \equiv 2M_1 = M_2 = \frac{1}{3}M_3 : 100 - 500, \quad A_{\tilde{f}} \equiv A_{\tilde{t}} = A_{\tilde{b}} = A_{\tilde{\tau}} : -3000 - 0, \quad tan\beta : 2 - 8,$$
$$\lambda : 0.58 - 0.70, \quad \kappa : 0.3 - 0.6, \quad \mu_{\rm eff} : 100 - 200, \quad A_\lambda : 200 - 1000, \quad A_\kappa : -300 - 0,$$
$$\phi_0 = \phi_{\frac{1}{2}} = \phi_{A_{\tilde{f}}} = \phi_\lambda = \phi_{A_\lambda} = \phi_{A_\kappa} : 0$$

[Phys.Rev. D 86, 071702 (2012),
Adv. High Energy Phys. 2015, 509847 (2015)]

- **Two separate scans:**
  - $\phi_\kappa = 0^o$ (CPC-NMSSM)
  - $\phi_\kappa = 3^o$ (CPV-NMSSM)

- **Mass-degeneracy condition:** $m_{H_2} - m_{H_1} < 2$ GeV (LHC mass resolution) [Phys.Rev.Lett. 114, 191803 (2015)]

  We assume

  $123 < M_{h_1} < 127$ GeV (± 2 GeV uncertainty from unknown higher order corrections)

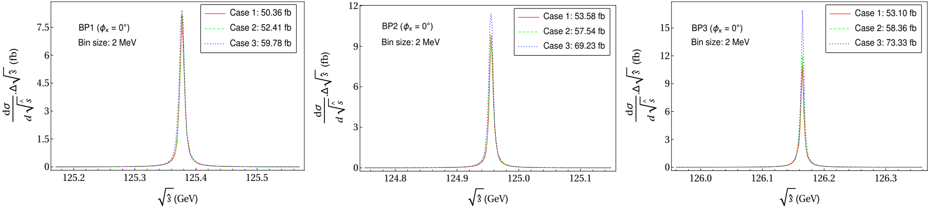
We have studied the distribution of differential cross sections with respect to $\sqrt{\hat{s}}$ for $pp \to H_{\rm obs}(H_1, H_2) \to \gamma\gamma$ at the LHC with $\sqrt{s} = 14$ TeV considering the following three cases:

- **Case 1:** Two independent Breit-Wigner (BW) resonances.
- **Case 2:** With tree-level interference between H_1 and H_2.
- **Case 3:** With full propagator matrix.

Light Higgs: Cross sections for $pp \to H_{\rm obs}(H_1, H_2) \to \gamma\gamma$ (CPC-NMSSM, $\phi_\kappa = 0^o$)

BP	ϕ_κ	M_0 (GeV)	$M_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	λ	κ	A_λ (GeV)	A_κ (GeV)	$\mu_{\rm eff}$ (GeV)
1	0°	1380.9	458.51	-2946.2	4.39	0.6970	0.4594	423.23	-5.271	113.60
2		1598.3	471.51	-2875.0	4.34	0.6907	0.4823	402.53	-17.117	110.86
3		1498.2	379.87	-2822.4	3.91	0.6969	0.4538	385.05	-16.566	117.92

Input values for the three selected **CPC-NMSSM** Benchmark Points (BPs)



Distributions of differential cross sections with respect to $\sqrt{\hat{s}}$ for the three BPs corresponding to Case 1 (Red curve), Case 2 (Green curve) and Case 3 (Blue curve)

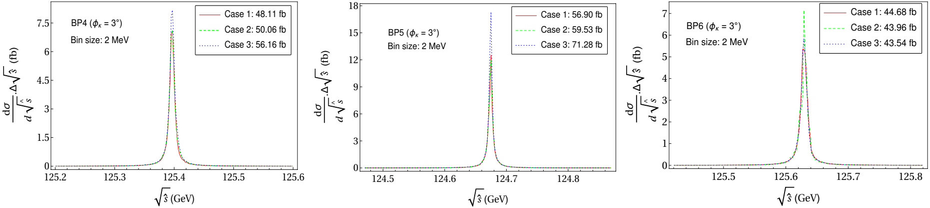
BP	m_{H_1} (GeV)	m_{H_2} (GeV)	Δm_H (MeV)	Γ_{H_1} (MeV)	Γ_{H_2} (MeV)	$\sigma_{pp}^{\gamma\gamma}$ (fb) Case 1	Case 2	Case 3
1	125.3688	125.3782	9.4	10.7	9.7	50.36	52.41	59.78
2	124.9498	124.9562	6.4	10.1	9.1	53.58	57.54	69.23
3	126.1641	126.1667	2.6	10.1	9.3	53.10	58.36	73.33

The masses, total decay widths and the integrated cross sections for the three cases

Light Higgs: Cross sections for $pp \to H_{\rm obs}(H_1, H_2) \to \gamma\gamma$ (CPV-NMSSM, $\phi_\kappa = 3^o$)

BP	ϕ_κ	M_0 (GeV)	$M_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	λ	κ	A_λ (GeV)	A_κ (GeV)	$\mu_{\rm eff}$ (GeV)
4	3°	1366.6	426.35	-2694.3	3.92	0.6878	0.4657	361.11	-13.780	112.79
5		1476.6	363.81	-2969.1	4.67	0.6725	0.4304	485.87	-35.335	120.41
6		1427.1	249.93	-2918.1	4.53	0.6852	0.3360	610.69	-26.038	147.10

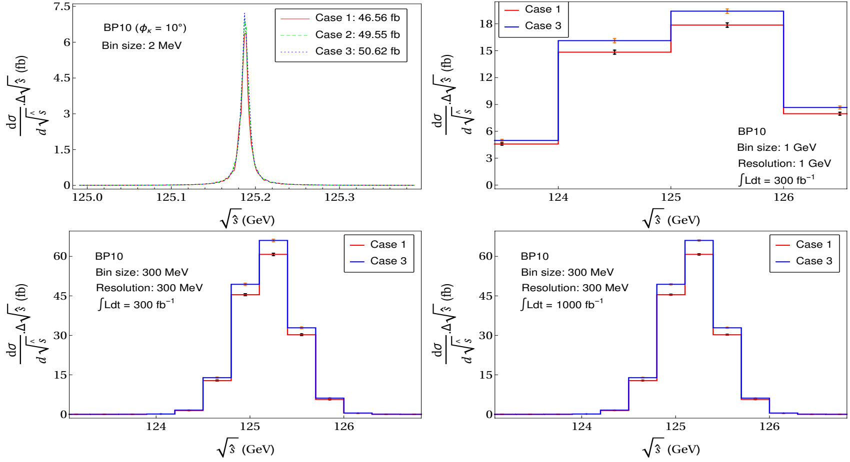
Input values for the four selected **CPV-NMSSM ($\phi_\kappa = 3^o$)** BPs



Distributions of differential cross sections with respect to $\sqrt{\hat{s}}$ for the four BPs corresponding to Case 1 (Red curve), Case 2 (Green curve) and Case 3 (Blue curve)

BP	m_{H_1} (GeV)	m_{H_2} (GeV)	Δm_H (MeV)	Γ_{H_1} (MeV)	Γ_{H_2} (MeV)	$\sigma_{pp}^{\gamma\gamma}$ (fb) Case 1	Case 2	Case 3
4	125.3960	125.4052	9.2	9.6	9.5	48.11	50.06	56.16
5	124.6742	124.6757	1.5	9.1	8.4	56.90	59.53	71.28
6	125.6285	125.6393	10.8	11.1	5.9	44.68	43.96	43.54

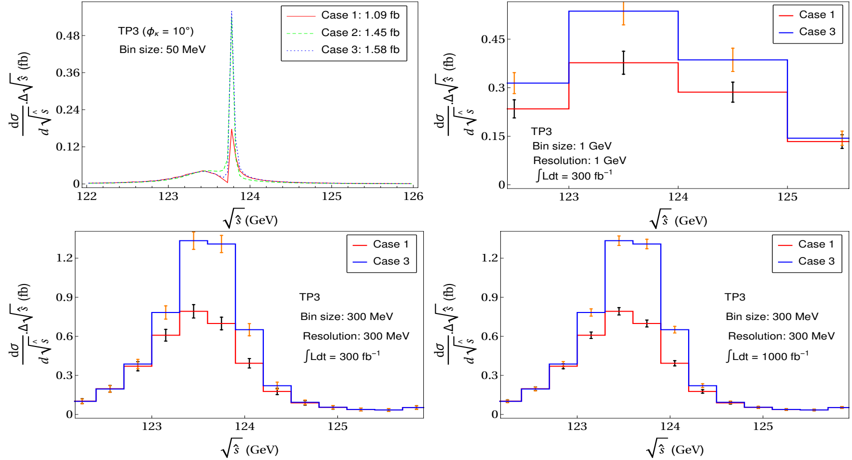
The masses, total decay widths and the integrated cross sections for the three cases



BP	ϕ_κ	M_0 (GeV)	$M_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	λ	κ	A_λ (GeV)	A_κ (GeV)	$\mu_{\rm eff}$ (GeV)
10		1378.0	173.35	−2291.7	3.99	0.6877	0.4483	564.66	−266.73	172.87

BP	m_{H_1} (GeV)	m_{H_2} (GeV)	Δm_H (MeV)	Γ_{H_1} (MeV)	Γ_{H_2} (MeV)	$\sigma_{pp}^{\gamma\gamma}$ (fb) Case 1	Case 2	Case 3
10	125.1874	125.1924	5.0	10.3	2.9	46.56	49.55	50.62

Light Higgs: Shape analysis of the Emerging Profiles



TP	ϕ_κ	M_0 (GeV)	$M_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	λ	κ	A_λ (GeV)	A_κ (GeV)	$\mu_{\rm eff}$ (GeV)
3	10°	1895.2	115.14	−835.20	1.76	0.6524	0.5752	74.865	−120.70	105.95

TP	m_{H_1} (GeV)	m_{H_2} (GeV)	Δm_H (MeV)	Γ_{H_1} (MeV)	Γ_{H_2} (MeV)	$\sigma_{pp}^{\gamma\gamma}$ (fb) Case 1	Case 2	Case 3
3	123.4590	123.7876	328.6	704.9	39.2	1.09	1.45	1.58

- **Our analysis does not exclude the possibility of non-SM explanations, particularly those with two Higgs bosons near 125 GeV with such a small mass difference that they cannot be resolved at the current experimental setup.**
- **Interference effects could be sizable, up to around 40% in cross sections, between the Breit-Wigner and the full propagator.**
- **Shape analysis of emerging profiles reveals some scope to distinguish Case 3 from Case 1 in future experiments.**

- The NMSSM offers possiblities of having strong mass-degeneracies between
  - the singlet-like and heavy doublet-like scalars
  - the singlet-like and doublet-like pseudoscalars
- To study interference effects by taking into account the full propagator matrix in the production of $\tau^+\tau^-$ in gluon fusion via heavier Higgs states at the LHC.

Heavy Higgs: $\tau^+\tau^-$pair Production in Gluon Fusion via Higgs Bosons

• The differential cross section for $pp \to H \to \tau^+\tau^-$ (H collectively denote the five neutral Higgses)

$$\frac{d\sigma_{pp\to\tau^+\tau^-}}{d\sqrt{\hat{s}}} = \int_\tau^1 \frac{2\sqrt{\hat{s}}}{s} \frac{dx_1}{x_1} \frac{g(x_1)g(\hat{\tau}x_1)}{1024\pi\hat{s}} \mathcal{A}^2_{gg\to\tau^+\tau^-}$$

with

$$\mathcal{A}^2_{gg\to\tau^+\tau^-} = \Big| \sum_{i,j=1-5} \sum_{\lambda,\sigma=\pm} \mathcal{M}_{P_i\lambda} D_{ij} \mathcal{M}_{D_j\sigma} \Big|^2$$

• We consider the total cross section calculated using NWA as

$$\sigma_{H_1\ldots H_n} = \sum_{H_i=H_1,\ldots,H_n} \sigma(gg \to H_i) \times \mathrm{BR}(H_i \to \tau^+\tau^-)$$

for all mass-degenerate H_i, which is the most common approach.

• We examine how much $\sigma_{H_1\ldots H_n}$ differs from the one obtained with individual BW propagators, which we refer to as $\sigma_{\rm BW}$.

• We assess the impact of interference effects on the cross section, $\sigma_{\rm Int}$, calculated with invoking the full proagator matrix.

- **Fixed parameter:**
  - $M_{Q_{1,2,3}} = M_{U_{1,2,3}} = M_{D_{1,2,3}} = 3\,\text{TeV}$
  - $M_{L_{1,2,3}} = M_{E_{1,2,3}} = 2\,\text{TeV}$
  - $2M_1 = M_2 = \frac{1}{3}M_3 = 1\,\text{TeV}$

  Variations in these parameters do not have a significant imact on this particular case study.
- A_λ and A_κ can be traded for the pseudoscalar masses m_P ($\sim m_{a_s}$) and m_A as inputs.
- $A_0 \equiv A_{\tilde{u},\tilde{c},\tilde{t}} = A_{\tilde{d},\tilde{s},\tilde{b}} = A_{\tilde{e},\tilde{\mu},\tilde{\tau}}$
- The Higgs mass spectra and BRs were calculated using NMSSMTools.
- **Free parameters:**

Parameter	Initial wide scanned range	Narrow range for scenario 1	Narrow range for scenario 2 with $m_{h_s} < m_h$	Narrow range for scenario 2 with $m_{h_s} > m_h$
A_0 (GeV)	-5000 – -1000	-5000 – -3800	-5000 – -3800	-5000 – -1000
$\tan\beta$	2 – 50	12 – 17	2 – 15	6 –17
λ	0.001 – 0.7	0.001 – 0.02	0.01 – 0.7	0.01 – 0.3
κ	0.001 – 0.7	0.001 – 0.04	0.01 – 0.7	0.01 – 0.7
μ_{eff} (GeV)	100 – 1000	100 – 300	100 – 250	100 – 400
m_A (GeV)	125 – 1000	860 – 1000	870 – 1000	880 – 1000
m_P (GeV)	10 – 1000	10 – 1000	880 – 1000	890 – 1000

Details of selected BPs:

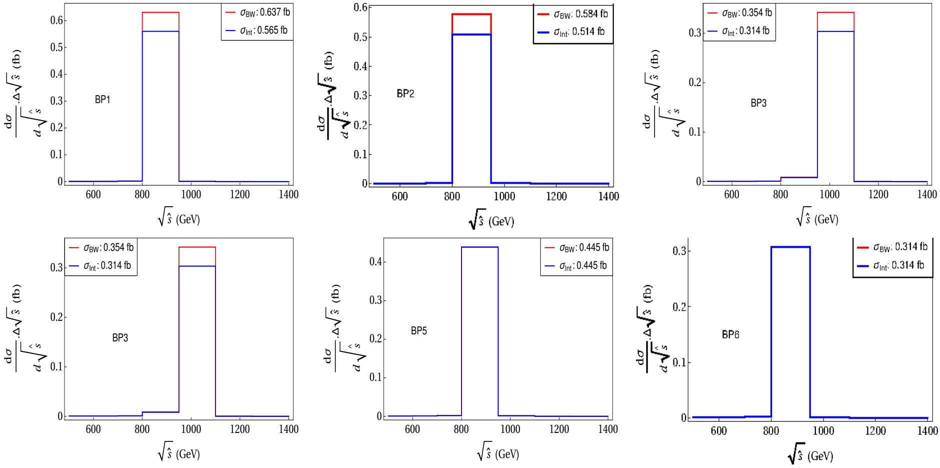
BP	1	2	3	4	5	6
A_0 (GeV)	-4624.6	-4516.5	-4371.9	-4574.8	-4967.9	-4518.8
$\tan\beta$	13.90	13.84	15.14	15.84	6.42	5.65
λ	0.0045	0.0034	0.0035	0.0041	0.2965	0.3948
κ	0.0092	0.0068	0.0112	0.0141	0.5486	0.6197
$\mu_{\rm eff}$ (GeV)	217.34	217.73	150.50	152.63	151.21	172.92
mA (GeV)	926.92	904.00	994.13	998.86	898.56	902.80
mP (GeV)	72.37	698.12	189.83	626.85	919.23	931.95
m_h (GeV)	124.13	124.16	123.84	124.23	123.04	124.21
m_{h_s} (GeV)	889.98	893.37	970.47	973.01	191.07	107.13
m_H (GeV)	891.39	894.86	971.11	973.85	895.73	900.11
m_{a_s} (GeV)	72.36	218.19	189.83	626.84	893.97	896.63
m_A (GeV)	891.21	894.63	970.87	973.61	892.45	896.46
Δm_H (GeV)	1.41	1.49	0.64	0.84		
Δm_A (GeV)					1.53	0.17
Γ_h (MeV)	4.11	4.11	4.04	4.08	4.09	2.90
Γ_{h_s} (GeV)	1.75	1.93	0.71	2.01		
Γ_H (GeV)	1.73	1.92	3.75	2.79	3.65	4.84
Γ_{a_s} (GeV)					2.86	5.14
Γ_A (GeV)	3.53	3.87	4.49	4.82	3.65	4.72
BR($h \to \tau^+\tau^-$)	0.069	0.069	0.069	0.068	0.071	0.061
BR($h_s \to \tau^+\tau^-$)	0.103	0.102	0.103	0.106	0.005	0.091
BR($H \to \tau^+\tau^-$)	0.102	0.100	0.100	0.105	0.021	0.012
BR($a_s \to \tau^+\tau^-$)	0.087	0.012	0.010	0.002	10^{-5}	10^{-7}
BR($A \to \tau^+\tau^-$)	0.101	0.101	0.103	0.105	0.021	0.013
$\sigma_{h_s HA}$ (fb)	0.547	0.537	0.334	0.322		
$\sigma_{H a_s A}$ (fb)					0.364	0.267
$\sigma_{\rm BW}$ (fb)	0.637	0.584	0.354	0.351	0.445	0.314
$\Delta\sigma_{\rm BW}$ (%)	16	9	6	9	22	17
$\sigma_{\rm Int}$ (fb)	0.565	0.514	0.314	0.286	0.445	0.314
$\Delta\sigma_{\rm Int}$ (%)	-11	-12	-11	-19	0	0

Differential cross sections: We calculated the differential $\sigma_{\rm BW}$ and $\sigma_{\rm Int}$ distributions w.r.t. the $\sqrt{\hat{s}}$ to examine if the interference effects can lead to visible differences between them to probe it at the LHC.

- **Binning template:** It replicates the one used by the ATLAS in the searches for heavy resonances in the $\tau^+\tau^-$ channel.
  [ATLAS Col. JHEP 01 (2018) 055]
- Based on an expected detector mass resolution of $\sim 15-20\%$ of $M_{\tau^+\tau^-}$, it assumes bins of width 50 GeV, 100 GeV, 150 GeV for $\sqrt{\hat{s}}=$ 0-500 GeV, 500-800 GeV, 800-1400 GeV.
- Since the mass-degenerate Higgses in both the scenarios are always heavier than 800 GeV and the remaining two are much lighter, the distributions have a lower cut-off at $\sqrt{\hat{s}}=500$ GeV.

Heavy Higgs: Cross Section Analysis

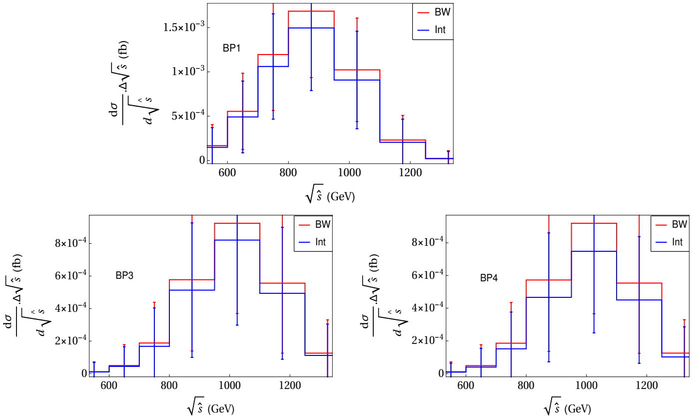
The differential $\sigma_{\rm BW}$ and $\sigma_{\rm Int}$ distributions do not reveal much beyond what can be inferred from the total cross sections, owing to the poor $M_{\tau^+\tau^-}$ resolution at the LHC.



Differential $\sigma_{\rm BW}$ and $\sigma_{\rm Int}$ distributions w.r.t. the $\sqrt{\hat{s}}$ for the six selected BPs.

Heavy Higgs: Cross Section Analysis

Prospects at the detectors: The differential $\sigma_{\rm BW}$ and $\sigma_{\rm Int}$ distributions for the BP1–BP4 are convolved with a Gaussian of width 150 GeV at an assumed integrated luminosity of 3000 fb^{-1}, using the `ListConvolve` function in `Mathematica`.



- The convolved distributions for $\sigma_{\rm Int}$ do not show any novel features.
- Even with an integrated luminosity of 3000 fb^{-1}, the LHC will not be able to exploit the interference effects in order to identify multiple Higgs resonances with highly identical masses.

- **The cross section can deviate considerably from that of the NWA approach, and even the BW approach.**
- **This deviation implies a reduction in the cross section for two mass-degenerate CP-even Higgs bosons. For CP-odd states, no interference effect appears.**
- **However, LHC will be unable to disentangle the two resonances, even if with a mass splitting of a few GeV and the integrated luminosity $\sim$ 3000 fb^{-1}.**