Challenges and opportunities for heavy scalars in $t\bar{t}$ resonance searches

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Based on work with M. Carena, to appear

Motivation

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Heavy scalars very common in new physics models (SUSY, 2HDM, Composite Models, Hidden-valley, Gauge symmetry extensions, scalar-assisted EWBG, etc.)

Couple to fermions hierarchically, decay dominantly to $t\bar{t}$

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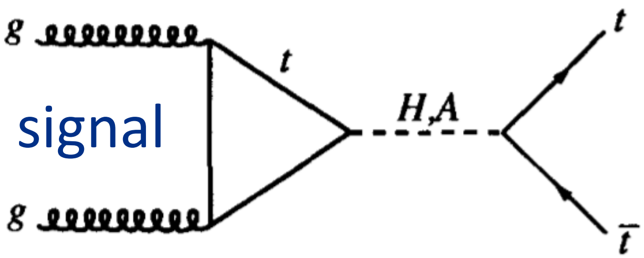
Starting with a very minimal baseline model

$$\mathcal{L}^{\text{Yukawa}} \supset \frac{y_i^s}{\sqrt{2}}\bar{t}tS + i\frac{\tilde{y}_i^s}{\sqrt{2}}\bar{t}\gamma_5 tS$$

$$\mathcal{L}^{\text{Yukawa}} \xrightarrow[\text{“effectively”}]{\text{loop−induced}} -\frac{1}{4}g_{Sgg}(\hat{s})G_{\mu\nu}G^{\mu\nu}S - \frac{i}{2}\tilde{g}_{Sgg}(\hat{s})\tilde{G}_{\mu\nu}G^{\mu\nu}S,$$

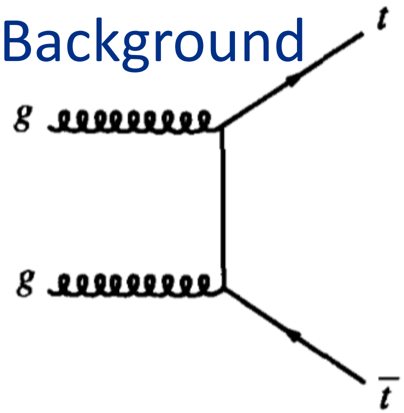
Challenges

signal



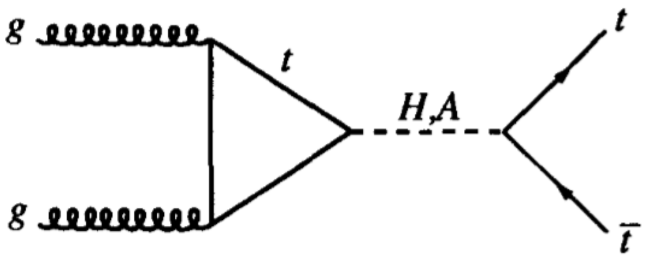
LHC being top factory, the $t\bar{t}$ statistics is very good. $S/\sqrt{B}$ is quite reasonable. However, the challenges lie in the interference effect.

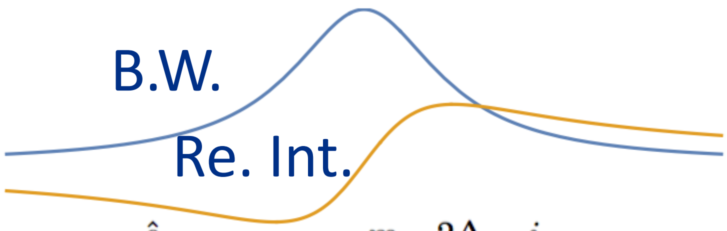
Background



Plus s- and u- channel
Plus s-channel $q\bar{q} \rightarrow t\bar{t}$

Challenges (interferences)





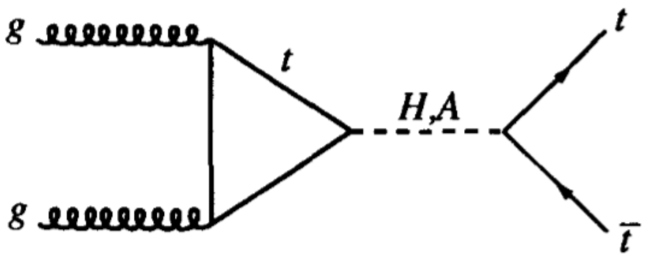
$$\frac{\hat{s}}{(\hat{s}-m_S^2)+i\Gamma_S m_S} \approx \frac{m_S}{\Gamma_S}\frac{2\Delta - i}{4\Delta^2+1}$$

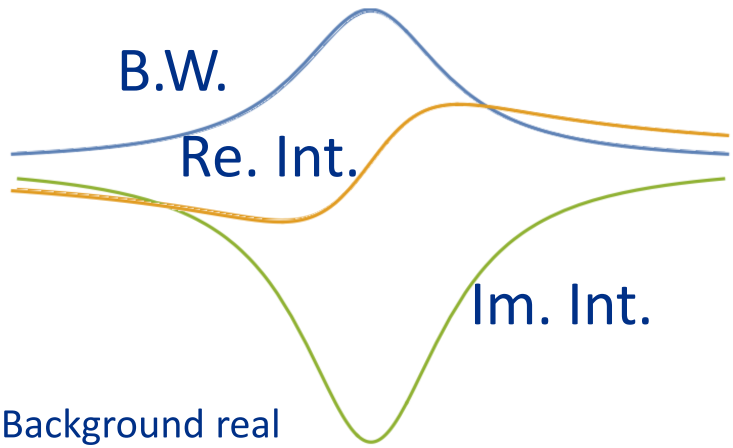
$$\text{with} \quad \Delta \equiv \frac{\hat{s}-m_S^2}{2m_S\Gamma_S} \approx \frac{\sqrt{\hat{s}}-m_S}{\Gamma_S} \text{ for } \frac{\hat{s}}{m_S^2}-1 \ll 1.$$

Background real

Re. Int.– Interference from the real part of the propagator (normal interference, parton level no contribution to the rate, shift the mass peak)

Challenges (interferences)





Background real
Re. Int.– Interference from the real part of the propagator (normal interference, parton level no contribution to the rate, shift the mass peak)
Im. Int.– Interference from the imaginary part of propagator (rare case, changes signal rate)

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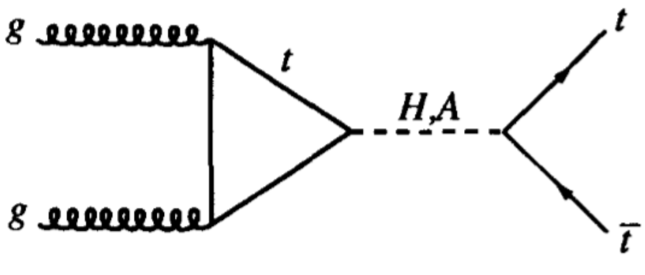
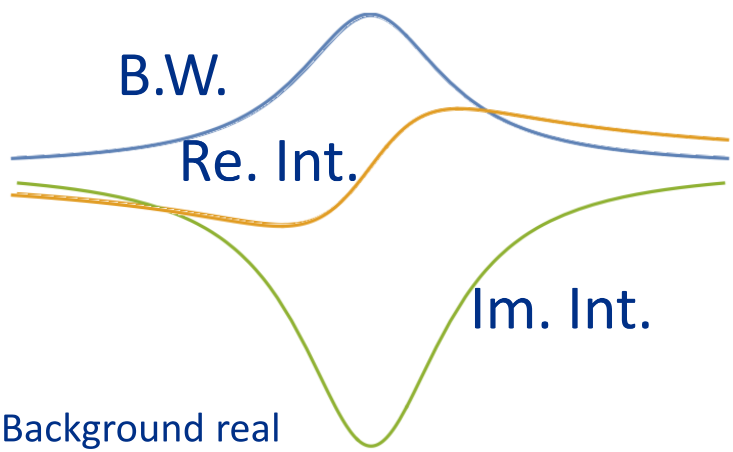
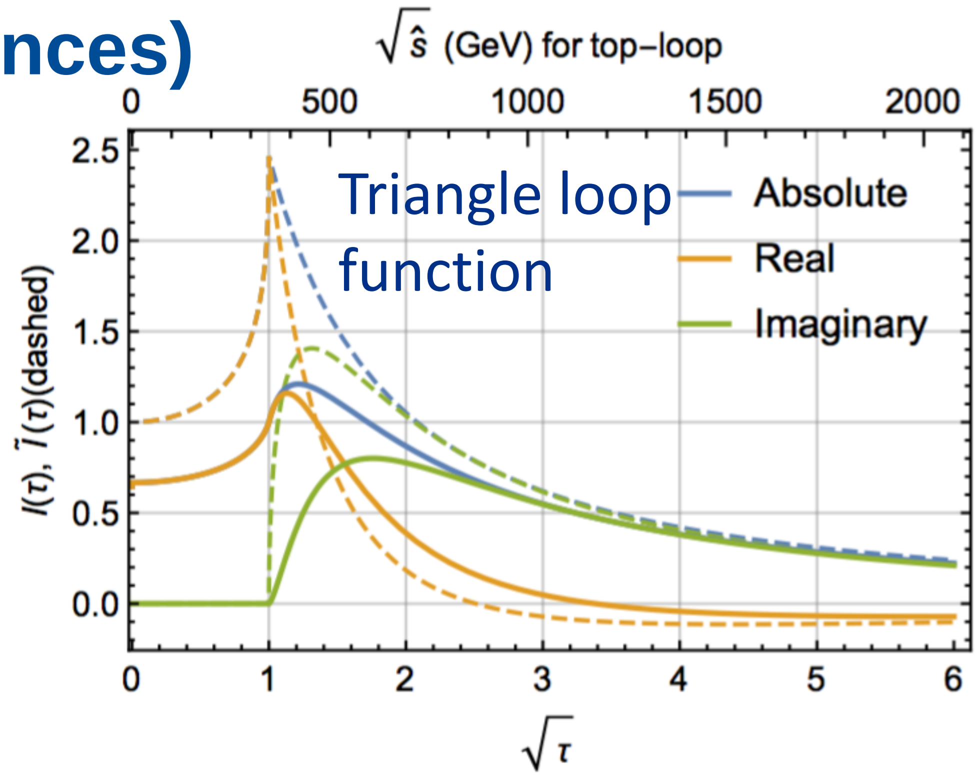
Challenges (interferences)







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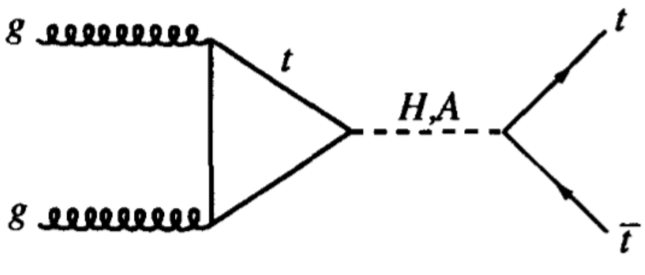
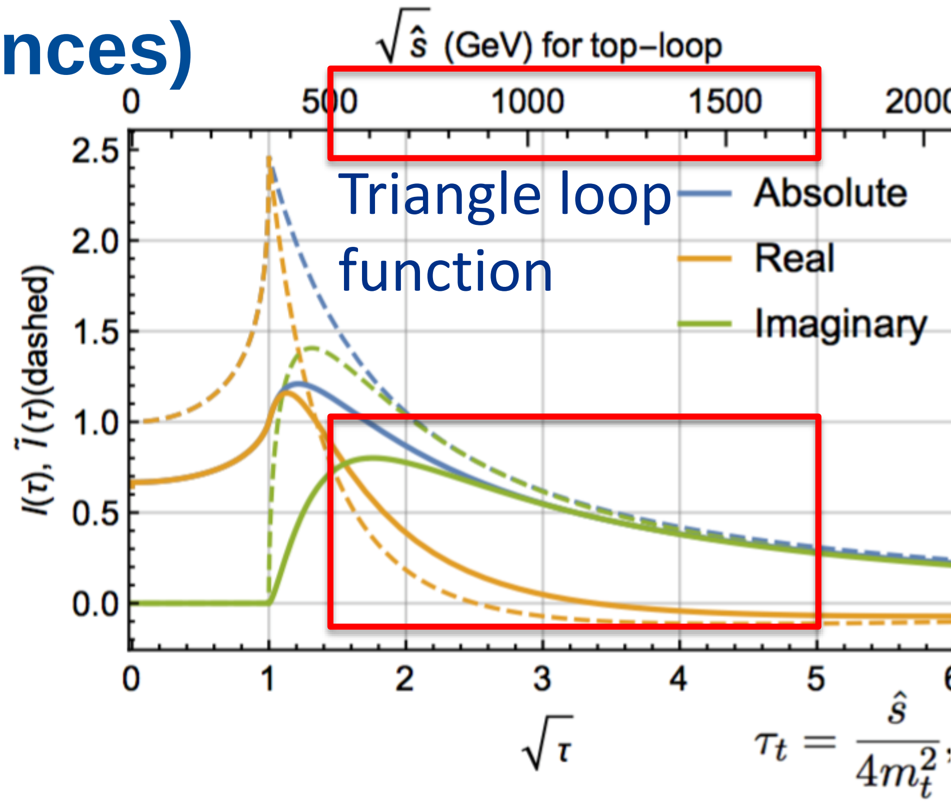
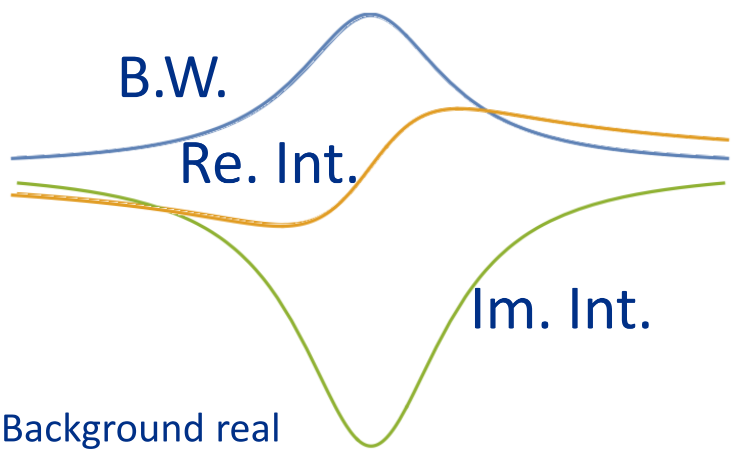






Once across the threshold, imaginary piece arises drastically and the real piece decreases.

Background real

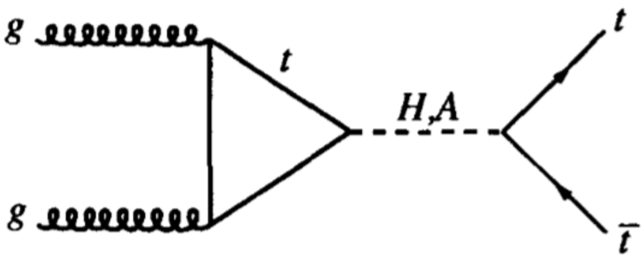
Re. Int.– Interference from the real part of the propagator (normal interference, parton level no contribution to the rate, shift the mass peak)

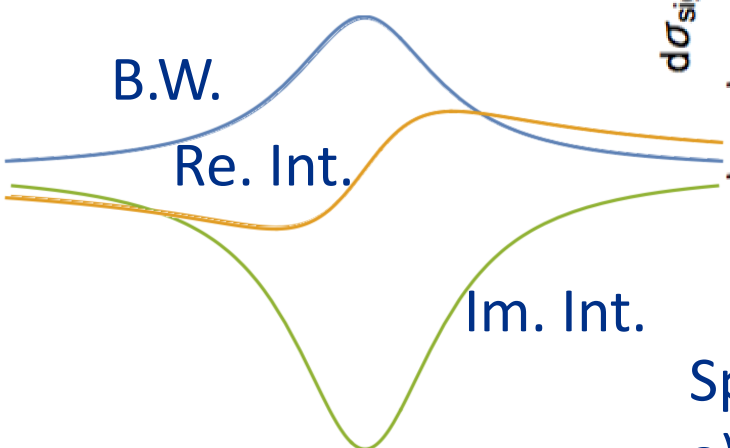
Im. Int.– Interference from the imaginary part of propagator (rare case, changes signal rate)

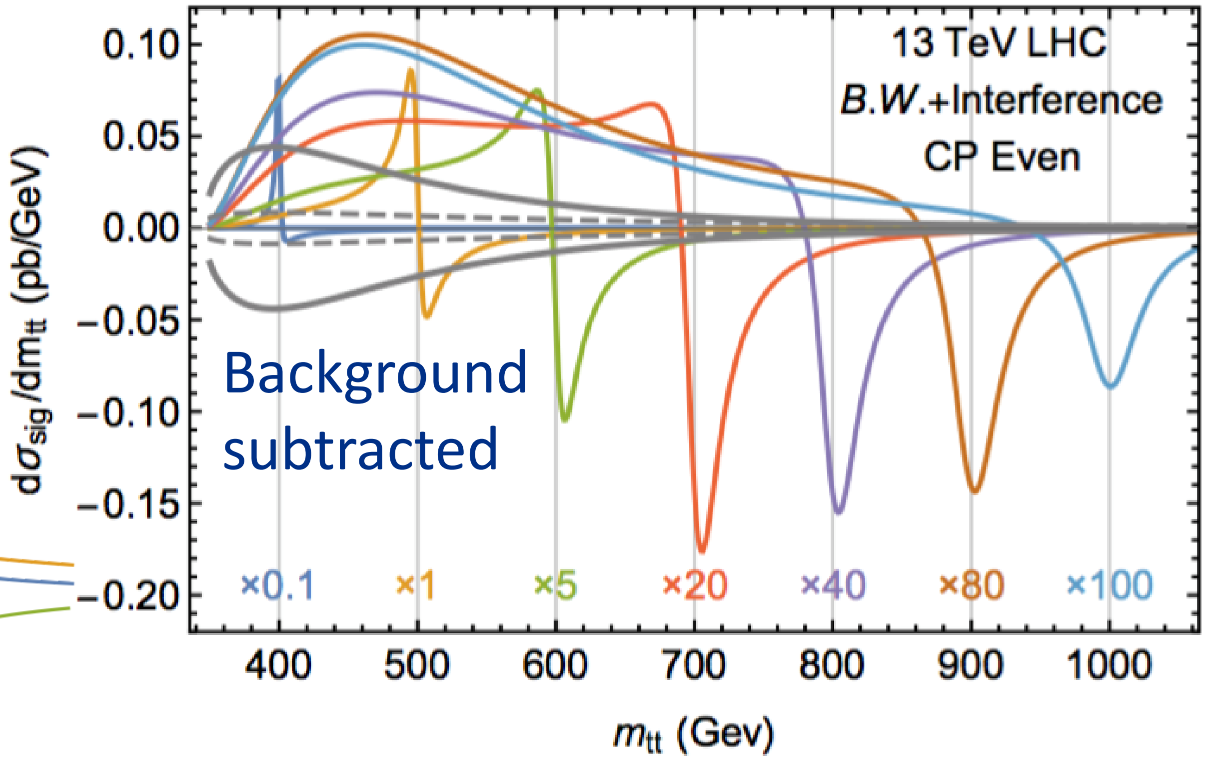
A strong phase ``insensitive”* to phase in the Yukawa as the signal amplitudes is proportional to $|y_t|^2$.

*subject to difference in loop functions

Challenges





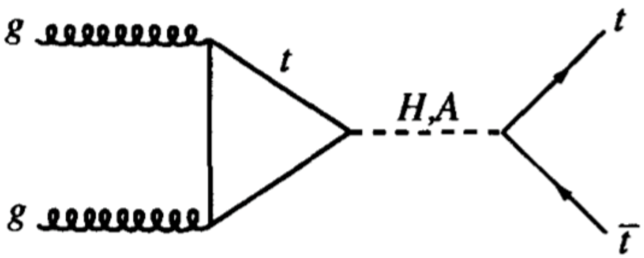


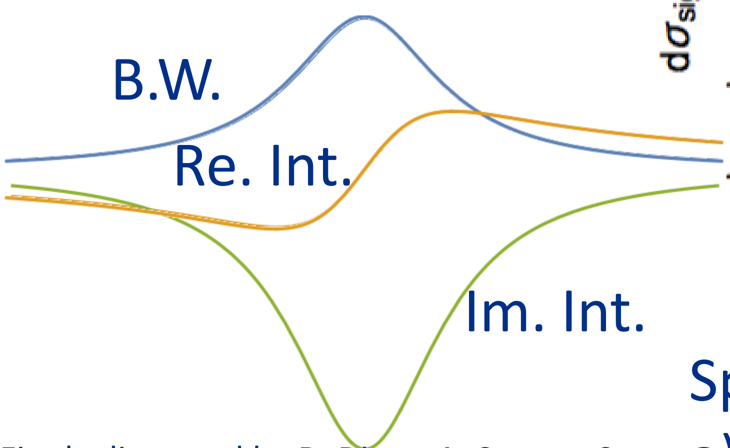
Special line shapes:

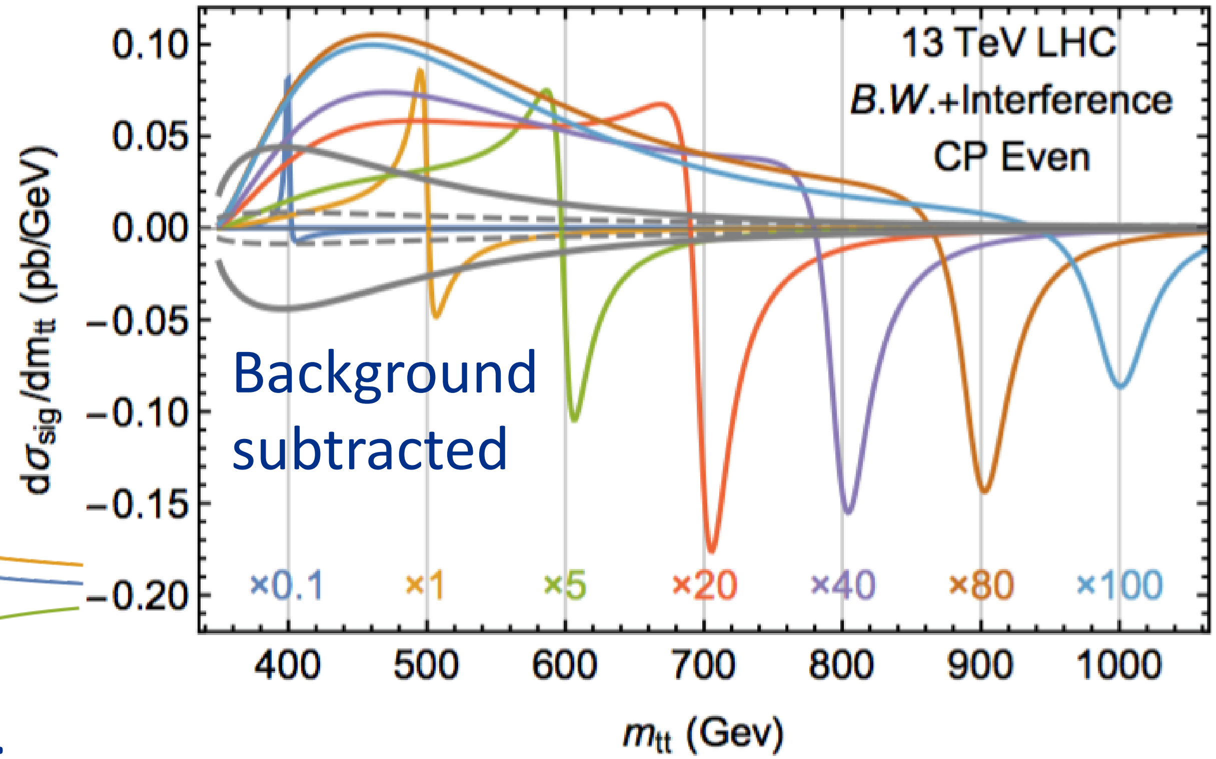
a) Bump search not designed/optimized for this, have to modify our current search;

b) Smearing effects fills the dips with the bumps, making this signal much harder.

Challenges







Firstly discussed by D. Dicus, A. Stange, S. Willenbrock, 1991;
See also recent work by V. Barger, Y. Keung, B. Yencho, arXiv:1112.5173, N. Craig, F. D'Eramo, P. Drapper, S. Thomas, H. Zhang arXiv:1504.04630 and also Jung, Sung, Yoon arXiv:1505.00291

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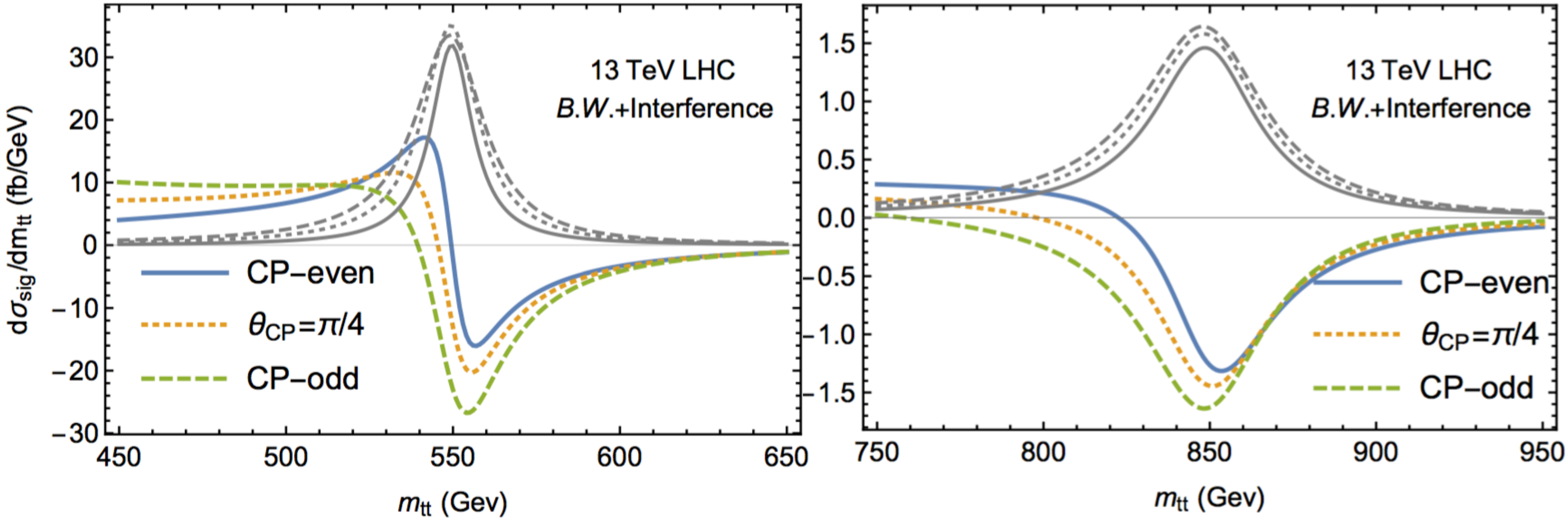
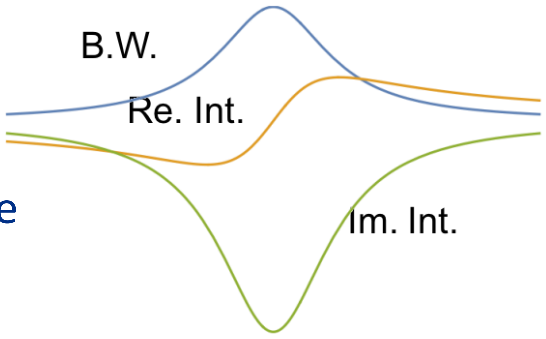


- Gray lines, Breit-Wigner contribution (subtle differences between the scalar case the pseudoscalar case);
- Colored lines, total BSM signal lineshapes;
- (Left panel) for 550 GeV scalars, the loop function has comparable real and imaginary components. The imaginary interference ``cancels'' the Breit-Wigner, leaving only Bump-dip structure;
- (Right panel) for 850 GeV scalar, the loop function is almost purely imaginary and the total lineshapes become a pure dip.



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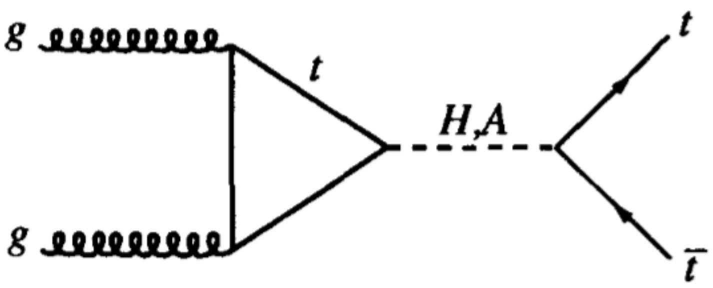
Opportunities



- Nearly degenerate CP-even and CP-odd scalars
- CP phases (new interferences emerges proportional to the loop-function difference between the even and odd one for nearly degenerate ones)
- Bottom-quark contributions (large $\tan\beta$, changes the relative phase)
- New colored particle contributions and threshold effects (stops, VLQs, etc., reduce the relative phases and recovers the bump search)
- New channels (associated production with top(s), bottoms, jet(s), etc. Potentially reducing the interference effect.)

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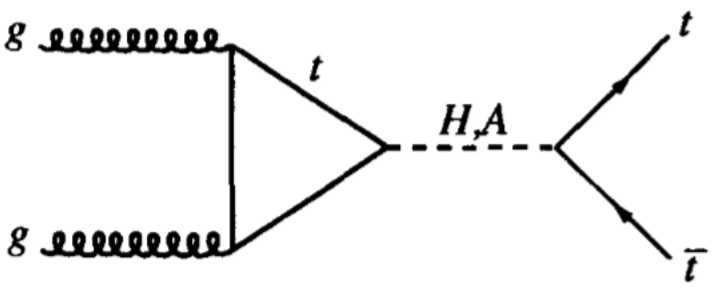

Covered in our study.

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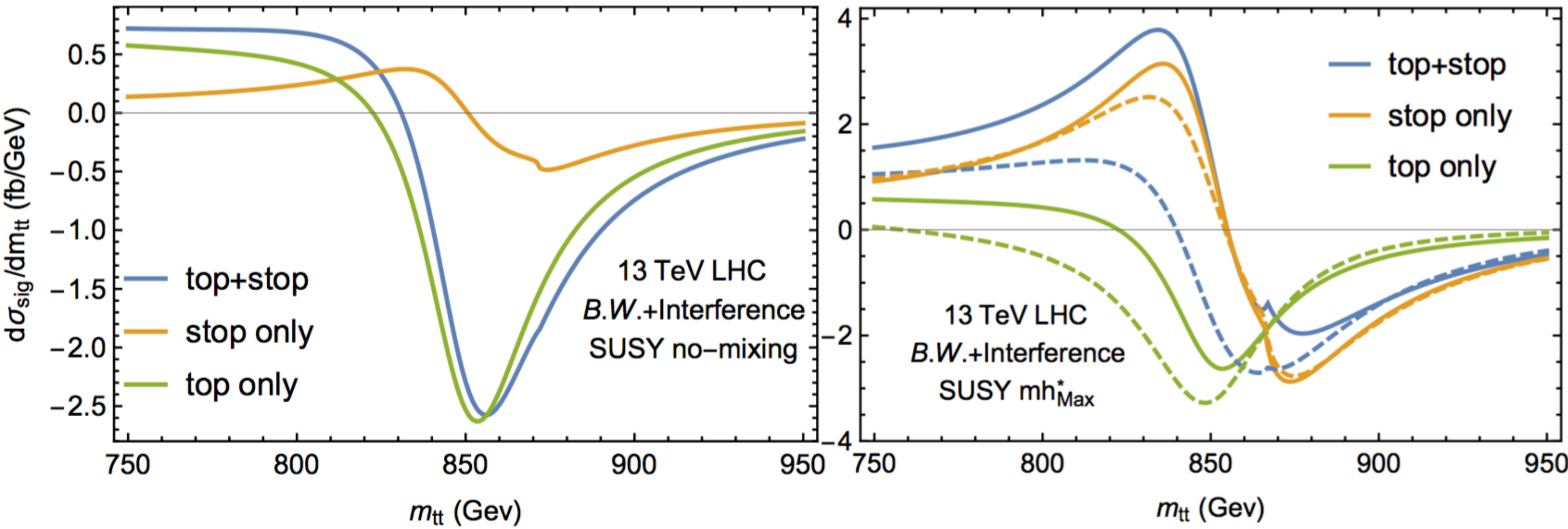
Opportunities– Stop contributions



SUSY TeV scale stop quarks are highly anticipated through naturalness argument; Green curves are top contribution only, orange curves are stop contribution only and blue curves are with both top and stop contributions.

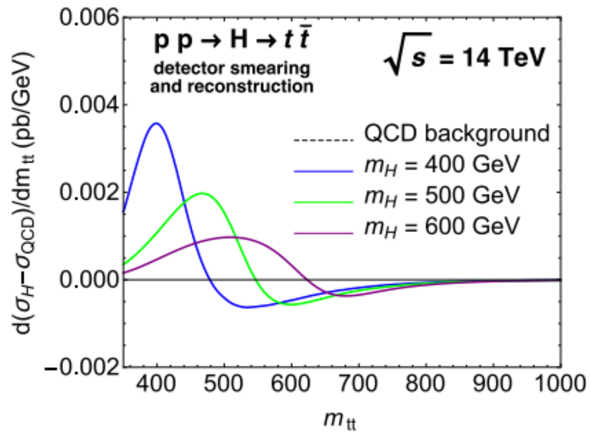
For 850 GeV scalars, we show two benchmark scenarios:

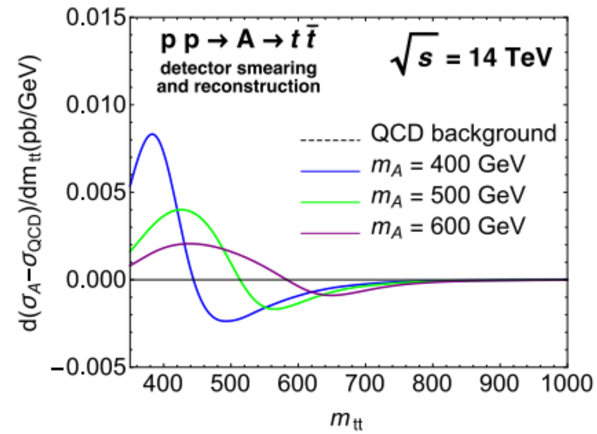
Stop zero L-R mixing, the stop contribution is only a small perturbation;

Stop large L-R mixing, mh^*_{max} scenario, the heavy Higgs to stop quark pair coupling is dominated by the mixing term, and significant changes could occur.

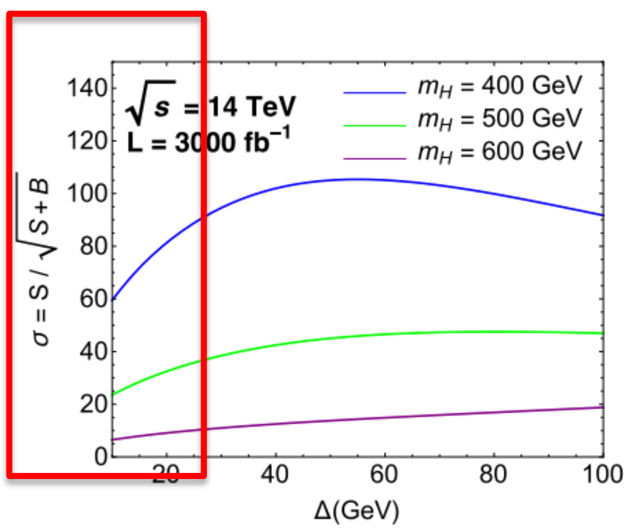
LHC perspectives—Challenges

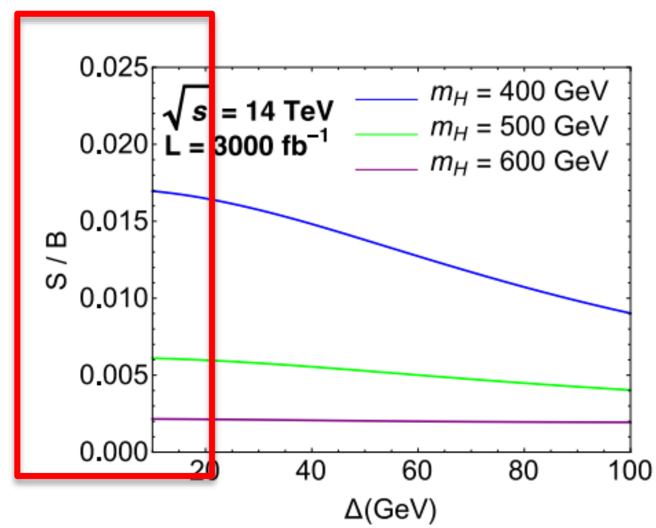
Statistically promising;
Systematically, challenging.



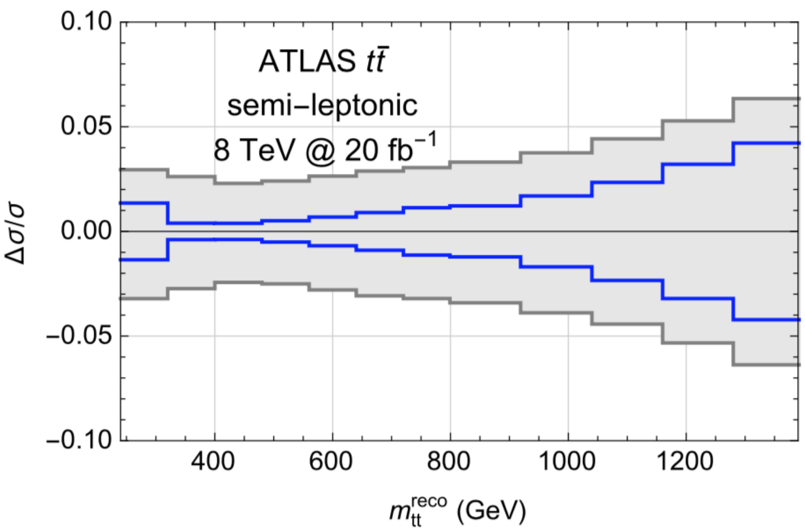


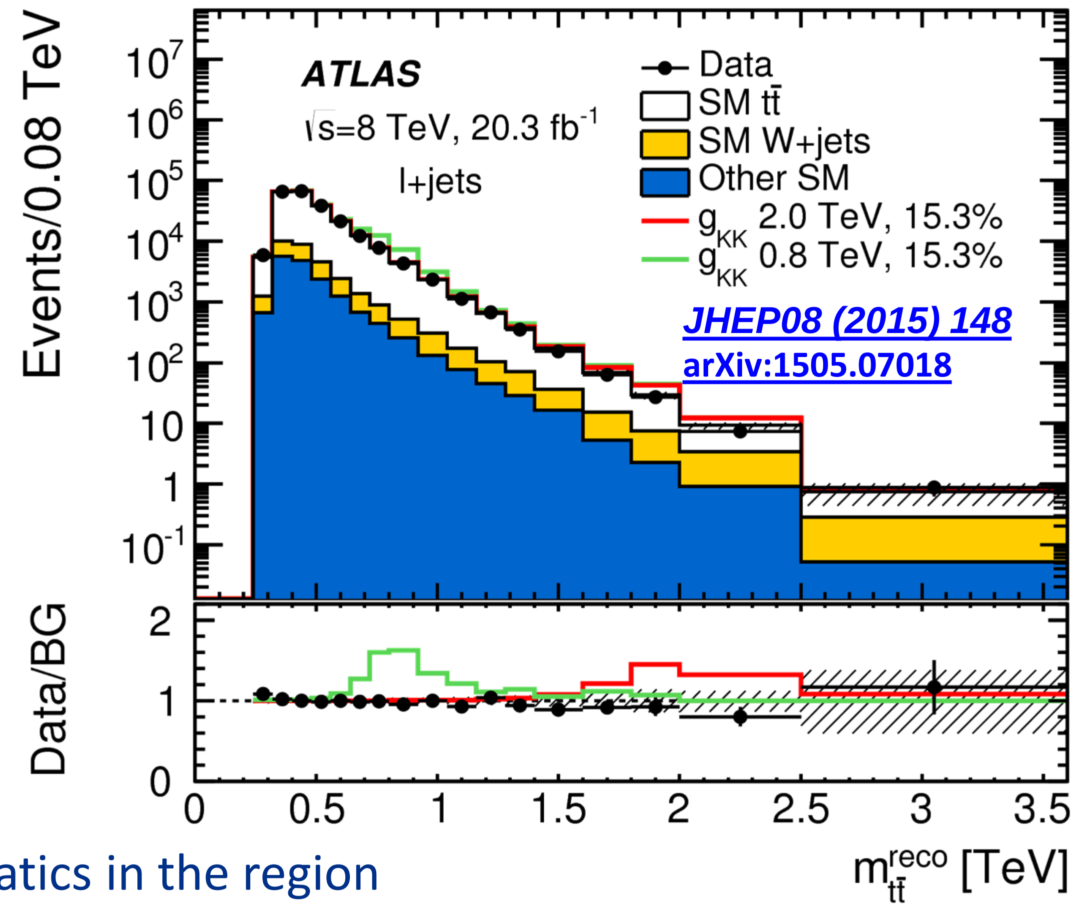
Craig, Draper, Erasmo, Thomas, Zhang '15





LHC perspectives



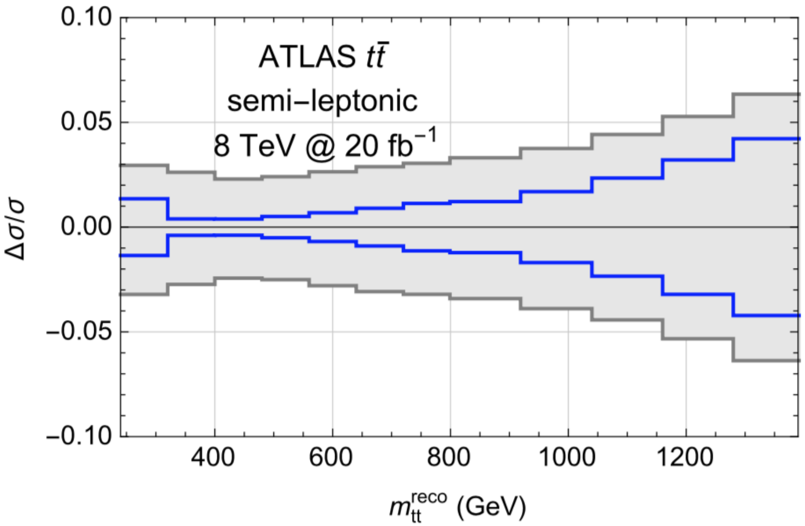


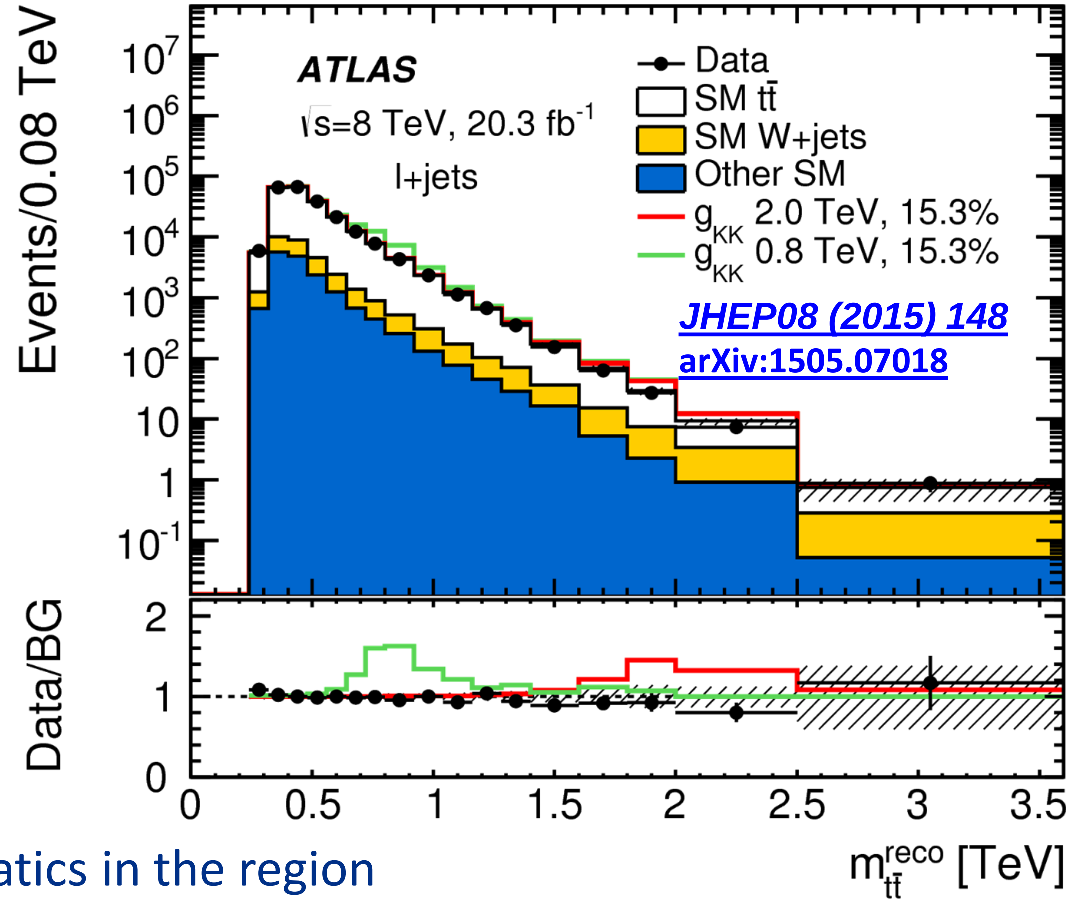
[JHEP08 (2015) 148](#)
[arXiv:1505.07018](#)

Already achieved sub 2-4% systematics in the region of interest, we see hope in this channel.

This is a crucial channel universally important for the understanding of heavy new resonances.

LHC perspectives





JHEP08 (2015) 148

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``Hitting a systematics wall'' is not an option, we need to try hard to improve the systematics by using the abundant data to calibrate and by selecting the data with best quality.

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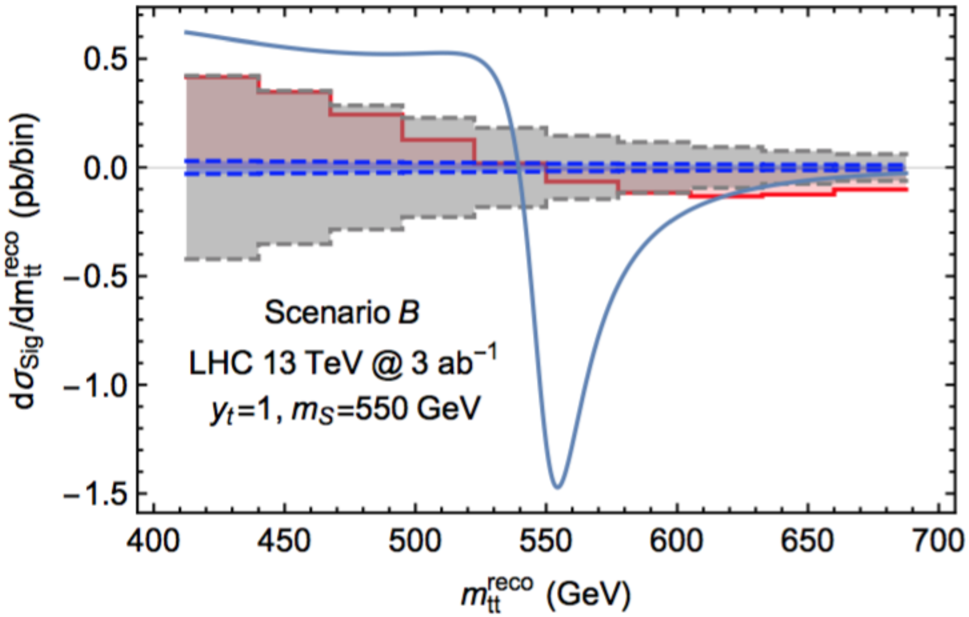
LHC perspectives

	$\Delta m_{t\bar{t}}$	Efficiency	Systematic Uncertainty
Scenario A	15%	8%	4% at 30 fb^{-1}, halved at 3 ab^{-1}
Scenario B	8%	5%	4% at 30 fb^{-1}, scaled with $\sqrt{L}$



Blue curve, the signal lineshape before mearing;
Red Histogram, the signal after smearing and binning;
Gray and blue histograms, the total and statistical uncertainties;

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LHC perspectives

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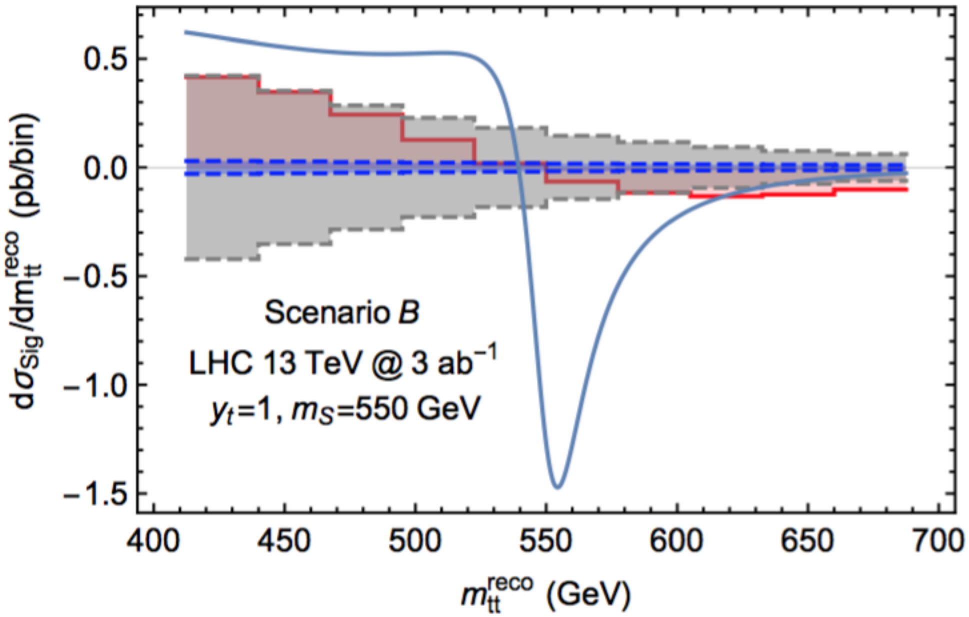

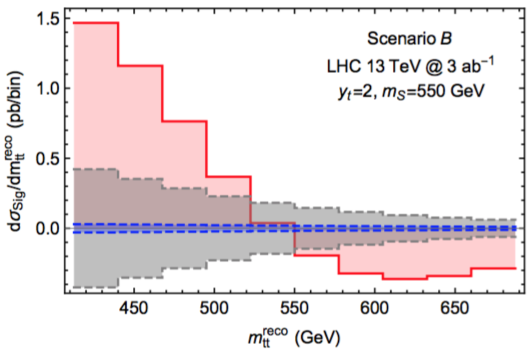

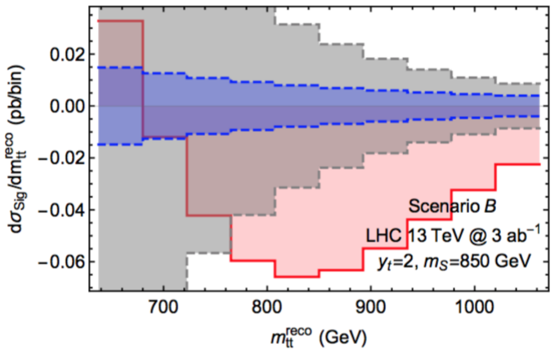

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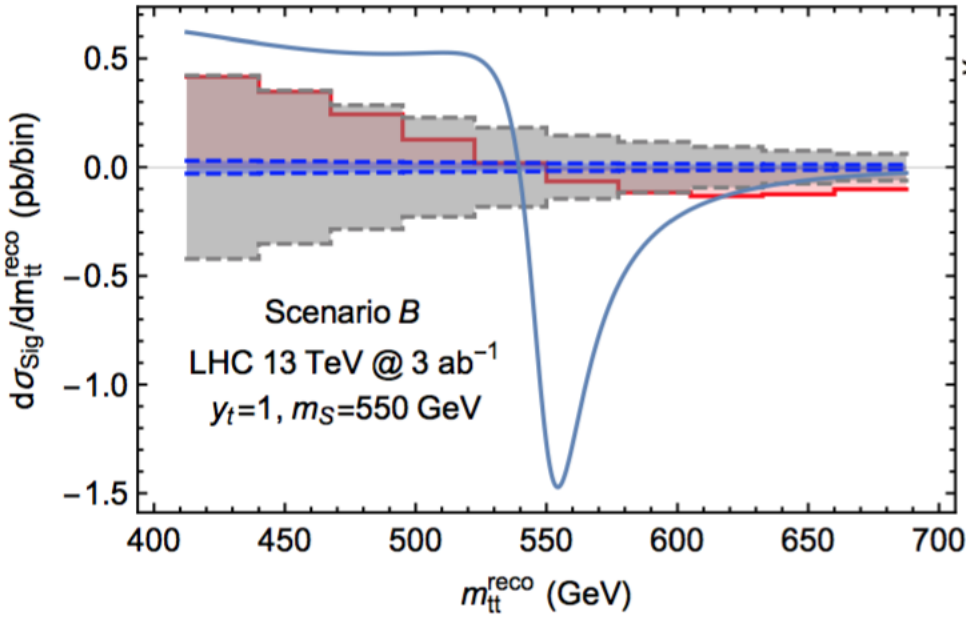
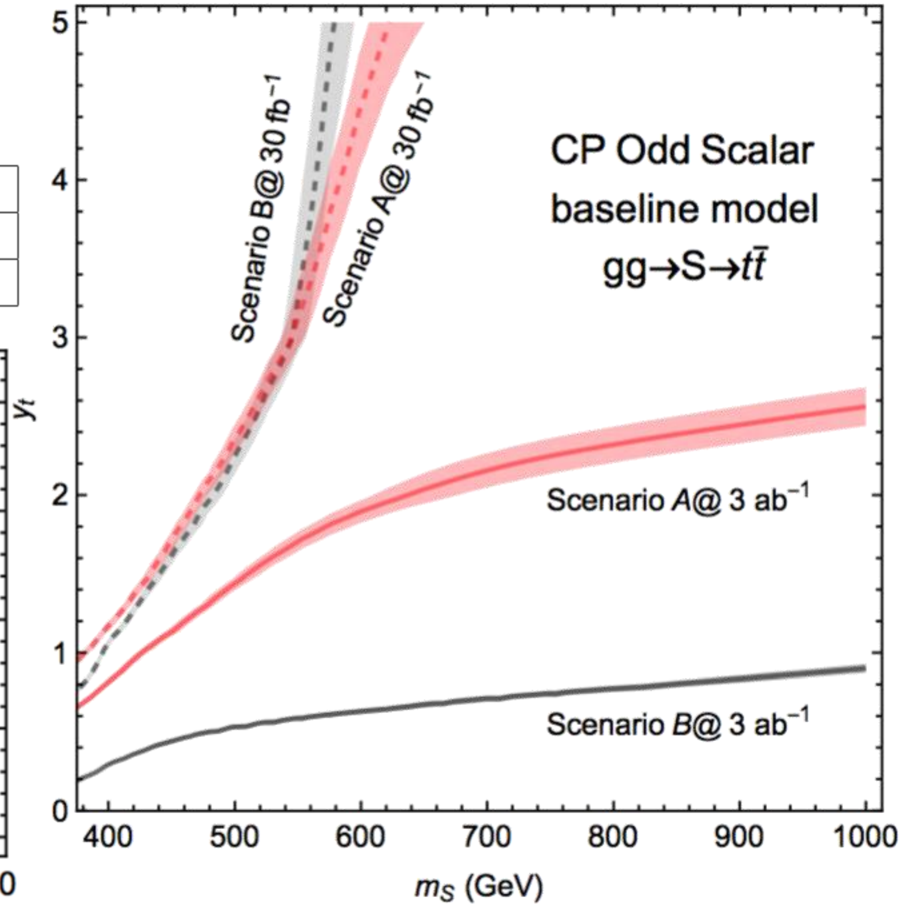
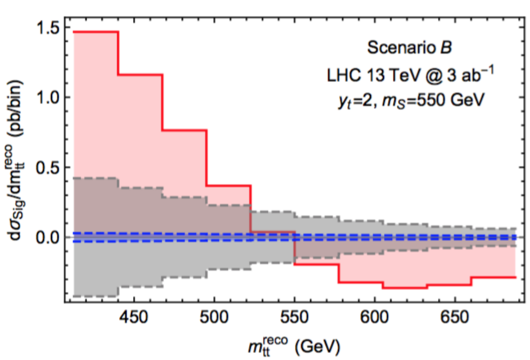
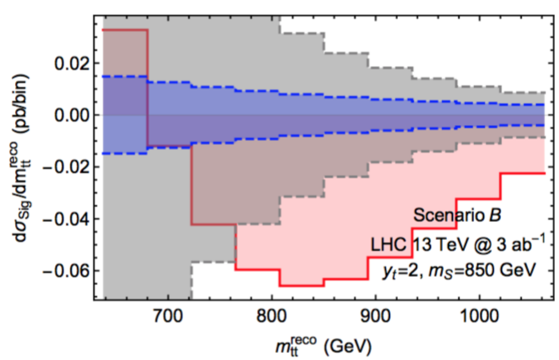


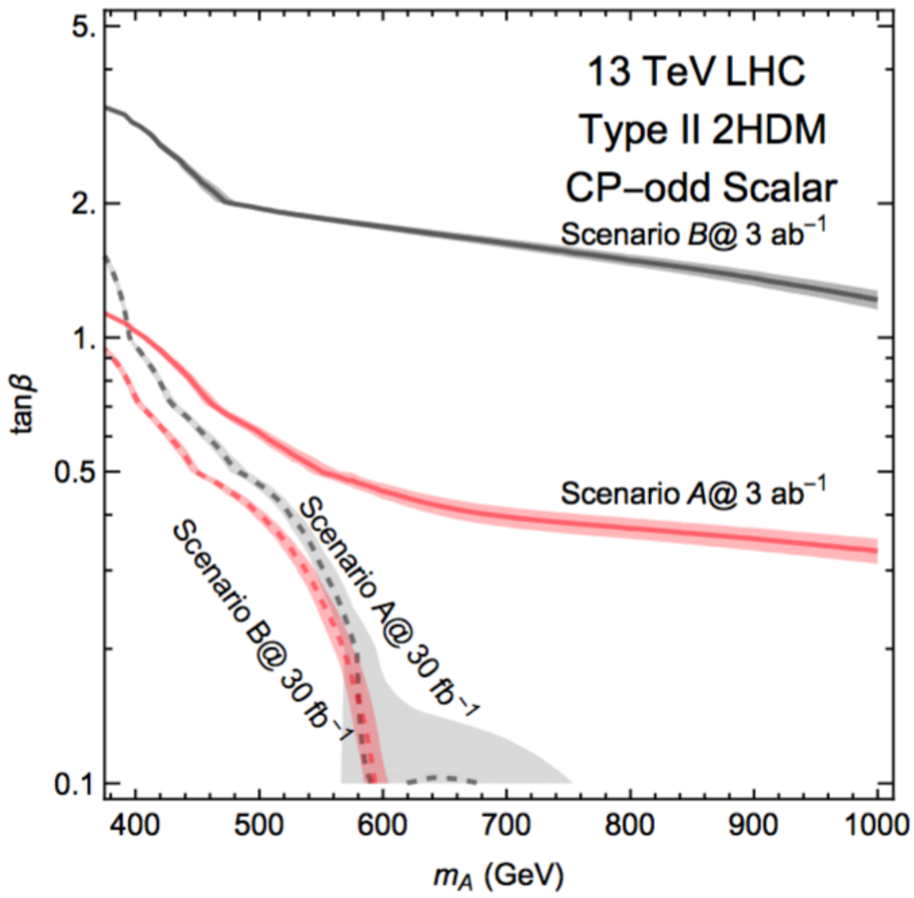






Lineshapes for a grid of mass and different Yukawas are generated
(because the signal is line-shape and does not scale as simple powers of Yukawa couplings).
After smearing, using bins near the scalar mass window, taking both excess and deficits, exclusion potential extracted.

LHC perspectives—2HDM projections

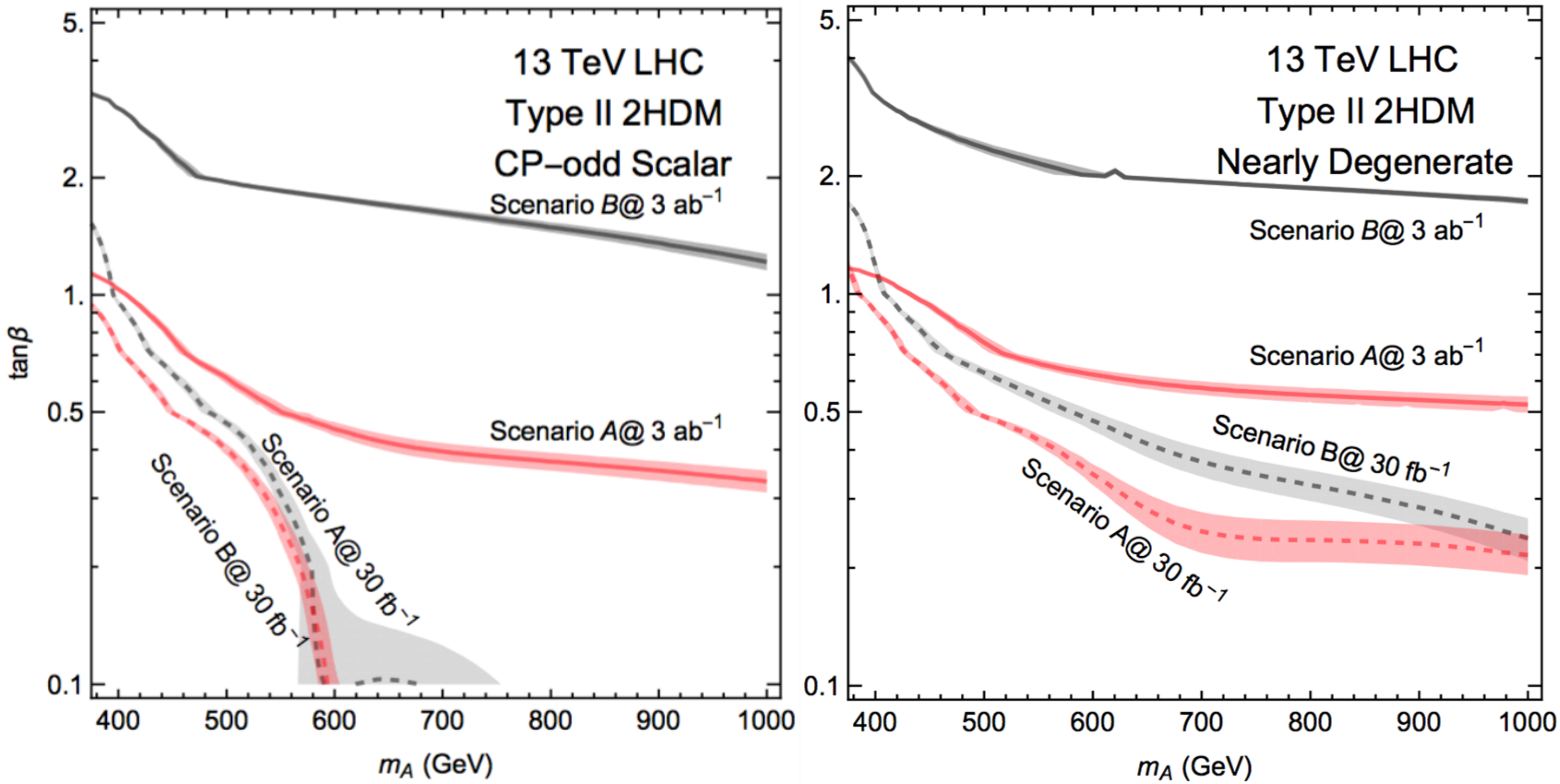


For a Type II 2HDM, the bottom quark effects are mainly in modifying the production vertex and provide some decay branching fraction suppression;

Regions below the curves are excluded;

In general can only cover the very low $tan\beta$ regime, optimistic LHC performance scenario B could cover up to $tan\beta$ around 1~2 up to 1 TeV.

LHC perspectives—2HDM projections



For the case of nearly degenerate heavy scalars, the physic reach is improved, especially for heavy heavy masses.

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Summary and outlook

$gg \to S \to t\bar{t}$ is a well—motivated channel for the hunt of heavy scalars

The interference effect augmented by the strong phase generated by the top loop generates funny shapes.

Opportunities to increase the observational aspects resides on both the theoretical side (including nearly degenerate bosons, CP phases, additional contributions form light quarks, and heavy colored particles) and experimental side (reducing the systematics with copious tops produced at the LHC, **starting to face this challenge by using line-shape profile search, and move on from there**.)

Other channels and effects, including ttH, tH (see in N. Craig, F. D'Eramo, P. Drapper, S. Thomas, H. Zhang **arXiv:1504.04630** and J. Hajer, Y.-Y. Li, T. Liu J. Shiu **arXiv:1504.07617**, N. Craig, J. Hajer, Y. Li, T. Liu, H. Zhang, **arXiv:1605.08744**, B. Hespel, F. Maltoni, E. Vryonidou **arXiv:1606.04149**) and H+jet and how stable such effects are against QCD corrections(see a case study in W. Bernreuther, P. Galler, C. Mellein, Z.-G. Si, P. Uwer **arXiv:1511.05584**), may have more potentials. Also other decay channels may have such effect large (see in Jung, Sung, Yoon, **arXiv:1510.03450**, **arXiv:1601.00006**).

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Thank you!

Backup

$$g_{1,2}^{\tilde{t}}(S)\frac{\sqrt{2}}{v} = \begin{cases} m_t^2 + \cos 2\beta (D^t_{L/R}\sin^2\theta_{\tilde{t}} + D^t_{R/L}\cos^2\theta_{\tilde{t}}) \pm \frac{1}{2}m_t X_t \sin 2\theta_{\tilde{t}} & , \text{ for } S = h \\ -\frac{m_t^2}{\tan\beta} - \sin 2\beta (D^t_{L/R}\sin^2\theta_{\tilde{t}} + D^t_{R/L}\cos^2\theta_{\tilde{t}}) \mp \frac{1}{2}m_t Y_t \sin 2\theta_{\tilde{t}} & , \text{ for } S = H \\ \mp\frac{1}{2}m_t Y_t \sin 2\theta_{\tilde{t}} & , \text{ for } S = A \end{cases}$$

$$\begin{aligned} D_L^u &= \frac{1}{2}m_W^2(1 - \frac{1}{3}\tan^2\theta_W)\cos 2\beta \\ D_R^u &= \frac{2}{3}m_W^2\tan^2\theta_W\cos 2\beta \\ D_L^d &= -\frac{1}{2}m_W^2(1 + \frac{1}{3}\tan^2\theta_W)\cos 2\beta \\ D_R^d &= -\frac{1}{3}m_W^2\tan^2\theta_W\cos 2\beta \\ X_u &= A_u - \frac{\mu}{\tan\beta} \\ X_d &= A_d - \mu\tan\beta \\ Y_u &= \frac{A_u}{\tan\beta} + \mu \\ Y_d &= A_b\tan\beta + \mu, \end{aligned}$$

$$X_t Y_t = \frac{A_t^2}{\tan\beta} - \frac{\mu^2}{\tan\beta} - A_t\mu(1 - \frac{1}{\tan^2\beta}).$$

$$\text{zero LR mixing}: \quad m_{Q_3} = 900 \text{ GeV}, m_{t_R} = 400 \text{ GeV}, X_t = 0$$

$$\text{mh}^*_{\text{max}}: \quad m_{Q_3} = 900 \text{ GeV}, m_{t_R} = 540 \text{ GeV}, Y_t = 2X_t = 3415 \text{ GeV}$$

$$g_{Sgg}(\hat{s}) = \frac{\alpha_s}{2\sqrt{2}\pi}\frac{y_t^s}{m_t}I_{\frac{1}{2}}(\tau_t), \qquad \tilde{g}_{Sgg}(\hat{s}) = \frac{\alpha_s}{2\sqrt{2}\pi}\frac{\tilde{y}_t^s}{m_t}\tilde{I}_{\frac{1}{2}}(\tau_t), \tag{2.3}$$

where $I_{\frac{1}{2}}(\tau_t)$ and $\tilde{I}_{\frac{1}{2}}(\tau_t)$ are the corresponding loop-functions and[1]

$$\tau_t = \frac{\hat{s}}{4m_t^2}, \quad f(\tau) = \begin{cases} -\arcsin^2(\sqrt{\tau}) & \text{for } \tau \leq 1, \\ \frac{1}{4}\left(\log\frac{1+\sqrt{1-1/\tau}}{1-\sqrt{1-1/\tau}} - i\pi\right)^2 & \text{for } \tau > 1 \end{cases}$$

$$I_{1/2}(\tau) = \frac{1}{\tau^2}(\tau + (\tau-1)f(\tau)), \quad \tilde{I}_{1/2}(\tau) = \frac{f(\tau)}{\tau}. \tag{2.4}$$

$$\mathcal{A}^{\text{even}} \propto y_t g_{Sgg} = y_t^2 I_{\frac{1}{2}}(\tau_t), \qquad \mathcal{A}^{\text{odd}} \propto \tilde{y}_t \tilde{g}_{Sgg} = \tilde{y}_t^2 \tilde{I}_{\frac{1}{2}}(\tau_t). \tag{2.8}$$

We can define the phase of the resonant amplitudes as,

$$\mathcal{A} = \frac{\hat{s}}{\hat{s} - m_S^2 + i\Gamma_S m_S}|\bar{\mathcal{A}}|e^{i\theta_{\bar{\mathcal{A}}}}, \qquad \text{with} \quad \theta_{\bar{\mathcal{A}}} \equiv \arg(\bar{\mathcal{A}}). \tag{2.9}$$

$$
\begin{aligned}
\hat{\sigma}^{\rm odd}_{\rm BSM}(\hat{s};\tilde{y}_t)(gg\to S\to t\bar{t}) &= \hat{\sigma}^{\rm odd}_{\rm B.W.}(\hat{s};\tilde{y}_t)+\hat{\sigma}^{\rm odd}_{\rm Int.}(\hat{s};\tilde{y}_t)\\
\frac{d\hat{\sigma}^{\rm odd}_{\rm B.W.}(\hat{s};\tilde{y}_t)}{dz} &= \frac{3\alpha_s^2\hat{s}^2}{4096\pi^3 v^2}\beta\left|\frac{\tilde{y}_t^2\tilde{I}_{\frac{1}{2}}(\tau_t)}{\hat{s}-m_S^2+im_S\Gamma_S(\hat{s})}\right|^2\\
\frac{\hat{\sigma}^{\rm odd}_{\rm Int.}(\hat{s};\tilde{y}_t)}{dz} &= -\frac{\alpha_s^2}{64\pi}\frac{\beta}{1-\beta^2 z^2}\,{\rm Re}\left[\frac{\tilde{y}_t^2\tilde{I}_{\frac{1}{2}}(\tau_t)}{\hat{s}-m_S^2+im_S\Gamma_S(\hat{s})}\right]
\end{aligned}
$$

$$
\begin{aligned}
\hat{\sigma}^{\rm even}_{\rm BSM}(\hat{s};y_t)(gg\to S\to t\bar{t}) &= \hat{\sigma}^{\rm even}_{\rm B.W.}(\hat{s};y_t)+\hat{\sigma}^{\rm even}_{\rm Int.}(\hat{s};y_t)\\
\frac{d\hat{\sigma}^{\rm even}_{\rm B.W.}(\hat{s};y_t)}{dz} &= \frac{3\alpha_s^2\hat{s}^2}{4096\pi^3 v^2}\beta^3\left|\frac{y_t^2 I_{\frac{1}{2}}(\tau_t)}{\hat{s}-m_S^2+im_S\Gamma_S(\hat{s})}\right|^2\\
\frac{d\hat{\sigma}^{\rm even}_{\rm Int.}(\hat{s};y_t)}{dz} &= -\frac{\alpha_s^2}{64\pi}\frac{\beta^3}{1-\beta^2 z^2}\,{\rm Re}\left[\frac{y_t^2 I_{\frac{1}{2}}(\tau_t)}{\hat{s}-m_S^2+im_S\Gamma_S(\hat{s})}\right]
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\sigma^{\rm S_1-S_2}_{\rm Int.}(\hat{s})(gg\to S_1,S_2\to t\bar{t})}{dz} &= \frac{3\alpha_s^2\hat{s}^2}{2048\pi^3 v^2}\\
&{\rm Re}\left[\frac{(y_{t,S_1}y_{t,S_2}|I_{\frac{1}{2}}(\tau_t)|^2+\tilde{y}_{t,S_1}\tilde{y}_{t,S_2}|\tilde{I}_{\frac{1}{2}}(\tau_t)|^2)(\beta^2 y_{t,S_1}y_{t,S_2}+\tilde{y}_{t,S_1}\tilde{y}_{t,S_2})}{(\hat{s}-m_{S_1}^2+im_{S_1}\Gamma_{S_1}(\hat{s}))(\hat{s}-m_{S_2}^2-im_{S_2}\Gamma_{S_2}(\hat{s}))}\right]
\end{aligned}
$$