Digging out (un)familiar heavy scalars from the $t\bar{t}$ channel at the LHC

Zhen Liu (Fermilab)

Higgs Couplings 2016@SLAC

Nov. 10th, 2016

Based on work M. Carena, ZL, **arXiv:1608.07282**, JHEP

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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This channel is **challenging** in some *interesting* way and we try to seek for physics opportunities through this challenge

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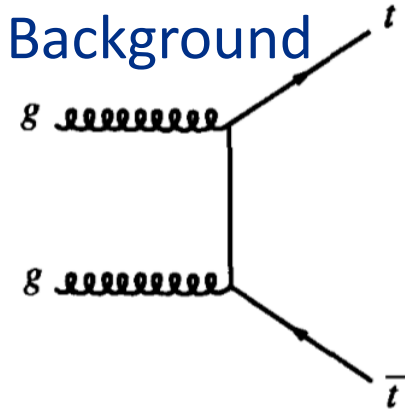
➡

Starting with a very minimal baseline model

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

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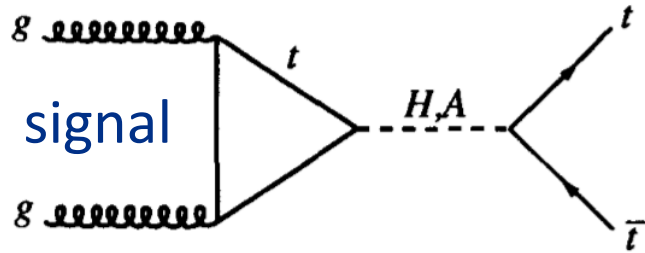
🎇 **Fermilab**

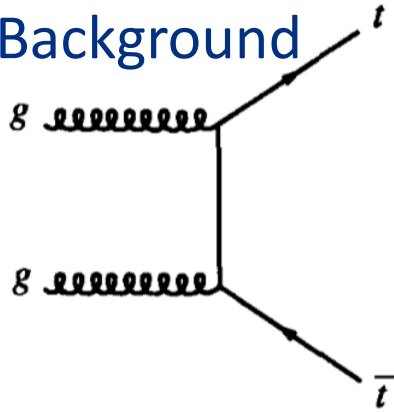# Unfamiliar look of heavy Scalars

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.

signal

Background

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

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Unfamiliar look of heavy Scalars

signal

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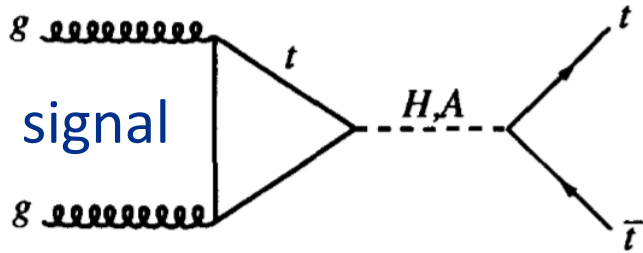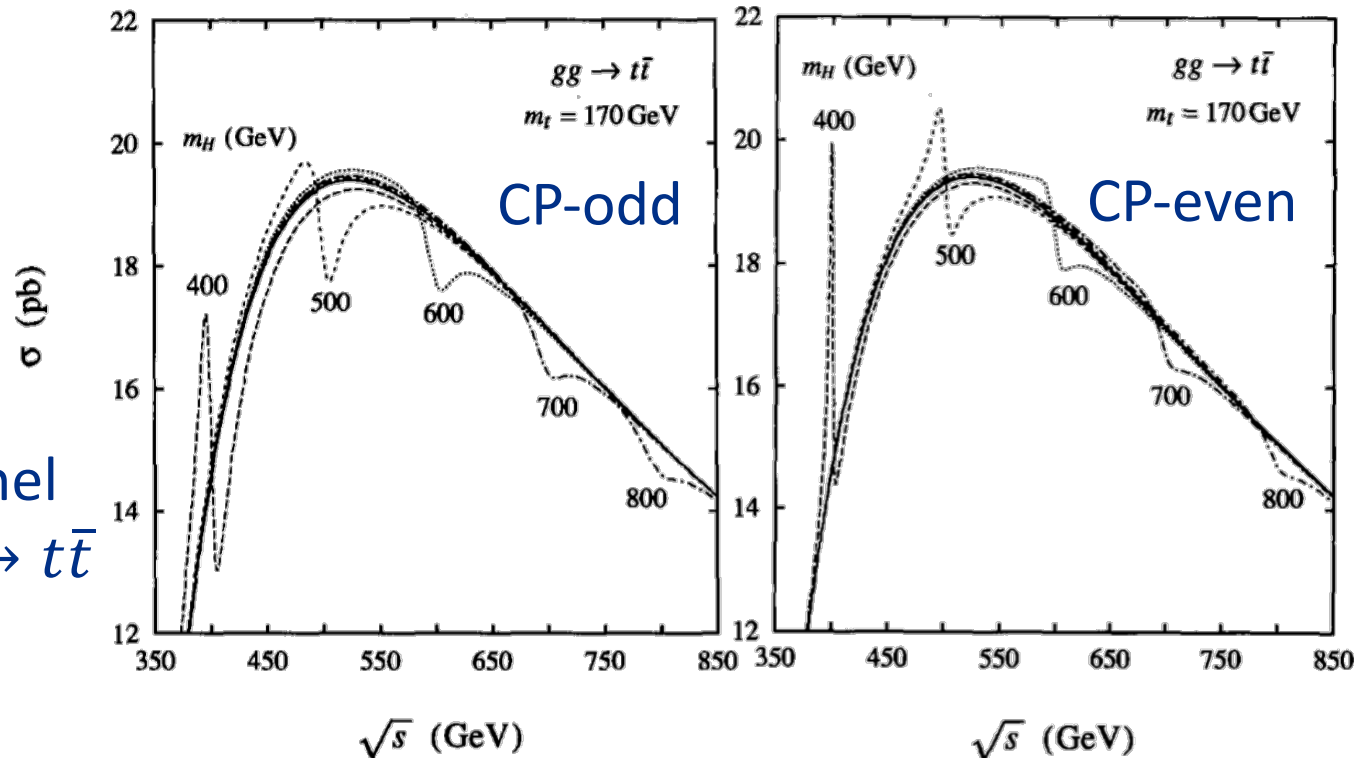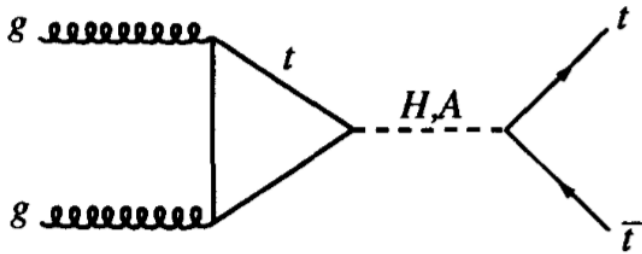
D. Dicus, A. Stange, S. Willenbrock, 1991

Background

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

See also recent work by N. Craig, F. D'Eramo, P. Drapper, S. Thomas, H. Zhang **arXiv:1504.04630** and also Jung, Sung, Yoon **arXiv:1505.00291**, S. Gori, I.-W. Kim, N. Shah, K. Zurek **arXiv:1602.02782**, M. Carena, ZL **arXiv:1608.07282**

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Challenges (interferences)

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

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

Background real
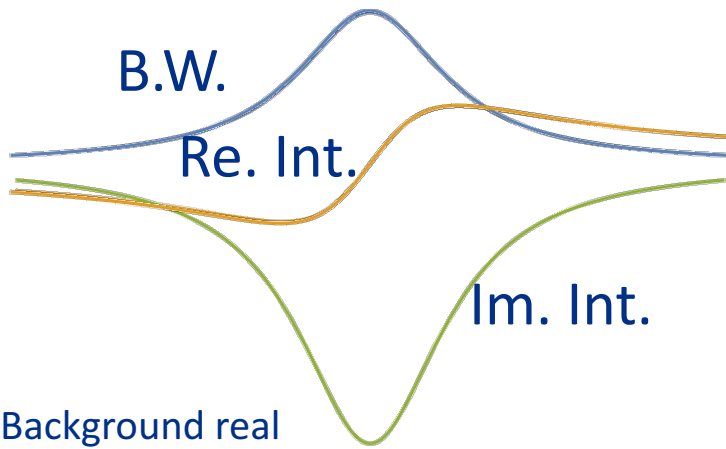
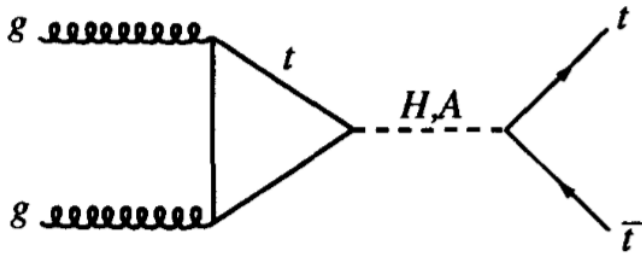Re. Int.– Interference from the real part of the propagator
(normal interference, parton level no contribution to the rate, shift the mass peak)
(When convoluting with PDF, may generate residual contribution to signal rate, see, e.g., S. Martin's talk yesterday; conventional wisdom, interference only important when width is large)

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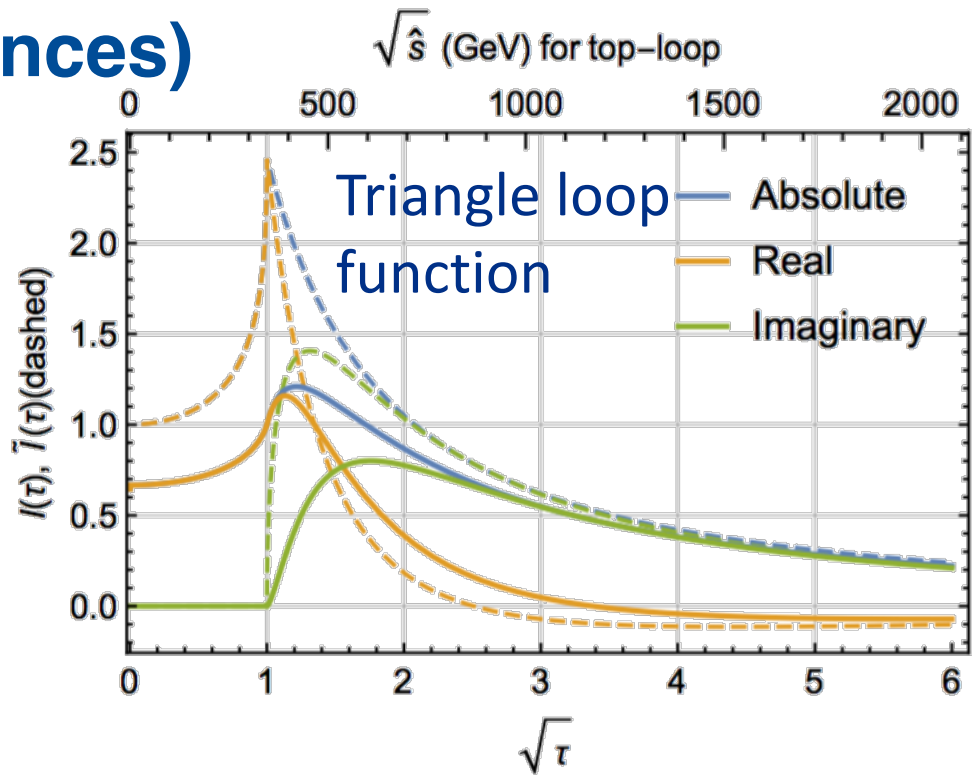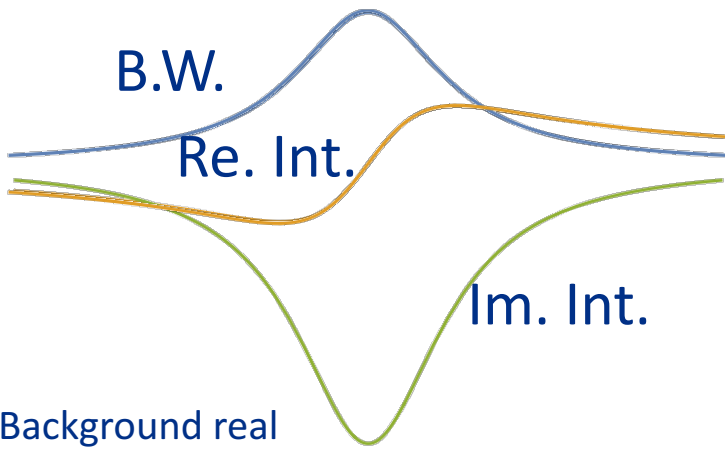# Challenges (interferences)
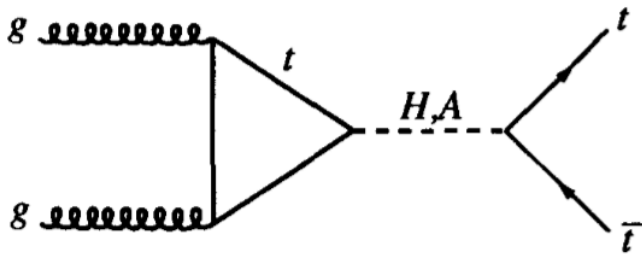

B.W.

Re. Int.

Im. Int.

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)
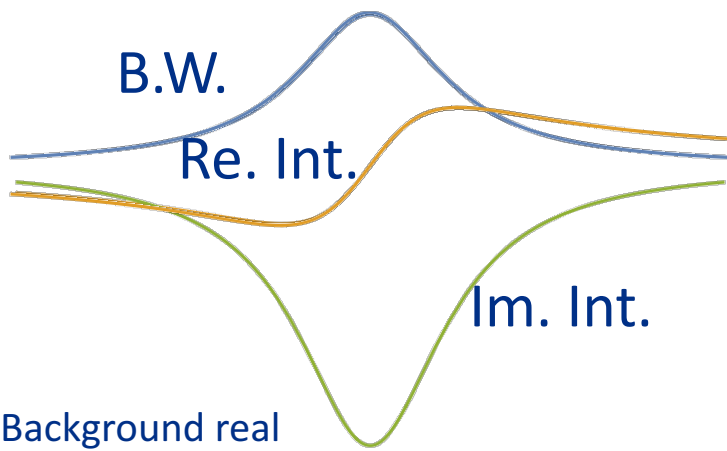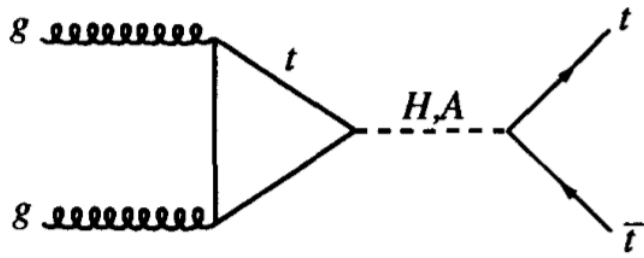
Triangle loop function

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Challenges (interferences)

Triangle loop function

SM Case
real and slowly varying
heavy (chiral) fermion decoupling
theorem (with Yukawa
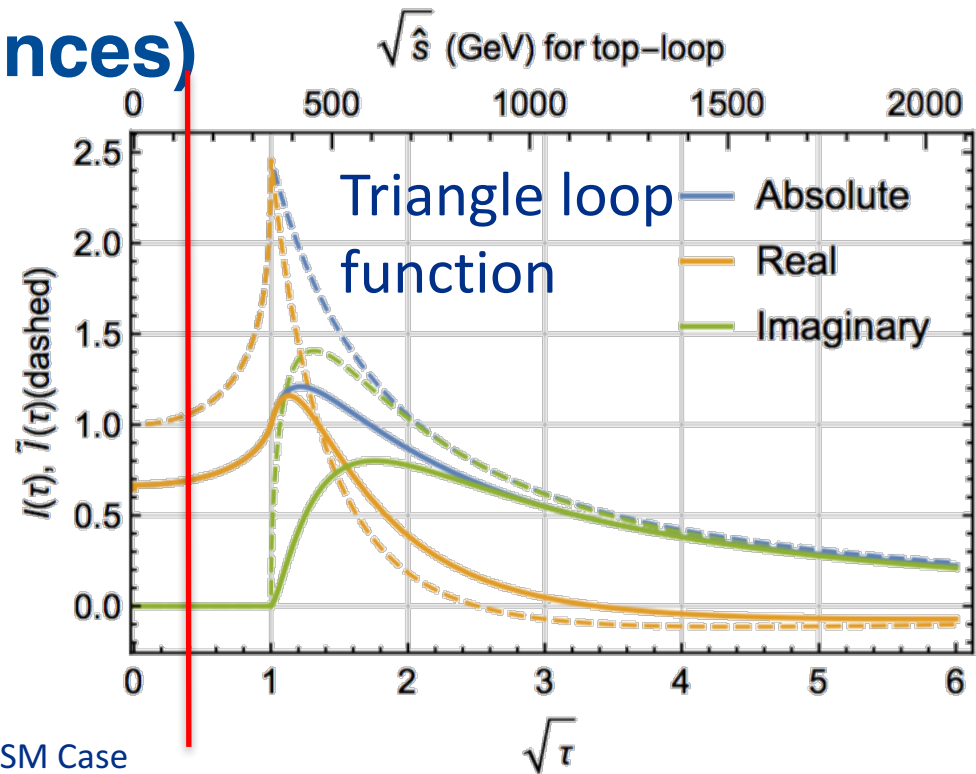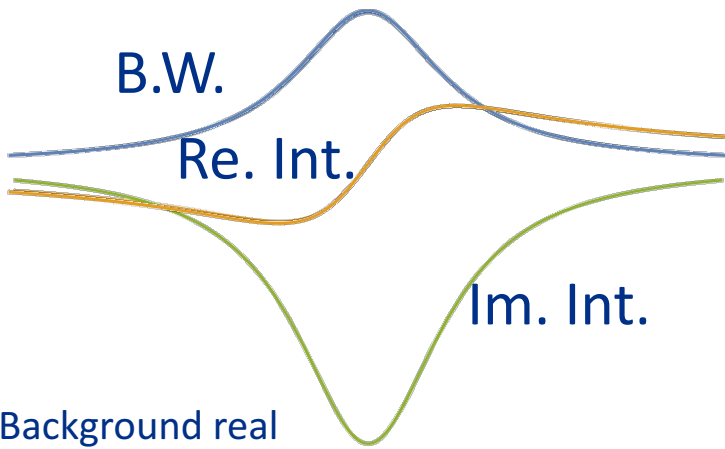proportional to the mass)

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Challenges (interferences)

Triangle loop function

$\sqrt{\hat{s}}$ (GeV) for top-loop

— Absolute
— Real
— Imaginary

$I(\tau), \tilde{I}(\tau)$ (dashed)

$\sqrt{\tau}$

B.W.
Re. Int.
Im. Int.

Once across the threshold, imaginary piece arises drastically and the real piece decreases.
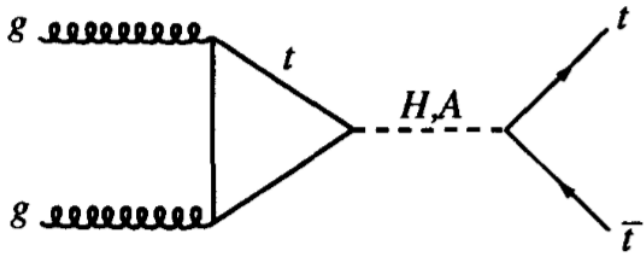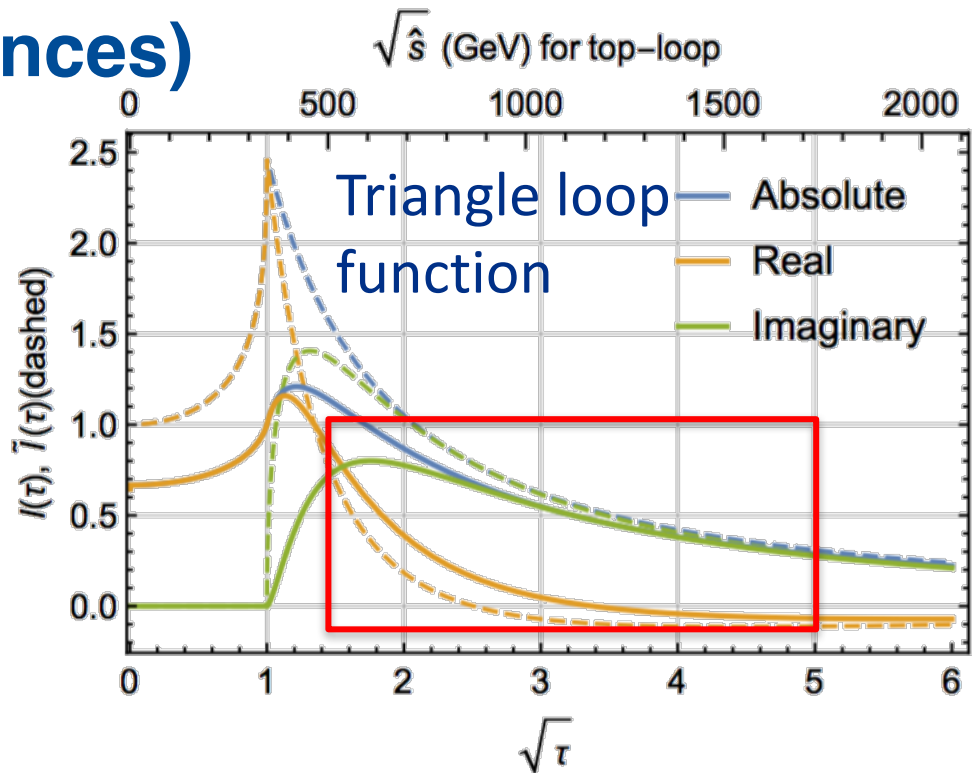
Background real
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Im. Int.– Interference from the imaginary part of propagator (rare case, changes signal rate)

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

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Challenges (interferences)

Triangle loop function

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

B.W.

Re. Int.

Im. Int.

Interference effect from this imaginary part is important, regardless of the width!
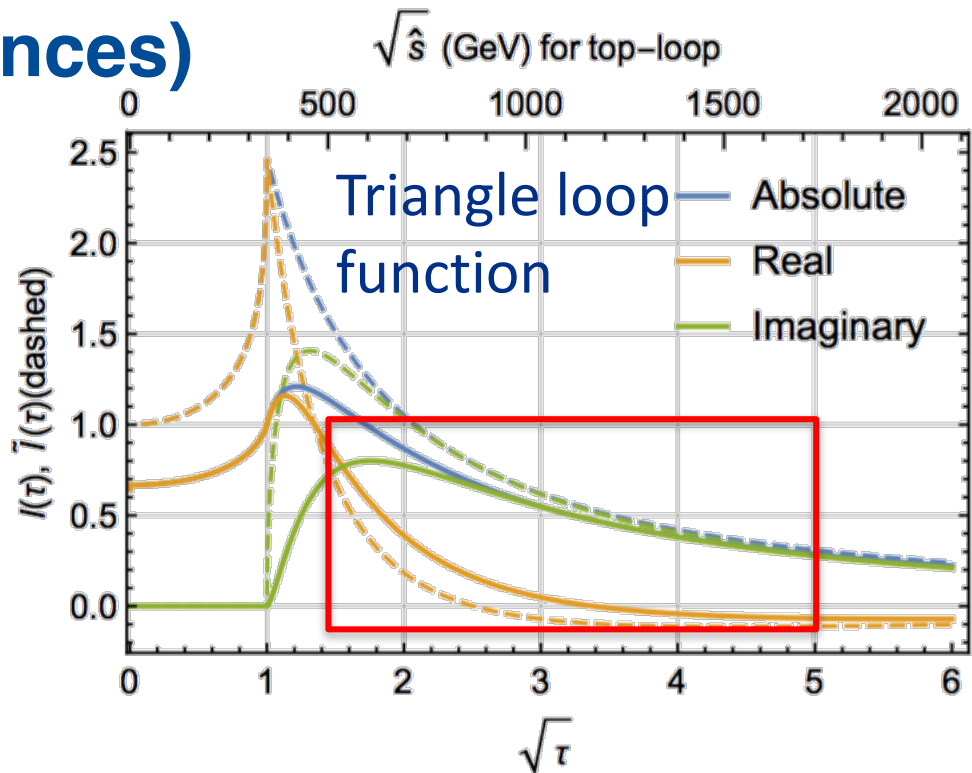
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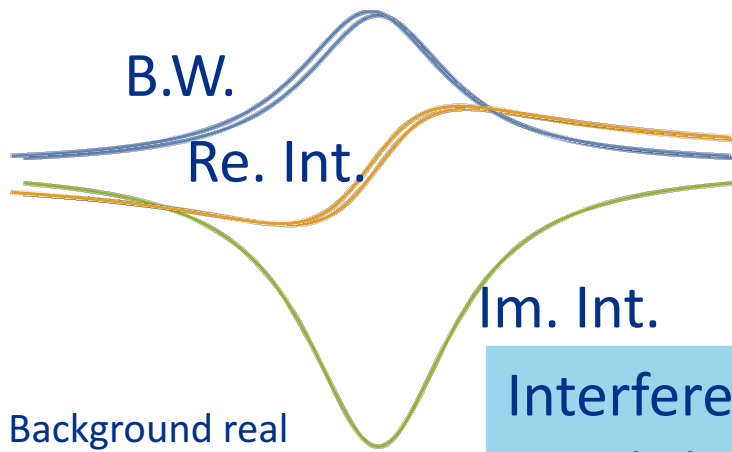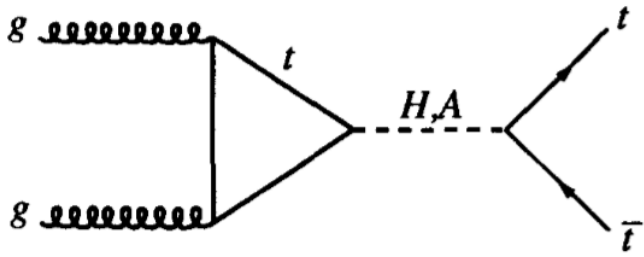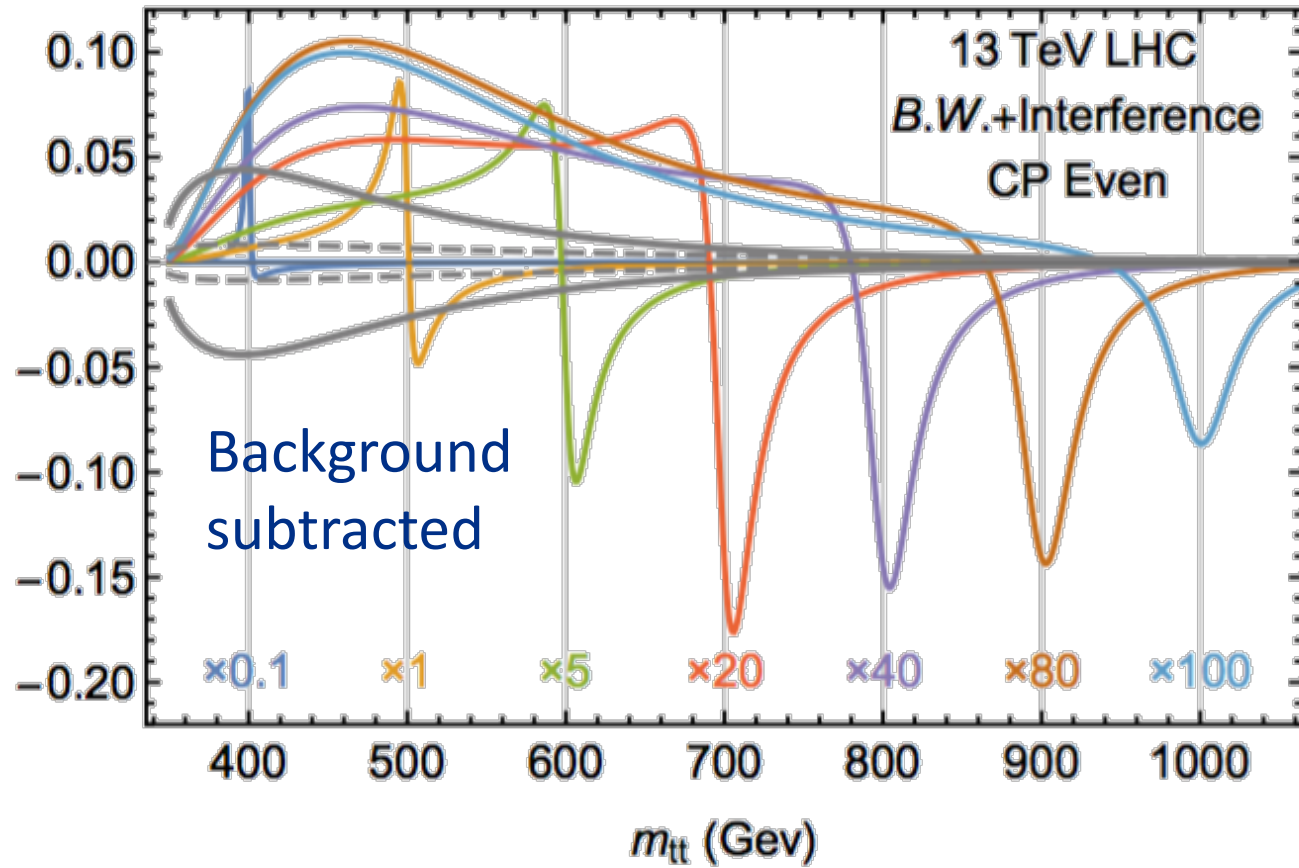propagator (rare case, changes signal rate)

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

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Challenges

Background subtracted
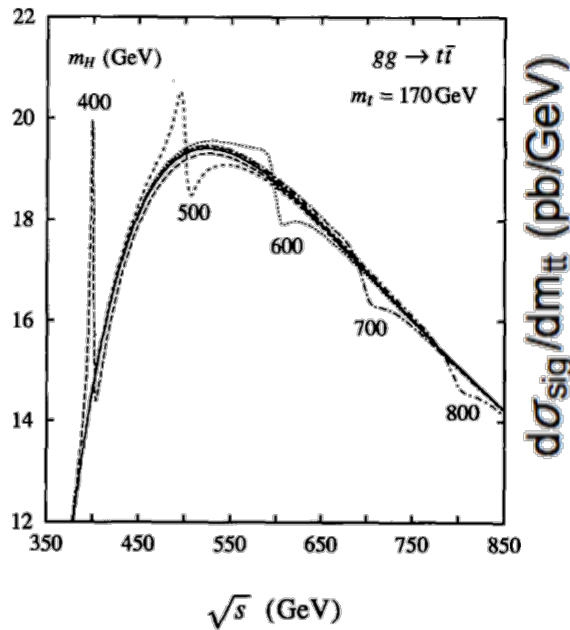
Special line shapes:
a) Bump search not designed/optimized for this, have to modify our current search;
b) Smearing effects erode the structure, making this signal much harder.

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Challenges

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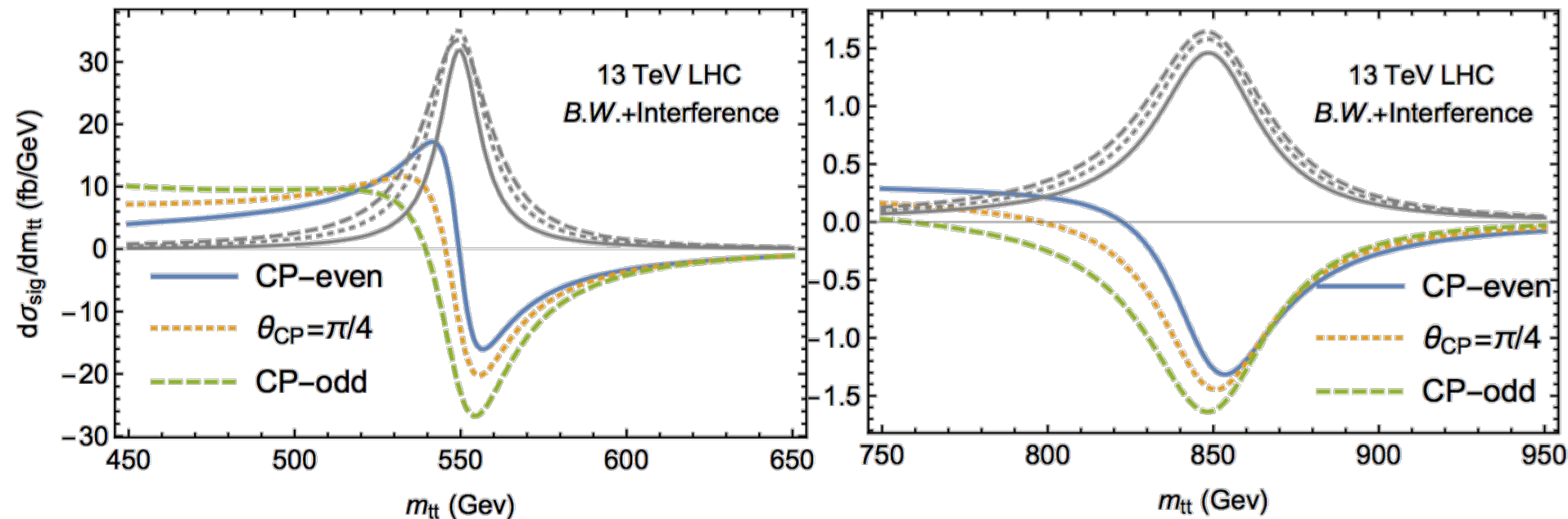- Colored lines, total BSM signal lineshapes;
- (Left panel) for 550 GeV scalars, the loop function has comparable real and imaginary components. The imaginary interference ``cancels'' the Breit-Wigner, leaving only Bump-dip structure;
- (Right panel) for 850 GeV scalar, the loop function is almost purely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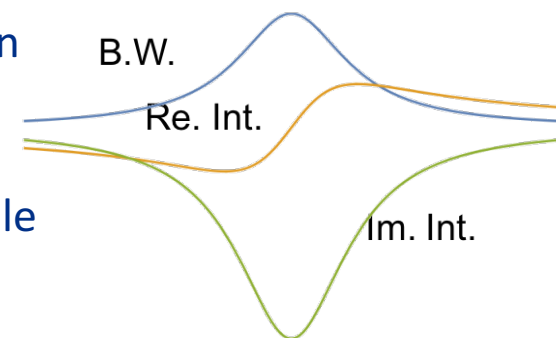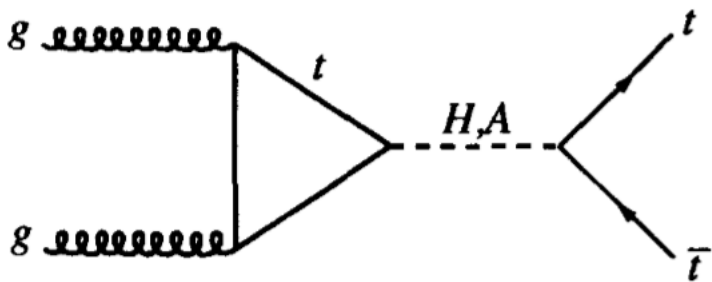
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Opportunities

- 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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Opportunities

Covered in our study.

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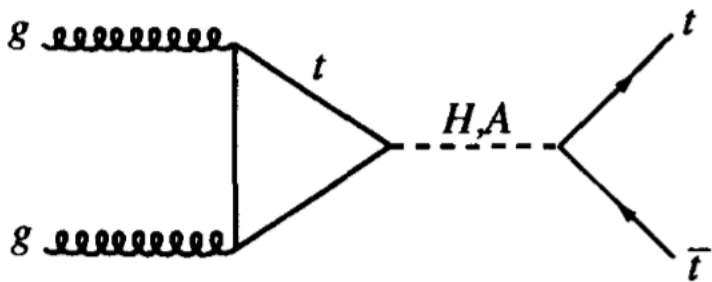
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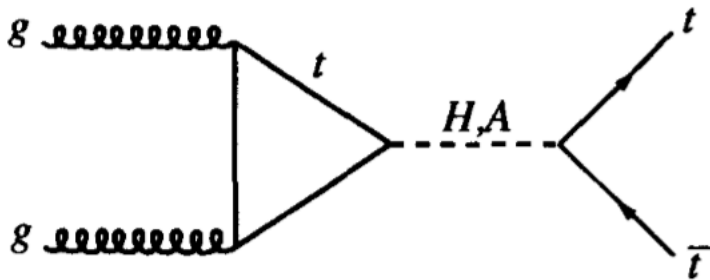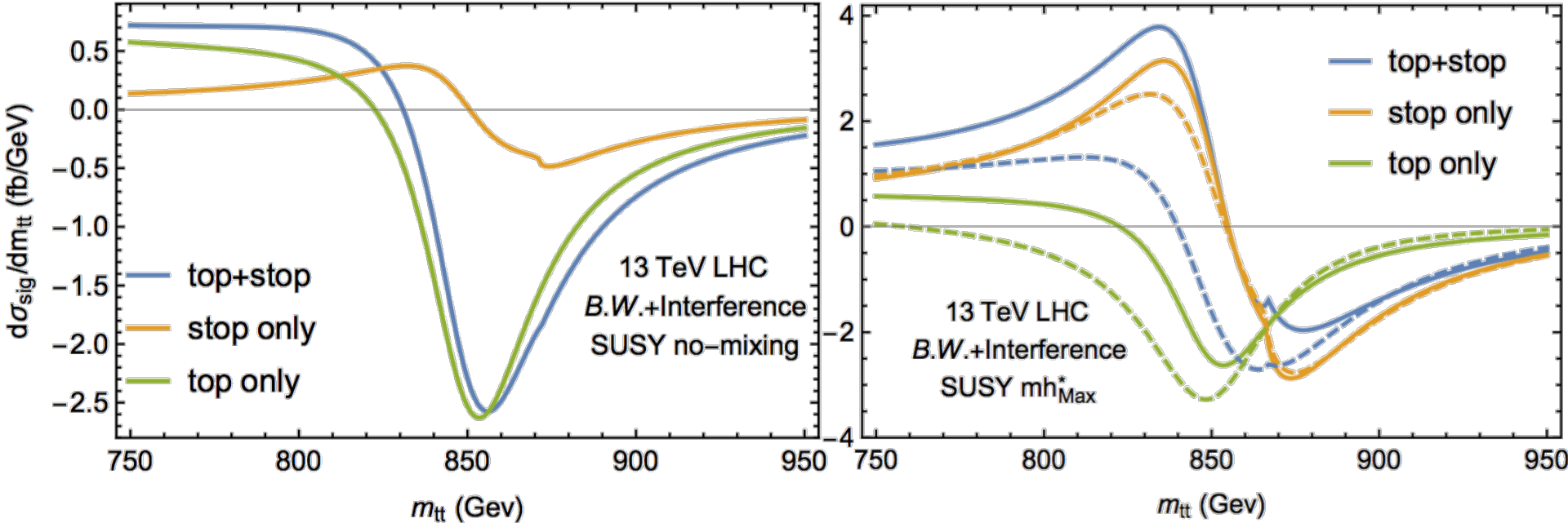
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Opportunities– Stop contributions

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.
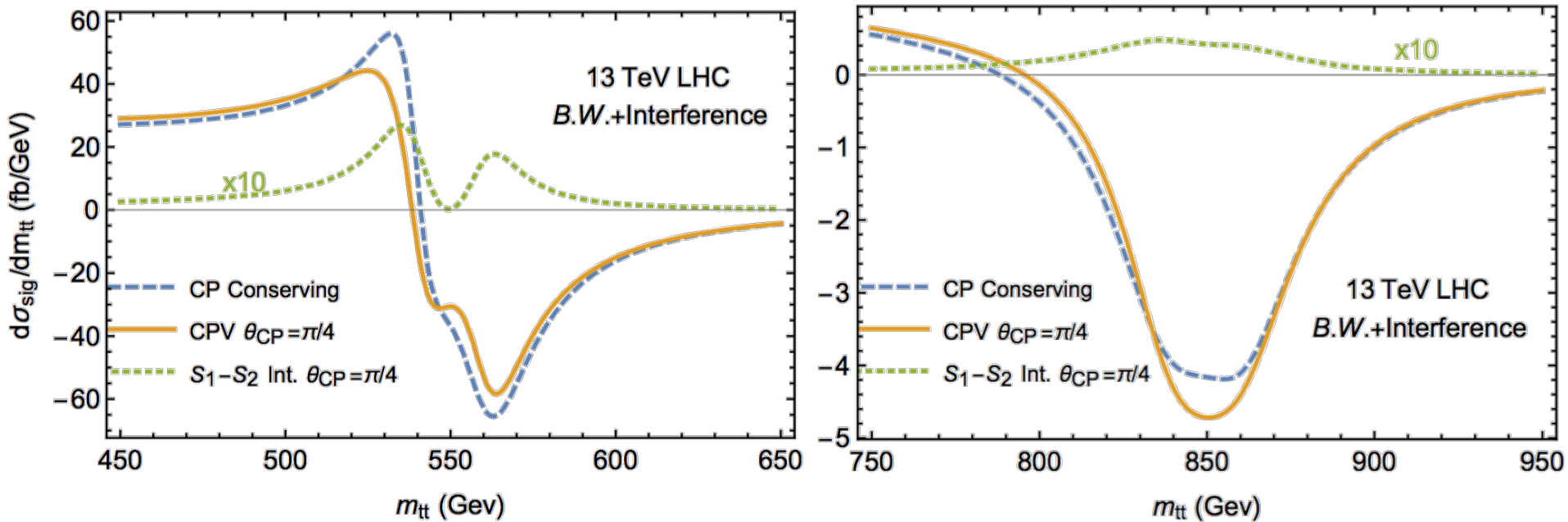For 850 GeV scalars, we show two benchmark scenarios:
Stop zero L-R mixing, the stop contribution is only a small perturbation;
Stop large L-R mixing, mh^*_{max} scenario, the heavy Higgs to stop quark pair coupling is dominated by the mixing term, and significant changes could occur.

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Opportunities—nearly degenerate with CPV

(left panel) 540 and 560 GeV scalars

(right panel) 840 and 860 GeV scalars
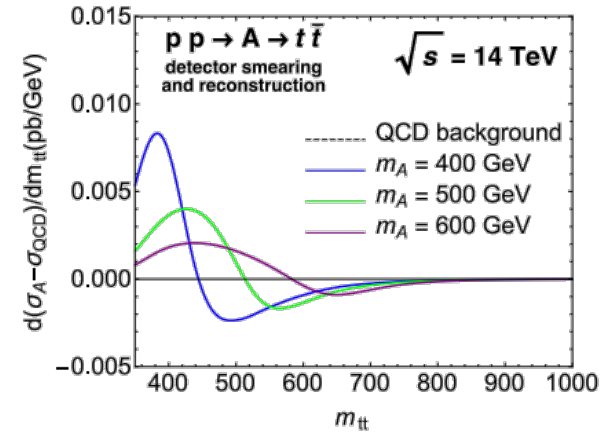
The signature—bumps and dips—roughly doubled, increasing the potential sensitivity;

With CPV, new interference between the two heavy nearly degenerate scalars occurs (although the effect might be small) but unique.

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LHC perspectives—Challenges

Statistically promising; Systematically, challenging.
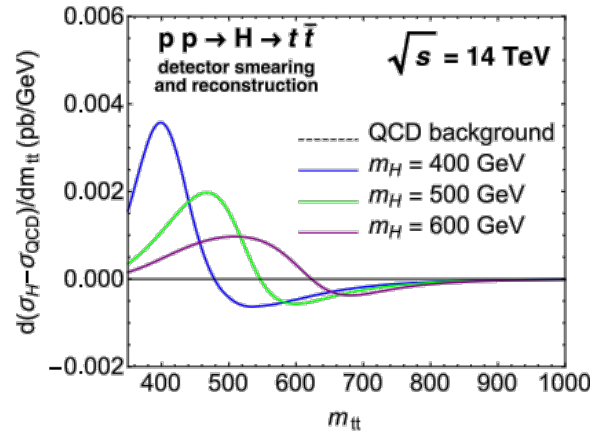
Craig, Draper, Erasmo, Thomas, Zhang '15

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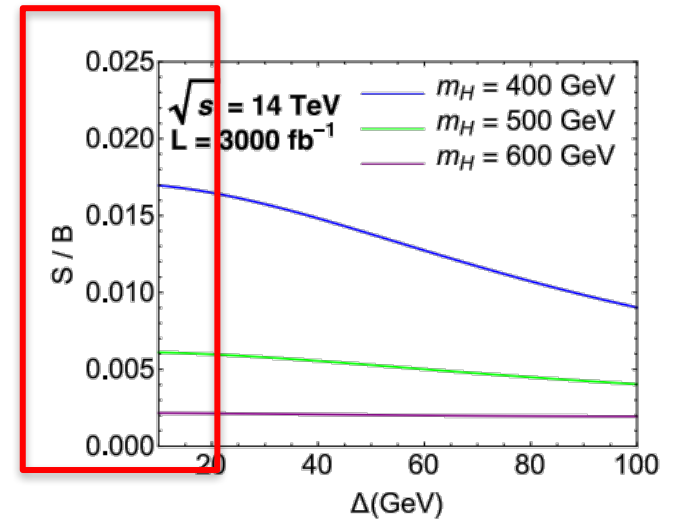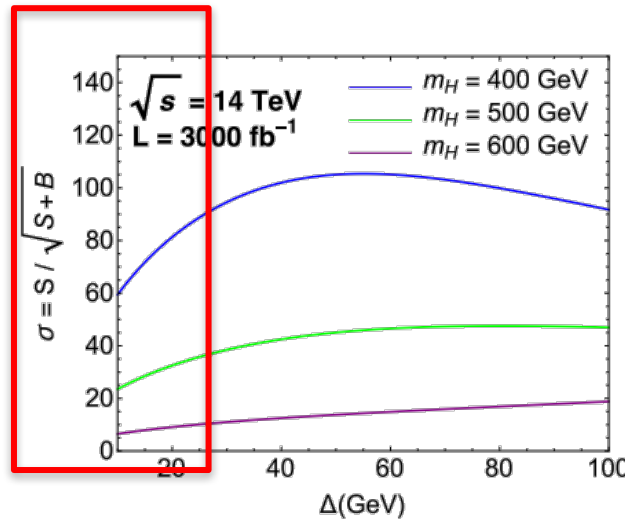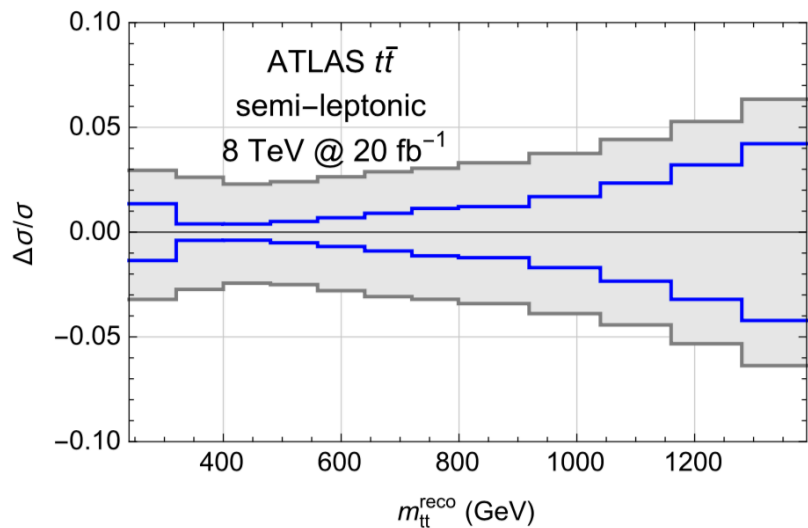
LHC perspectives

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.

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LHC perspectives

ATLAS $t\bar{t}$ semi−leptonic
8 TeV @ 20 fb^{-1}

ATLAS
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
l+jets

- Data
- SM $t\bar{t}$
- SM W+jets
- Other SM
- g_{KK} 2.0 TeV, 15.3%
- g_{KK} 0.8 TeV, 15.3%

JHEP08 (2015) 148
arXiv:1505.07018
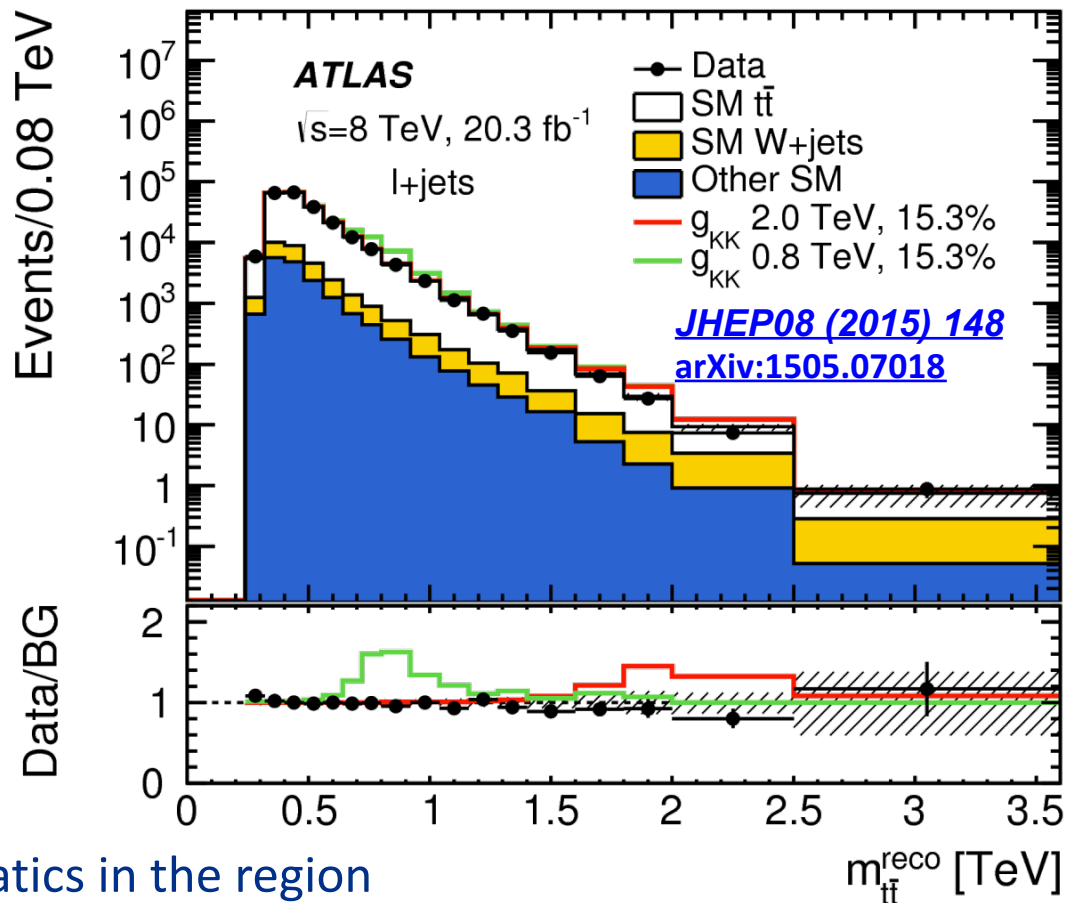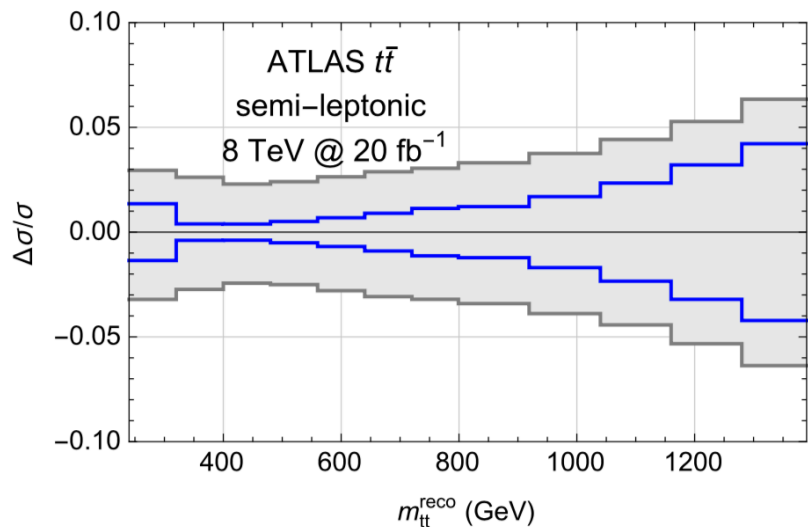
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``Hitting a systematics wall'' is not an option, we need to try hard to improve the systematics by using the abundant data to calibrate and by selecting the data with best quality.

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

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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 $\sqrt{L}$
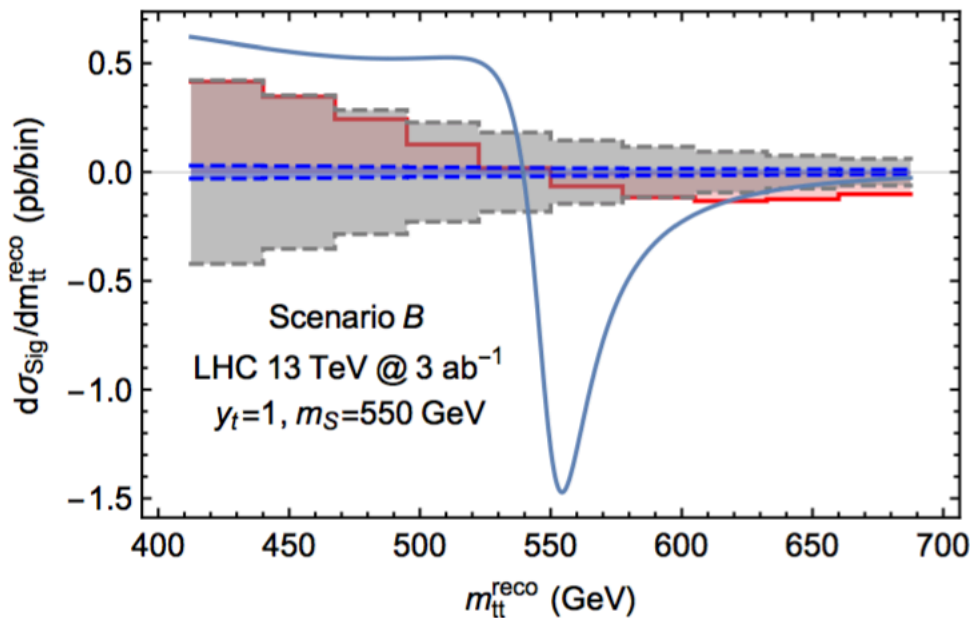
Blue curve, the signal lineshape before mearing;

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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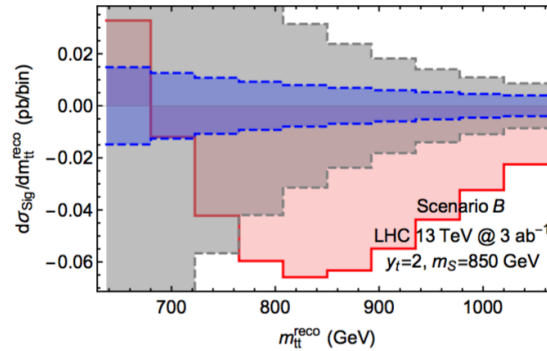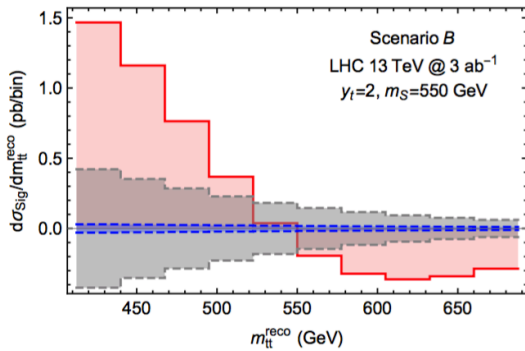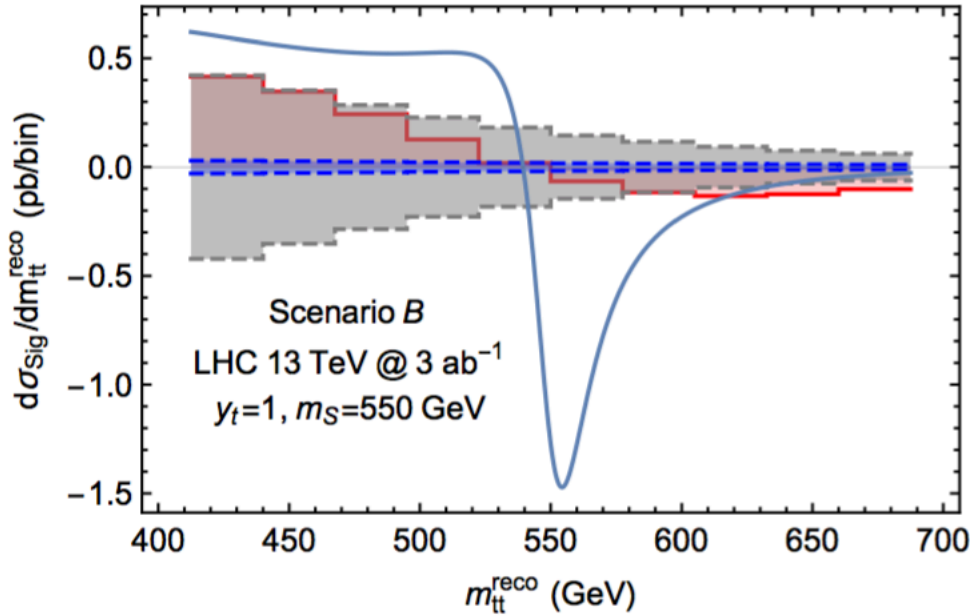
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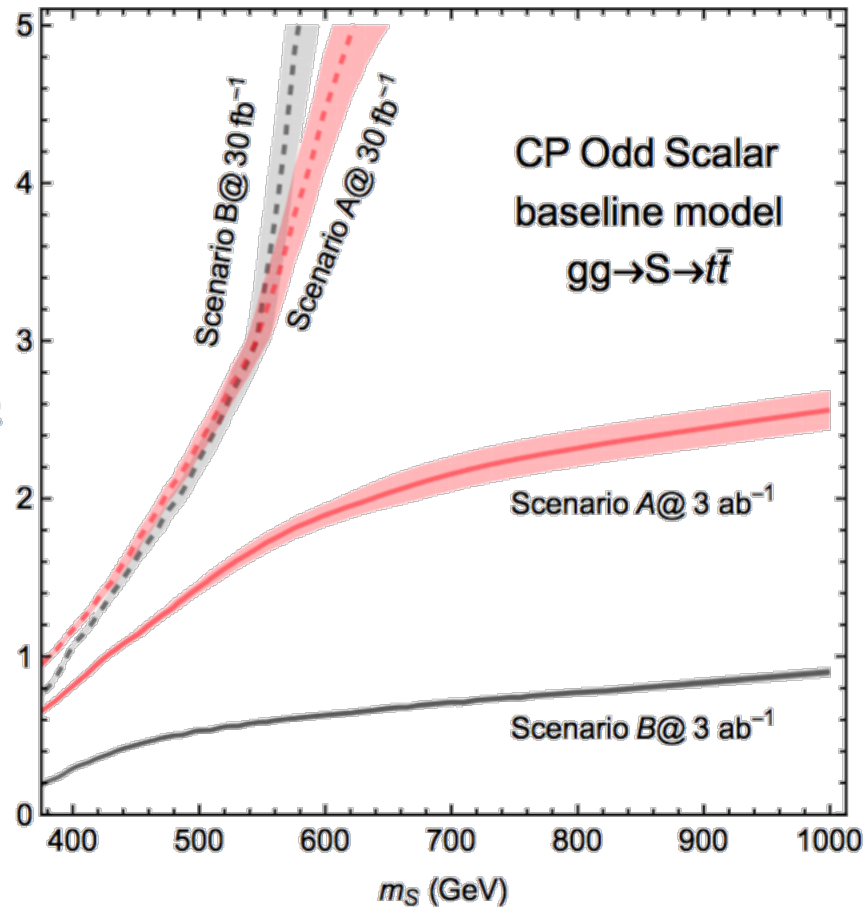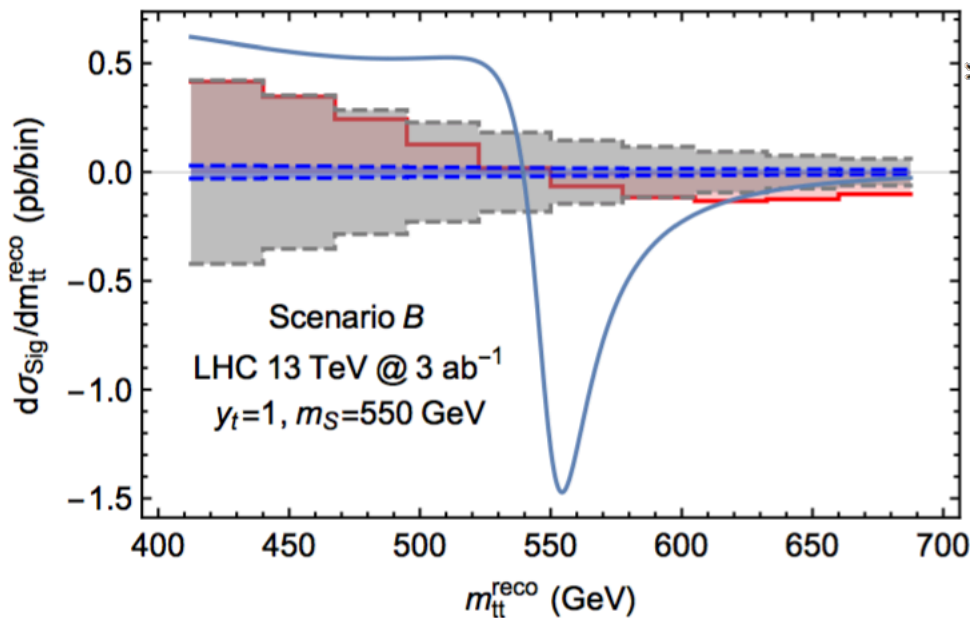
Lineshapes for a grid of mass and different Yukawas are generated (because the signal is line-shape and does not scale as simple powers of Yukawa couplings).

After smearing, using bins near the scalar mass window, taking both excess and deficits, exclusion potential extracted.

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LHC perspectives—2HDM projections

13 TeV LHC
Type II 2HDM
CP-odd Scalar
Scenario B@ 3 ab^{-1}

Scenario A@ 3 ab^{-1}

Scenario B@ 30 fb^{-1}

Scenario A@ 30 fb^{-1}
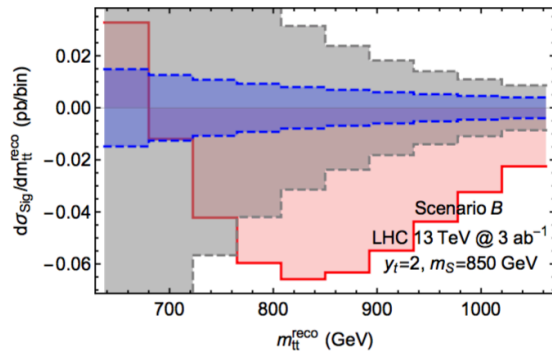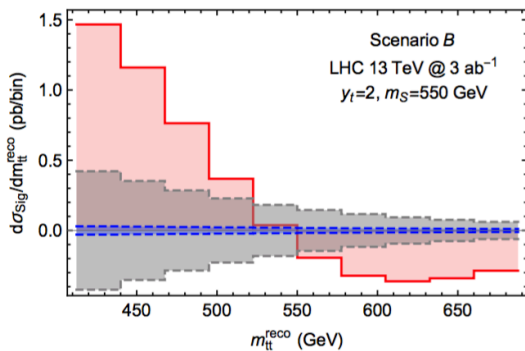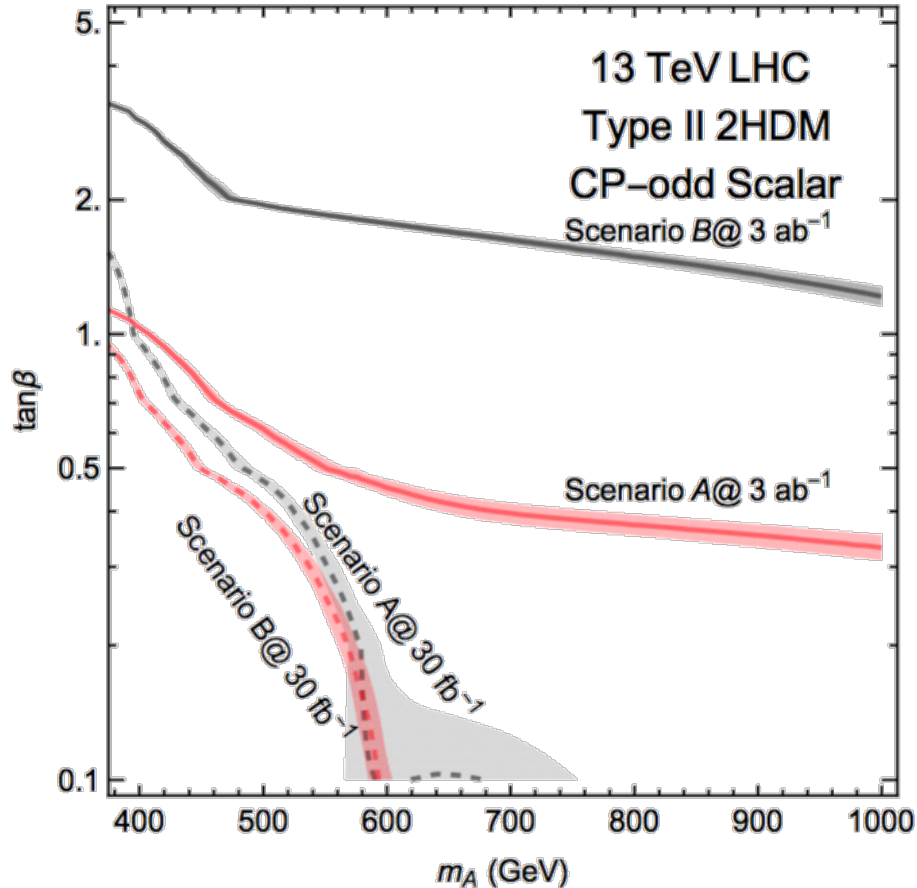
For a Type II 2HDM, the bottom quark effects are mainly in modifying the production vertex and provide some decay branching fraction suppression;

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.

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LHC perspectives—2HDM projections
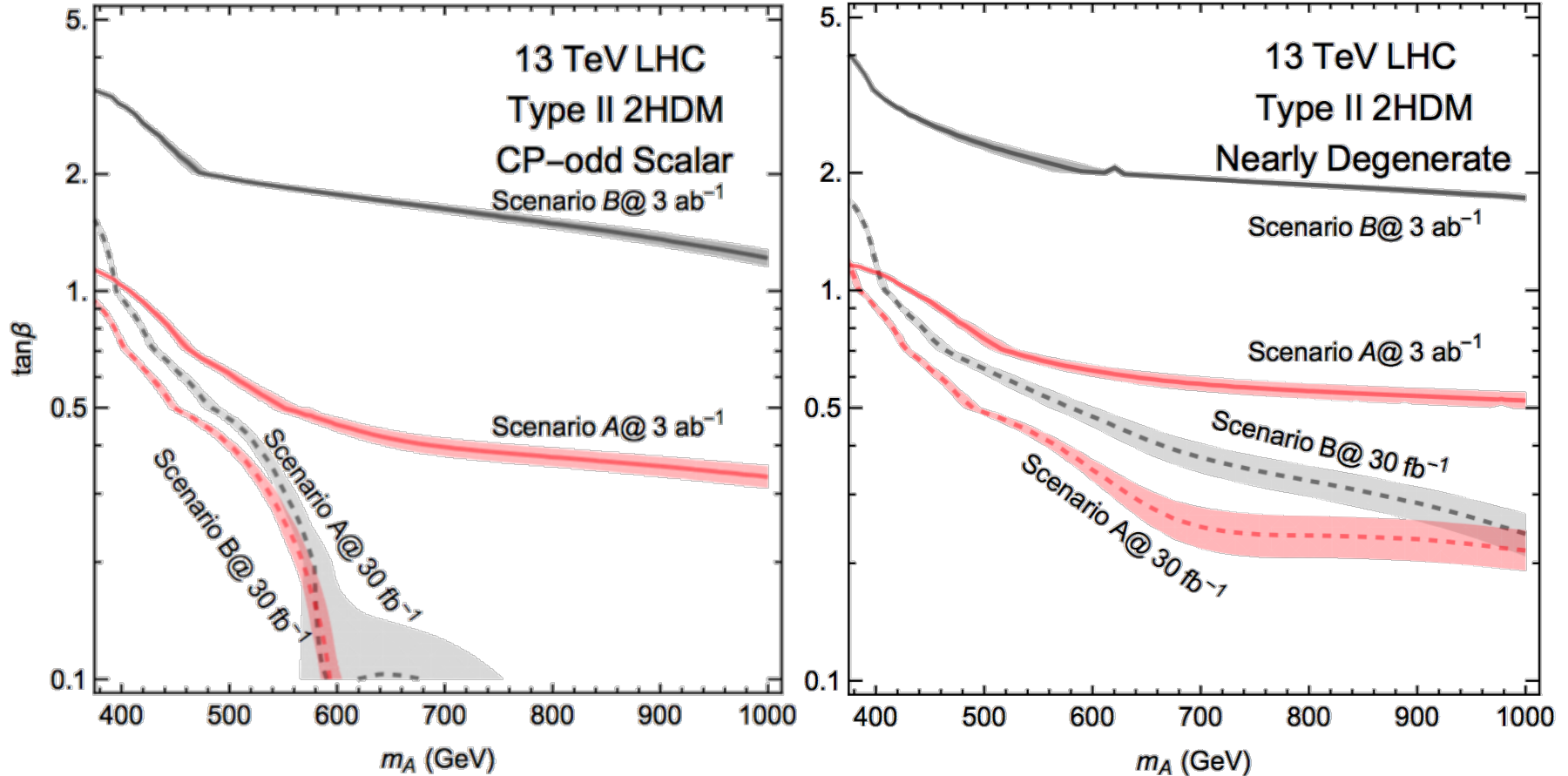
For the case of nearly degenerate heavy scalars, the physic reach is improved, especially for heavy heavy masses.

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Summary and outlook

$gg \rightarrow S \rightarrow t\bar{t}$ 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 interesting shapes. **(The effect is always there regardless of the width!)**

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** ATLAS-2016-073**, 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**, S. Gori, I.-W. Kim, N. Shah, K. Zurek **arXiv:1602.02782 ,** N. Craig, J. Hajer, Y. Li, T. Liu, H. Zhang, **arXiv:1605.08744**, B. Hespel, F. Maltoni, E. Vryonidou **arXiv:1606.04149**),H+jet, charged Higgs searches, 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**).

Interference effect is important for many BSM bump hunting, especially for the case of better and better limits. (as the relative strength of the interference pieces increases relatively to the B.W. piece.)

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$gg \rightarrow S \rightarrow t\bar{t}$ 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 interesting shapes. **(The effect is always there regardless of the width!)**

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** ATLAS-2016-073**, 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**, S. Gori, I.-W. Kim, N. Shah, K. Zurek **arXiv:1602.02782 ,** 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:1601.00006**).

Thank you!

Interference effect is important for many BSM bump hunting, especially for the case of better and better limits. (as the relative strength of the interference pieces increases relatively to the B.W. piece.)

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Backup

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

$$D^u_L = \frac{1}{2}m_W^2(1 - \frac{1}{3}\tan^2\theta_W)\cos 2\beta$$

$$D^u_R = \frac{2}{3}m_W^2\tan^2\theta_W\cos 2\beta$$

$$D^d_L = -\frac{1}{2}m_W^2(1 + \frac{1}{3}\tan^2\theta_W)\cos 2\beta$$

$$D^d_R = -\frac{1}{3}m_W^2\tan^2\theta_W\cos 2\beta$$

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

$$X_u = A_u - \frac{\mu}{\tan\beta}$$

$$X_d = A_d - \mu\tan\beta$$

$$Y_u = \frac{A_u}{\tan\beta} + \mu$$

$$Y_d = A_b\tan\beta + \mu,$$

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

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

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

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,

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

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$$\hat{\sigma}_{\text{BSM}}^{\text{odd}}(\hat{s}; \tilde{y}_t)(gg \to S \to t\bar{t}) = \hat{\sigma}_{\text{B.W.}}^{\text{odd}}(\hat{s}; \tilde{y}_t) + \hat{\sigma}_{\text{Int.}}^{\text{odd}}(\hat{s}; \tilde{y}_t)$$

$$\frac{d\hat{\sigma}_{\text{B.W.}}^{\text{odd}}(\hat{s}; \tilde{y}_t)}{dz} = \frac{3\alpha_s^2 \hat{s}^2}{4096\pi^3 v^2} \beta \left| \frac{\tilde{y}_t^2 \tilde{I}_{\frac{1}{2}}(\tau_t)}{\hat{s} - m_S^2 + i m_S \Gamma_S(\hat{s})} \right|^2$$

$$\frac{d\hat{\sigma}_{\text{Int.}}^{\text{odd}}(\hat{s}; \tilde{y}_t)}{dz} = -\frac{\alpha_s^2}{64\pi} \frac{\beta}{1 - \beta^2 z^2} \text{Re}\left[\frac{\tilde{y}_t^2 \tilde{I}_{\frac{1}{2}}(\tau_t)}{\hat{s} - m_S^2 + i m_S \Gamma_S(\hat{s})} \right]$$

$$\hat{\sigma}_{\text{BSM}}^{\text{even}}(\hat{s}; y_t)(gg \to S \to t\bar{t}) = \hat{\sigma}_{\text{B.W.}}^{\text{even}}(\hat{s}; y_t) + \hat{\sigma}_{\text{Int.}}^{\text{even}}(\hat{s}; y_t)$$

$$\frac{d\hat{\sigma}_{\text{B.W.}}^{\text{even}}(\hat{s}; y_t)}{dz} = \frac{3\alpha_s^2 \hat{s}^2}{4096\pi^3 v^2} \beta^3 \left| \frac{y_t^2 I_{\frac{1}{2}}(\tau_t)}{\hat{s} - m_S^2 + i m_S \Gamma_S(\hat{s})} \right|^2$$

$$\frac{d\hat{\sigma}_{\text{Int.}}^{\text{even}}(\hat{s}; y_t)}{dz} = -\frac{\alpha_s^2}{64\pi} \frac{\beta^3}{1 - \beta^2 z^2} \text{Re}\left[\frac{y_t^2 I_{\frac{1}{2}}(\tau_t)}{\hat{s} - m_S^2 + i m_S \Gamma_S(\hat{s})} \right]$$

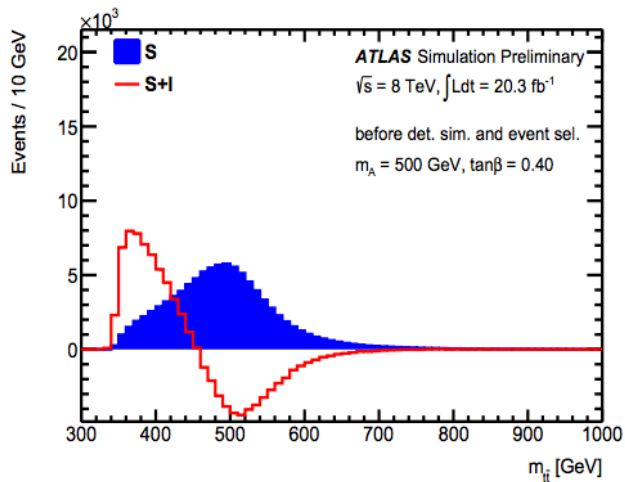$$\frac{d\sigma_{\text{Int.}}^{S_1 - S_2}(\hat{s})(gg \to S_1, S_2 \to t\bar{t})}{dz} = \frac{3\alpha_s^2 \hat{s}^2}{2048\pi^3 v^2}$$

$$\text{Re}\left[\frac{(y_{t,S_1} y_{t,S_2} |I_{\frac{1}{2}}(\tau_t)|^2 + \tilde{y}_{t,S_1} \tilde{y}_{t,S_2} |\tilde{I}_{\frac{1}{2}}(\tau_t)|^2)(\beta^2 y_{t,S_1} y_{t,S_2} + \tilde{y}_{t,S_1} \tilde{y}_{t,S_2})}{(\hat{s} - m_{S_1}^2 + i m_{S_1} \Gamma_{S_1}(\hat{s}))(\hat{s} - m_{S_2}^2 - i m_{S_2} \Gamma_{S_2}(\hat{s}))} \right]$$
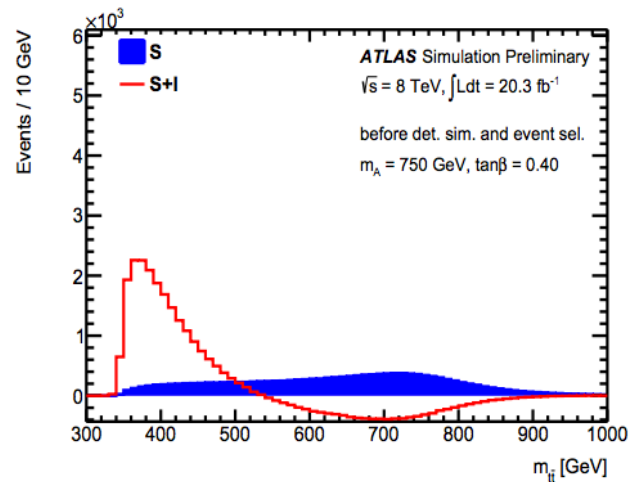
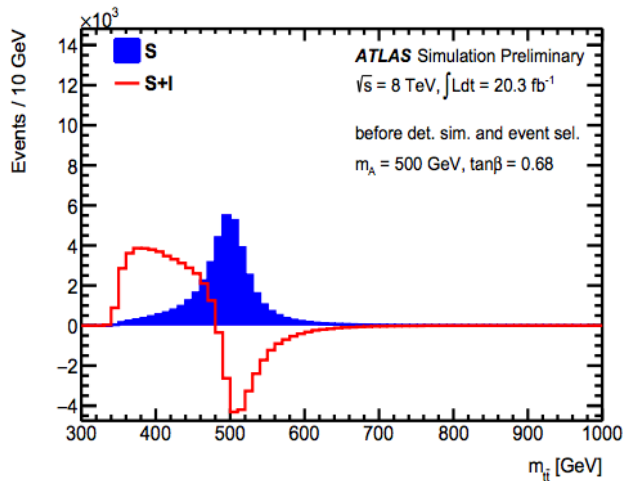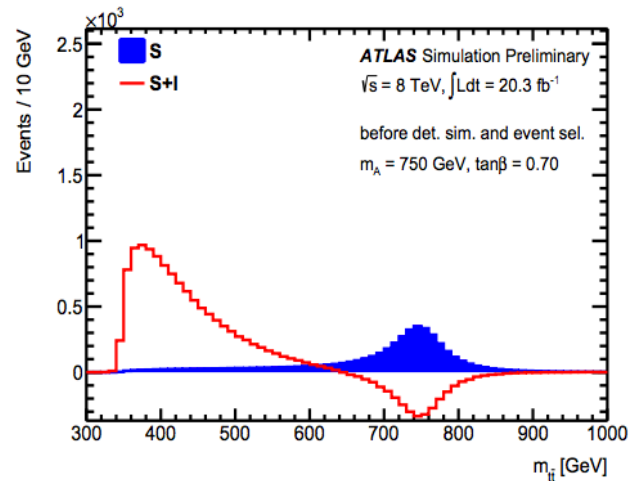First interference studies at ATLAS
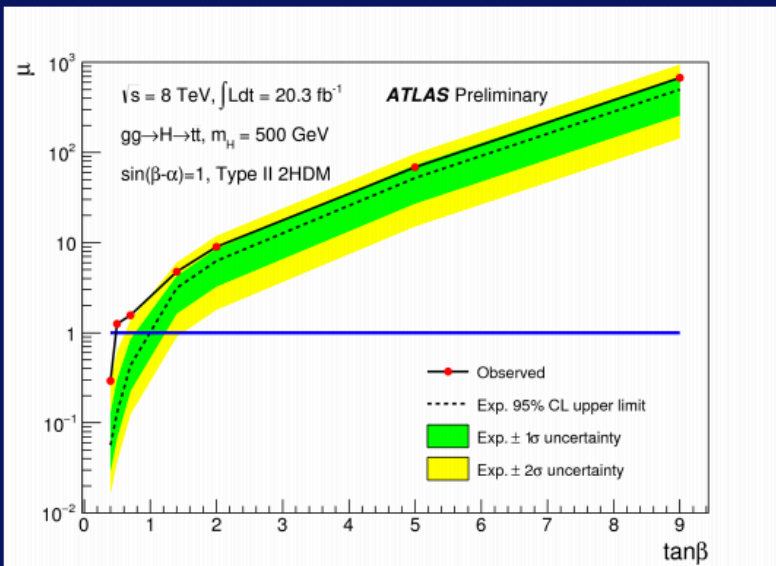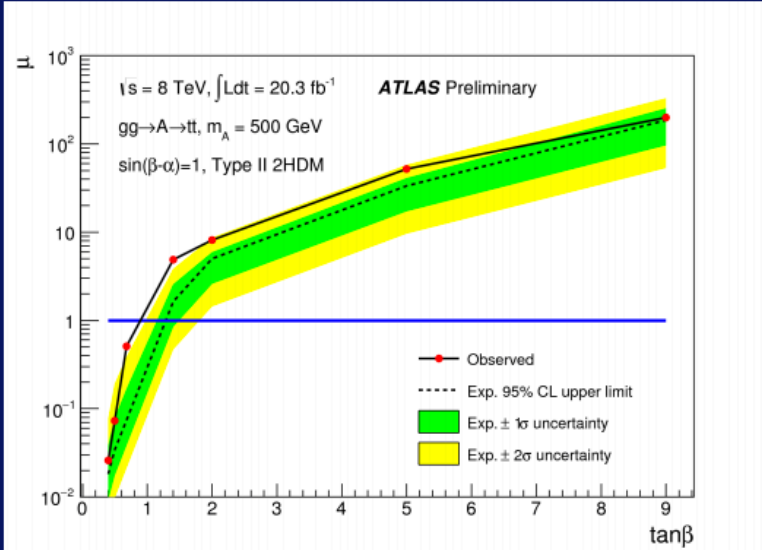
ATLAS-2016-073

(a) $m_A = 500$ GeV, $\tan \beta = 0.40$
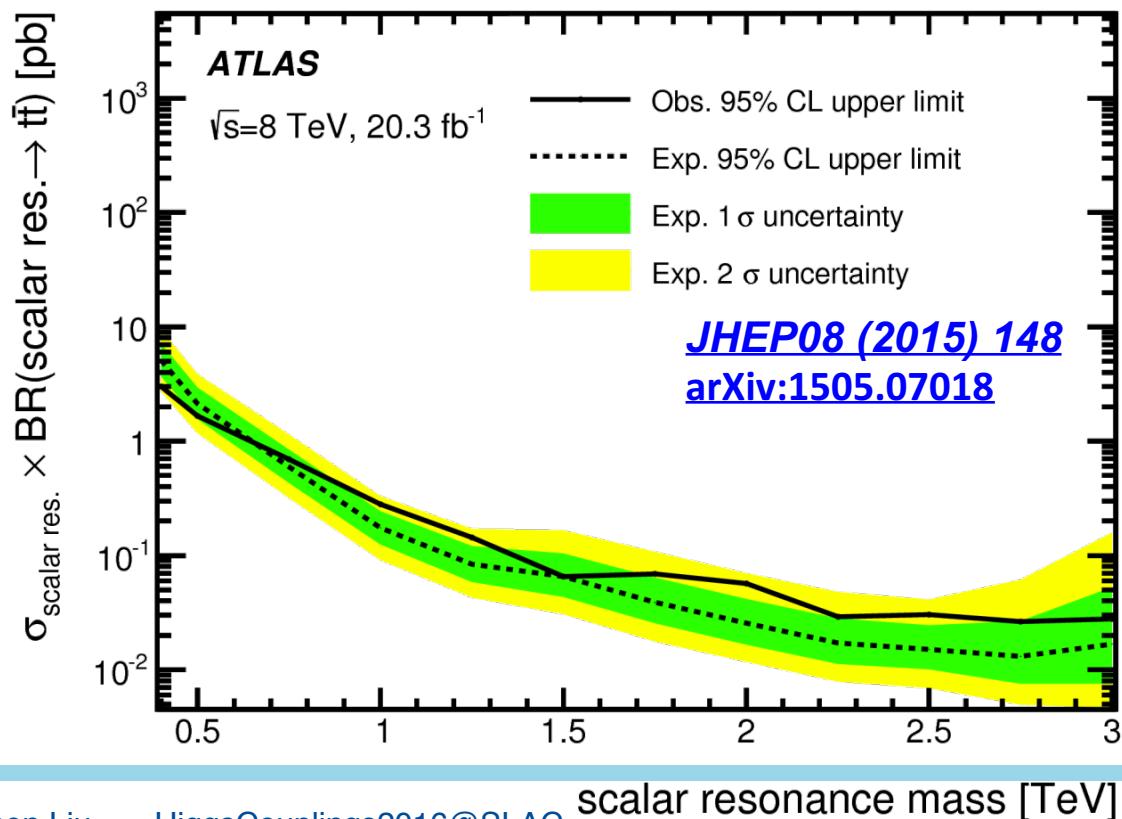
(b) $m_A = 750$ GeV, $\tan \beta = 0.40$
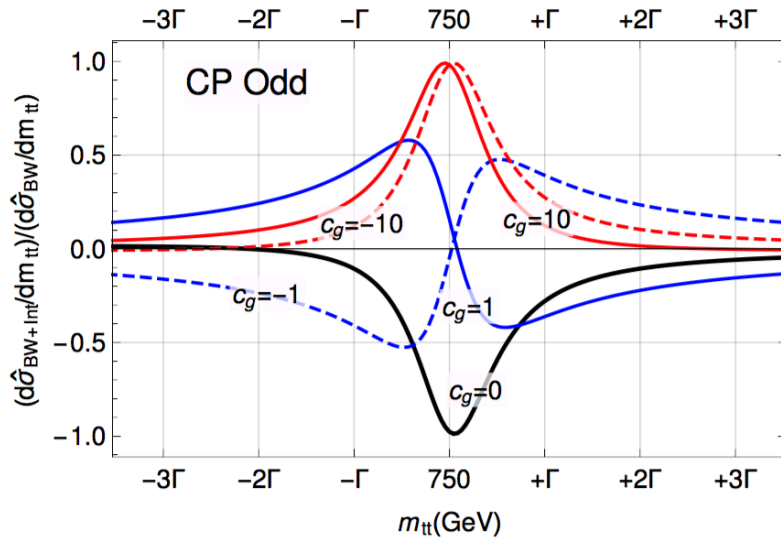
(c) $m_A = 500$ GeV, $\tan \beta = 0.68$

(d) $m_A = 750$ GeV, $\tan \beta = 0.70$

2.4 Spin-0 colour singlet

The last class of models examined here produces colour-singlet scalar particles via gluon fusion which decay to $t\bar{t}$. The approach previously adopted by the CMS Collaboration [18] is followed, in which narrow scalar resonance benchmarks are generated while the interference with SM $t\bar{t}$ production is neglected. Even though such signals with negligible interference are not predicted by any particular BSM model, they can be used to evaluate the experimental sensitivities and set upper limits on the production cross-sections. The CMS Collaboration excluded such resonances with production cross-sections greater than 0.8 pb and 0.3 pb for masses of 500 and 750 GeV, respectively.

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

—— Obs. 95% CL upper limit
········ Exp. 95% CL upper limit
Exp. 1 σ uncertainty
Exp. 2 σ uncertainty

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y-axis: $\sigma_{\text{scalar res.}} \times \text{BR(scalar res.} \to t\bar{t})$ [pb]

x-axis: scalar resonance mass [TeV]

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"Random" example of a hypothetical 750 GeV scalar

c_g is the additional contributions from heavy colored particles in the induces gg-750 GeV scalar coupling.

$$\mathcal{L}_{int} \supset \frac{S}{f}(y_t \bar{Q}_L \tilde{H} t_R + h.c.) + c_G \frac{\alpha_s}{8\pi f_G} S G \tilde{G}.$$
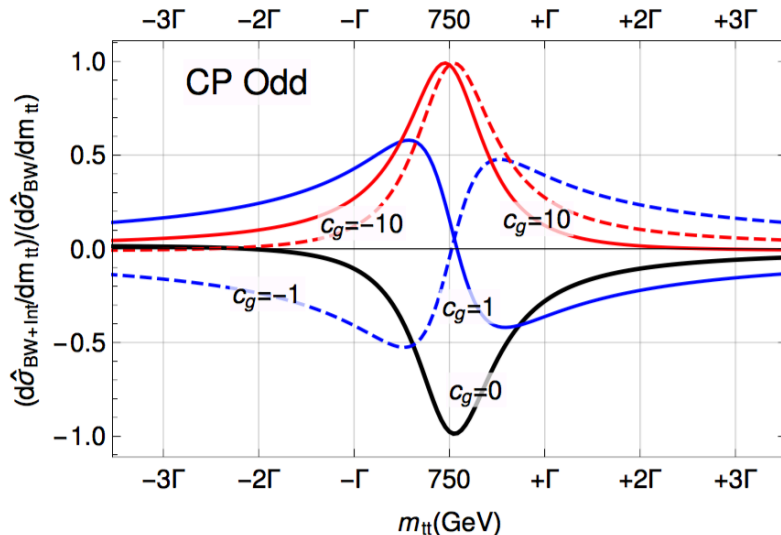
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"Random" example of a hypothetical 750 GeV scalar

c_g is the additional contributions from heavy colored particles in the induces gg-750 GeV scalar coupling.

$$\mathcal{L}_{int} \supset \frac{S}{f}(y_t \bar{Q}_L \tilde{H} t_R + h.c.) + c_G \frac{\alpha_s}{8\pi f_G} SG\tilde{G}.$$

Three cases:
a) dominated by top-loop, pure dip;
b) dominant by heavy particles in the loop, pure bump;
c) comparable contributions, bump-dip or dip-bump.

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"Random" example of a hypothetical 750 GeV scalar

c_g is the additional contributions from heavy colored particles in the induces gg-750 GeV scalar coupling.
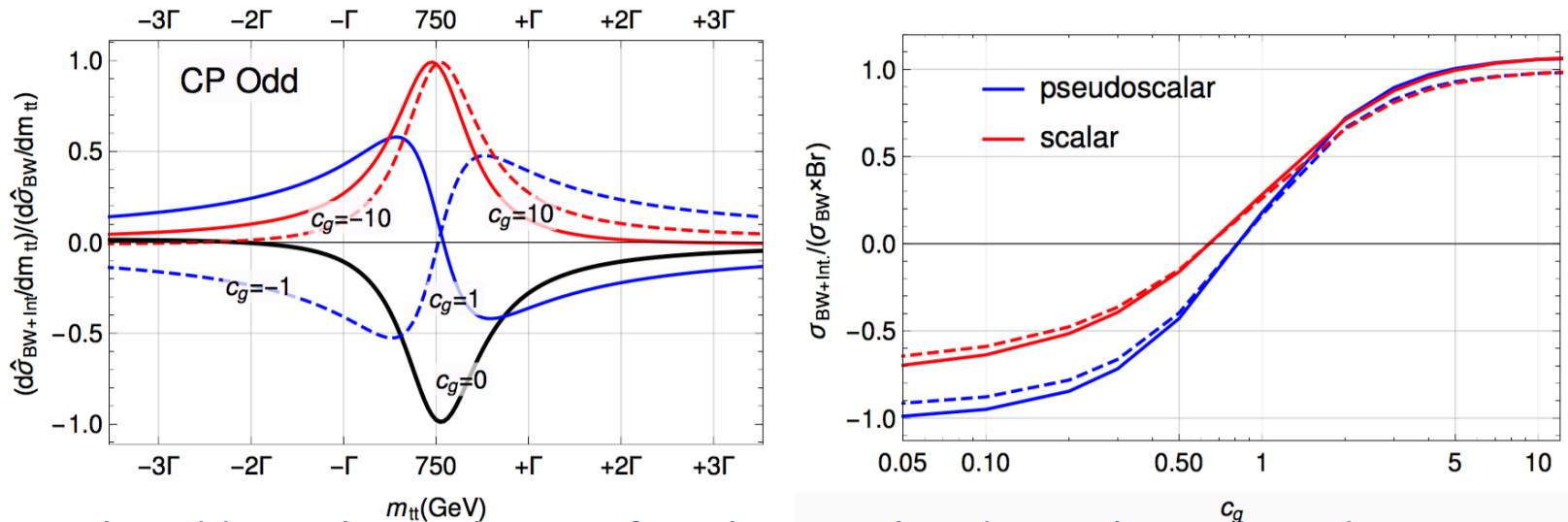
$$\mathcal{L}_{int} \supset \frac{S}{f}(i\tilde{y}_t \bar{Q}_L \tilde{H} t_R + h.c.) + c_G \frac{\alpha_s}{8\pi f_G} S G \tilde{G}$$

Even before proceed on the opportunities and observational aspects, already tells us the interpretations of current bounds for $750 \rightarrow t\bar{t}$ should be with great care. **(Right panel)** (see also recent overlapping discussion by Djouadi, Ellis and Quevillon **arXiv:1605.00542**, N. Craig, S. Renner, D. Sutherland **arXiv:1607.06074**)

Ratio of the total signal rate (after integrating the $\pm 3\Gamma_S$ region around the scalar mass) over the naïve rate using $\sigma(gg \rightarrow S) \times BR(S \rightarrow t\bar{t})$ are shown in the right panel.

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Motivation

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

Couples to fermions proportional to their masses, dominantly to ttbar

=>

gg->S->ttbar is an important channel for heavy scalar discovery and identification

signal

background

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