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

Zhen Liu (Fermilab)

Simplicity II workshop

Fermilab, Sep. 7th, 2016

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

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.)

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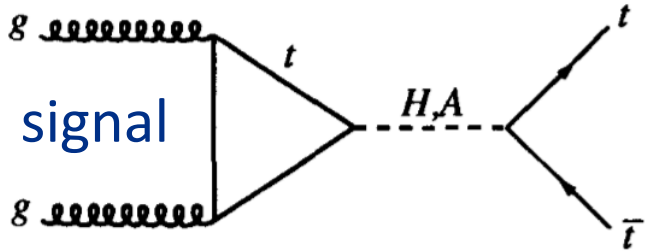
Starting with a very minimal baseline model

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

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

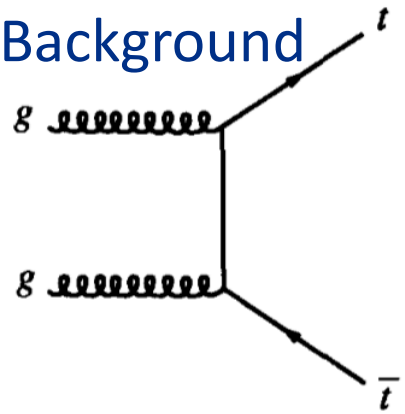
Challenges



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.

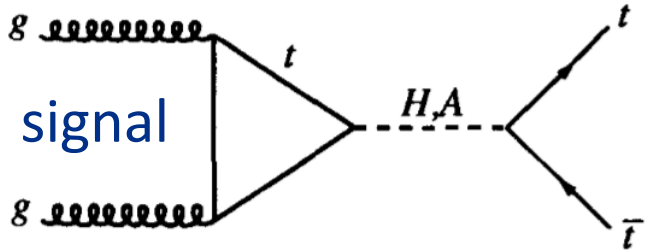
Background



Plus s- and u- channel

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

Challenges



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

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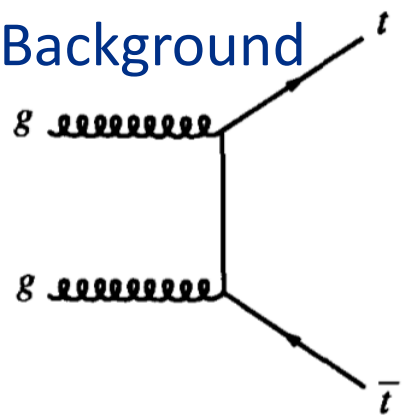

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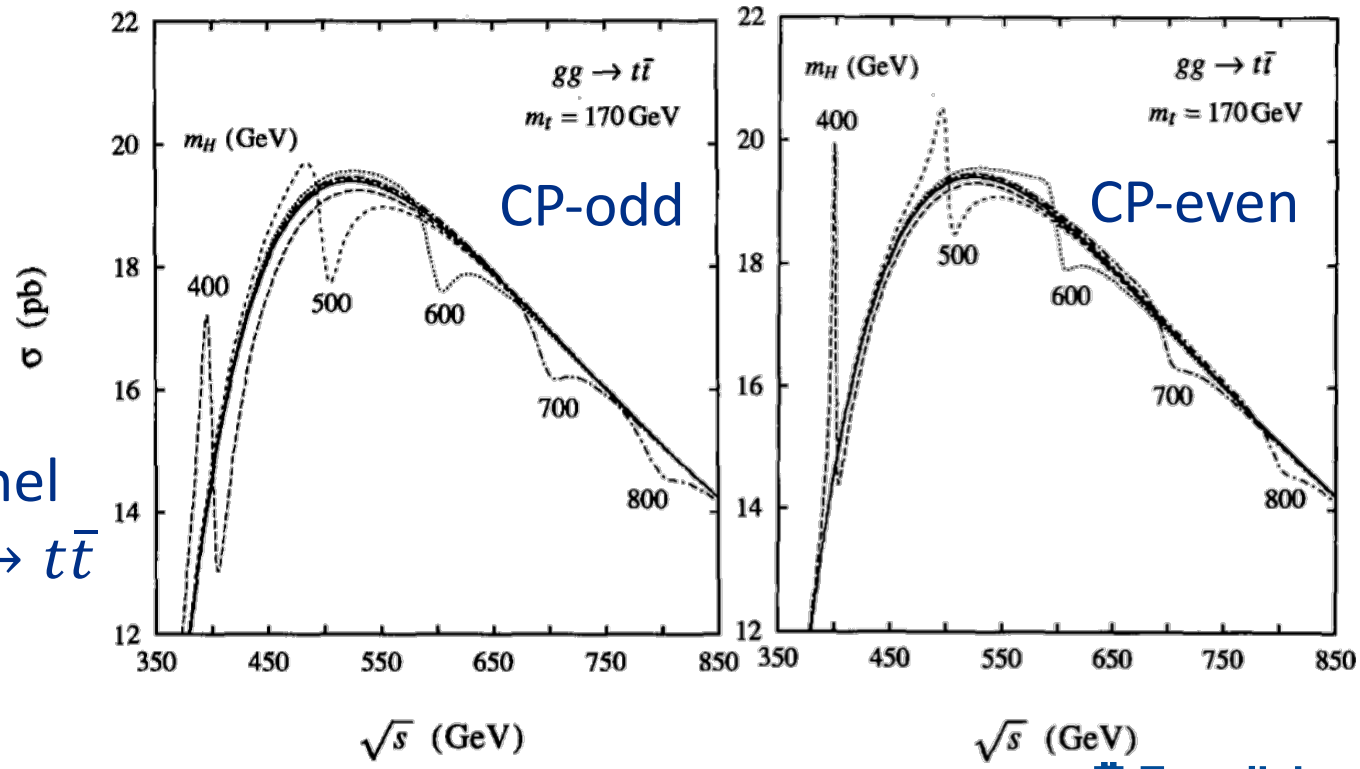
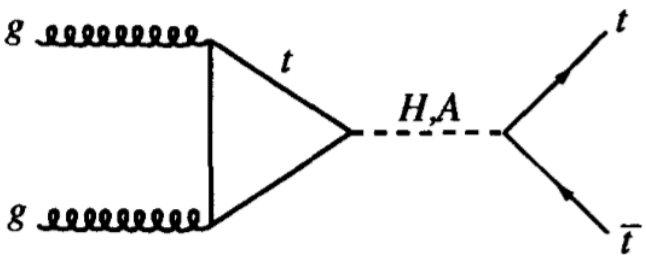
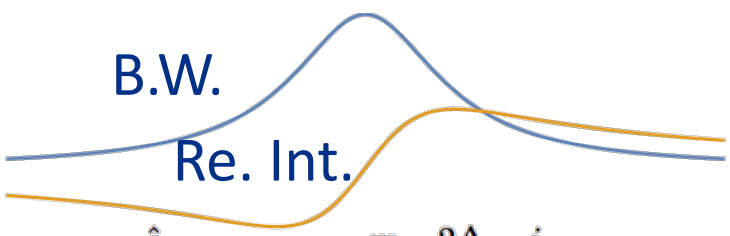


See also recent work by N. Craig, F. D'Eramo, P. Drapper, S. Thomas, H. Zhang **arXiv:1504.04630** and also Jung, Sung, Yoon **arXiv:1505.00291**

Challenges (interferences)





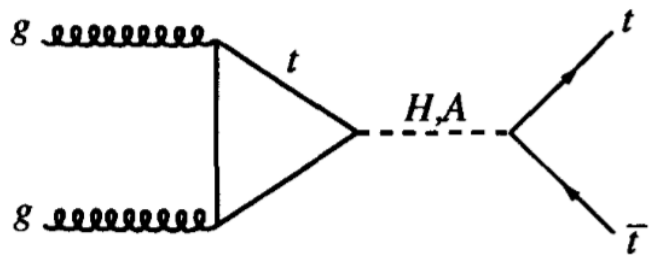
$$\frac{\hat{s}}{(\hat{s}-m_S^2)+i\Gamma_S m_S} \approx \frac{m_S}{\Gamma_S}\frac{2\Delta - i}{4\Delta^2+1}$$

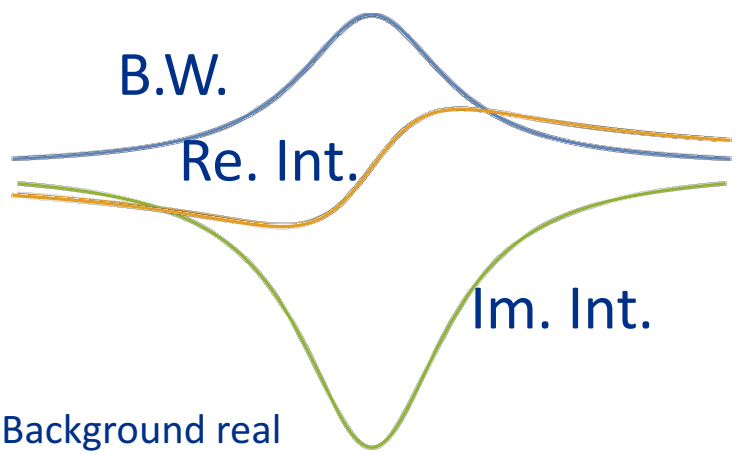
$$\text{with} \quad \Delta \equiv \frac{\hat{s}-m_S^2}{2m_S\Gamma_S} \approx \frac{\sqrt{\hat{s}}-m_S}{\Gamma_S} \text{ for } \frac{\hat{s}}{m_S^2}-1 \ll 1.$$

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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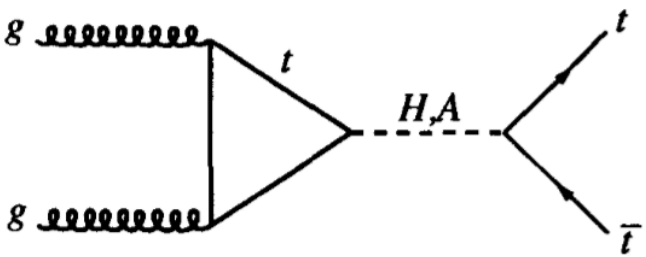

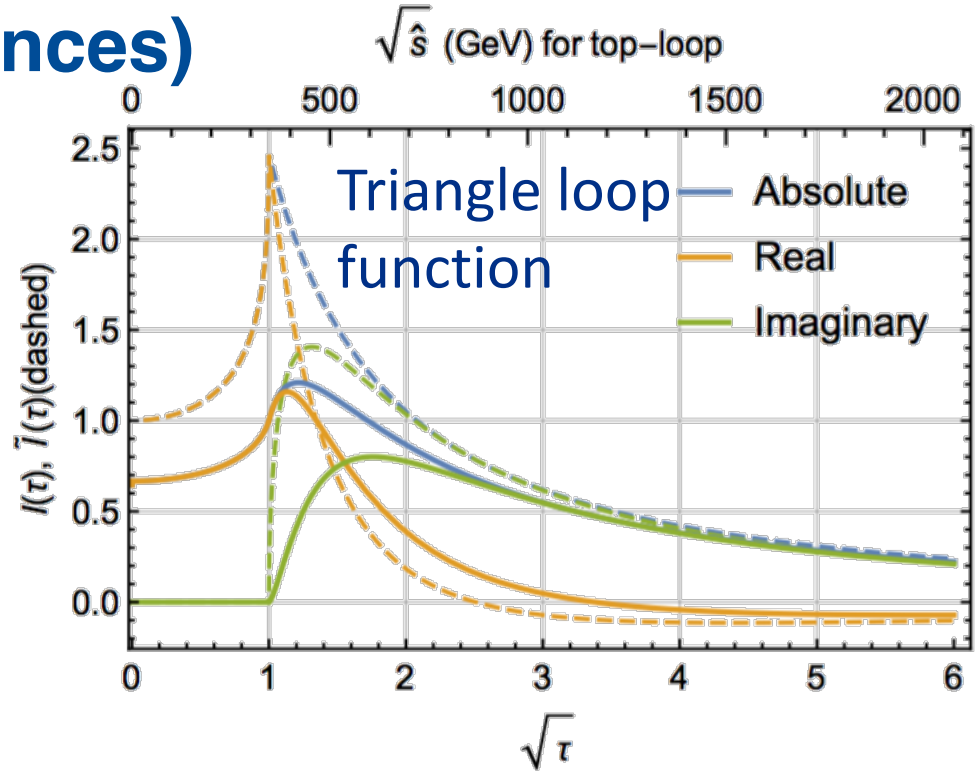

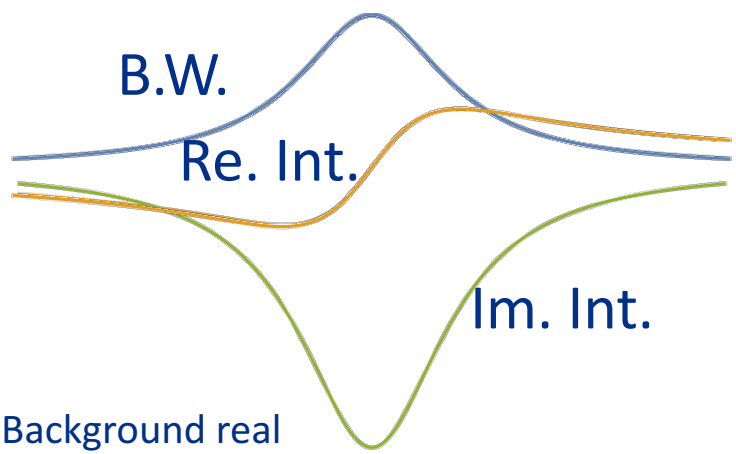

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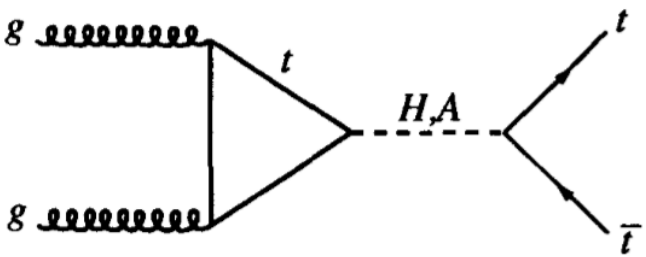

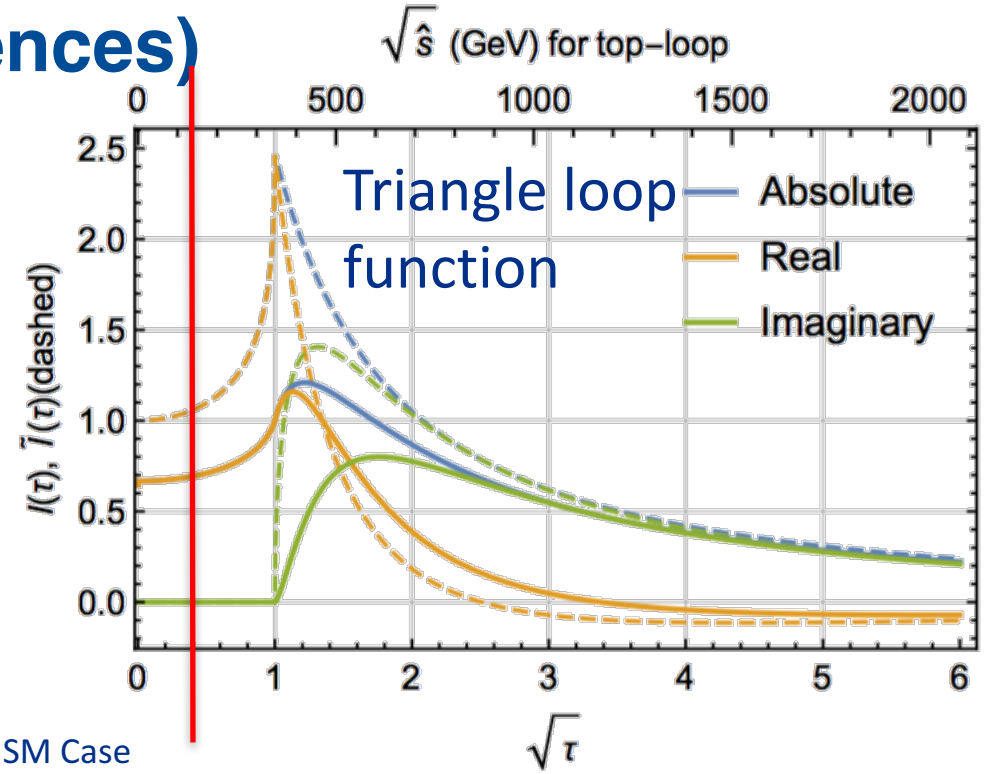

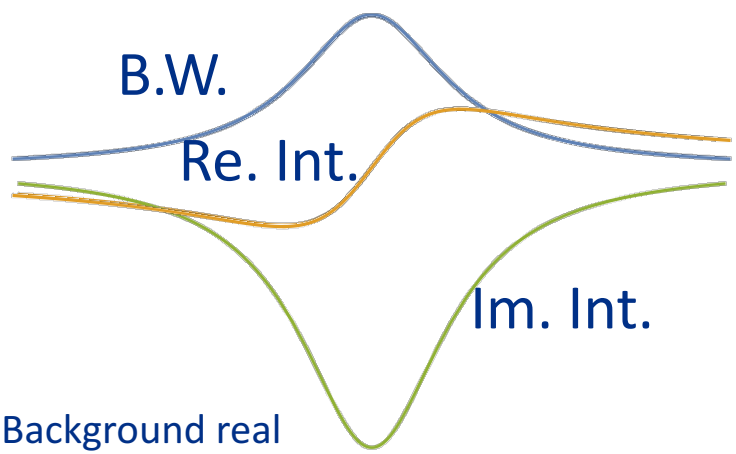

SM Case
real and slowly varying
heavy (chiral) fermion decoupling theorem (with Yukawa proportional to the mass)

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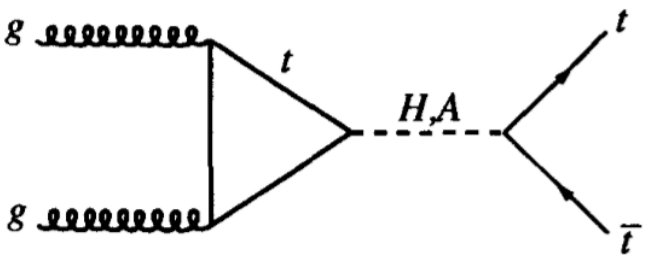
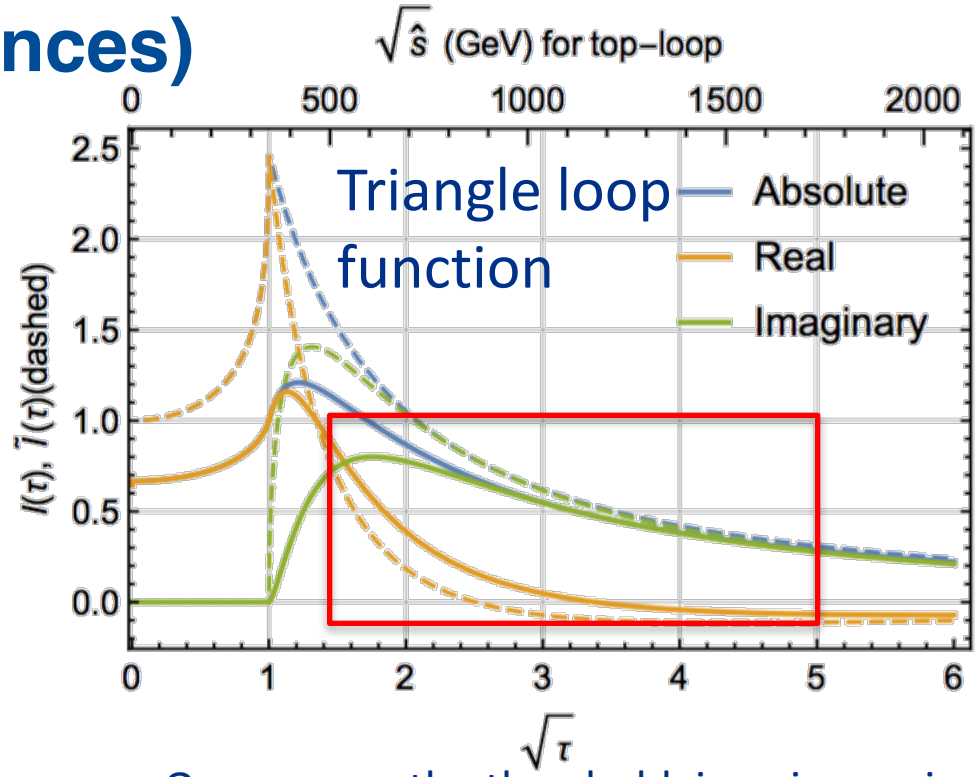
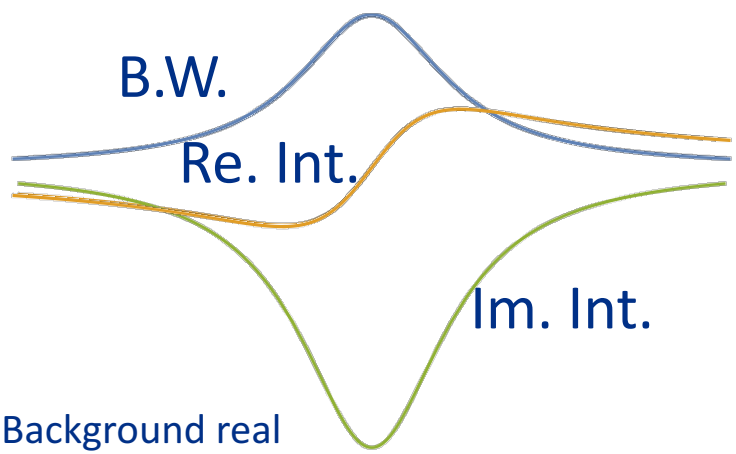
Fermilab

Challenges (interferences)





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



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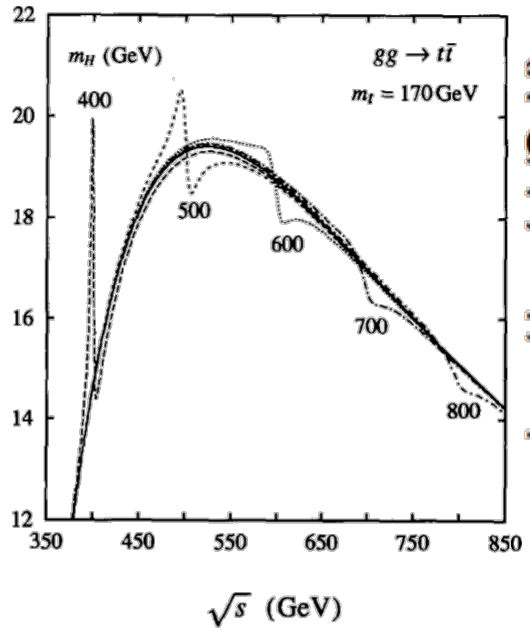
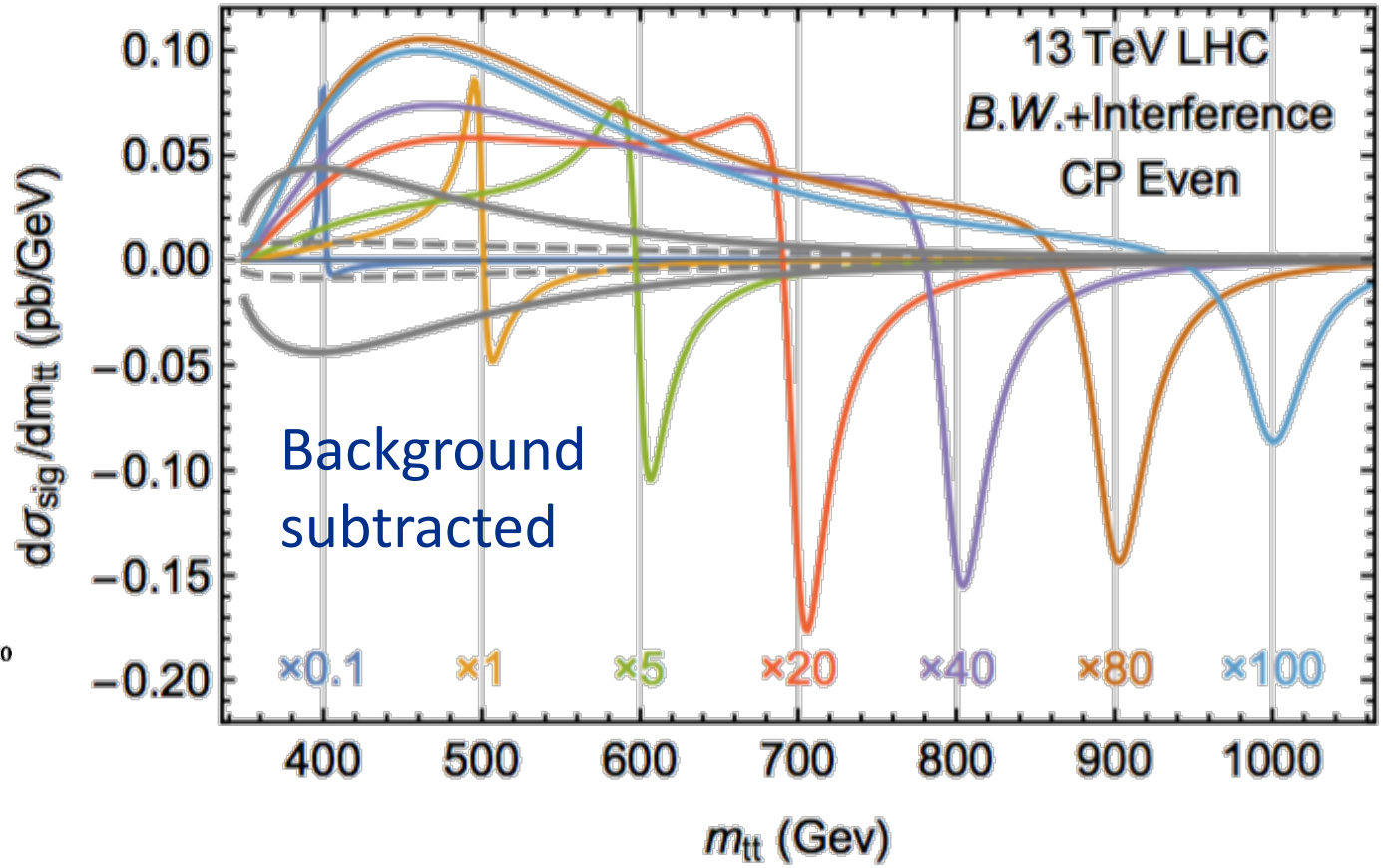
A strong phase ``insensitive"* to phase in the Yukawa as the signal amplitudes is proportional to $|y_t|^2$.

*subject to difference in loop functions

Fermilab

Challenges



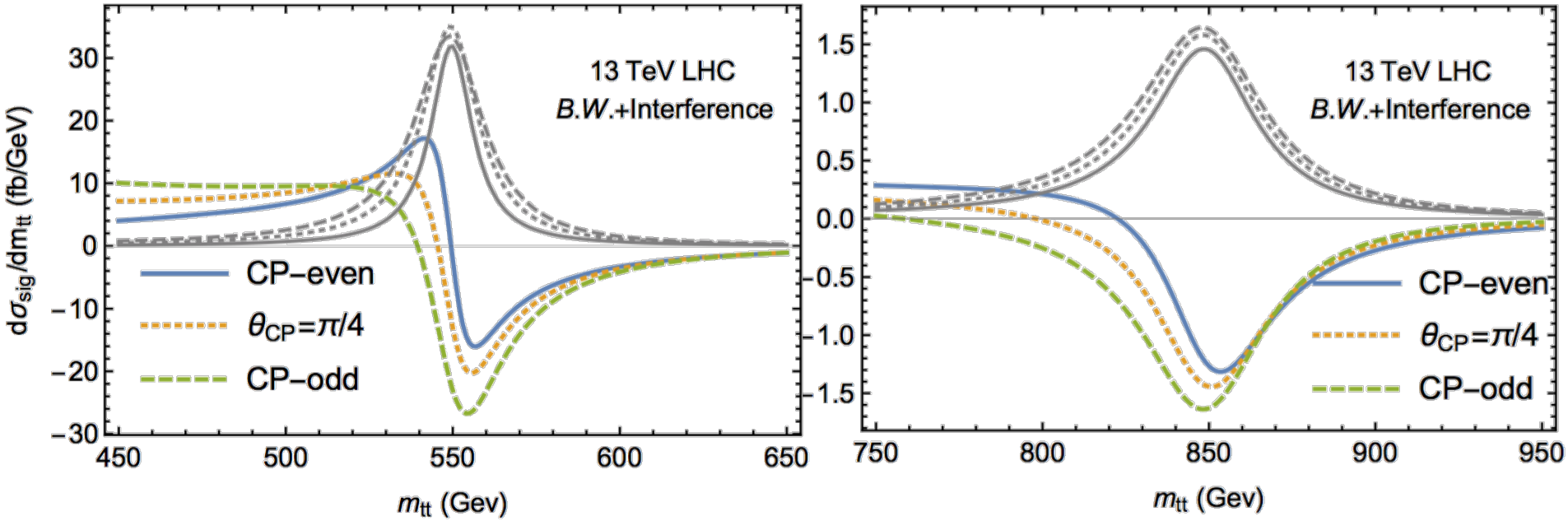


Special line shapes:

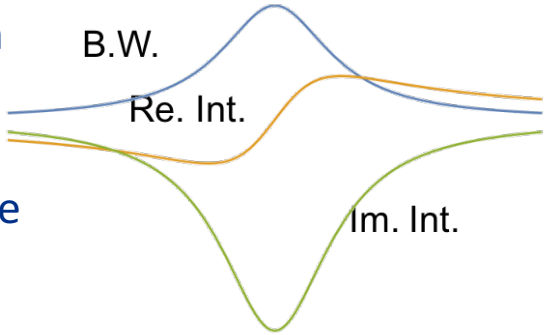
a) Bump search not designed/optimized for this, have to modify our current search;

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

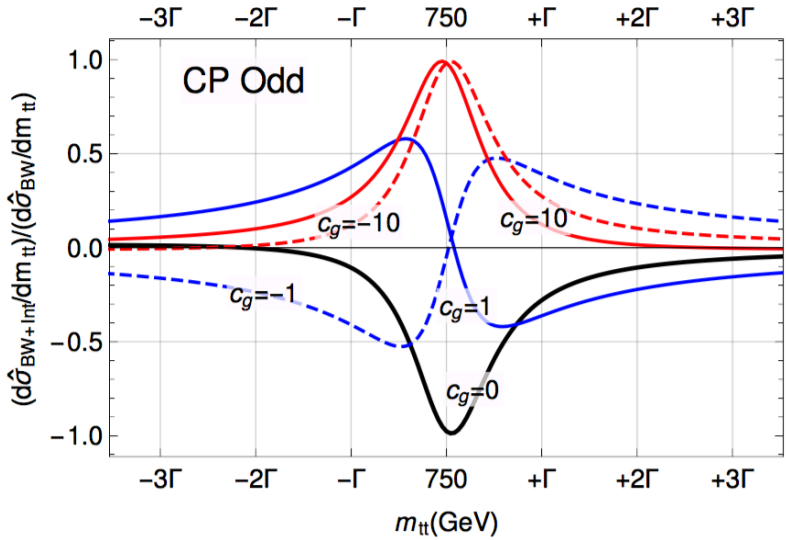
Challenges



- 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.



“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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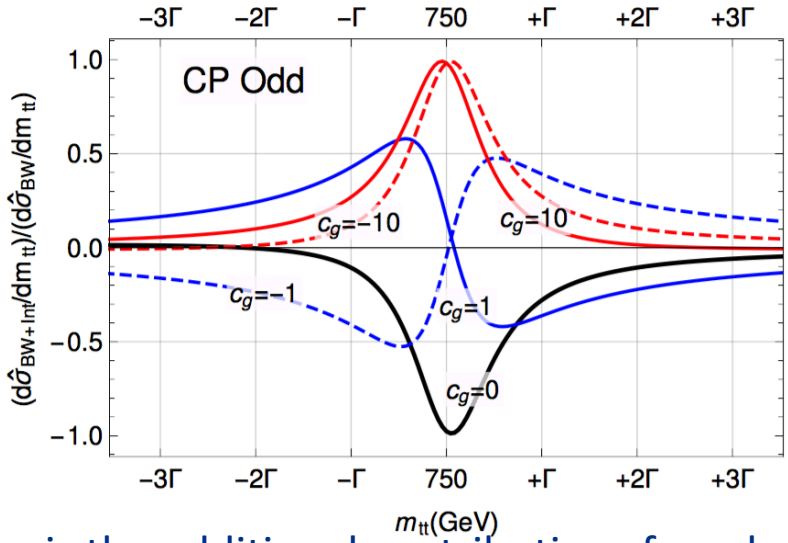

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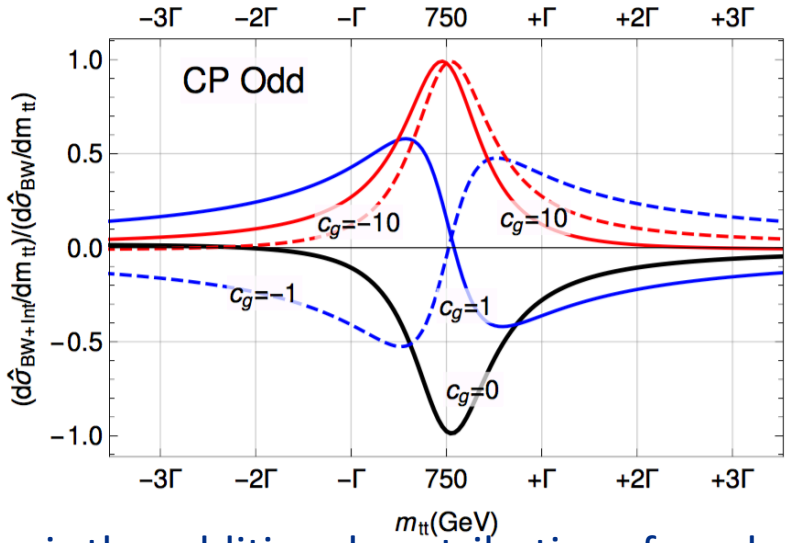
Three cases:

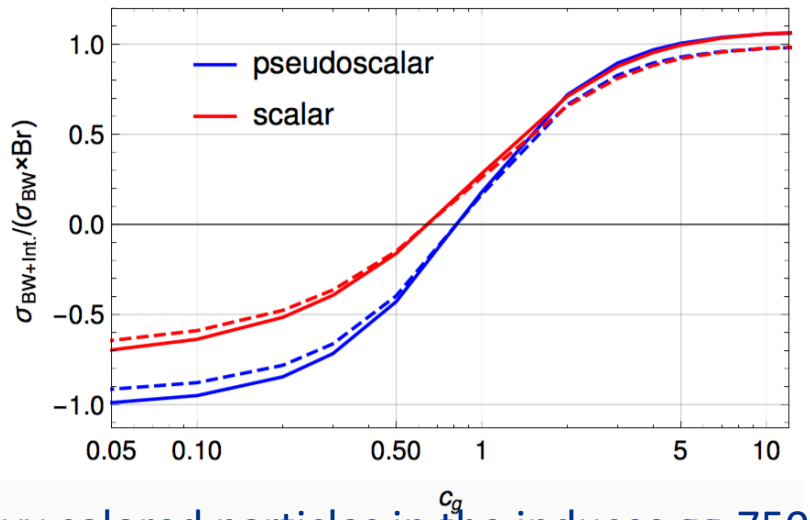
a) dominated by top-loop, pure dip;

b) dominant by heavy particles in the loop, pure bump;

c) comparable contributions, bump-dip or dip-bump.

“Random” example of a hypothetical 750 GeV scalar





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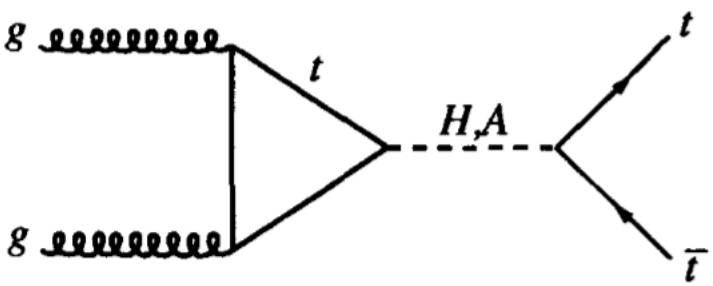
Even before proceed on the opportunities and observational aspects, already tells us the interpretations of current bounds for $750 \to t\bar{t}$ should be with great care.

(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 $\sigma(gg \to S)\times BR(S \to t\bar{t})$ are shown in the right panel.

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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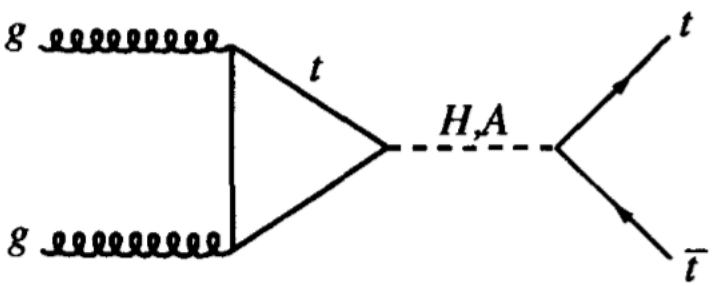

Covered in our study.

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Fermilab

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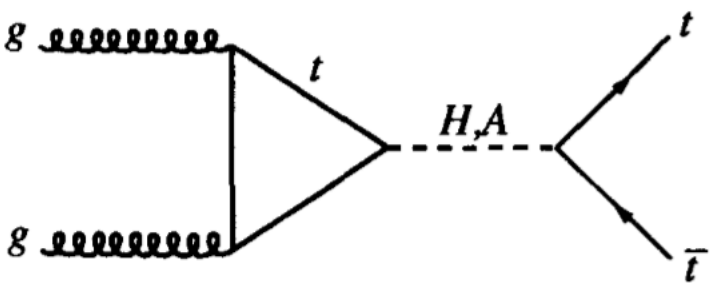

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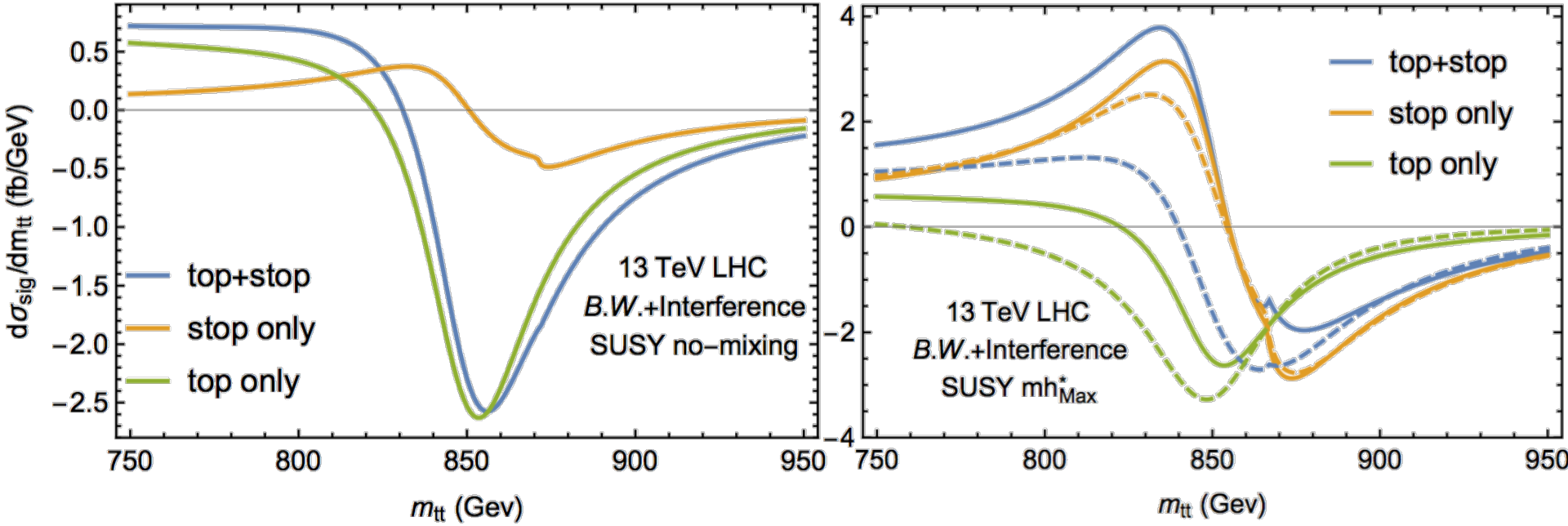
Fermilab

Opportunities– Stop contributions



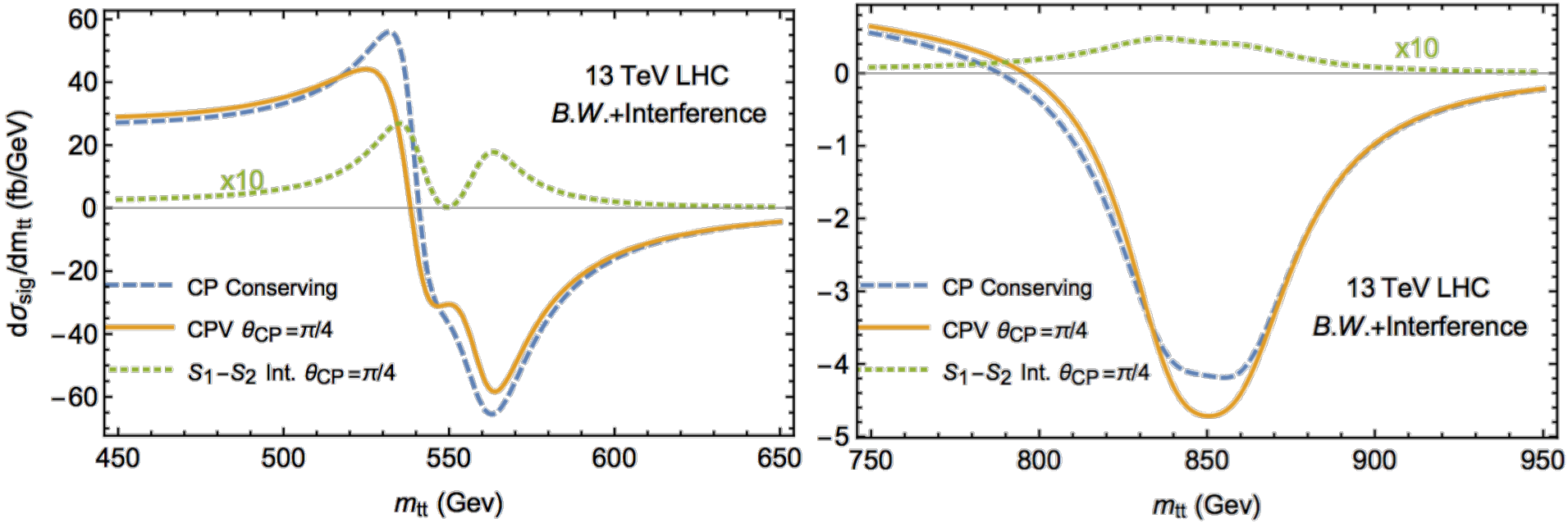
SUSY TeV scale stop quarks are highly anticipated through naturalness argument; Green curves are top contribution only, orange curves are stop contribution only and blue curves are with both top and stop contributions.

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.

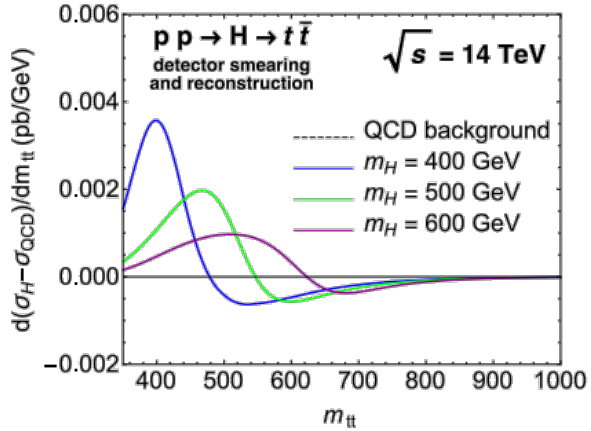
Opportunities—nearly degenerate with CPV

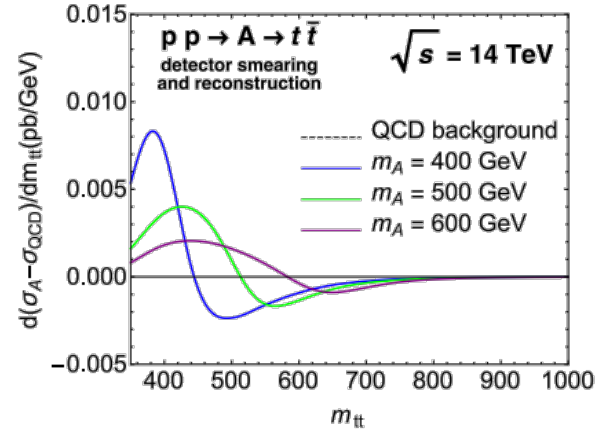


(left panel) 540 and 560 GeV scalars
(right panel) 840 and 860 GeV scalars
The signature—bumps and dips—roughly doubled, increasing the potential sensitivity;
With CPV, new interference between the two heavy nearly degenerate scalars occurs (although the effect might be small) but unique.

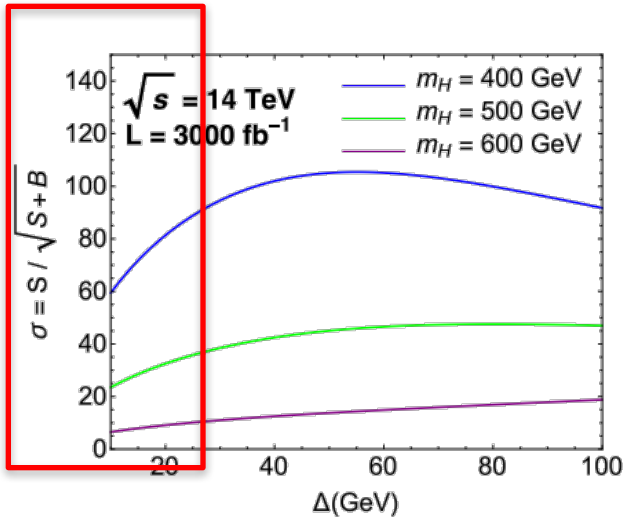
LHC perspectives—Challenges

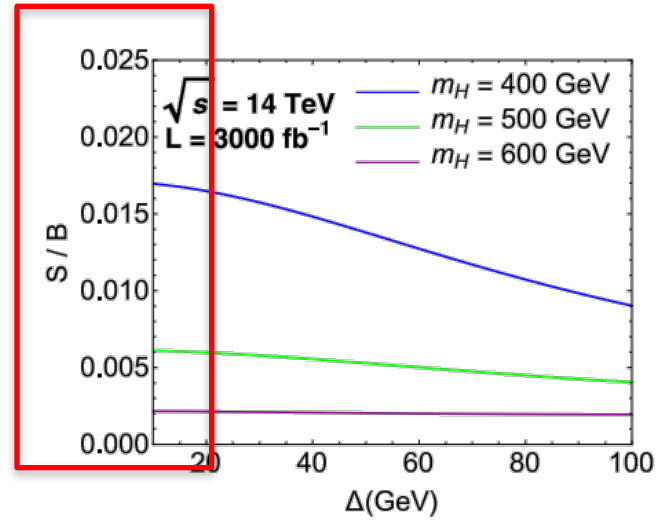
Statistically promising; Systematically, challenging.





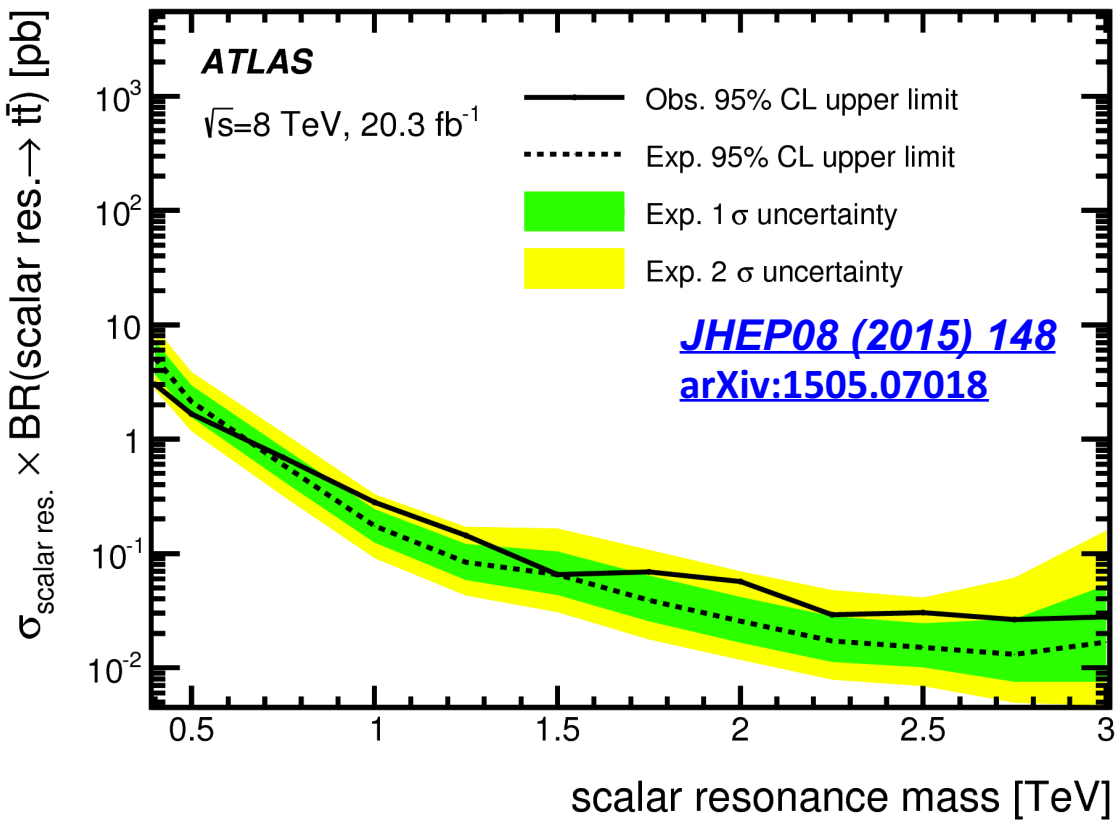
Craig, Draper, Erasmo, Thomas, Zhang '15



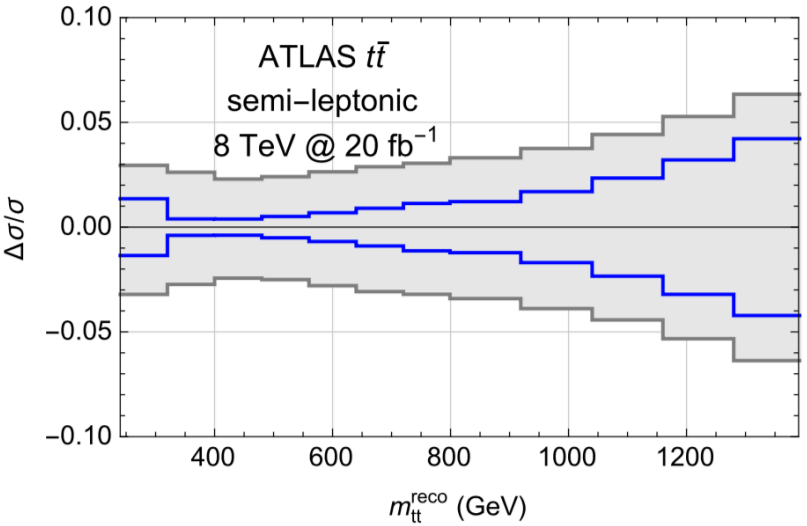


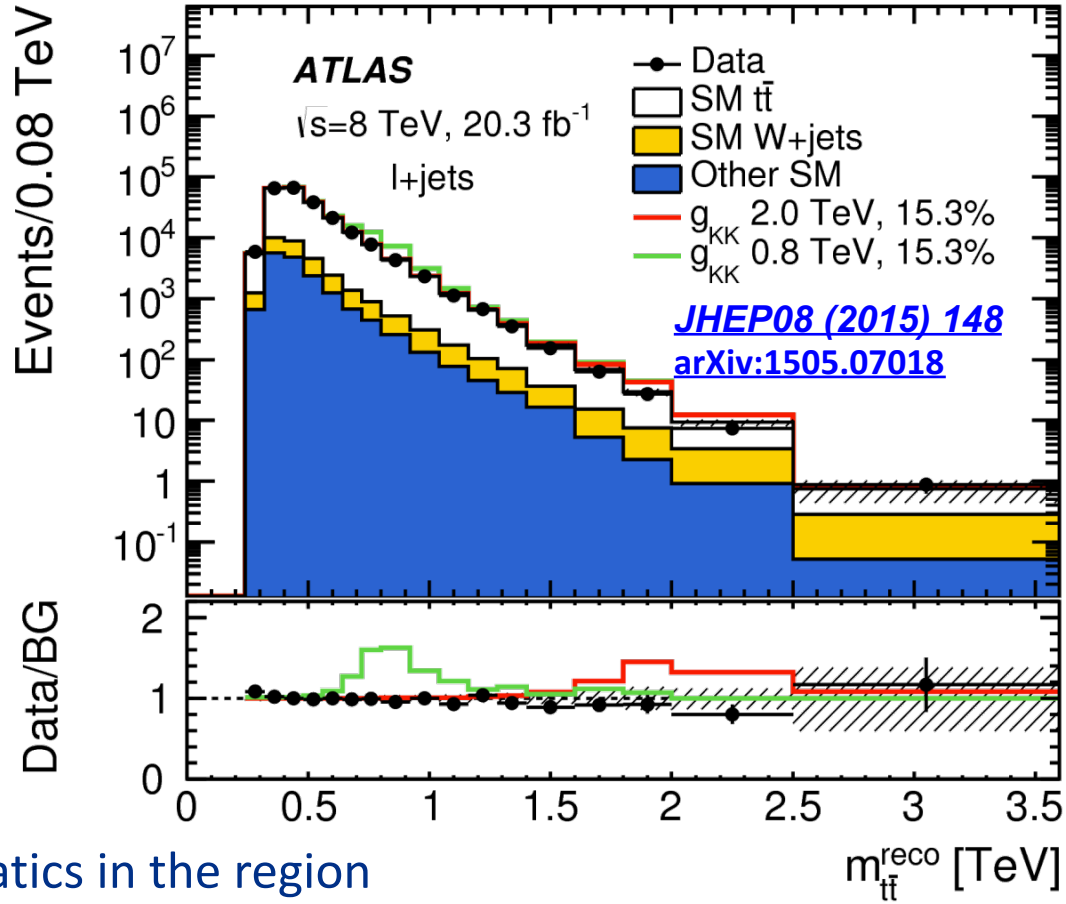
2.4 Spin-0 colour singlet

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.



LHC perspectives



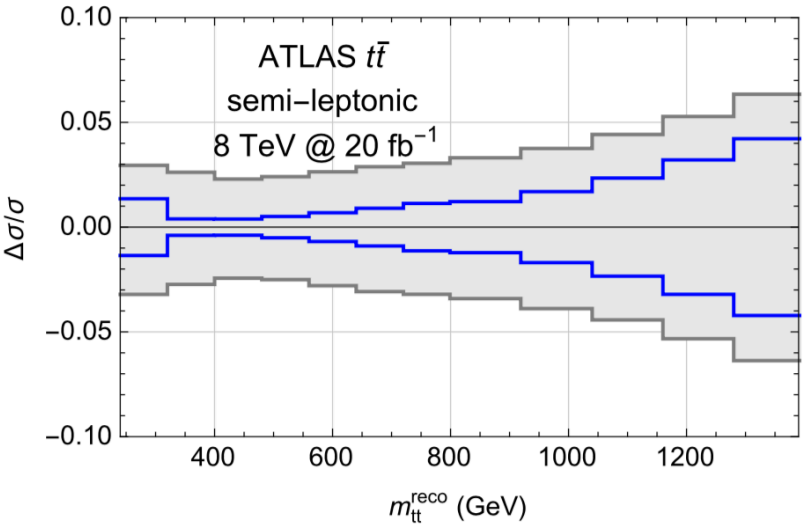


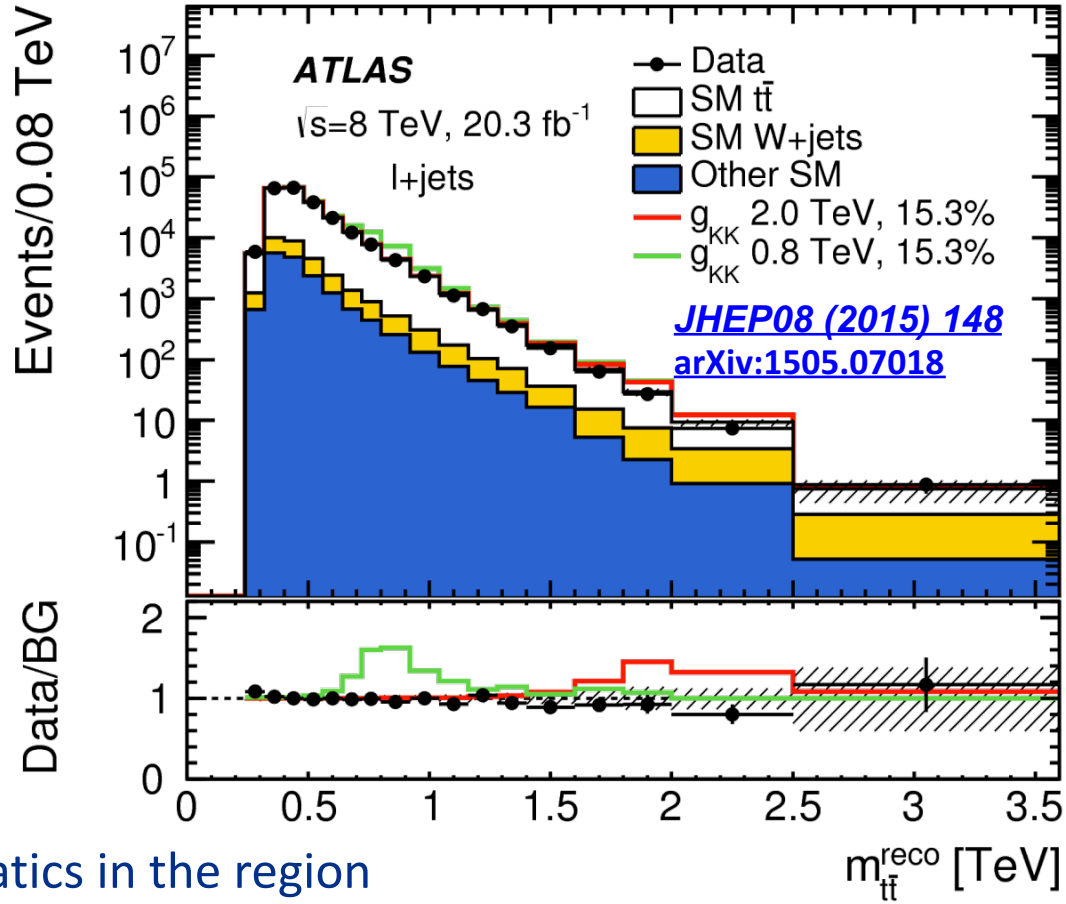
Already achieved sub 2-4% systematics in the region of interest, we see hope in this channel.

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

Fermilab

LHC perspectives





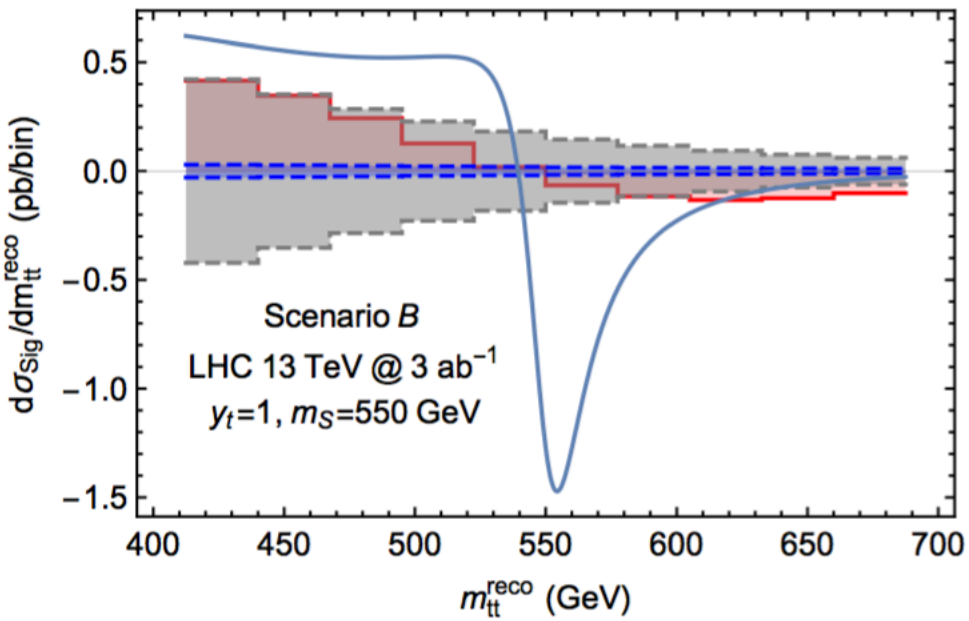
Already achieved sub 2-4% systematics in the region of interest, we see hope in this channel.

``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.

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;

LHC perspectives

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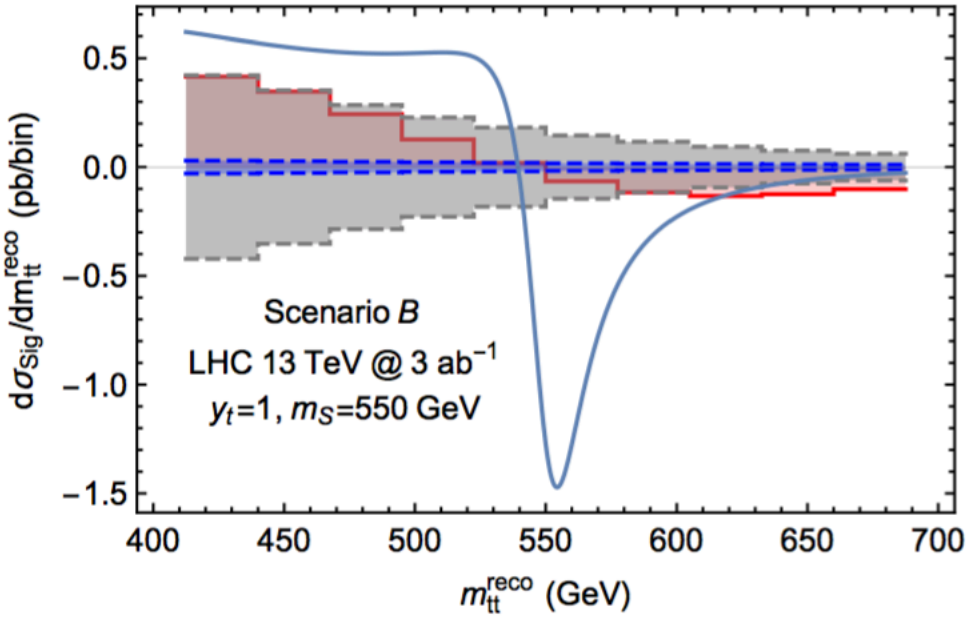

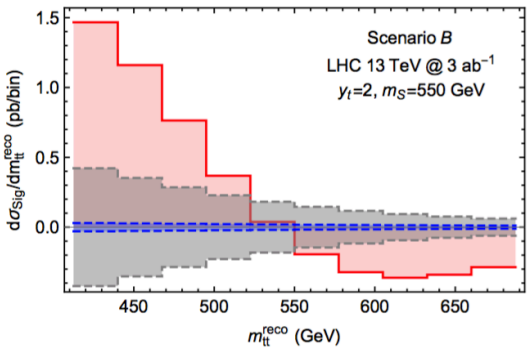

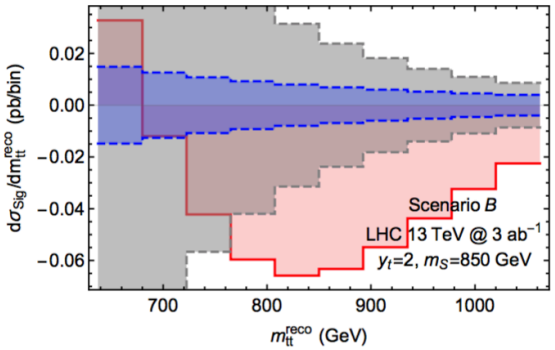

LHC perspectives

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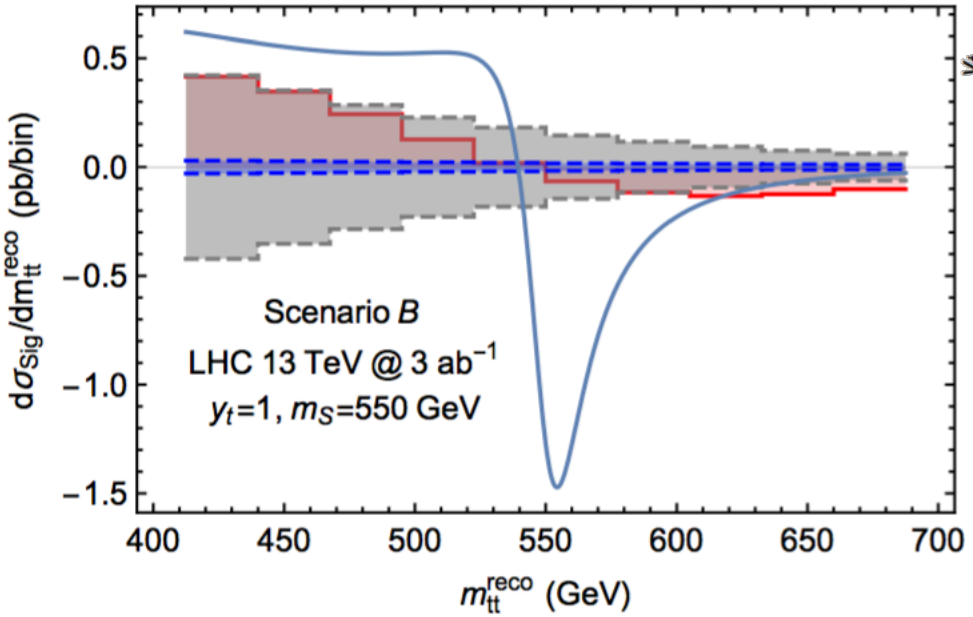
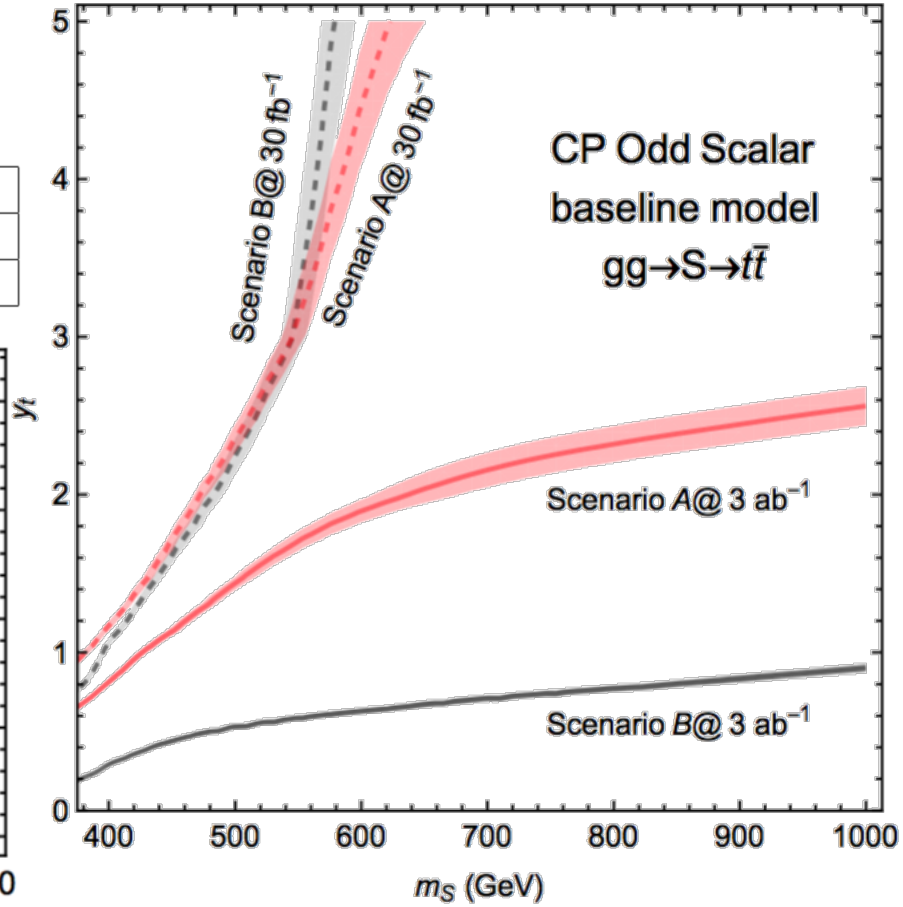
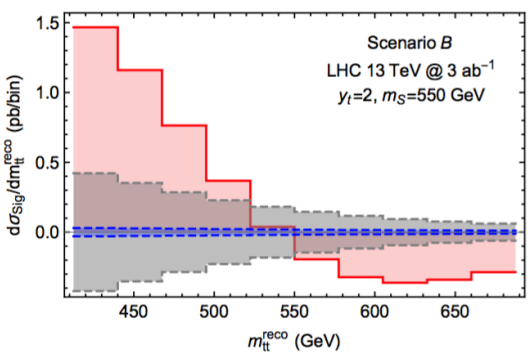
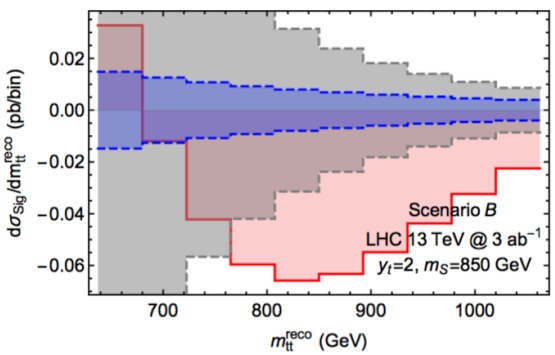




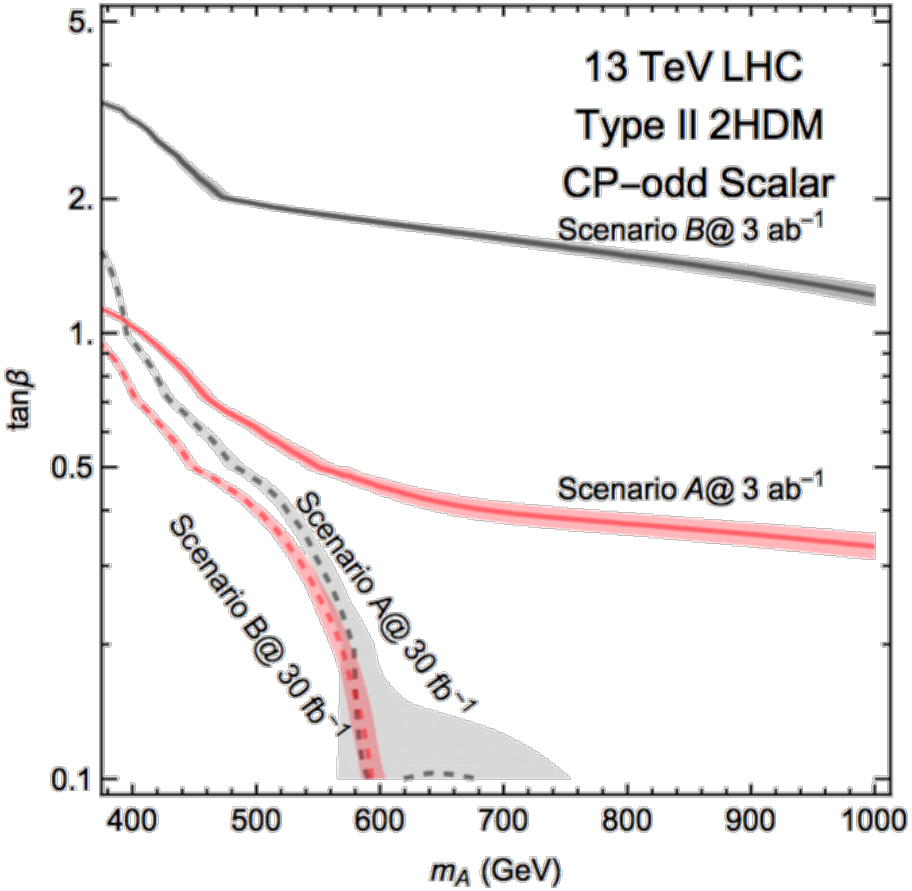




Lineshapes for a grid of mass and different Yukawas are generated
(because the signal is line-shape and does not scale as simple powers of Yukawa couplings).
After smearing, using bins near the scalar mass window, taking both excess and deficits, exclusion potential extracted.

Fermilab

LHC perspectives—2HDM projections

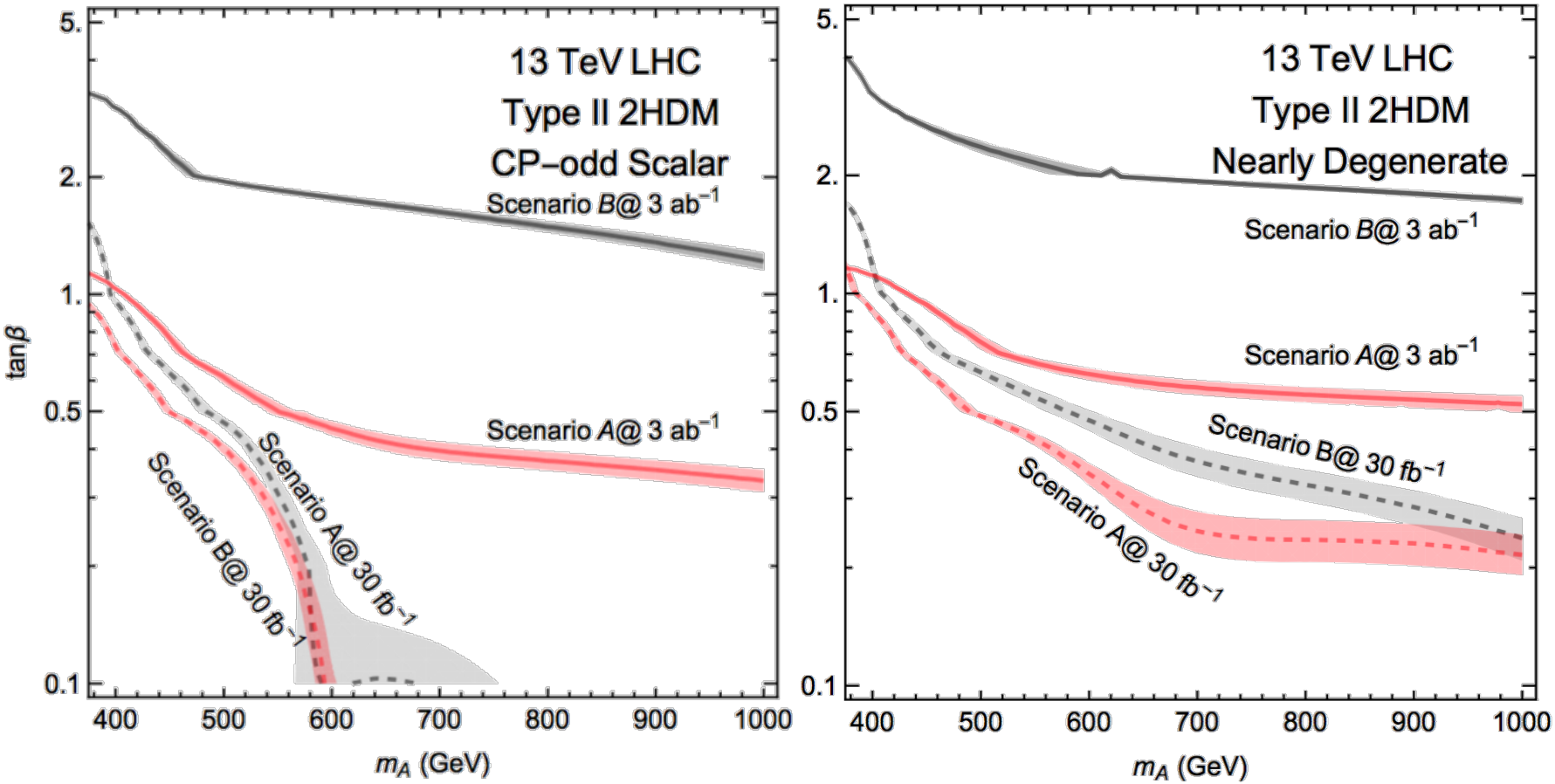


For a Type II 2HDM, the bottom quark effects are mainly in modifying the production vertex and provide some decay branching fraction suppression;

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.

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** 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**, 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**).

This effect is important for 750 GeV and any new scalars couples to ttbar, especially for the case of better and better limits. (as the relative strength of the interference pieces increases relatively to the B.W. piece.)

Backup

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

$$\begin{aligned} D^u_L &= \frac{1}{2}m_W^2(1 - \frac{1}{3}\tan^2\theta_W)\cos 2\beta \\ D^u_R &= \frac{2}{3}m_W^2\tan^2\theta_W\cos 2\beta \\ D^d_L &= -\frac{1}{2}m_W^2(1 + \frac{1}{3}\tan^2\theta_W)\cos 2\beta \\ D^d_R &= -\frac{1}{3}m_W^2\tan^2\theta_W\cos 2\beta \\ X_u &= A_u - \frac{\mu}{\tan\beta} \\ X_d &= A_d - \mu\tan\beta \\ Y_u &= \frac{A_u}{\tan\beta} + \mu \\ Y_d &= A_b\tan\beta + \mu, \end{aligned}$$

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

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

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

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

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,

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

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

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

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

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

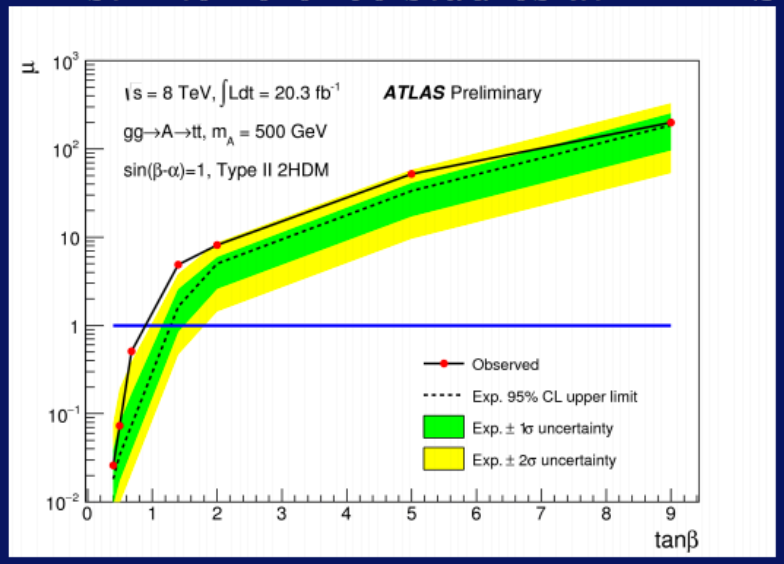
$$\frac{d\hat{\sigma}^{\rm even}_{\rm B.W.}(\hat{s};y_t)}{dz} = \frac{3\alpha_s^2\hat{s}^2}{4096\pi^3 v^2}\beta^3\left|\frac{y_t^2 I_{\frac{1}{2}}(\tau_t)}{\hat{s}-m_S^2+im_S\Gamma_S(\hat{s})}\right|^2$$

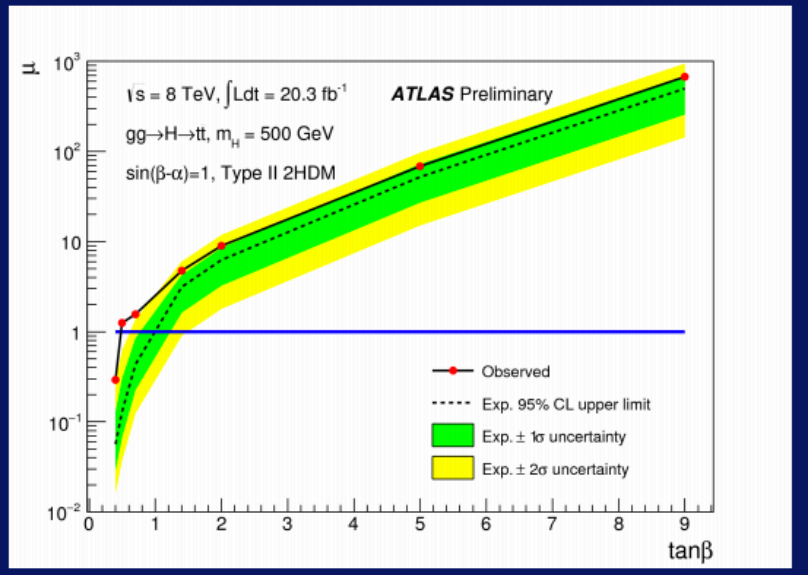
$$\frac{d\hat{\sigma}^{\rm even}_{\rm Int.}(\hat{s};y_t)}{dz} = -\frac{\alpha_s^2}{64\pi}\frac{\beta^3}{1-\beta^2 z^2}\,{\rm Re}\left[\frac{y_t^2 I_{\frac{1}{2}}(\tau_t)}{\hat{s}-m_S^2+im_S\Gamma_S(\hat{s})}\right]$$

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

$$\times\,{\rm Re}\left[\frac{(y_{t,S_1}y_{t,S_2}|I_{\frac{1}{2}}(\tau_t)|^2+\tilde{y}_{t,S_1}\tilde{y}_{t,S_2}|\tilde{I}_{\frac{1}{2}}(\tau_t)|^2)(\beta^2 y_{t,S_1}y_{t,S_2}+\tilde{y}_{t,S_1}\tilde{y}_{t,S_2})}{(\hat{s}-m_{S_1}^2+im_{S_1}\Gamma_{S_1}(\hat{s}))(\hat{s}-m_{S_2}^2-im_{S_2}\Gamma_{S_2}(\hat{s}))}\right]$$

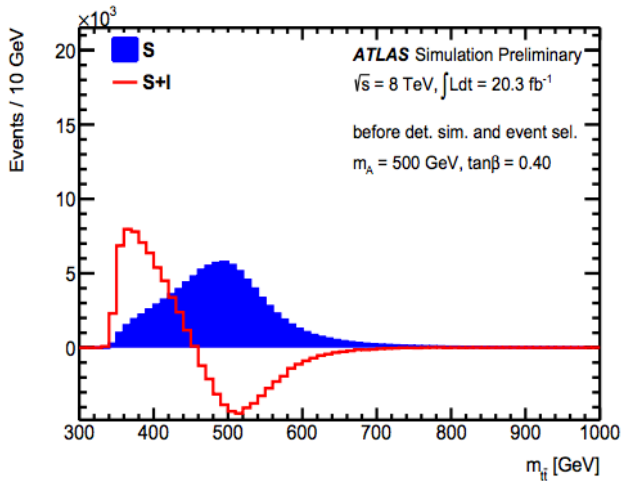
First interference studies at ATLAS



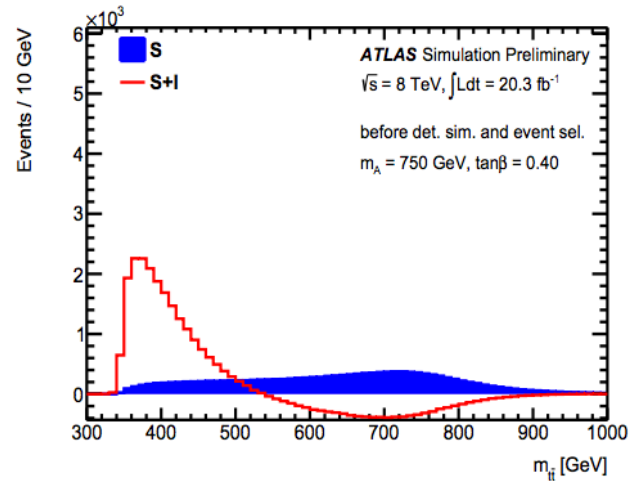


ATLAS-2016-073

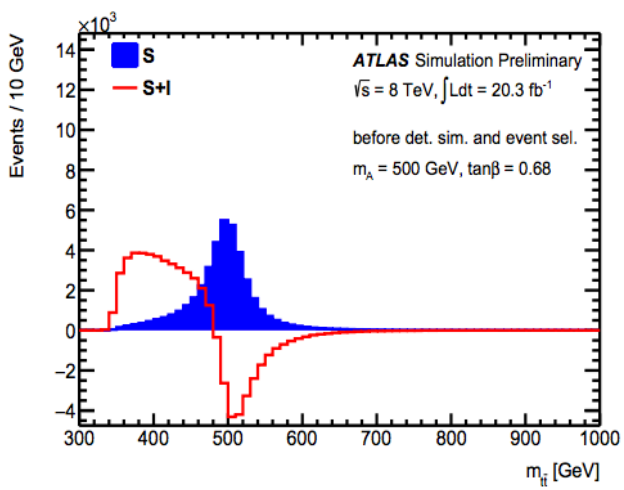
Fermilab



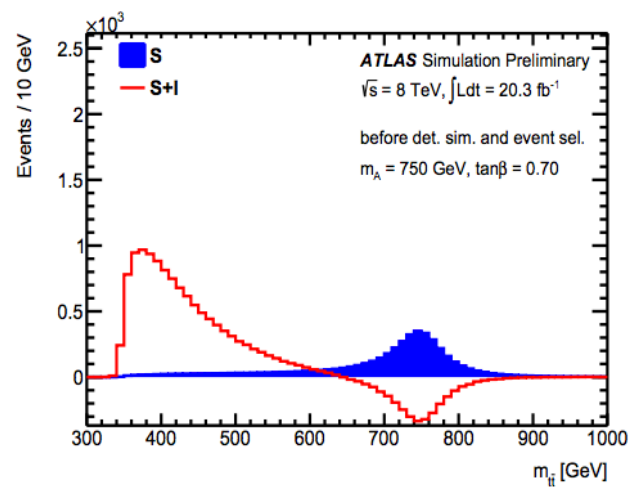
(a) $m_A = 500$ GeV, $\tan\beta = 0.40$



(b) $m_A = 750$ GeV, $\tan\beta = 0.40$



(c) $m_A = 500$ GeV, $\tan\beta = 0.68$



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

Motivation

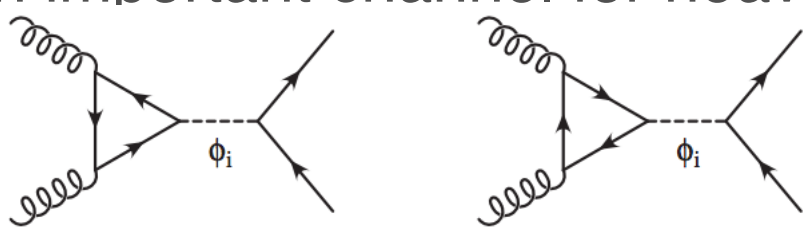
Heavy scalars very common in new physics models (SUSY,2HDM,Composite Models, Hidden-valley, Gauge symmetry extensions, etc.)

Couples to fermions proportional to their masses, dominantly to ttbar

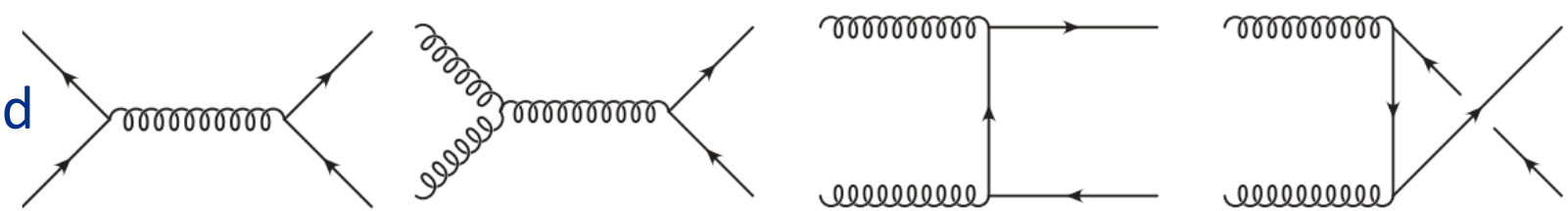
=>

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

signal



background



Fermilab