Strong phase at colliders:

new physics opportunities for $t\bar{t}$ **resonance searches** and **Higgs physics**

Zhen Liu (Fermilab)

Particle Physics Seminar @ CERN-TH

Apr. 28th, 2017

Based on M. Carena, ZL, arXiv:1608.07282, JHEP
and J. Campbell, M. Carena, R. Harnik, ZL, arXiv:1704.08259

Motivation

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 into $t\bar{t}$

Motivation

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 into $t\bar{t}$
➔
$gg \to S \to t\bar{t}$ is an important channel for heavy scalar discovery and identification

Motivation

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 into $t\bar{t}$

➔

$gg \to S \to t\bar{t}$ **is an important channel for heavy scalar discovery and identification**

➔

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

Motivation

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 into $t\bar{t}$

➔

$gg \to S \to t\bar{t}$ **is an important channel for heavy scalar discovery and identification**

➔

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

➔

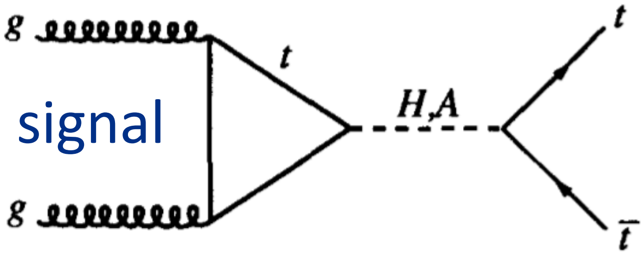
Starting with a very minimal baseline model

$$\mathcal{L}^{Yukawa} \supset \frac{y}{\sqrt{2}} \bar{Q}_{3L} \widetilde{H} t_R + h.c.$$

$$\mathcal{L}^{Yukawa} \xrightarrow{\text{loop}-\text{induced}} -\frac{1}{4} g_{Sgg}(\hat{s}) G_{\mu\nu} G^{\mu\nu} S$$

denote the neutral CP-even component S, after EWSB; similar expressions for CP-odd and CP-admixture states

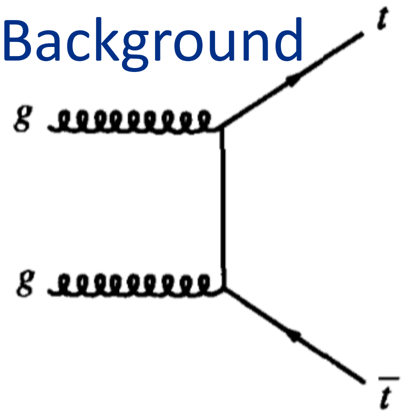
Unfamiliar look of heavy Scalars



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.

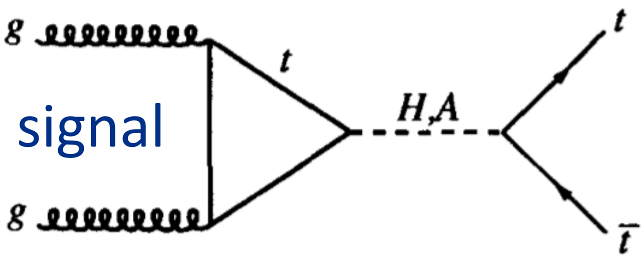
Background



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

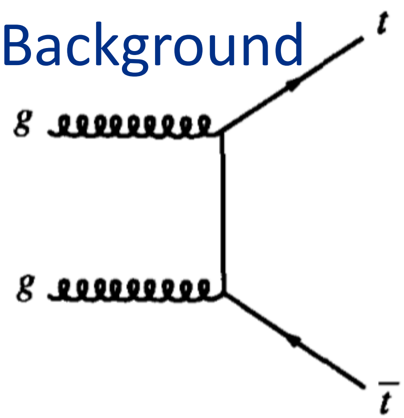
Unfamiliar look of heavy Scalars

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.

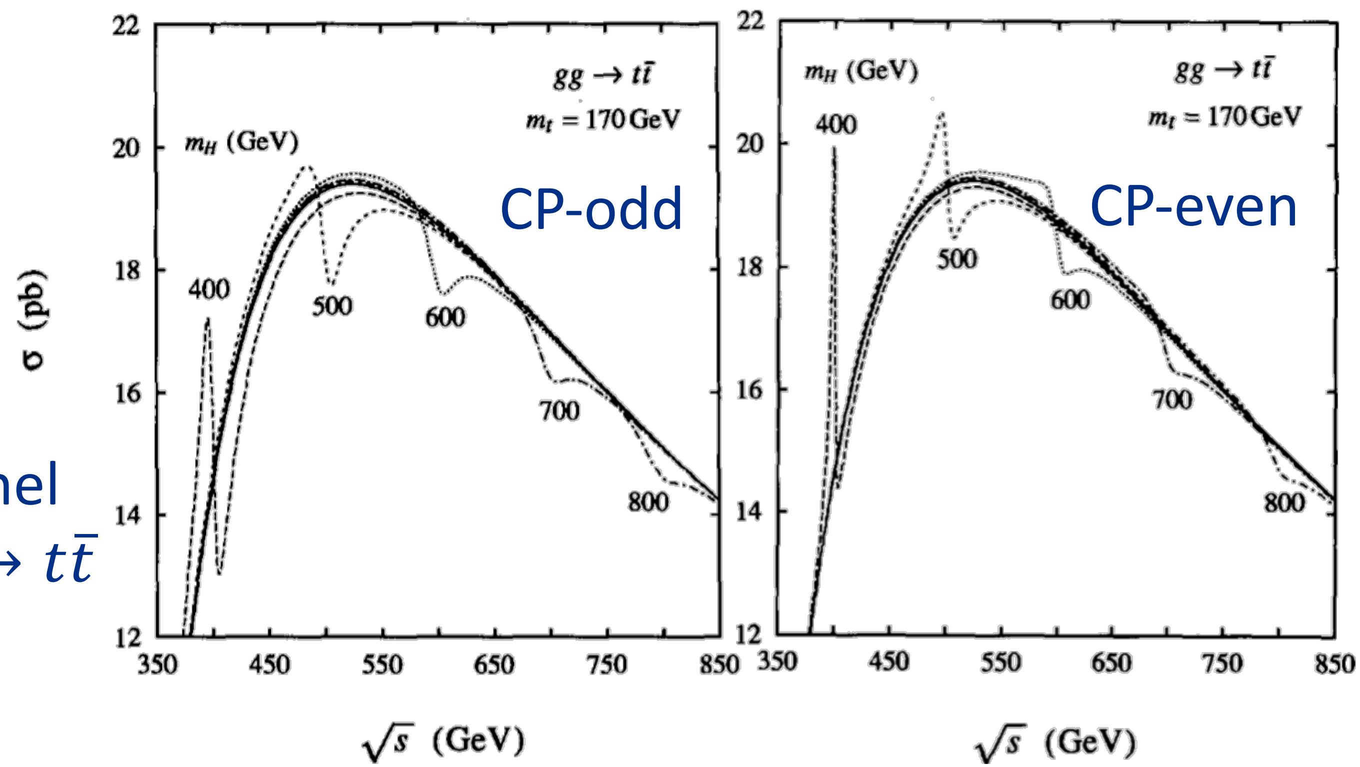
Background



Plus s- and u- channel

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

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



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**

Sketching the interference

$$A_{sig} = c_{sig} \frac{\hat{s}}{\hat{s} - m^2 + i\,\Gamma m} = \mathrm{c}_{sig}\ \mathrm{P}(\hat{s})$$

$A_{bkg} = c_{bkg}$ (slowing varying, treated as constant; redefine c_{sig} respectively to keep c_{bkg} real for simplicity)

$$|A|^2 = \left|A_{sig} + A_{bkg}\right|^2$$
$$= \left|A_{sig}\right|^2 + \left|A_{bkg}\right|^2 + 2Re\left[A_{sig} A^*_{bkg}\right]$$
$$= B.W. + BKG$$
$$+ 2Re\left[c_{sig}\right] c_{bkg} Re[P(\hat{s})]$$
$$- 2Im\left[c_{sig}\right] c_{bkg} Im[P(\hat{s})]$$

Sketching the interference

$$A_{sig} = c_{sig}\frac{\hat{s}}{\hat{s} - m^2 + i\,\Gamma m} = c_{sig}\,P(\hat{s})$$

$A_{bkg} = c_{bkg}$ (slowing varying, treated as constant; redefine c_{sig} respectively to keep c_{bkg} real for simplicity)

$$|A|^2 = \left|A_{sig} + A_{bkg}\right|^2$$
$$= \left|A_{sig}\right|^2 + \left|A_{bkg}\right|^2 + 2Re\left[A_{sig}A^*_{bkg}\right]$$
$$= B.W. + BKG$$
$$+\, 2Re\left[c_{sig}\right]c_{bkg}Re\left[P(\hat{s})\right]$$
$$-\, 2Im\left[c_{sig}\right]c_{bkg}Im\left[P(\hat{s})\right]$$

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

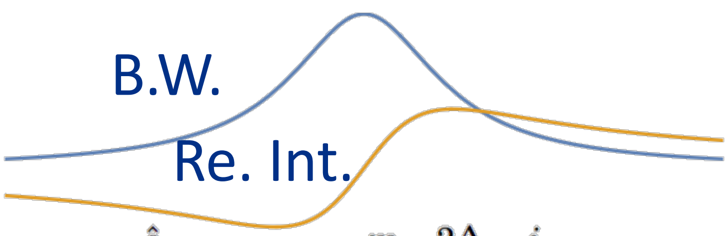
$$\text{with} \quad \Delta \equiv \frac{\hat{s}-m_S^2}{2m_S\Gamma_S} \approx \frac{\sqrt{\hat{s}}-m_S}{\Gamma_S} \text{ for } \frac{\hat{s}}{m_S^2} - 1 \ll 1.$$

Sketching the interference

$$A_{sig} = c_{sig} \frac{\hat{s}}{\hat{s} - m^2 + i\,\Gamma m} = c_{sig}\, \mathrm{P}(\hat{s})$$

$A_{bkg} = c_{bkg}$ (slowing varying, treated as constant; redefine c_{sig} respectively to keep c_{bkg} real for simplicity)

$$|A|^2 = \left|A_{sig} + A_{bkg}\right|^2$$
$$= \left|A_{sig}\right|^2 + \left|A_{bkg}\right|^2 + 2Re\left[A_{sig}A^*_{bkg}\right]$$
$$= B.W. + BKG$$
$$+\, 2Re\left[c_{sig}\right]c_{bkg}Re[P(\hat{s})]$$
$$-\, 2Im\left[c_{sig}\right]c_{bkg}Im[P(\hat{s})]$$



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

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

Background real

Re. Int.– Interference from the real part of the propagator

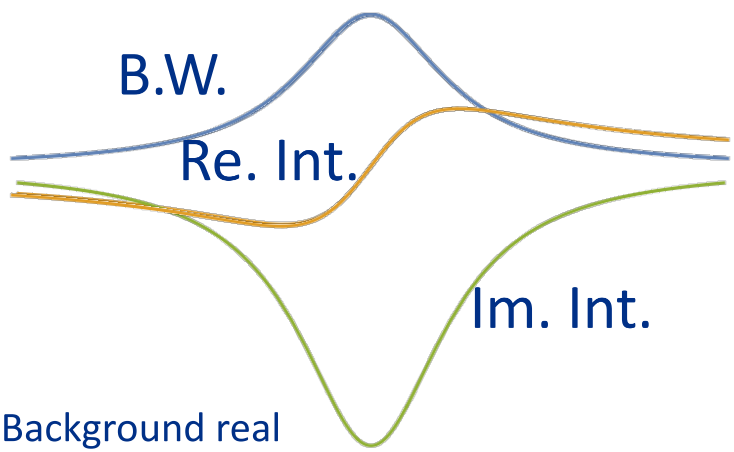
- normal interference, parton level no contribution to the rate, shift the mass peak
- When convoluting with PDF, may generate residual contribution to signal rate, see, e.g., S. Martin **arXiv:1606.03026**;
- conventional wisdom, interference only important when width is large)

Sketching the interference

$$A_{sig} = c_{sig}\frac{\hat{s}}{\hat{s}-m^2+i\,\Gamma m} = \mathrm{c}_{sig}\,\mathrm{P}(\hat{s})$$

$A_{bkg} = c_{bkg}$ (slowing varying, treated as constant; redefine c_{sig} respectively to keep c_{bkg} real for simplicity)

$$|A|^2 = \left|A_{sig}+A_{bkg}\right|^2$$
$$= \left|A_{sig}\right|^2 + \left|A_{bkg}\right|^2 + 2Re\left[A_{sig}A^*_{bkg}\right]$$
$$= B.W. + BKG$$
$$+\,2Re\left[c_{sig}\right]c_{bkg}Re\left[P(\hat{s})\right]$$
$$-\,2Im\left[c_{sig}\right]c_{bkg}Im\left[P(\hat{s})\right]$$

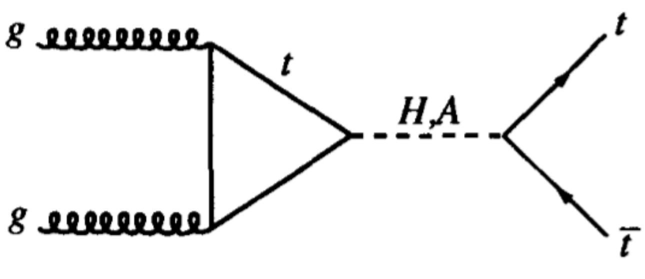


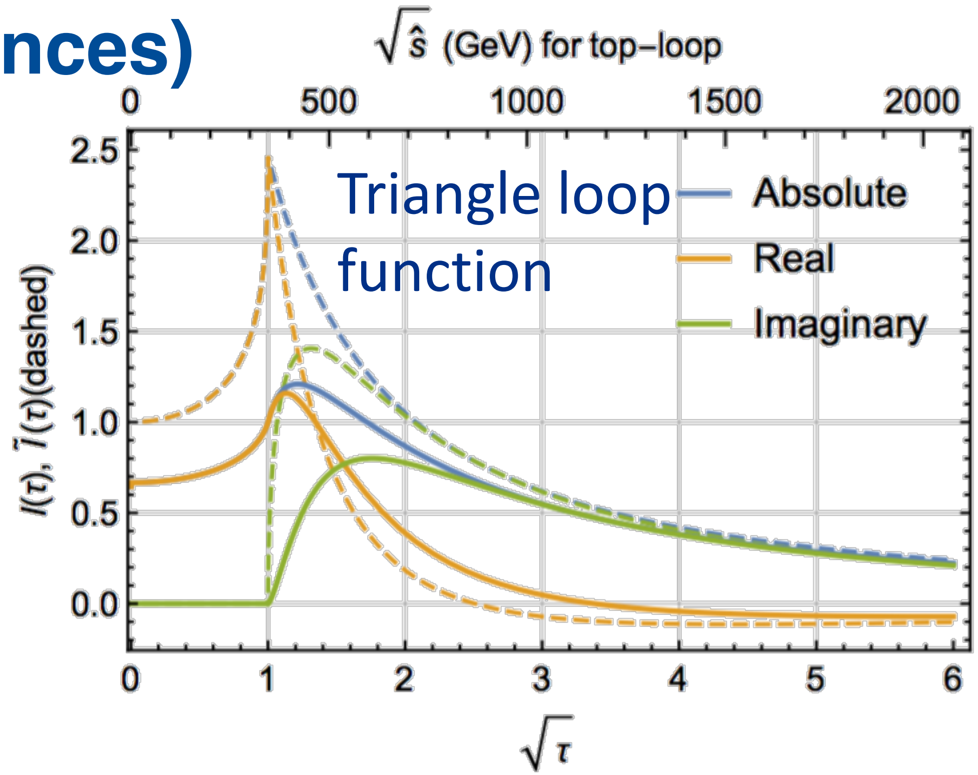
Background real

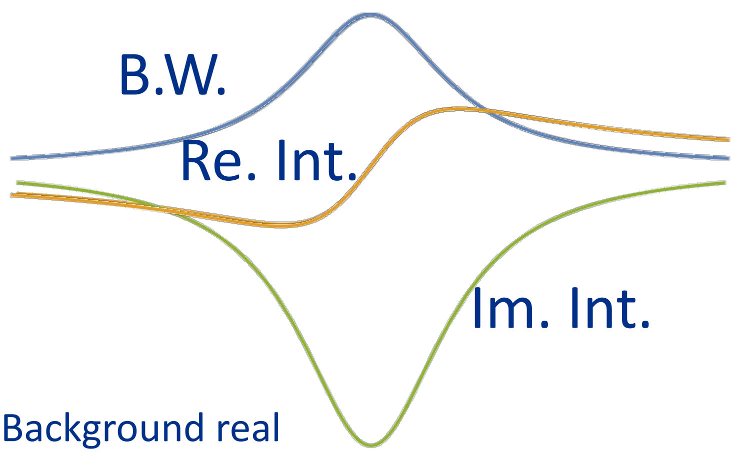
Re. Int.– Interference from the real part of the propagator (normal interference, parton level no contribution to the rate, shift the mass peak)

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

Challenges (interferences)





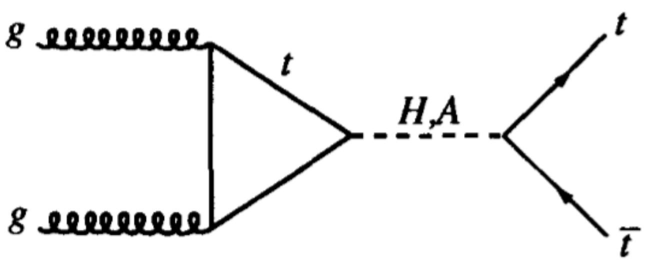


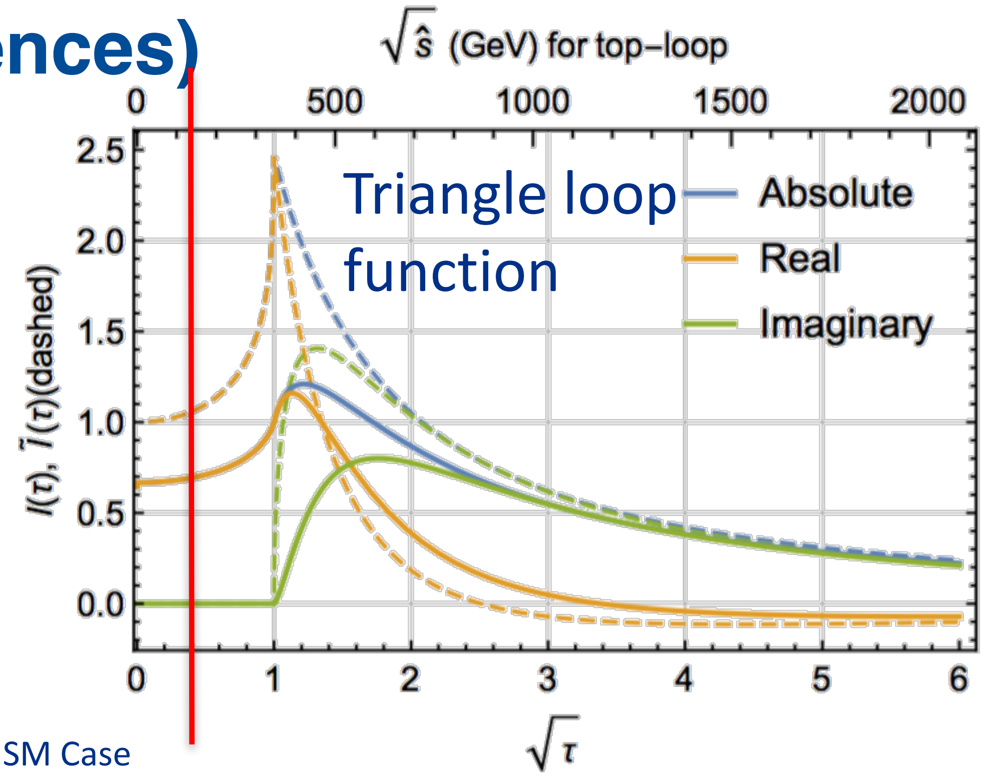
Background real

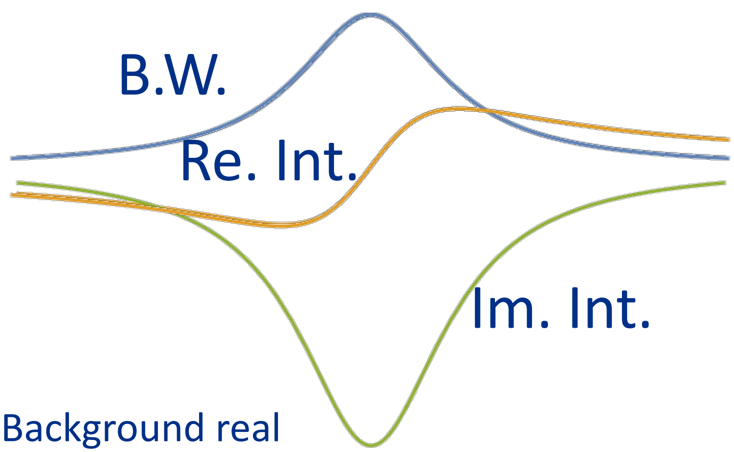
Re. Int.– Interference from the real part of the propagator (normal interference, parton level no contribution to the rate, shift the mass peak)

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

Challenges (interferences)



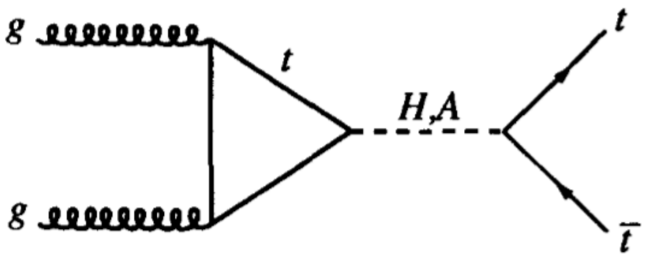


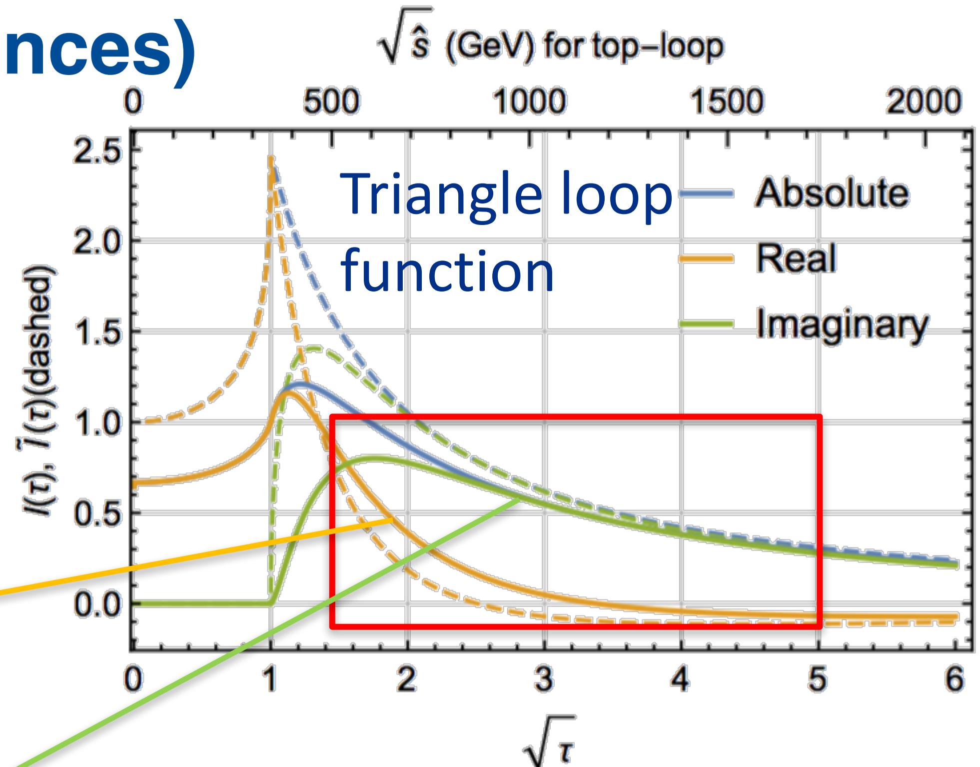


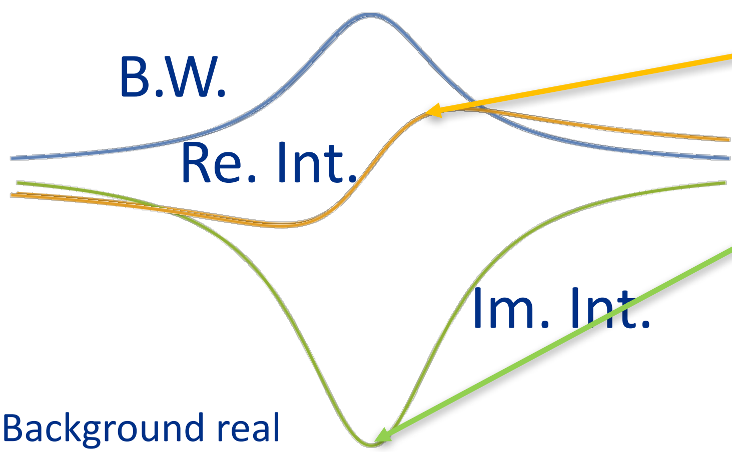
SM Case
real and slowly varying
``heavy (chiral) fermion
decoupling theorem'' (with
Yukawa proportional to the mass)

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)

Challenges (interferences)







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

Background real

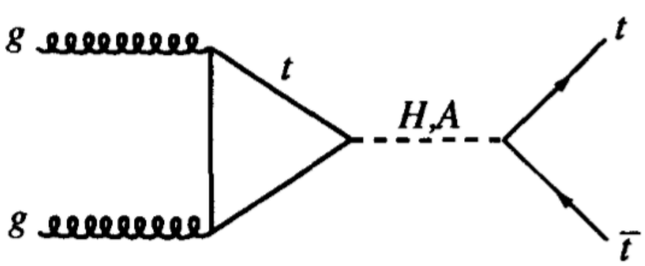
Re. Int.– Interference from the real part of the propagator (normal interference, parton level no contribution to the rate, shift the mass peak)

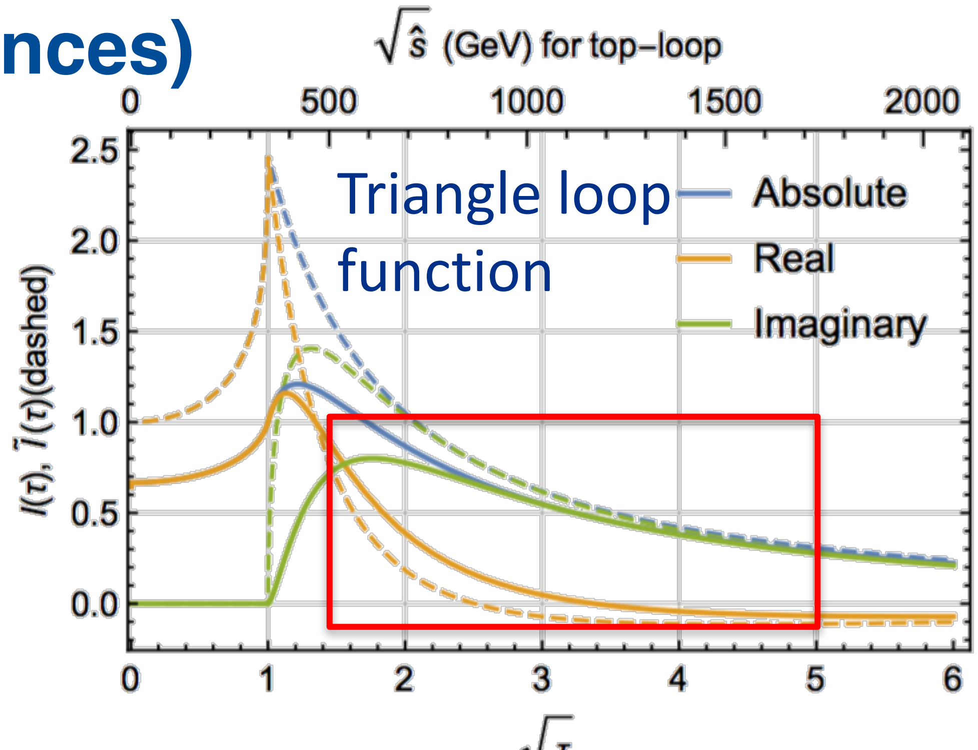
Im. Int.– Interference from the imaginary part of propagator (rare case, changes signal rate)

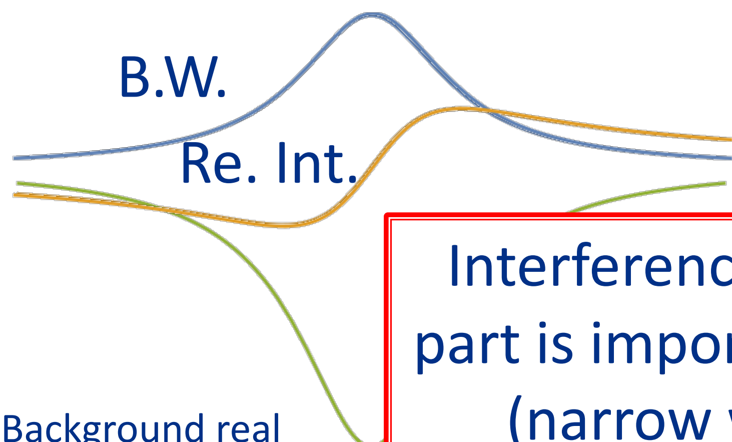
A strong phase ``insensitive”* to phase in the Yukawa as the signal amplitudes is proportional to $|y_t|^2$.

*subject to difference in loop functions

Challenges (interferences)







Interference effect from this imaginary part is important, regardless of the width! (narrow width approximation fails)

ginary piece

iece

Background real

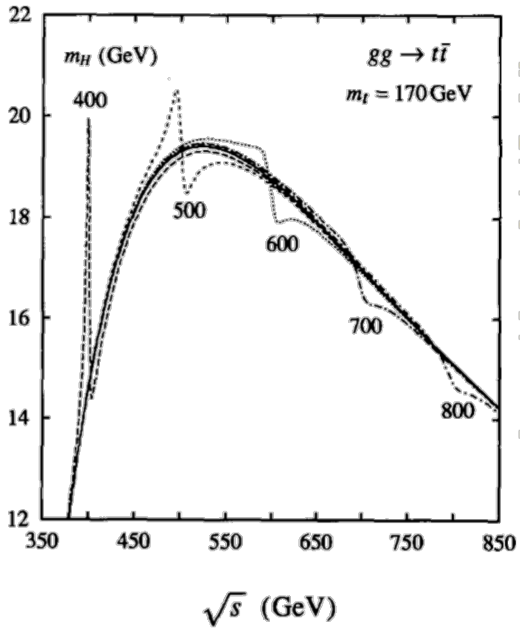
Re. Int.– Interference from the real part of the propagator (normal interference, parton level no contribution to the rate, shift the mass peak)

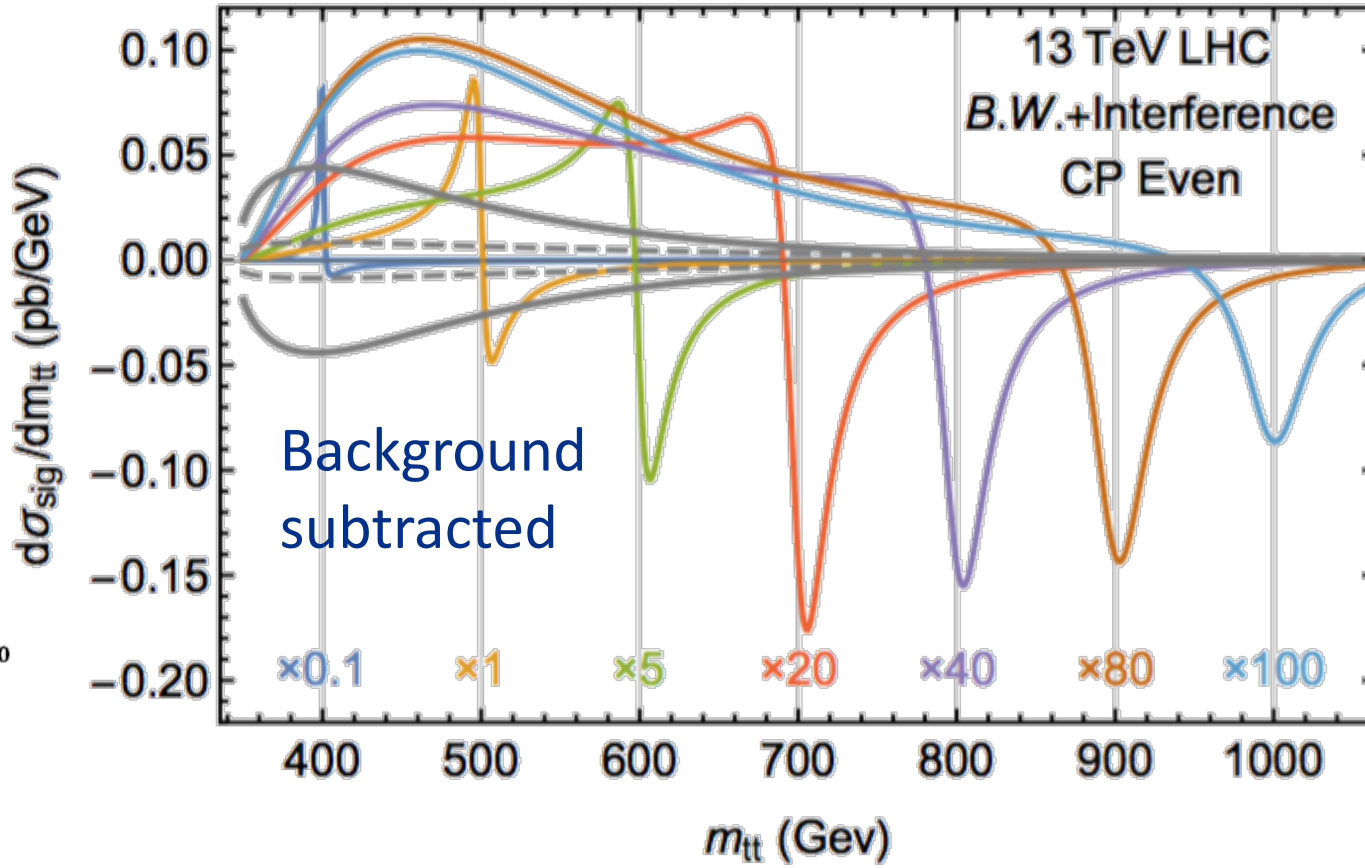
Im. Int.– Interference from the imaginary part of propagator (rare case, changes signal rate)

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



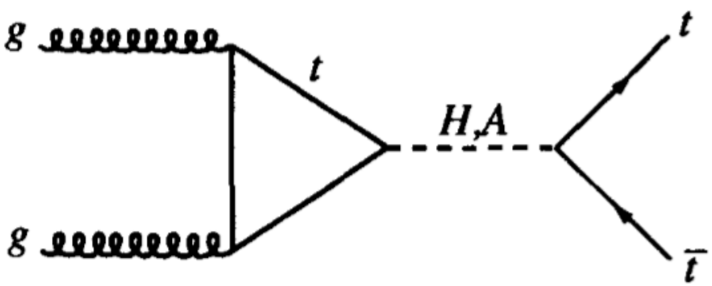


Special line shapes:

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

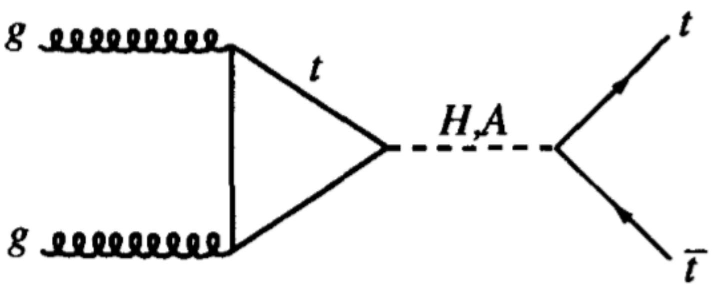
b) Smearing effects erode the structure, making this signal much harder.

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.)

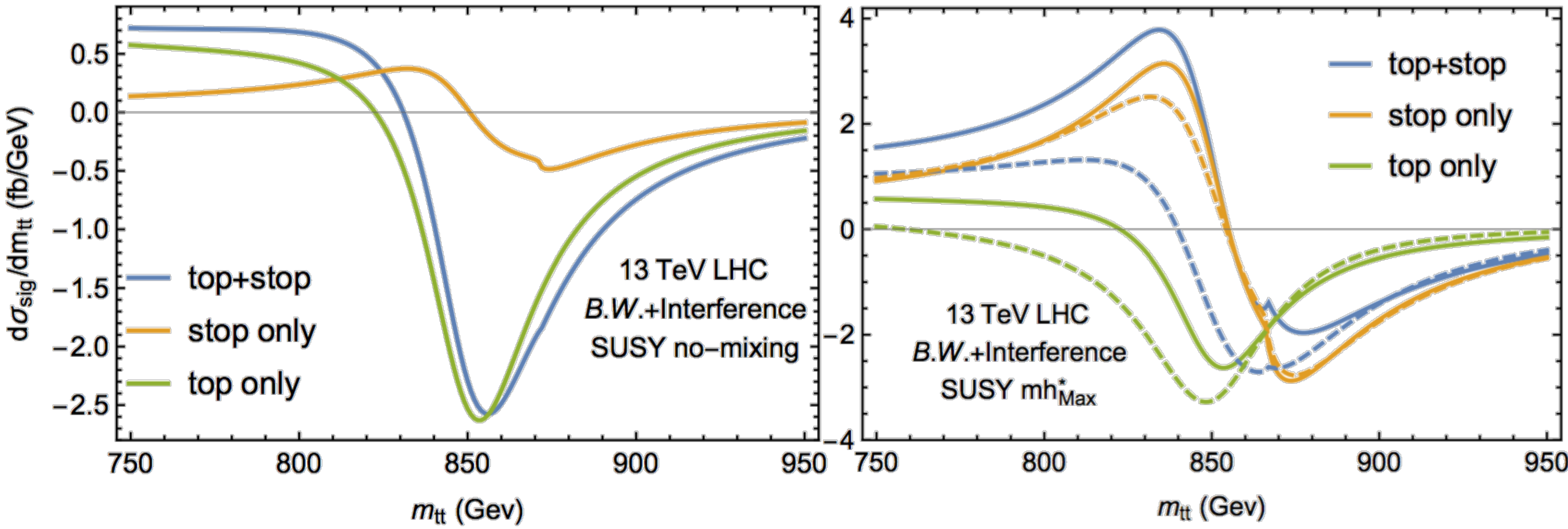
Opportunities



Covered in our study
M. Carena, ZL,
arXiv:1608.07282, JHEP

- 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.)

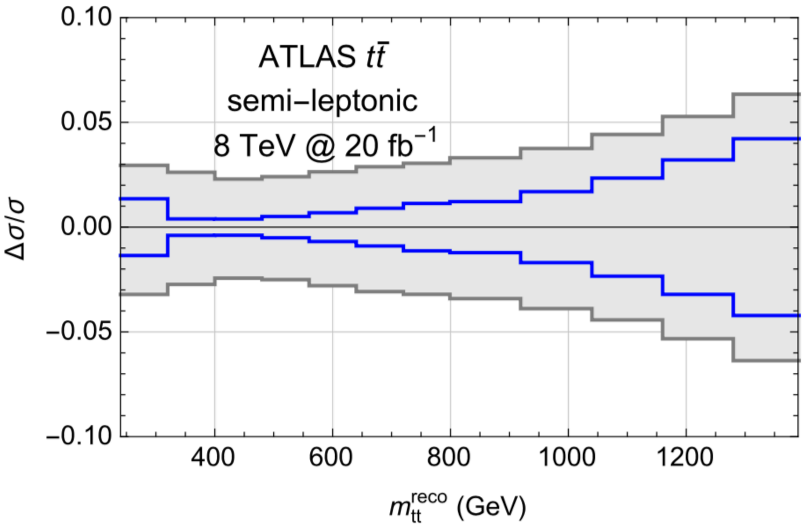
Opportunities– Stop contributions

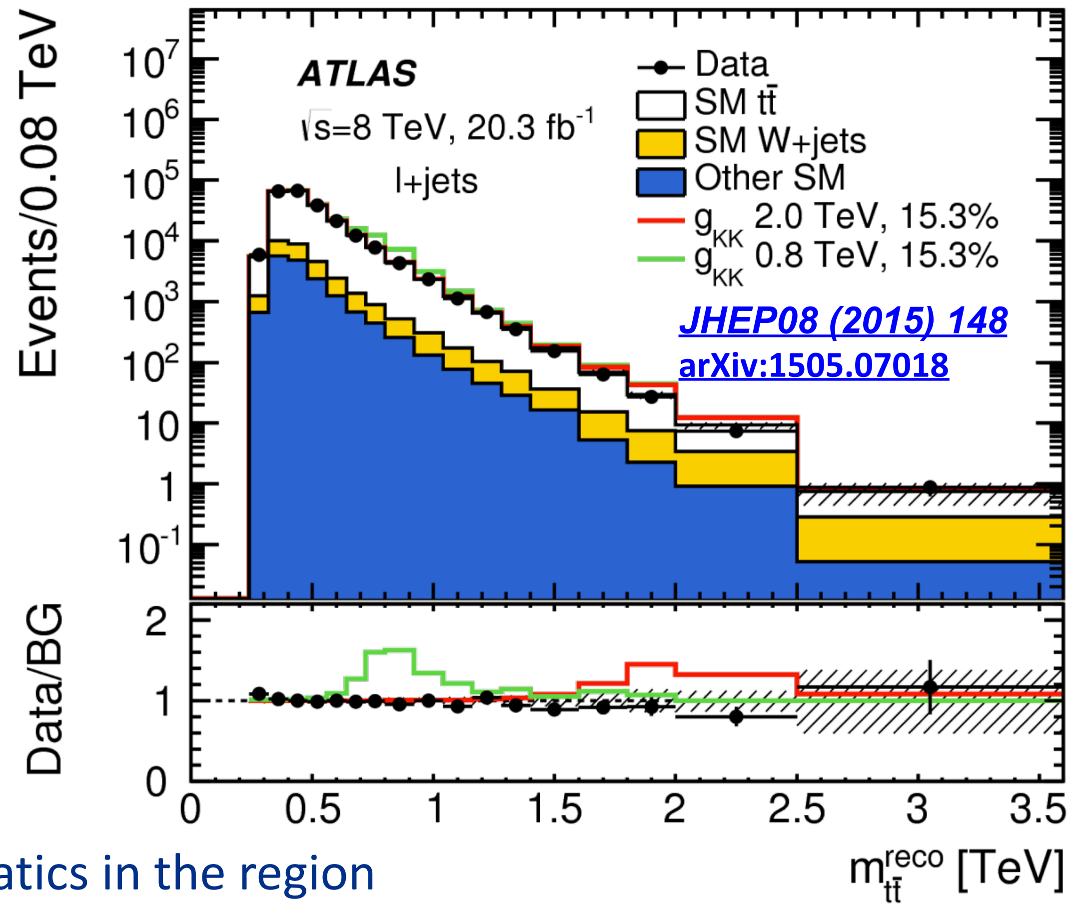


SUSY TeV scale stop quarks are highly anticipated through naturalness argument

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

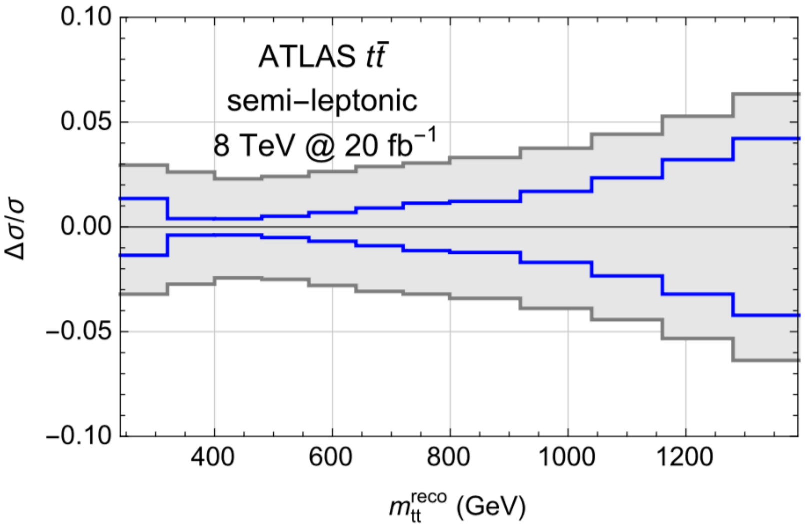


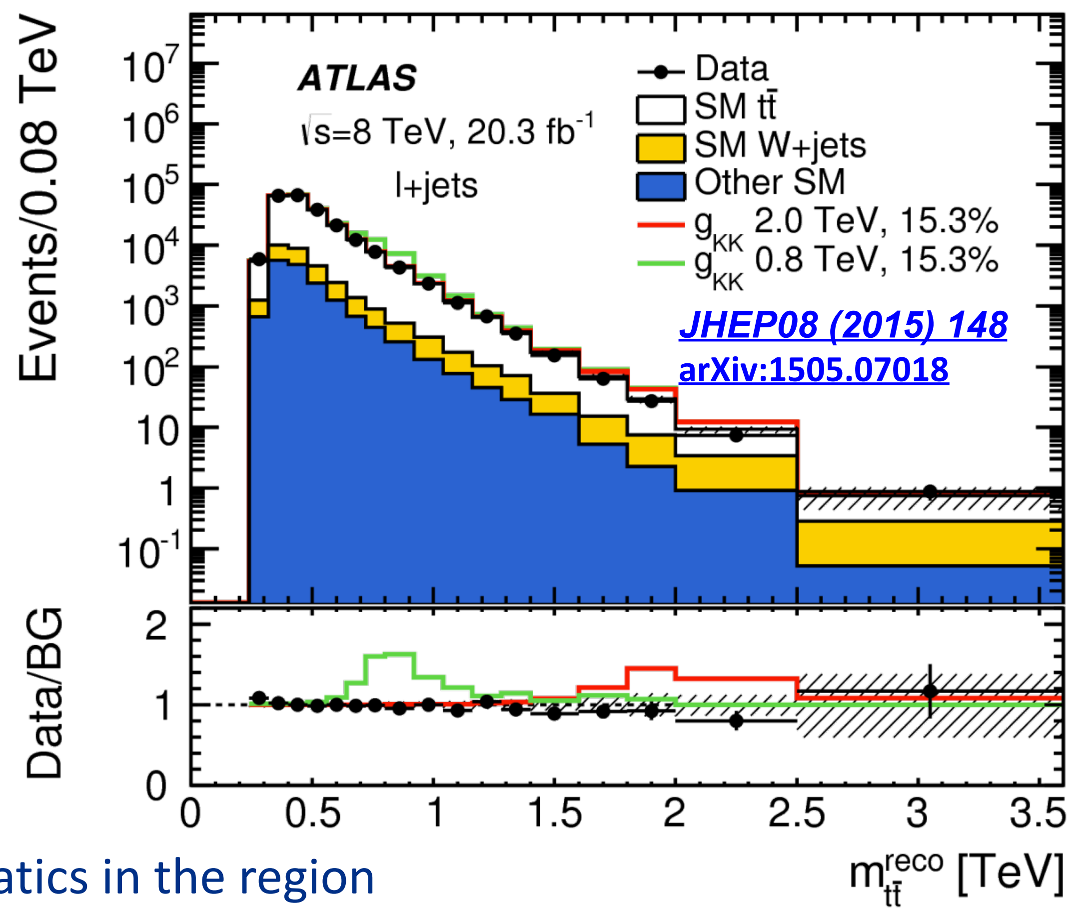


Already achieved sub 2-4% systematics in the region of interest, we see hope in this channel.

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

LHC perspectives





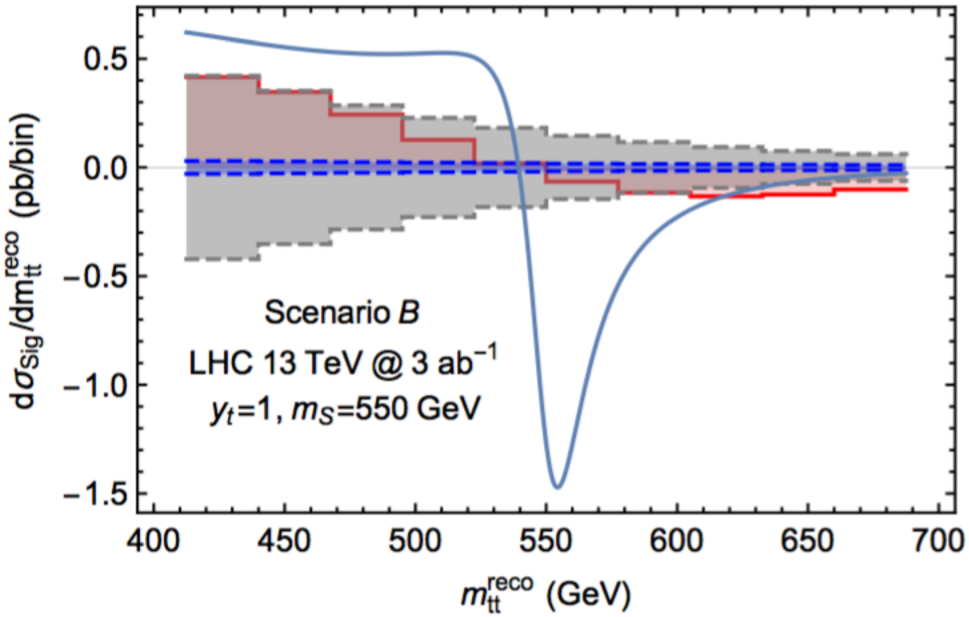
Already achieved sub 2-4% systematics in the region of interest, we see hope in this channel.

``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

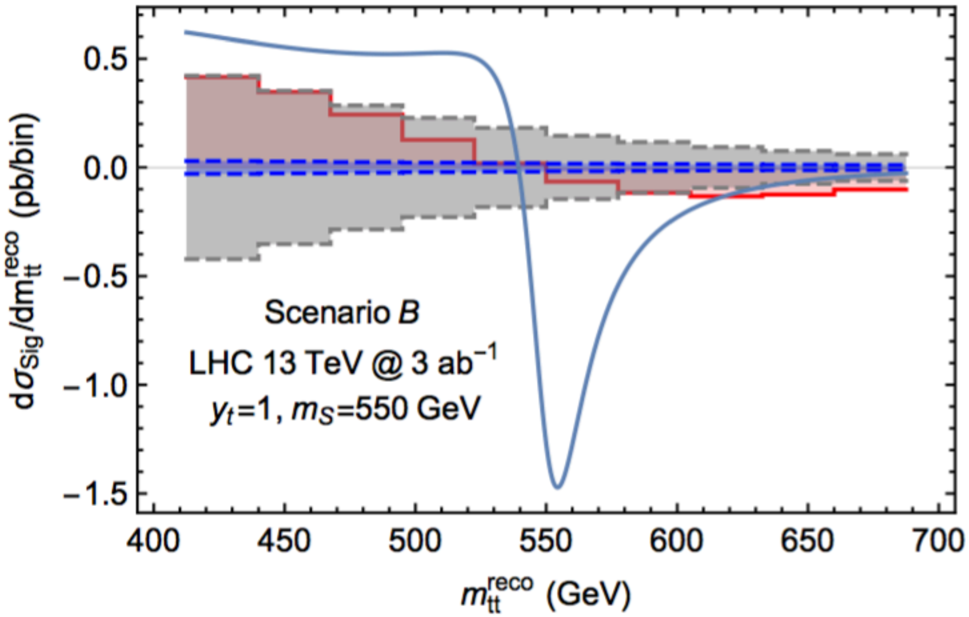
	$\Delta m_{t\bar{t}}$	Efficiency	Systematic Uncertainty
Scenario A	15%	8%	4% at 30 fb^{-1}, halved at 3 ab^{-1}
Scenario B	8%	5%	4% at 30 fb^{-1}, scaled with $\sqrt{L}$

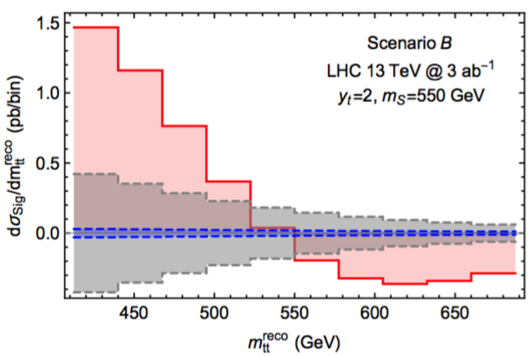


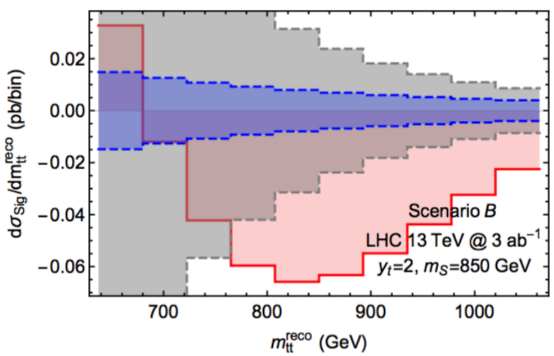
Blue curve, the signal lineshape before mearing;
Red Histogram, the signal after smearing and binning;
Gray and blue histograms, the total and statistical uncertainties;

LHC perspectives

	$\Delta m_{t\bar{t}}$	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 $\sqrt{L}$

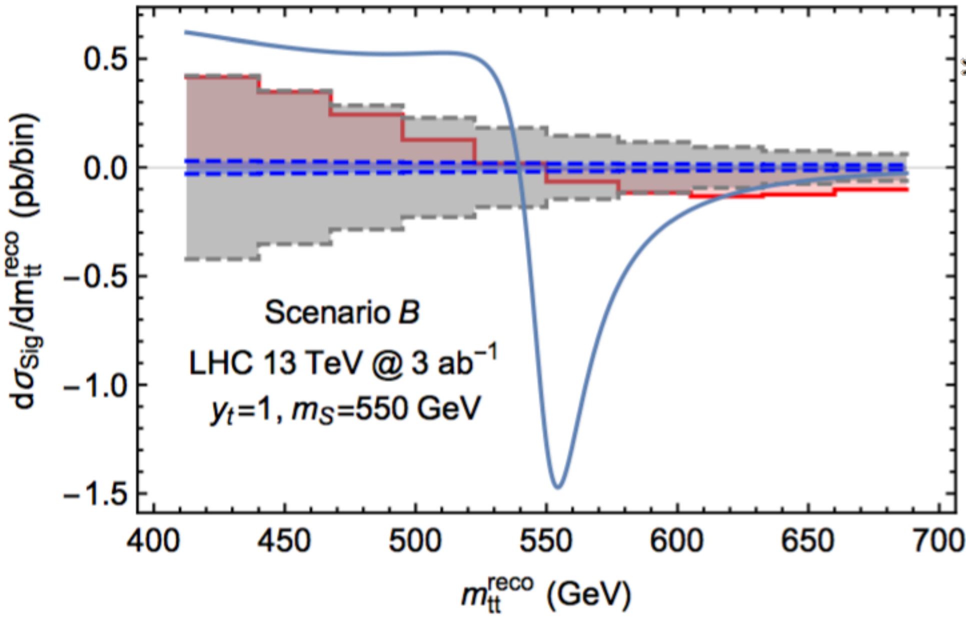


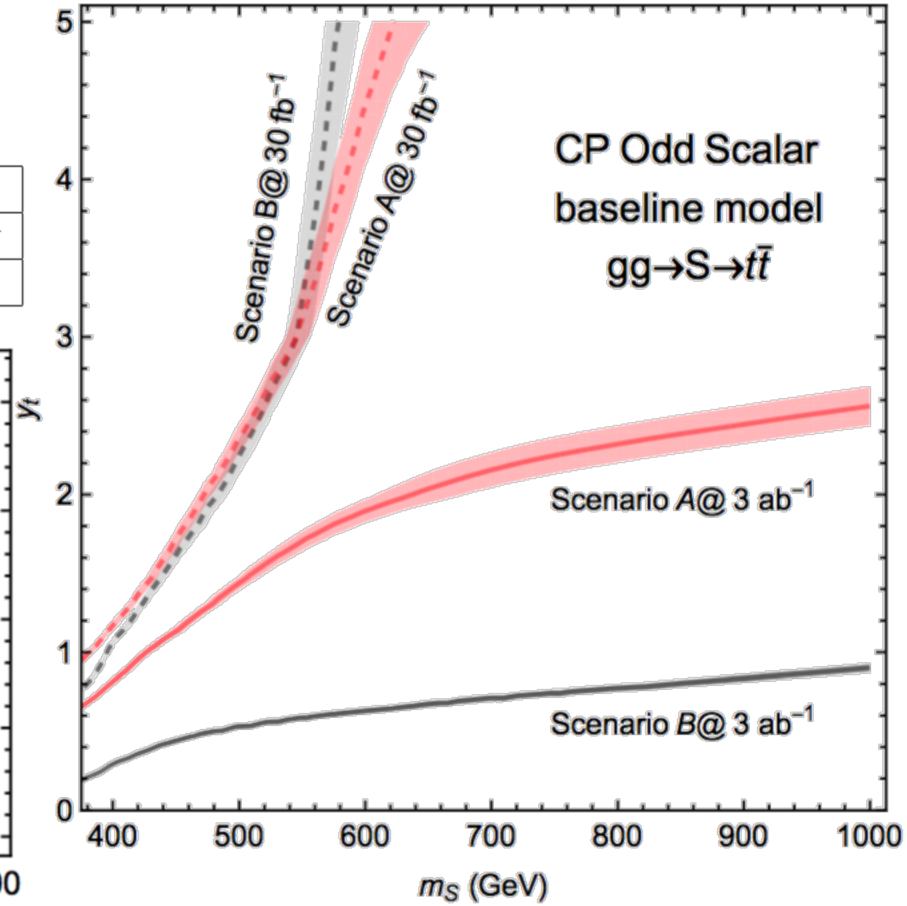


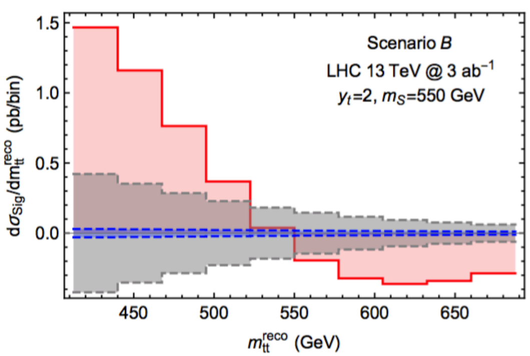


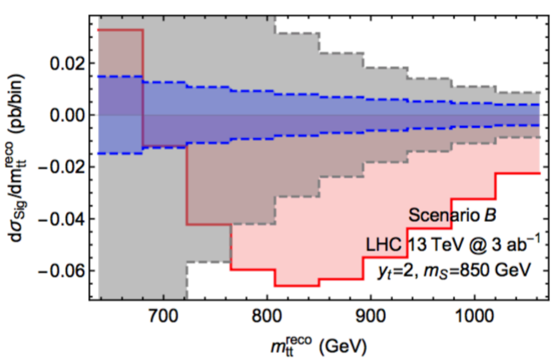
LHC perspectives

	$\Delta m_{t\bar{t}}$	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 $\sqrt{L}$



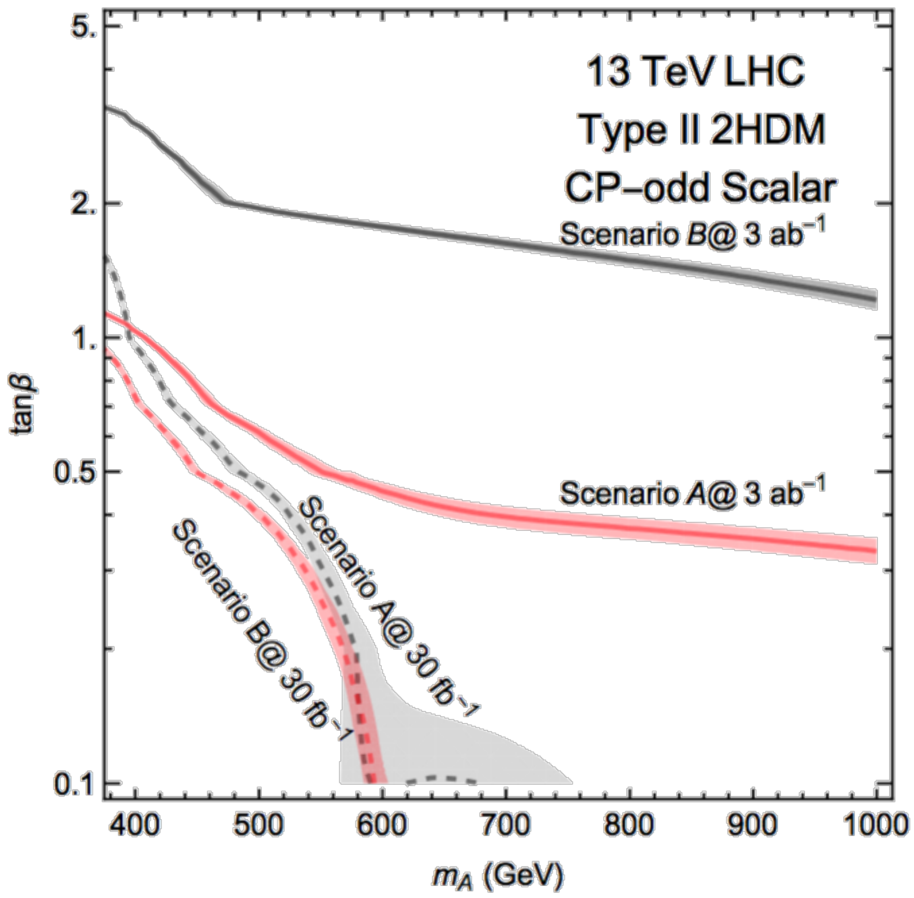






Lineshapes for a grid of mass and different Yukawas are generated
(because the signal is line-shape and does not scale as simple powers of Yukawa couplings).
After smearing, using bins near the scalar mass window, taking both excess and deficits, exclusion potential extracted.

LHC perspectives—2HDM projections

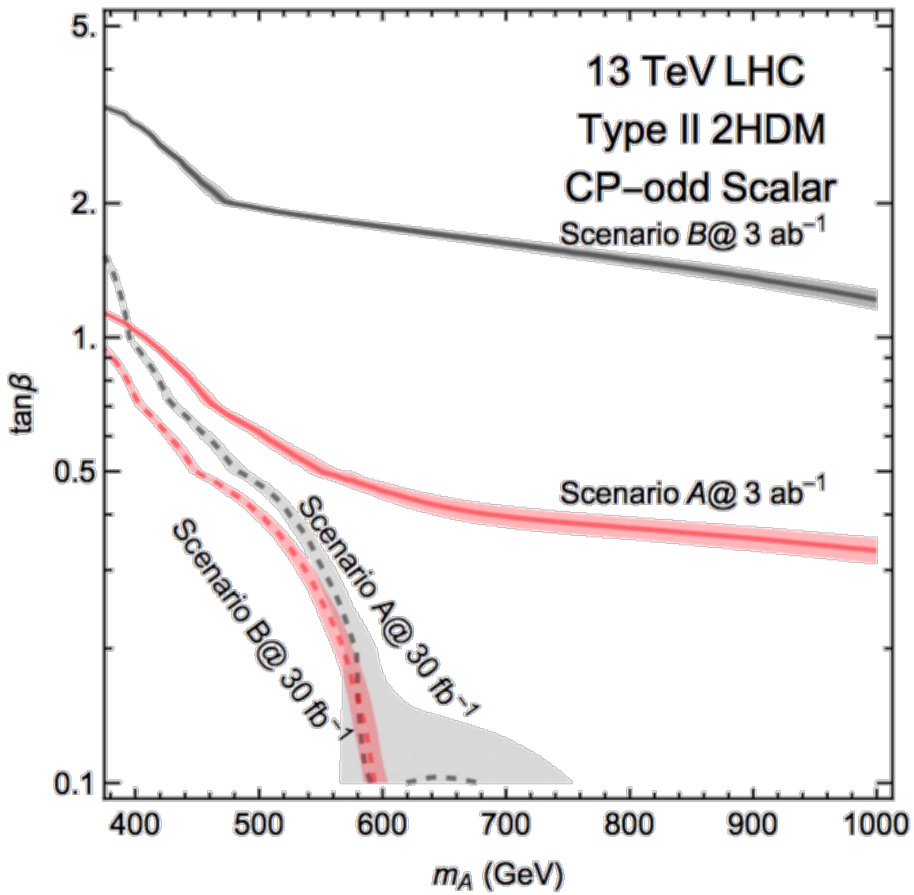


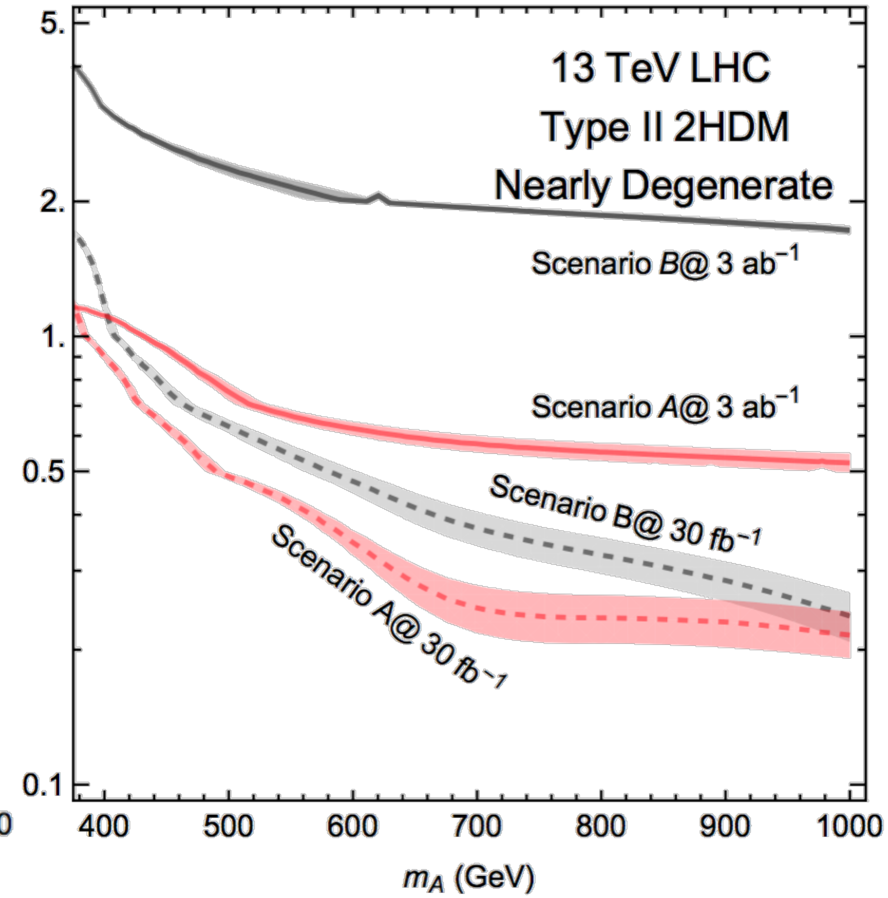
For a Type II 2HDM, the bottom quark effects are mainly in modifying the production vertex and provide some decay branching fraction suppression;

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

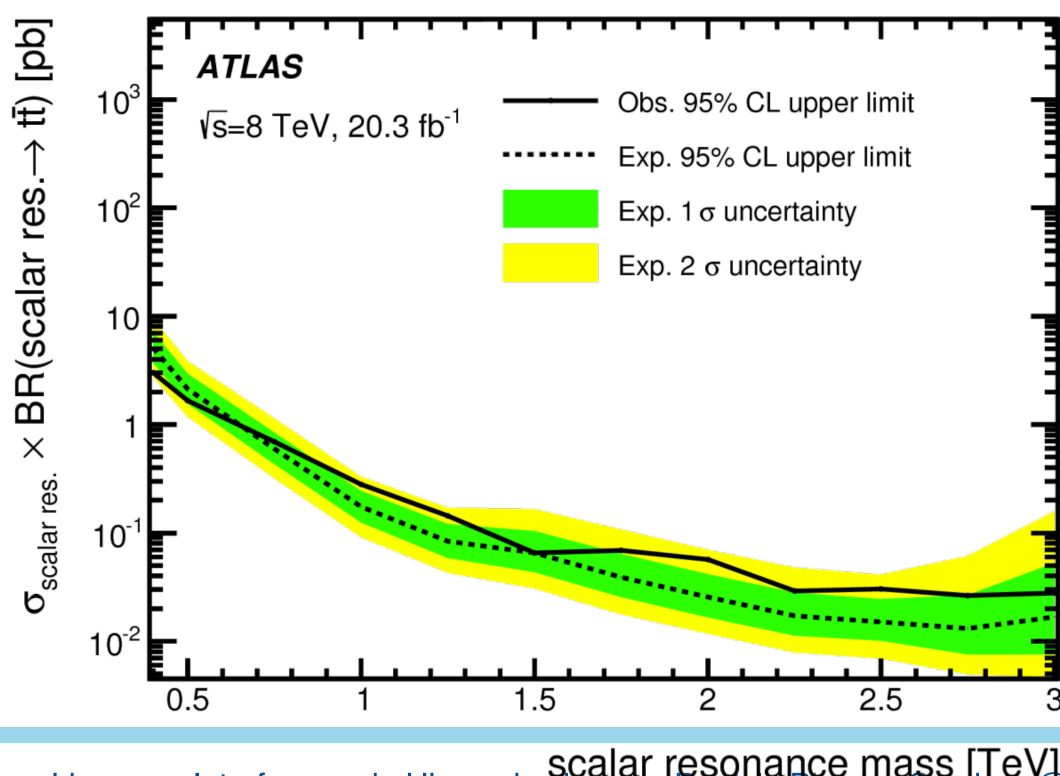




For the case of nearly degenerate heavy scalars, the physic reach is improved, especially for heavy heavy masses.

LHC perspectives—Experimental progress

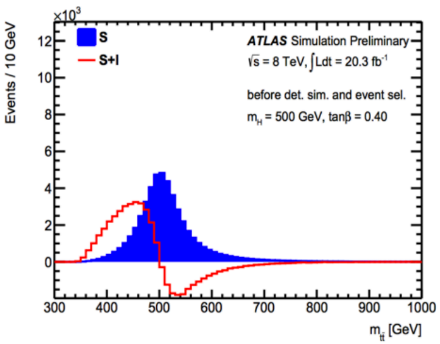
The last class of models examined here produces colour-singlet scalar particles via gluon fusion which decay to $t\bar{t}$. The approach previously adopted by the CMS Collaboration [18] is followed, in which narrow scalar resonance benchmarks are generated while the interference with SM $t\bar{t}$ production 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.

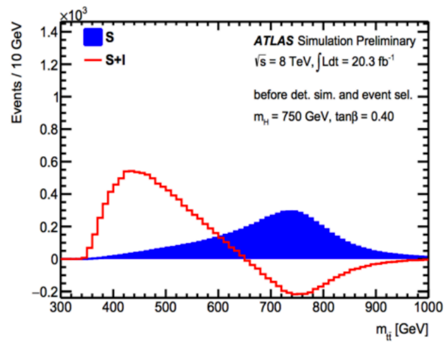


LHC perspectives — Experimental progress

Signal Modeling (A/H→ttbar)

- The signal process is simulated using the generator MadGraph5 v2.0.1 with the Higgs Effective Couplings Form Factor model (implements the production of scalar and pseudoscalar particles through loop-induced gluon fusion)
  - Loop contributions from both bottom and top quarks are taken into account
  - Signal shape is distorted from a simple Breit-Wigner peak, to a peak-dip structure
  - Statistical interpretation of measured event rates in data are compared to the total sum of Signal + Interference + Background (S + I + B)
  - The mass of the SM-like Higgs boson, h, is chosen to be 125 GeV and sin(β-α) is set to 1



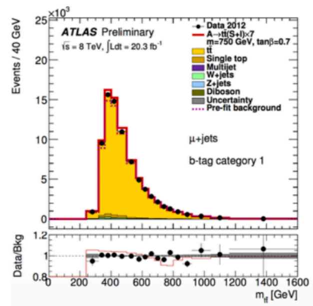


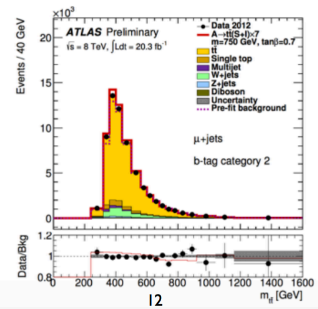
Event Selection / Mass Reconstruction (A/H→ttbar)

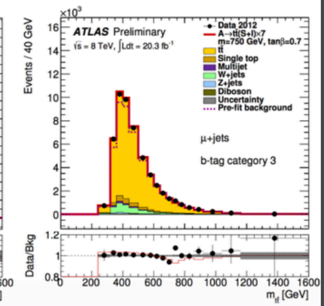
- Analysis targets the ttbar lepton+jets channel (one W to hadrons one to leptons)
  - Single electron or single muon triggers are used—2 categories (one for e; one for μ)
  - One high p_T electron or muon; high MET from the escaping neutrino; presence of at least 4 high p_T jets in the event; at least one jet originating from b quarks must be tagged (70%); Sum of MET and m_T > 60 GeV (multi-jets suppression) $m_T^W = \sqrt{2 \cdot p_T^\ell \cdot E_T^{\text{miss}} \cdot (1 - \cos\phi_{\ell\nu})}$
- A chi-squared fit is used for assignment of the decay products, then m_{tt} is reconstructed
  - Events further classified depending on the b-tagged jet(s) assignment—3 categories

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h - W}}{\sigma_{t_h - W}}\right]^2 + \left[\frac{m_{j\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,j\ell\nu}) - (p_{T,t_h} - p_{T,t_\ell})}{\sigma_{\text{diff}\,p_T}}\right]^2$$

6 categories in total (2 lepton types) x (3 b-tagging classifications)



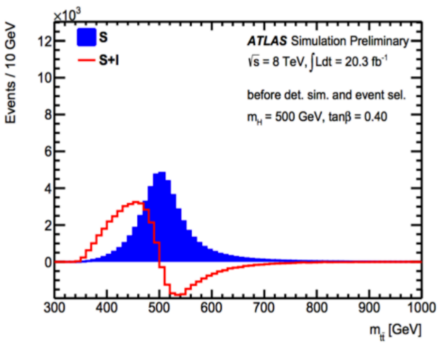


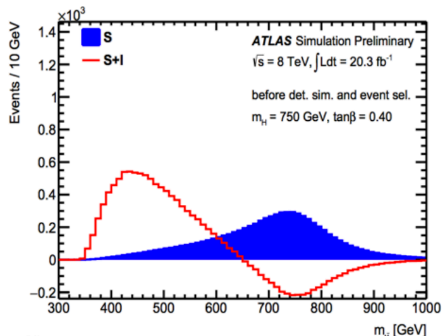


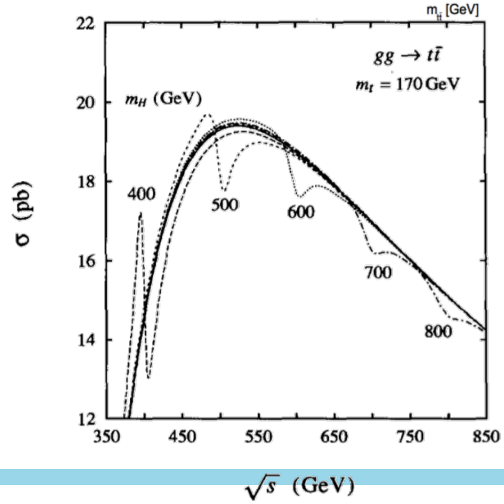
LHC perspectives—Experimental progress

Signal Modeling (A/H→ttbar)

- The signal process is simulated using the generator MadGraph5 v2.0.1 with the Higgs Effective Couplings Form Factor model (implements the production of scalar and pseudoscalar particles through loop-induced gluon fusion)
  - Loop contributions from both bottom and top quarks are taken into account
  - Signal shape is distorted from a simple Breit-Wigner peak, to a peak-dip structure
  - Statistical interpretation of measured event rates in data are compared to the total sum of Signal + Interference + Background (S + I + B)
  - The mass of the SM-like Higgs boson, h, is chosen to be 125 GeV and sin(β-α) is set to 1





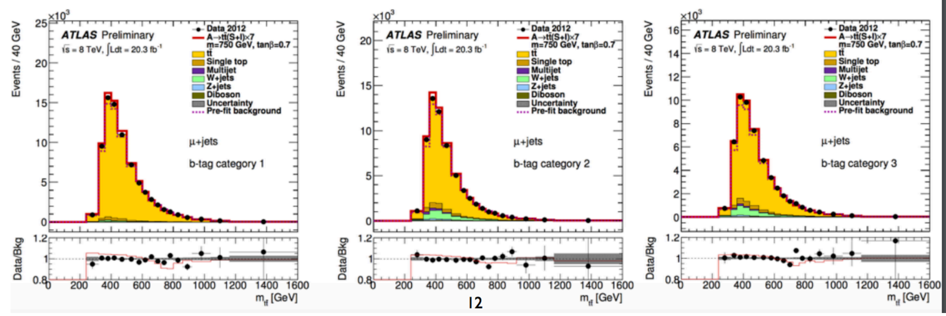


Event Selection / Mass Reconstruction (A/H→ttbar)

- Analysis targets the ttbar lepton+jets channel (one W to hadrons one to leptons)
  - Single electron or single muon triggers are used—2 categories (one for e; one for μ)
  - One high p_T electron or muon; high MET from the escaping neutrino; presence of at least 4 high p_T jets in the event; at least one jet originating from b quarks must be tagged (70%); Sum of MET and m_T > 60 GeV (multi-jets suppression) $m_T^W = \sqrt{2 \cdot p_T^\ell \cdot E_T^{\rm miss} \cdot (1-\cos\phi_{\ell\nu})}$
- A chi-squared fit is used for assignment of the decay products, then m_{tt} is reconstructed
  - Events further classified depending on the b-tagged jet(s) assignment—3 categories

$$\chi^2 = \left[\frac{m_{jj}-m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb}-m_{jj}-m_{t_h-W}}{\sigma_{t_h-W}}\right]^2 + \left[\frac{m_{j\ell\nu}-m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{T,jjb}-p_{T,j\ell\nu})-(p_{T,t_h}-p_{T,t_\ell})}{\sigma_{\mathrm{diff}\,p_T}}\right]^2$$

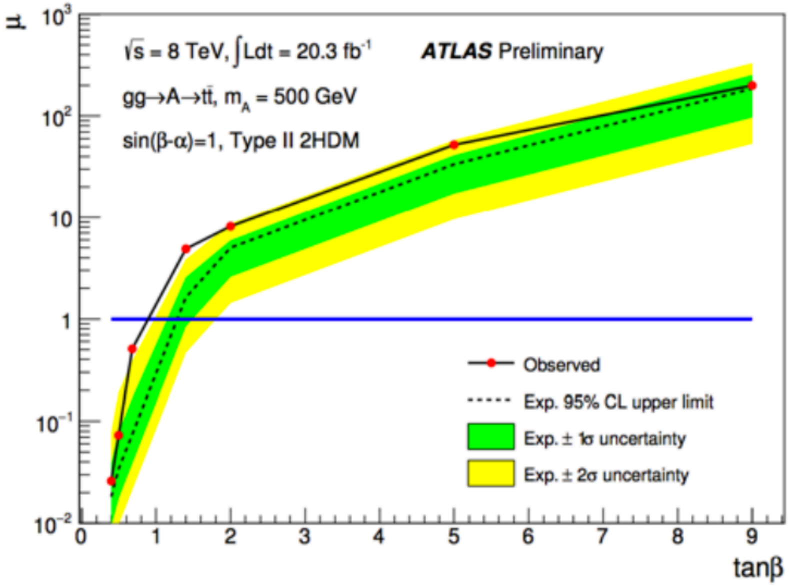
6 categories in total (2 lepton types) x (3 b-tagging classifications)

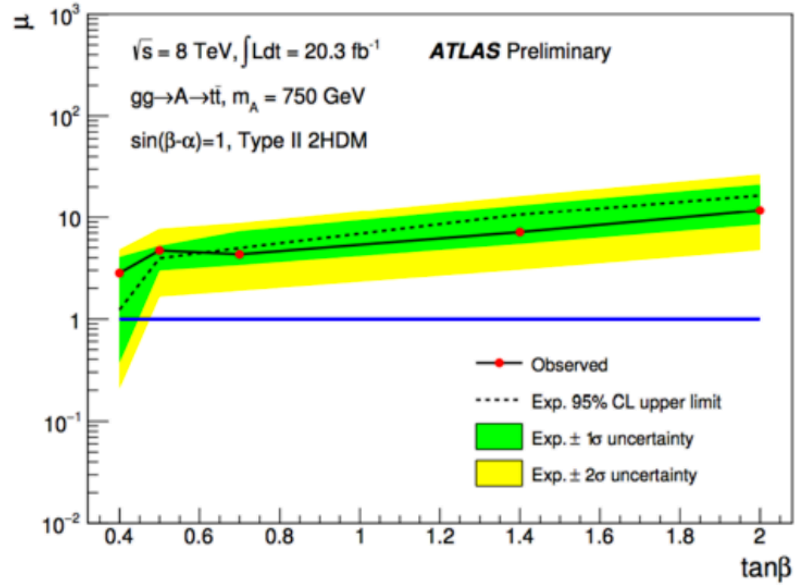


12

High-mass Higgs Search Results (A/H→ttbar)

- No significant excess over Standard Model background expectations is observed
- We set upper limits on the signal strength parameter μ as a function of the parameter tanβ for a neutral pseudoscalar A with a mass of 500 GeV and 750 GeV
- NB: The blue line at μ=1 corresponds to the signal strength in the Type-II 2HDM





- For a neutral pseudoscalar A, with a mass of m_A=500 GeV, parameter values of tanβ < 0.85 in the Type-II 2HDM are excluded at the 95% CL. No tanβ values can be excluded for the higher mass point at 750 GeV.

Summary and outlook for $gg \to S \to t\bar{t}$

$gg \to S \to t\bar{t}$ 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 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**), ttbar differential observables (W. Bernreuther, P. Galler, C. Mellein, Z.-G. Si, P. Uwer **arXiv:1702.06063**). 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.)

Recap of the strong phase physics

Strong phase plays important roles in various aspects of physics

- $t\bar{t}$ heavy resonances (dominant effect in the search)
- Hadron physics (strong phase mapping out CPV)
- Leptogenesis (weak phase from heavy neutrino decay interferes with strong phase part, generating asymmetry)

Recap of the strong phase physics

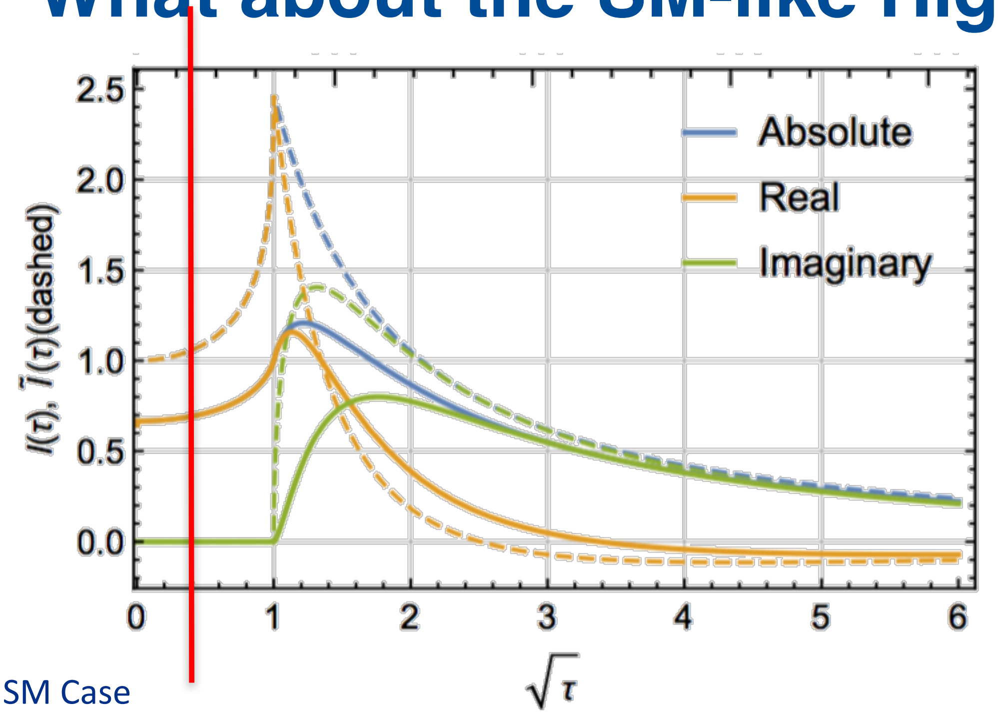
Strong phase plays important roles in various aspects of physics

- $t\bar{t}$ heavy resonances (dominant effect in the search)
- Hadron physics (strong phase mapping out CPV)
- Leptogenesis (weak phase from heavy neutrino decay interferes with strong phase part, generating asymmetry)

Question:
how about the strong phase in the SM Higgs?

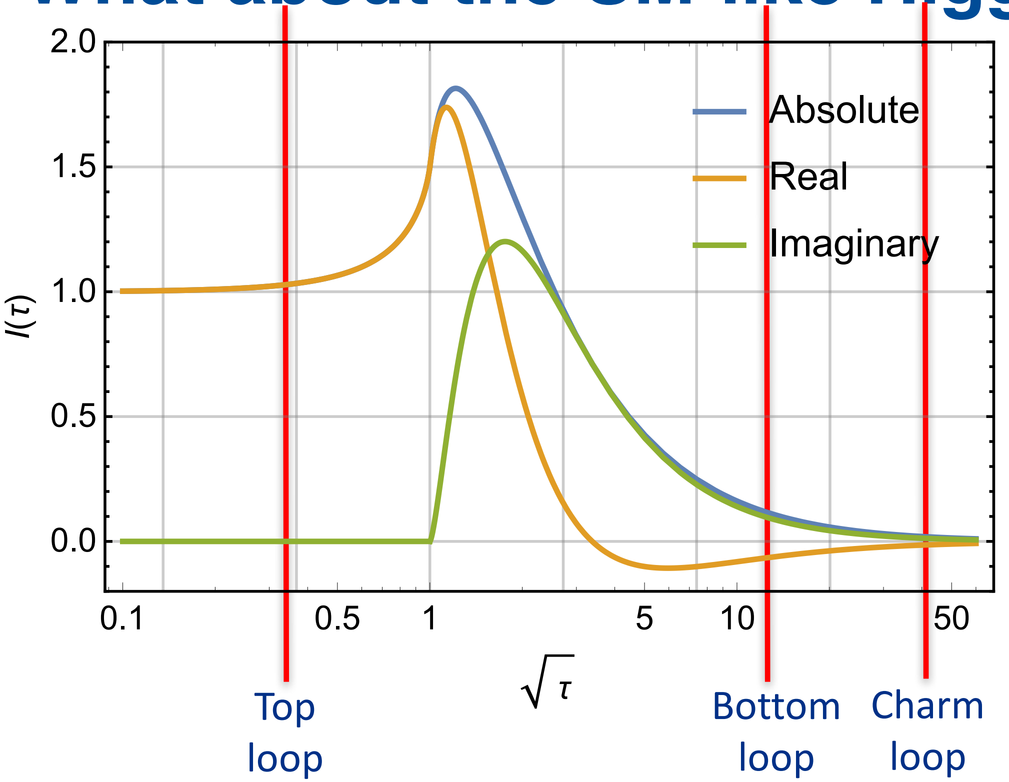
J. Campbell, M. Carena, R. Harnik, ZL, [arXiv:1704.08259]

What about the SM-like Higgs ~125 GeV?



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

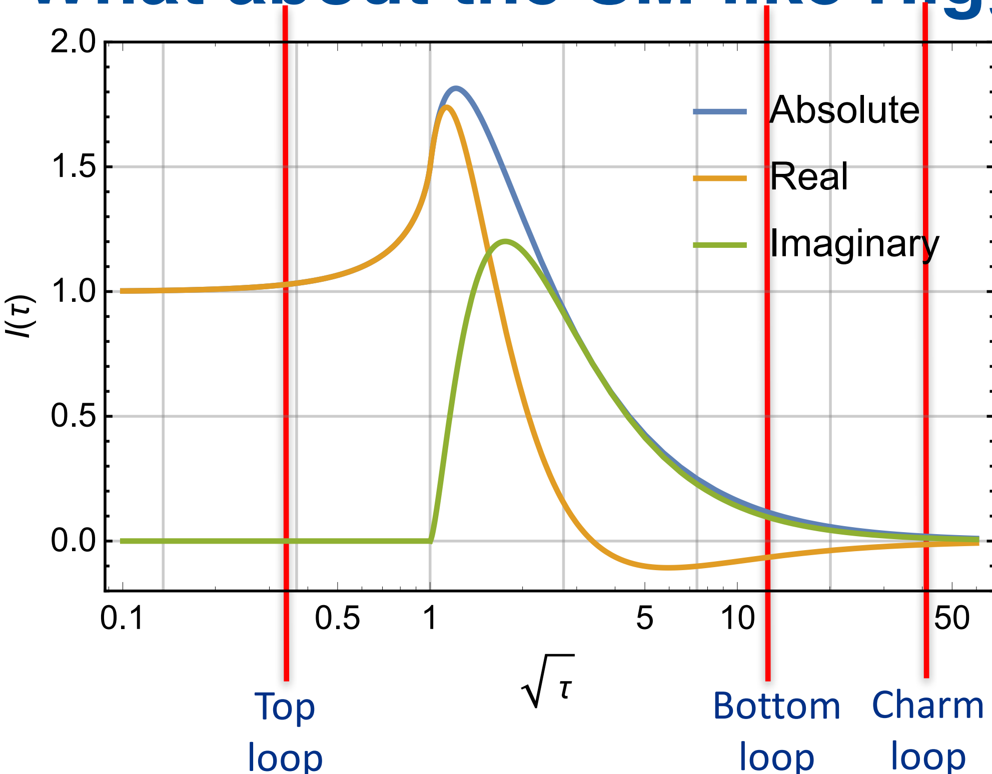
What about the SM-like Higgs ~125 GeV?



- All quark contributions normalized the same way, the plot represents the relative contributions
- Numerically*:
  - t-loop $+1.03$
  - b-loop $-0.054 + 0.071i$
  - c-loop $-0.014 + 0.012i$

*some input parameter dependence

What about the SM-like Higgs ~125 GeV?



- All quark contributions normalized the same way, the plot represents the relative contributions
- Numerically*:
  - t-loop $+1.034$
  - b-loop $-0.035 + 0.039i$
  - c-loop $-0.004 + 0.002i$

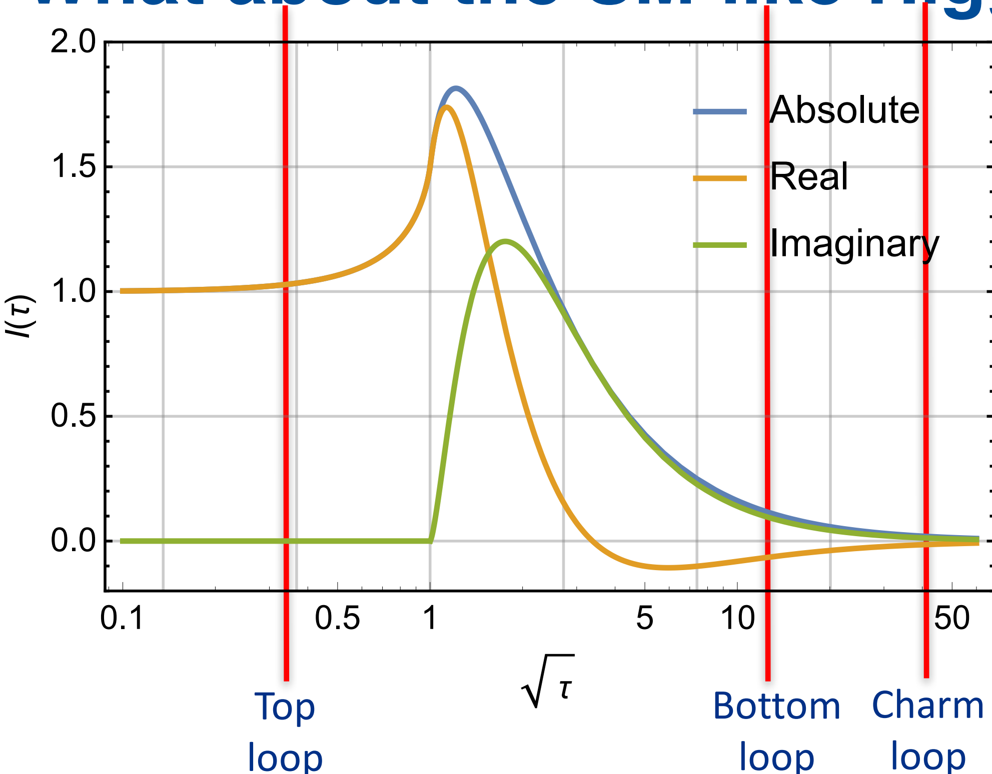
$$\frac{\sigma_{\rm BW}}{\sigma_{\rm BW}^{\rm SM}} = 1.078\kappa_t^2 - 0.074\kappa_t\kappa_b - 0.008\kappa_t\kappa_c + 0.003\kappa_b^2 + O(< 0.001; \kappa_t, \kappa_b, \kappa_c).$$

➔ two important consequences

- Destructive interference between the top-loop and light quarks for gluon-gluon fusion (real part)

*some input parameter dependence
HXWG recommends:
$\sigma(gg \to h) \propto 1.06\kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$

What about the SM-like Higgs ~125 GeV?



- All quark contributions normalized the same way, the plot represents the relative contributions
- Numerically*:
  - t-loop $+1.034$
  - b-loop $-0.035 + 0.039i$
  - c-loop $-0.004 + 0.002i$

➔two important consequences

- A strong phase in the gluon-gluon fusion production at hadron colliders (imaginary part) and will not see the strong-phase effect using narrow-width-approximation

Phase in gluon-gluon-fusion $\mathbf{0.042}$

Higgs interferences

Many occasions where interference are important for Higgs physics

- Higgs total width from $\gamma\gamma$ invariant mass shift
- Higgs total width from off-shell measurement
- Double Higgs production (destructive interference between the box diagram and the trilinear Higgs diagram)
- Higgs diphoton CPV effects from converted photon and its interference with $h \to ZZ^{*} \to 4e$ (Chen, Harnik and Vegas-Morales, **arXiv:1404.1336**, **arXiv:1503.05855**, **etc.**)
- ...

Fermilab

Higgs interferences

Many occasions where interference are important for Higgs physics

- Higgs total width from $\gamma\gamma$ invariant mass shift
- Higgs total width from off-shell measurement
- Double Higgs production (destructive interference between the box diagram and the trilinear Higgs diagram)
- Higgs diphoton CPV effects from converted photon and its interference with $h \to ZZ^* \to 4e$ (Chen, Harnik and Vegas-Morales, **arXiv:1404.1336**, **arXiv:1503.05855**, **etc.**)
- ...

But none of above make use of the strong phase in Higgs physics.

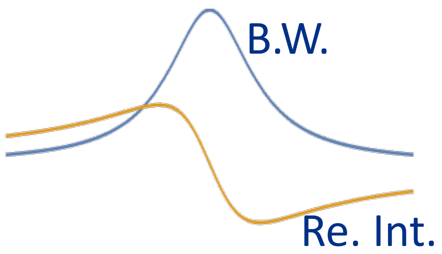
Higgs interferences

Many occasions where interference are important for Higgs physics

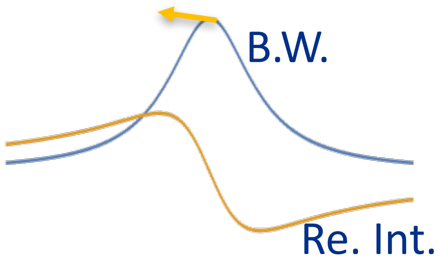
- Higgs total width from $\gamma\gamma$ invariant mass shift
- Higgs total width from off-shell measurement
- Double Higgs production (destructive interference between the box diagram and the trilinear Higgs diagram)
- Higgs diphoton CPV effects from converted photon and its interference with $h \to ZZ^* \to 4e$ (Chen, Harnik and Vegas-Morales, **arXiv:1404.1336**, **arXiv:1503.05855**, **etc.**)
- ...

But none of above make use of this strong phase in Higgs.
Let's have a brief review.

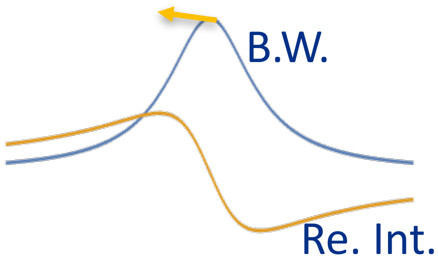
Higgs interferences (shifting diphoton)

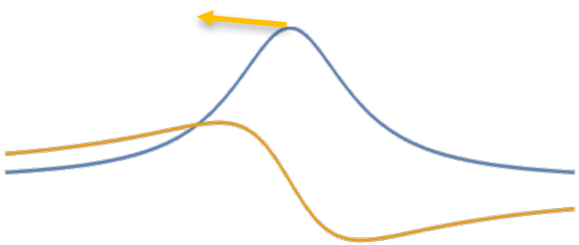


Higgs interferences (shifting diphoton)



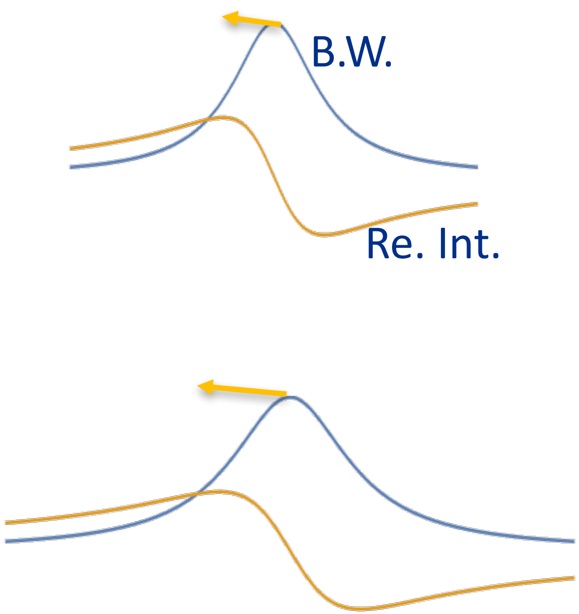
Higgs interferences (shifting diphoton)

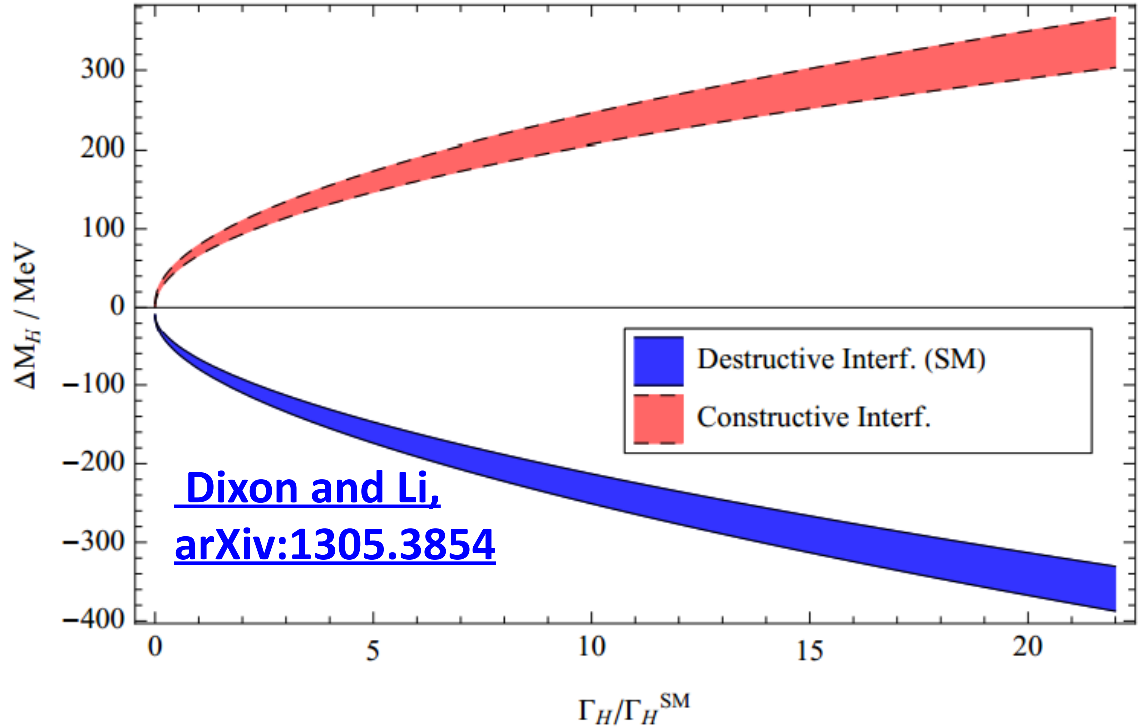




Interference with the irreducible background shifts the invariant mass peak.

Higgs interferences (shifting diphoton)





Interference with the irreducible background shifts the invariant mass peak.

By comparing with the 4l invariant mass (where little interference due to the smallness of the irreducible background), ideally, one can see the shift in the invariant mass of the final states.

Higgs interferences (on-shell and off-shell)

Higgs interferences (on-shell and off-shell)

All on-shell cross sections for the narrow Higgs can be parametrized as (NWA):

$$\sigma(i \to h \to f) \propto \frac{g_i^2 g_f^2}{f_{\Gamma_{tot}}}$$

Treating all couplings and total width as free parameters, there will always be a flat/runaway direction allowing increasing all parameters universally.

Higgs interferences (on-shell and off-shell)

All on-shell cross sections for the narrow Higgs can be parametrized as (NWA):

$$\sigma(i \to h \to f) \propto \frac{g_i^2 g_f^2}{f_{\Gamma_{tot}}}$$

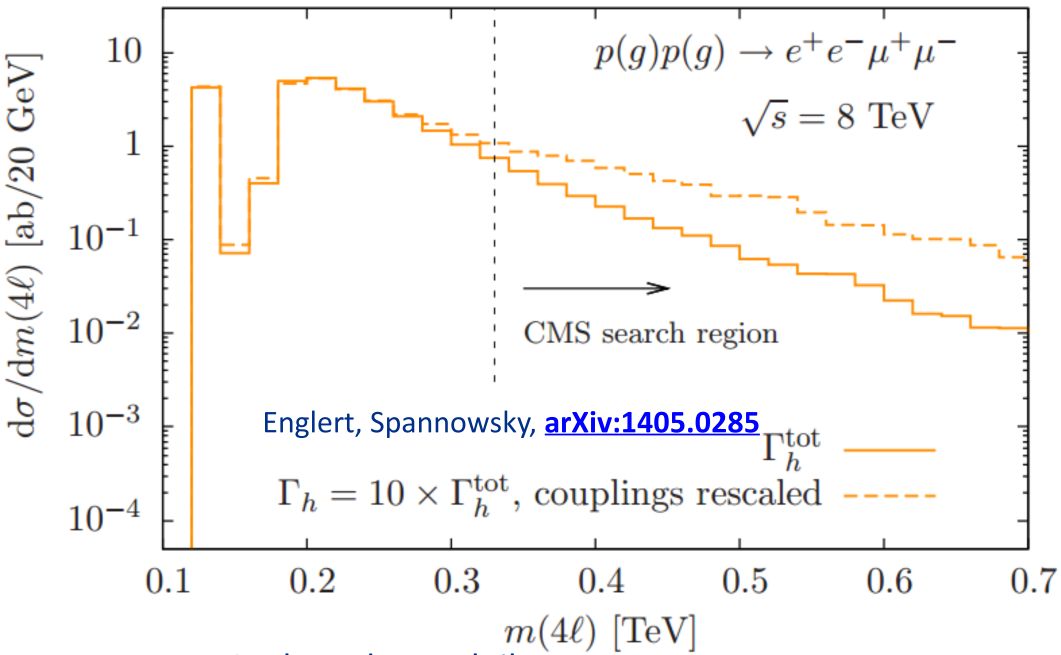
Treating all couplings and total width as free parameters, there will always be a flat/runaway direction allowing increasing all parameters universally.

Cross sections:

On-shell: $\frac{g_{ggh}^2 g_{ZZh}^2}{\Gamma_{tot}}$

Off-shell: $g_{ggh}^2 g_{ZZh}^2$

Higgs interferences (on-shell and off-shell)

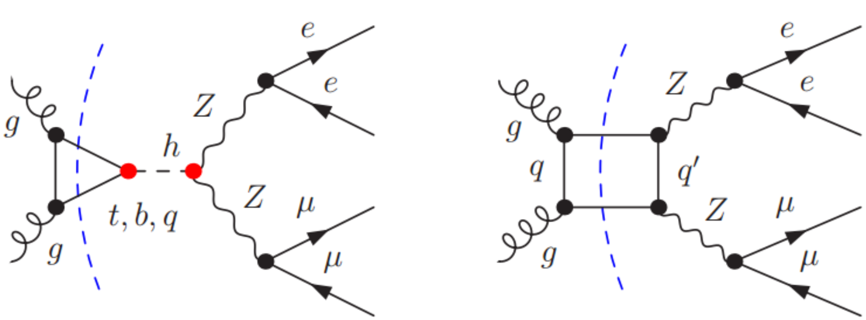


Cross sections:

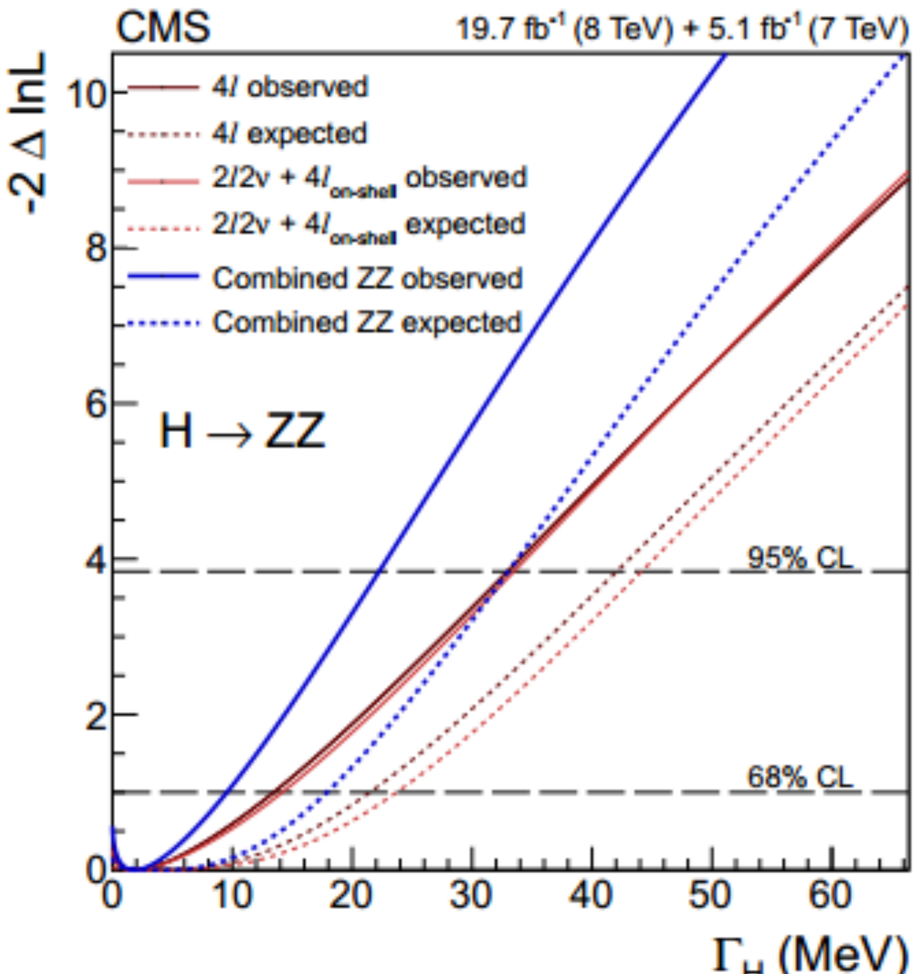
On-shell: $\frac{g_{ggh}^2 g_{ZZh}^2}{\Gamma_{tot}}$

Off-shell: $g_{ggh}^2 g_{ZZh}^2$

F. Caola and K. Melnikov arXiv:1307.4935
And N. Kauer and G.Passarino arXiv:1206.4803 estimated an "eventual" reach of ~10 SM width;
CMS with current data ~5.4 SM width;



Higgs interferences (on-shell and off-shell)



Higher order corrections at Hadron colliders is going limit the precision of this measurement at O(1) level.
Improvement hard to achieve.

Cross sections:

On-shell: $\frac{g_{ggh}^2 g_{ZZh}^2}{\Gamma_{tot}}$

Off-shell: $g_{ggh}^2 g_{ZZh}^2$

F. Caola and K. Melnikov estimated an "eventually" reach of ~10 SM width;
CMS with current data ~5.4 SM width;

Great measurement, but:

1) On-shell rate uncertainty
2) Loop-running⇔interplay of (at least) undetermined Top Yukawa
3) Many possible NP input at higher inv. masses.
4) Higher order corrections.

See discussions in e.g., **arXiv:1405.0285**, **arXiv:1410.5440**, **arXiv:1412.7577**, **arXiv:1502.04678** , …

Strong phase and Higgs (our study)

In the SM, there are two main loop-induced Higgs couplings (where the strong phase could be sizable):

- Hgg: 0.042
- $H\gamma\gamma$: $\pi - 0.006$
- $HZ\gamma$: $\sim H\gamma\gamma$

Strong phase and Higgs (our study)

In the SM, there are two main loop-induced Higgs couplings (where the strong phase could be sizable):

- $Hgg: 0.042$
- $H\gamma\gamma: \pi - 0.006$
- $HZ\gamma: \sim H\gamma\gamma$

Choosing the channel to study at the LHC:

Fermilab

Strong phase and Higgs (our study)

In the SM, there are two main loop-induced Higgs couplings (where the strong phase could be sizable):

- Hgg: 0.042
- $H\gamma\gamma$: $\pi - 0.006$
- $HZ\gamma$: $\sim H\gamma\gamma$

Choosing the channel to study at the LHC:

- Production and/or decay has strong phase
  - gluon-gluon-fusion production chosen;

Strong phase and Higgs (our study)

In the SM, there are two main loop-induced Higgs couplings (where the strong phase could be sizable):

- $Hgg: 0.042$
- $H\gamma\gamma: \pi - 0.006$
- $HZ\gamma: \sim H\gamma\gamma$

Choosing the channel to study at the LHC:

- Production and/or decay has strong phase
  - gluon-gluon-fusion production chosen;
- Signal and interfering background are comparable:
  - If background too large, hard to observe signal;
  - If background too small, interference effect would be tiny

Strong phase and Higgs (our study)

In the SM, there are two main loop-induced Higgs couplings (where the strong phase could be sizable):

- Hgg: 0.042
- $H\gamma\gamma$: $\pi - 0.006$
- $HZ\gamma$: $\sim H\gamma\gamma$

Choosing the channel to study at the LHC:

- Production and/or decay has strong phase
  - gluon-gluon-fusion production chosen;
- Signal and interfering background are comparable:
  - If background too large, hard to observe signal;
  - If background too small, interference effect would be tiny
- Preferably a channel where precision study could be performed (choose from currently observed Higgs channels)

Strong phase and Higgs (our study)

In the SM, there are two main loop-induced Higgs couplings (where the strong phase could be sizable):

- Hgg: 0.042
- $H\gamma\gamma$: $\pi - 0.006$
- $HZ\gamma$: $\sim H\gamma\gamma$

Choosing the channel to study at the LHC:

- Production and/or decay has strong phase
  - gluon-gluon-fusion production chosen;
- Signal and interfering background are comparable:
  - If background too large, hard to observe signal;
  - If background too small, interference effect would be tiny
- Preferably a channel where precision study could be performed (choose from currently observed Higgs channels)

$$gg \to H \to \gamma\gamma$$

*other channels in progress

Strong phase and Higgs $gg \to h \to \gamma\gamma$

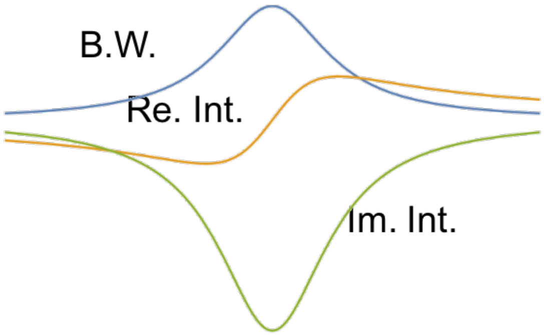
Strong phase of the signal process:

$$\delta_S = \pi + 0.036$$

$$\frac{Im\ e^{i\delta_S}}{Re\ e^{i\delta_S}} = 0.04$$

- The overall phase important to determine both signs of Re.Interference and Im.Interference
- The ratio of Im/Re for small Im useful to determine relative cross section change
- Signal helicity amplitudes (due to scalar nature, and without CPV) has

$$A_{++++} = A_{----} = A_{++--} = A_{--++}$$



Strong phase and Higgs $gg \to h \to \gamma\gamma$

Strong phase of the signal process:

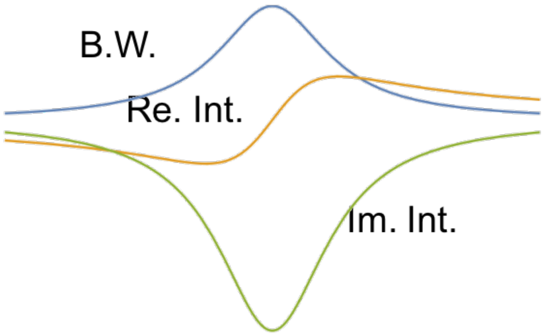
$$\delta_S = \pi + 0.036$$

$$\frac{Im\ e^{i\delta_S}}{Re\ e^{i\delta_S}} = 0.04$$

- The overall phase important to determine both signs of Re.Interference and Im.Interference
- The ratio of Im/Re for small Im useful to determine relative cross section change
- Signal helicity amplitudes (due to scalar nature, and without CPV) has

$A_{++++} = A_{----} = A_{++--} = A_{--++}$

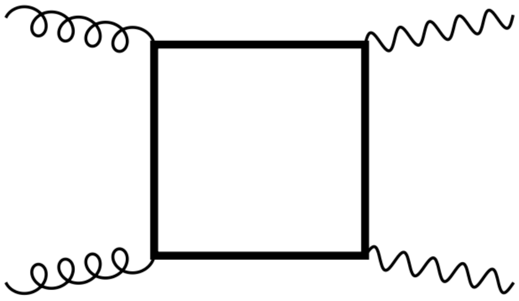
- O(1) shift in the strong phase as function of Yukawas

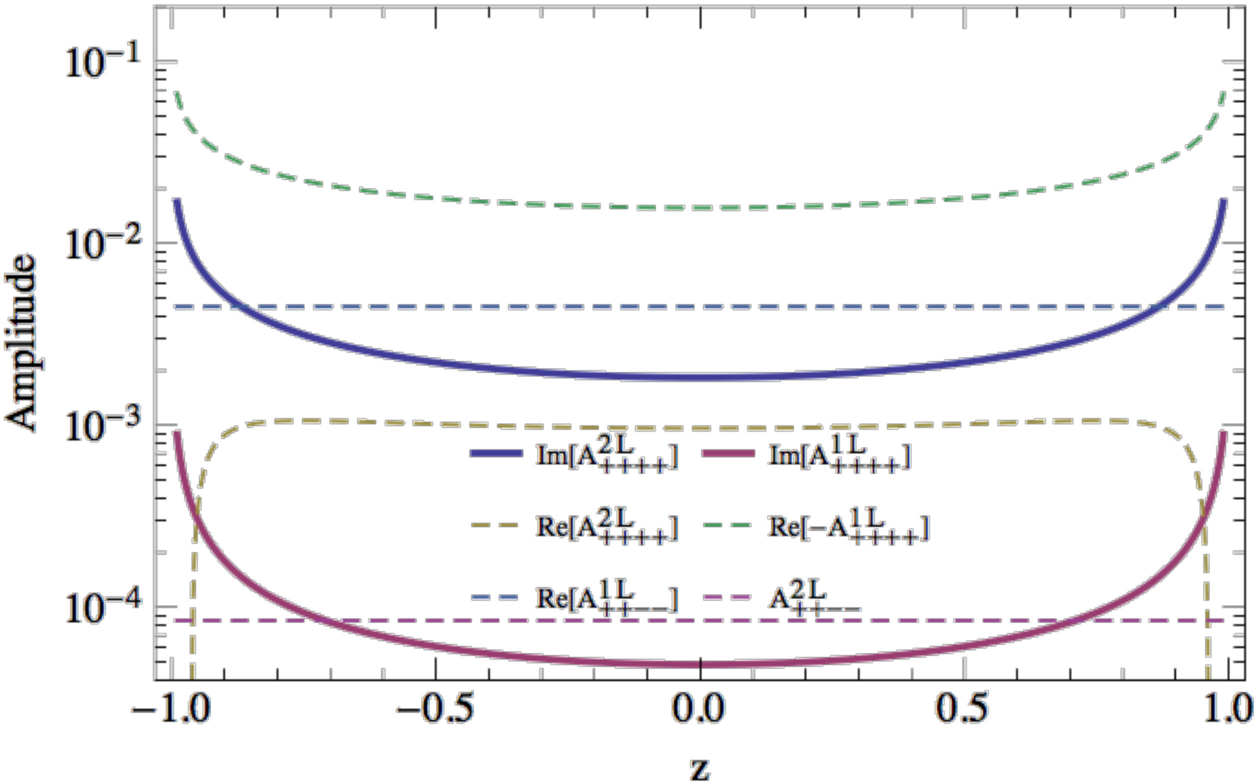


Strong phase and Higgs $gg \to h \to \gamma\gamma$

Interfering background are from SM box diagram of $gg \to \gamma\gamma$

The overall sizes of different helicity amplitudes are

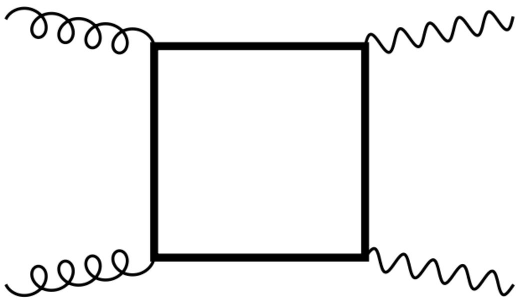


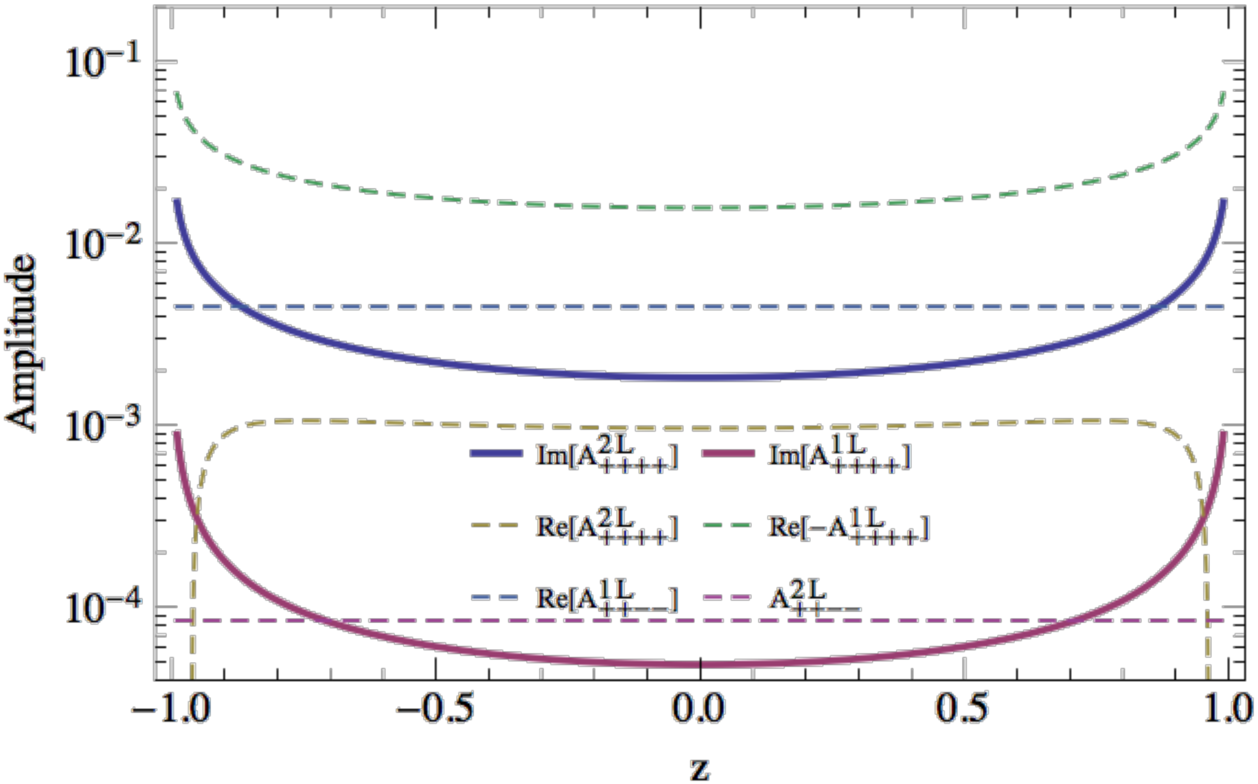


- $A_{++++} = A_{----}$ dominants, $A_{++--} = A_{--++}$ much smaller
- Light quark dominants
- Angular dependence

Strong phase and Higgs $gg \to h \to \gamma\gamma$

Interfering background are from SM box diagram of $gg \to \gamma\gamma$
There is also a strong phase in the background:



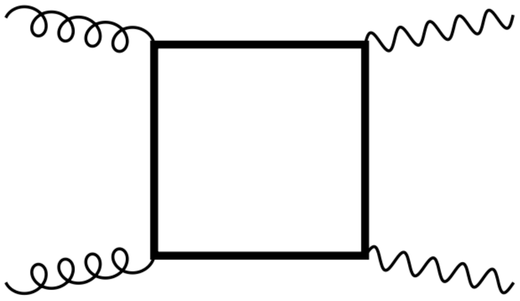


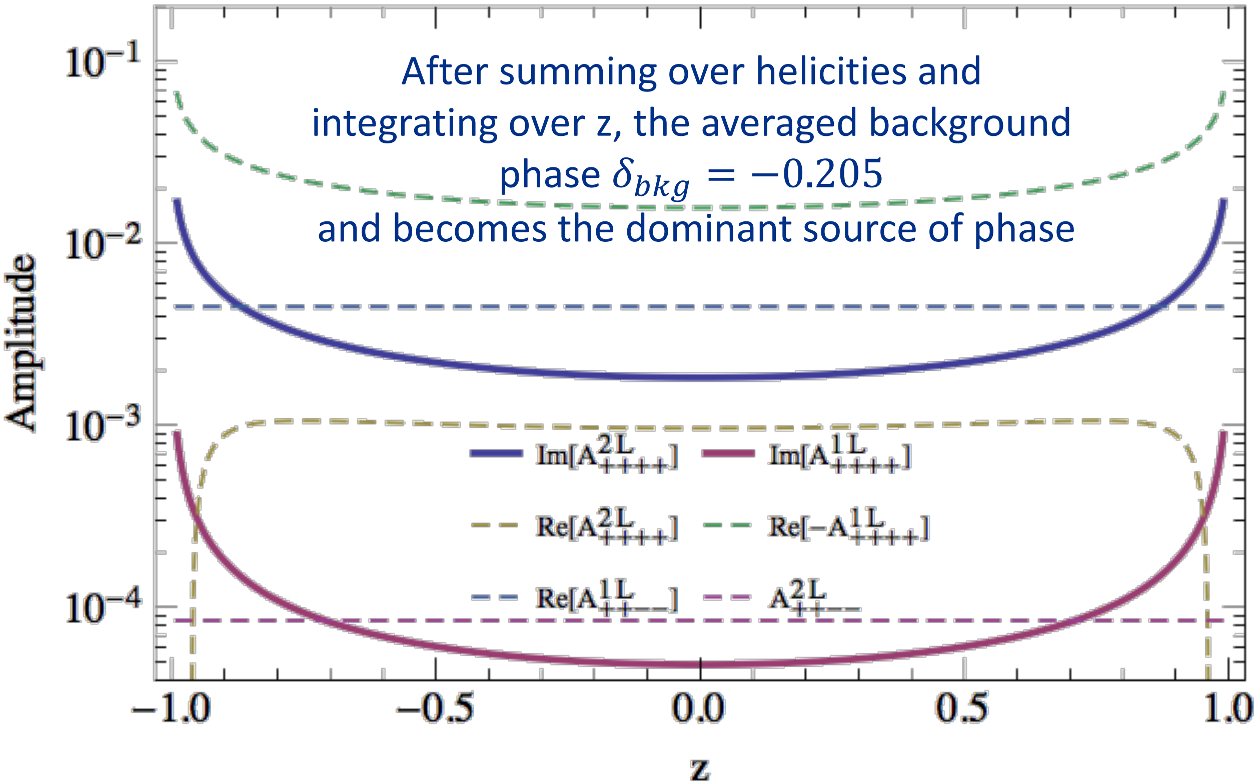
- Angular dependence
- a smaller but negative phase w.r.t to the signal
- At IL, the imaginary part is mainly from $A_{++++} = A_{----}$ with bottom and charm contributions
- Imaginary part dominated by the 2L MHV amplitude.

Strong phase and Higgs $gg \to h \to \gamma\gamma$

Interfering background are from SM box diagram of $gg \to \gamma\gamma$

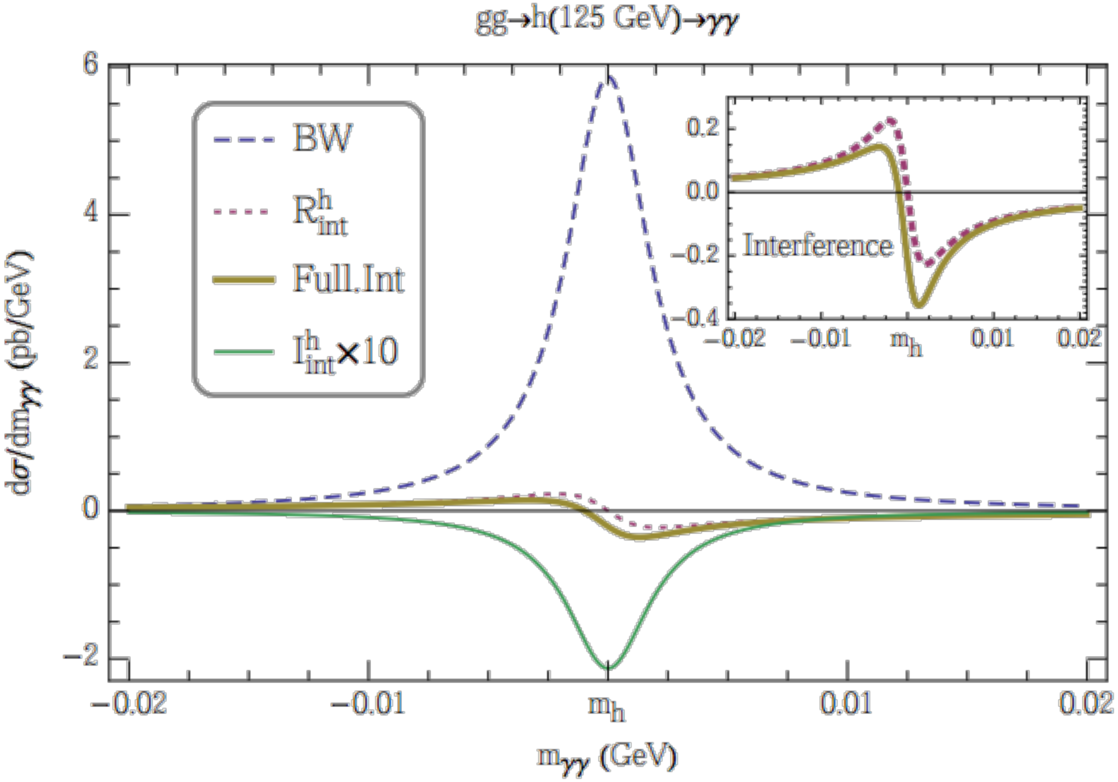
There is also a strong phase in the background:





- Angular dependence
- a smaller but negative phase w.r.t to the signal
- At lL, the imaginary part is mainly from $A_{++++} = A_{----}$ with bottom and charm contributions
- Imaginary part dominated by the 2L MHV amplitude.

Strong phase and Higgs $gg \to h \to \gamma\gamma$

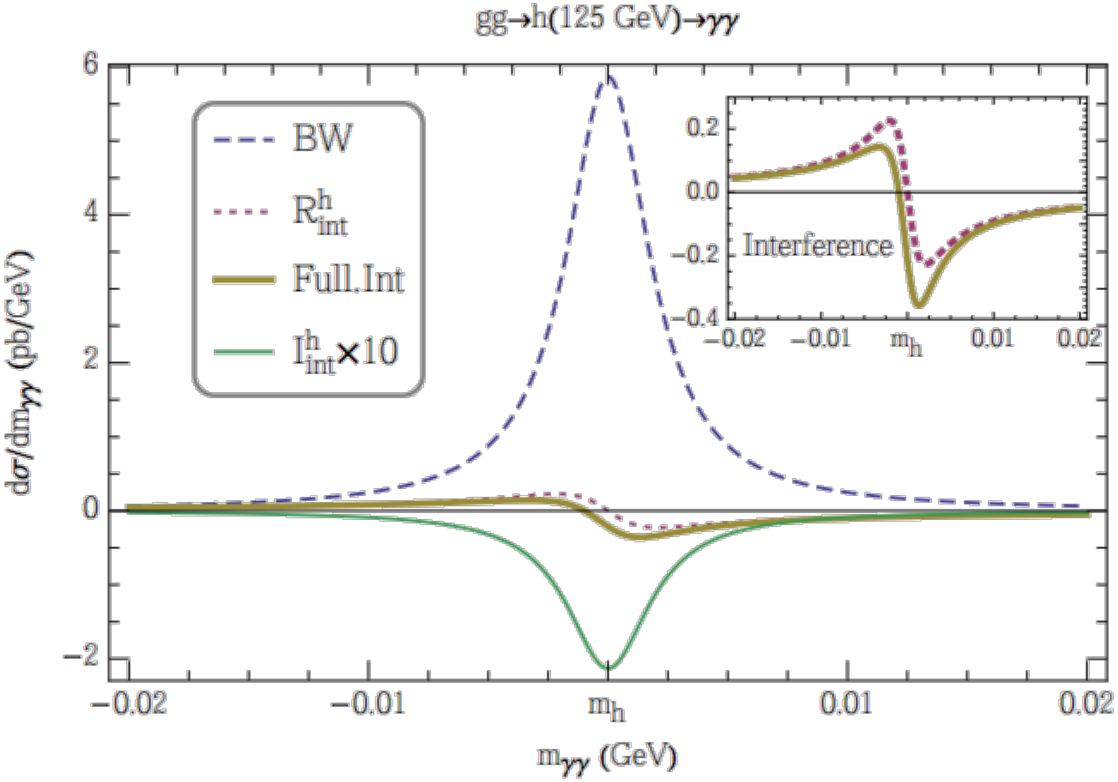


Define the relative strong phase $\delta = \delta_{sig} - \delta_{bkg}$, average over helicity amplitudes and polar angles, one can calculate this new interference piece between signal and background

Long been overlooked, the interference term from the strong phase does change the SM rate prediction by $\sim -2.\%$*

*This agrees with Dixon and Siu's partial calculation in 03

Strong phase and Higgs $gg \to h \to \gamma\gamma$



Define the relative strong phase $\delta = \delta_{sig} - \delta_{bkg}$, average over helicity amplitudes and polar angles, one can calculate this new interference piece between signal and background

Long been overlooked, the interference term from the strong phase does change the SM rate prediction by $\sim -2.\%$*

Production	Resolved scaling factor
$\sigma(ggF)$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	κ_W^2

ATLAS and CMS legacy combination paper, JHEP

- The size of this effect is relevant
- This effect cannot be factorized into production times decay branching fractions, the framework fails to capture this;

*This agrees with Dixon and Siu's partial calculation in 03

Strong phase and Higgs $gg \to h \to \gamma\gamma$ (BSM)

This rate change as a new probe of Higgs total width

$$\sigma(gg \to h \to \gamma\gamma) \propto \frac{g_{ggh}^2 g_{\gamma\gamma h}^2}{\Gamma_{tot}} - (\sim 2.\%) g_{ggh} g_{\gamma\gamma h}$$

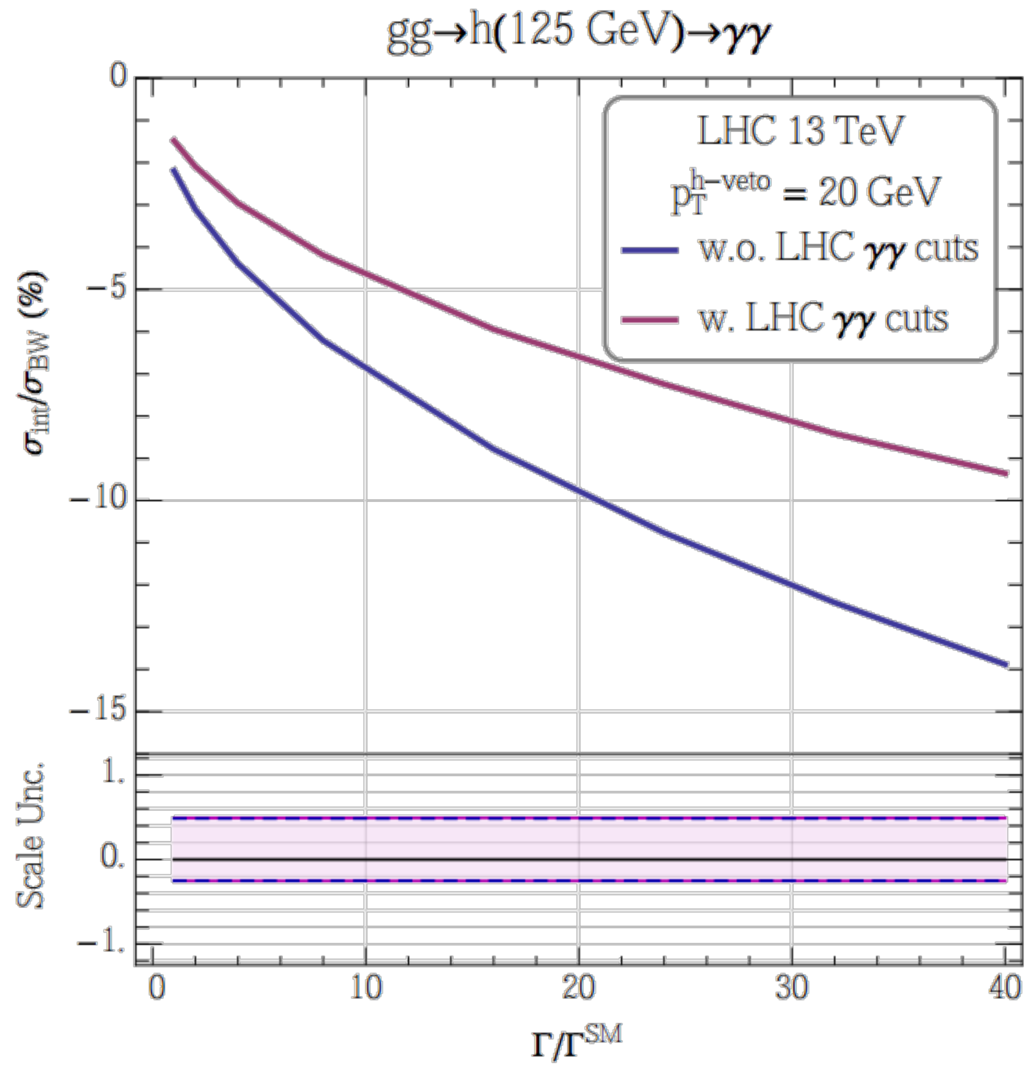
- Unique piece that does not depend on total width;
- Similar to off-shell ZZ measurement;
- Negligible dependence on coupling at different scales.

Strong phase and Higgs $gg \to h \to \gamma\gamma$ (BSM)

This rate change as a new probe of Higgs total width

$$\sigma(gg \to h \to \gamma\gamma) \propto \frac{g_{ggh}^2 g_{\gamma\gamma h}^2}{\Gamma_{tot}} - (\sim 2.\%) g_{ggh} g_{\gamma\gamma h}$$

- Unique piece that does not depend on total width;
- Similar to off-shell ZZ measurement;
- Negligible dependence on coupling at different scales.

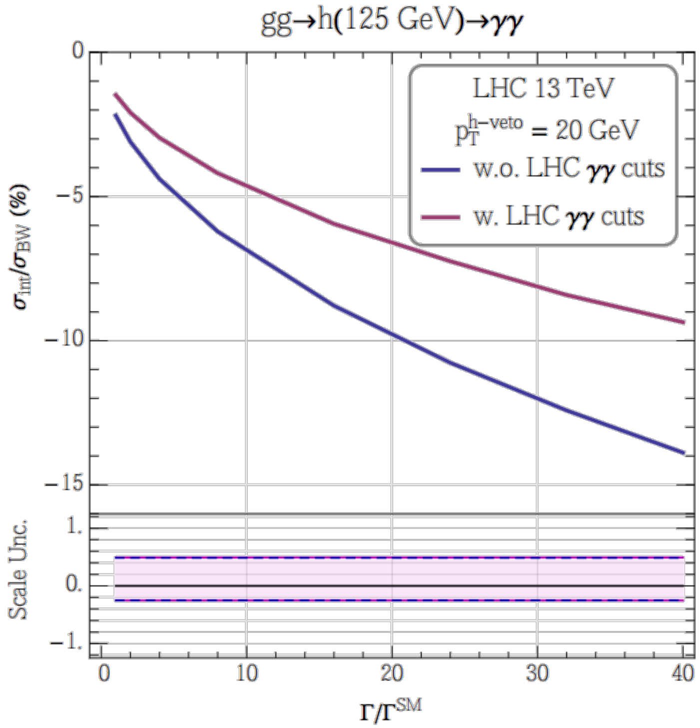


Strong phase and Higgs $gg \to h \to \gamma\gamma$ (BSM)

This rate change as a new probe of Higgs total width

$$\sigma(gg \to h \to \gamma\gamma) \propto \frac{g_{ggh}^2 g_{\gamma\gamma h}^2}{\Gamma_{tot}} - (\sim 2.\%) g_{ggh} g_{\gamma\gamma h}$$

- Unique piece that does not depend on total width;
- Similar to off-shell ZZ measurement;
- Negligible dependence on coupling at different scales.



Suppose the extreme nightmare case of all observed Higgs couplings increase by factor f, and Higgs total width by factor f^4.

All on-shell cross sections remains the same as SM predictions.

However, the process $gg \to h \to \gamma\gamma$ will be altered by

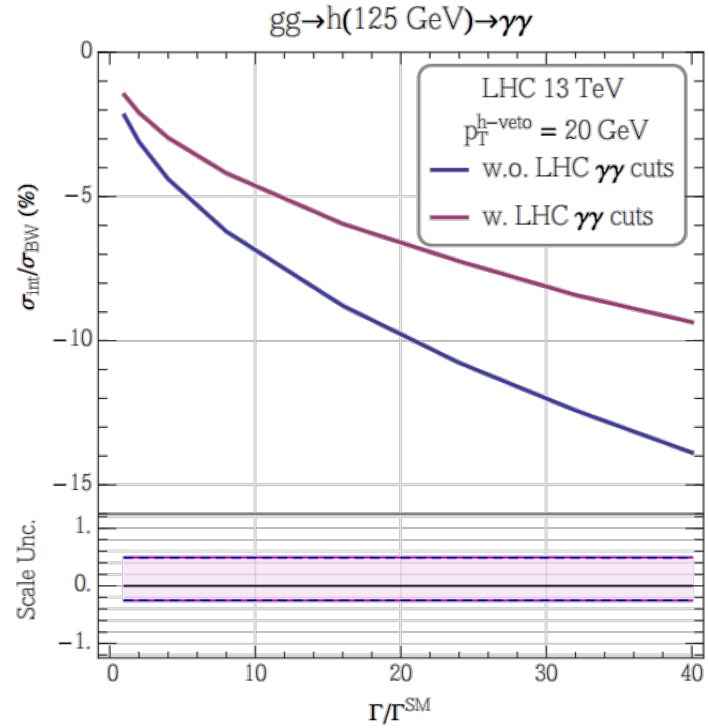
$$-(\sim 2\% \times f^2)$$

Strong phase and Higgs $gg \to h \to \gamma\gamma$ (BSM)

This rate change as a new probe of Higgs total width

$$\sigma(gg \to h \to \gamma\gamma) \propto \frac{g_{ggh}^2 g_{\gamma\gamma h}^2}{\Gamma_{tot}} - (\sim 2.\%) g_{ggh} g_{\gamma\gamma h}$$

- Unique piece that does not depend on total width;
- Similar to off-shell ZZ measurement;
- Negligible dependence on coupling at different scales.



Suppose the extreme nightmare case of all observed Higgs couplings increase by factor f, and Higgs total width by factor f^4.

All on-shell cross sections remains the same as SM predictions.

However, the process $gg \to h \to \gamma\gamma$ will be altered by

$$-(\sim 2\% \times f^2)$$

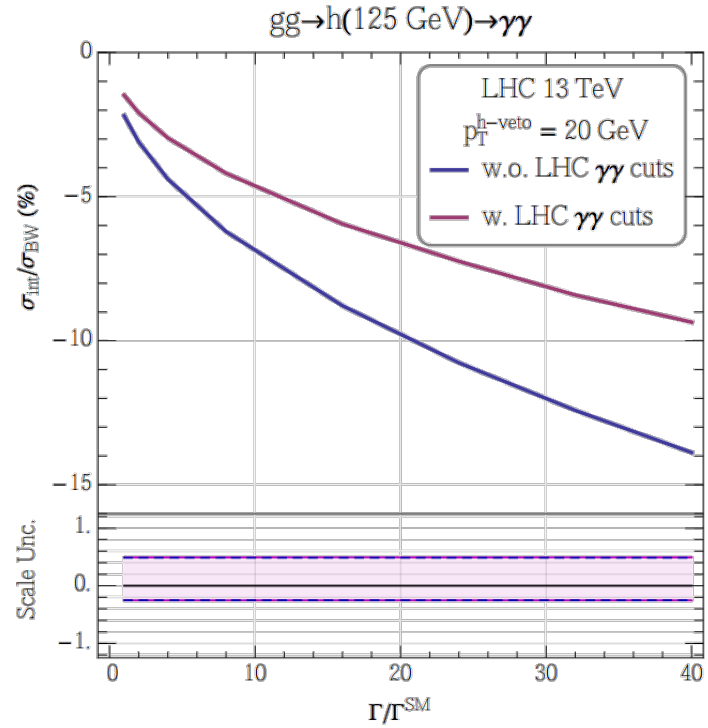
Suppose HL-LHC will measure this effect (e.g., the ratio of $\sigma_{\gamma\gamma}/\sigma_{4l}$) to 4%, it will constraint Higgs total width to ~13 times SM value

Strong phase and Higgs $gg \to h \to \gamma\gamma$ (BSM)

This rate change as a new probe of Higgs total width

$$\sigma(gg \to h \to \gamma\gamma) \propto \frac{g_{ggh}^2 g_{\gamma\gamma h}^2}{\Gamma_{tot}} - (\sim 2.\%) g_{ggh} g_{\gamma\gamma h}$$

- Unique piece that does not depend on total width;
- Similar to off-shell ZZ measurement;
- Negligible dependence on coupling at different scales.



However, the process $gg \to h \to \gamma\gamma$ will be altered by

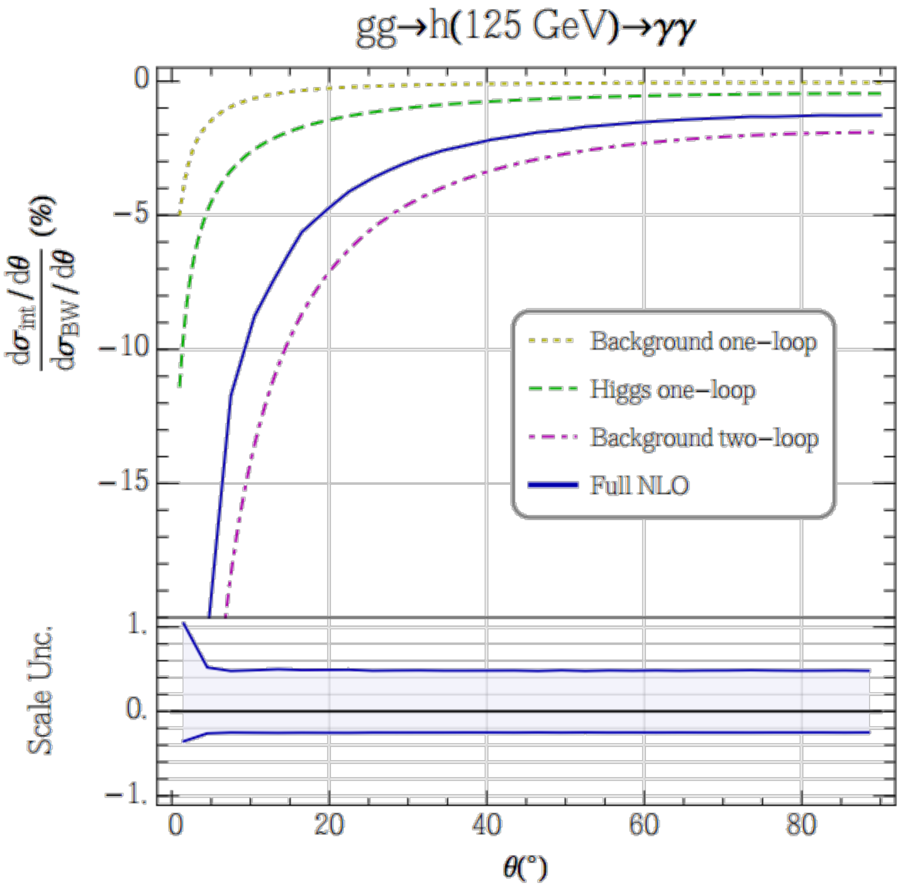
$$-(\sim 2\% \times f^2)$$

Suppose HL-LHC will measure this effect (e.g., the ratio of $\sigma_{\gamma\gamma}/\sigma_{4l}$) to 4%, it will constraint Higgs total width to ~13 times SM value;

The FCC-hh will increase the precision by at least one order of magnitude, yielding a 3-σ measurement of the interference effect and bounding the Higgs width

$$0.5 < \Gamma/\Gamma_{SM} < 1.6$$

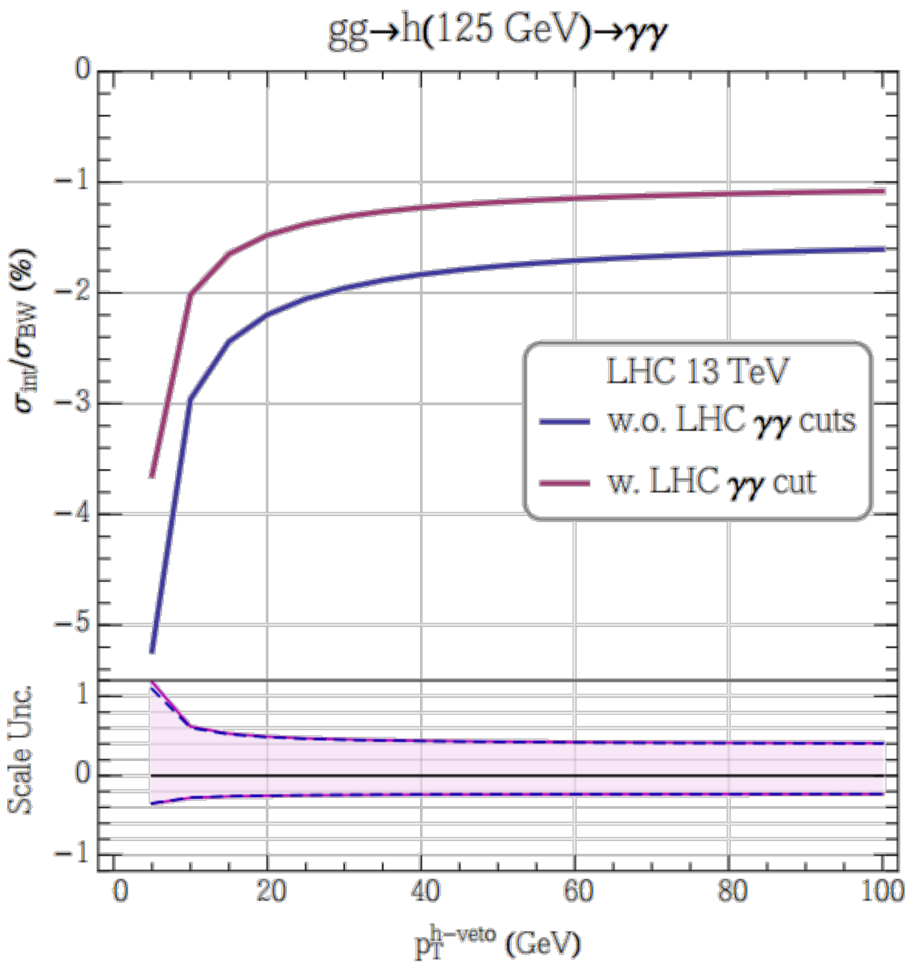
Kinematic features of the interference effect



Angular distribution:

- Interference effects larger in the forward direction, driven by background amplitude kinematics;
- Interference effects ~0.5% at LO
- Interference effects increases to ~2% at NLO, driven by the 2L MHV amplitude's large imaginary part
- Fully inclusive cross section has larger B.W. cross section while the interference effect does not increase much, resulting in a smaller relative correction.

Kinematic features of the interference effect



pT-veto distribution:

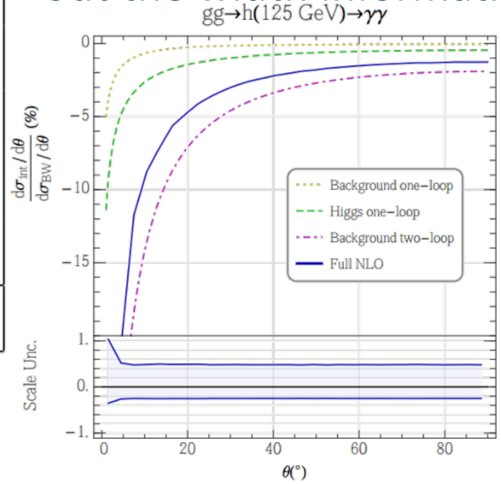
Consequently, one can also use jet-veto distribution to see the difference;

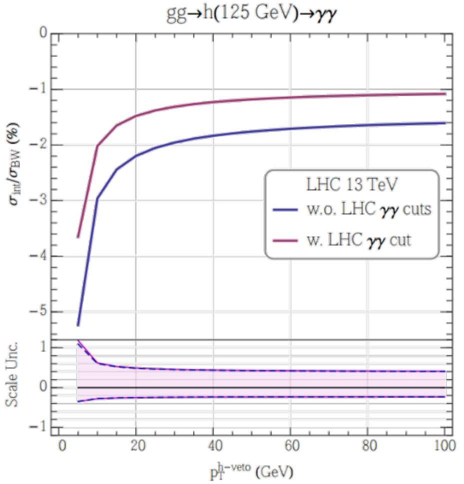
Larger veto-pT, smaller relative size

Kinematic features of the interference effect

$\|\cos\theta\|$	$-\sigma_{\rm int}/\sigma_{\rm BW}$ (%)		
	no cuts	p_T^h veto	$\gamma\gamma$ cuts+veto
0.0–0.2	$0.87^{+0.34}_{-0.20}$	$1.28^{+0.62}_{-0.32}$	$1.34^{+0.68}_{-0.34}$
0.2–0.4	$0.91^{+0.36}_{-0.21}$	$1.35^{+0.65}_{-0.34}$	$1.41^{+0.72}_{-0.36}$
0.4–0.6	$1.04^{+0.41}_{-0.24}$	$1.53^{+0.74}_{-0.38}$	$1.62^{+0.83}_{-0.42}$
0.6–0.8	$1.37^{+0.53}_{-0.31}$	$1.99^{+0.96}_{-0.50}$	$1.65^{+0.75}_{-0.40}$
0.8–1.0	$3.55^{+1.45}_{-0.82}$	$4.85^{+2.37}_{-1.23}$	–
0.0–1.0	$1.52^{+0.60}_{-0.35}$	$2.20^{+1.06}_{-0.55}$	$1.48^{+0.73}_{-0.38}$

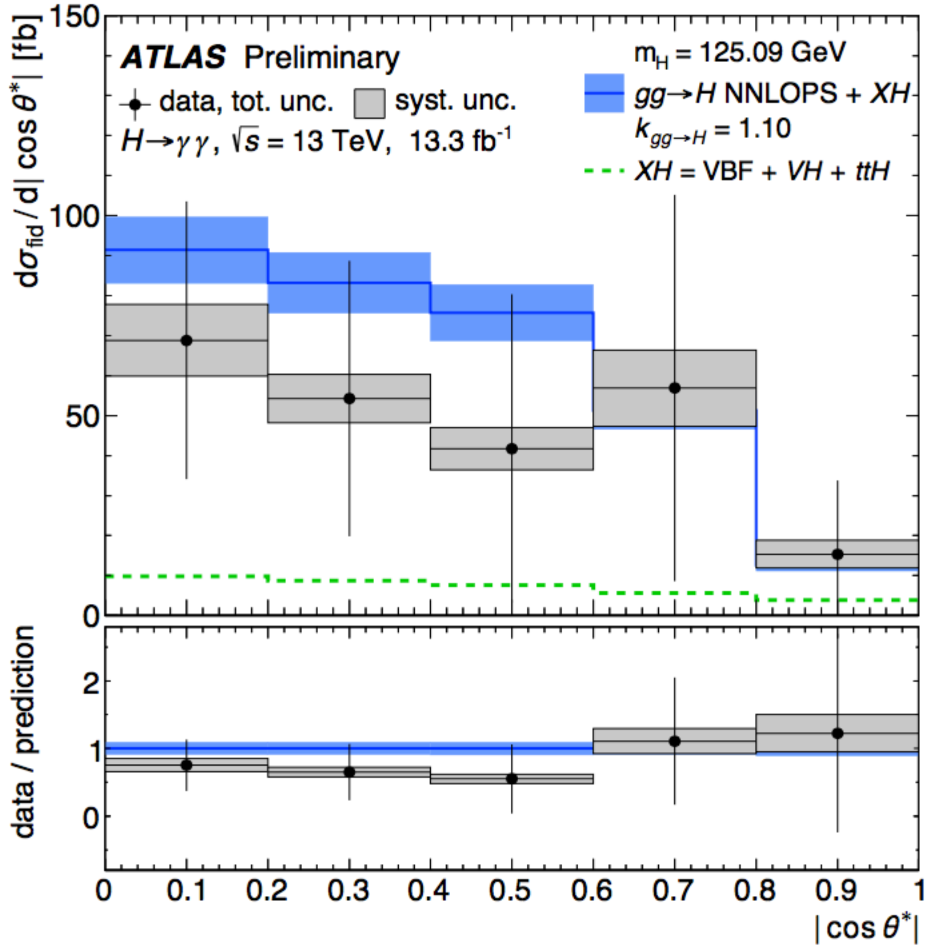
Differential distributions help map out the interference effect, and it can help mapping out the width information!





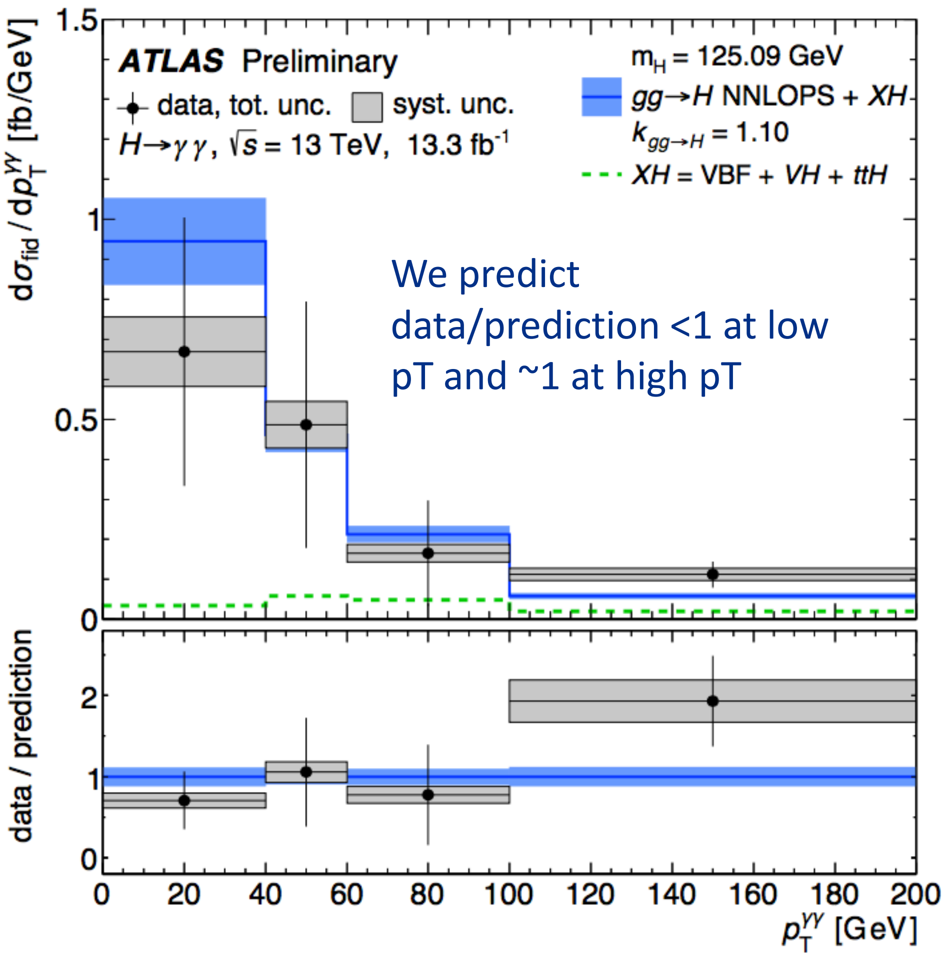
Kinematic features of the interference effect

$\lvert\cos\theta\rvert$	$-\sigma_{\rm int}/\sigma_{\rm BW}$ (%)		
	no cuts	p_T^h veto	$\gamma\gamma$ cuts+veto
0.0–0.2	$0.87^{+0.34}_{-0.20}$	$1.28^{+0.62}_{-0.32}$	$1.34^{+0.68}_{-0.34}$
0.2–0.4	$0.91^{+0.36}_{-0.21}$	$1.35^{+0.65}_{-0.34}$	$1.41^{+0.72}_{-0.36}$
0.4–0.6	$1.04^{+0.41}_{-0.24}$	$1.53^{+0.74}_{-0.38}$	$1.62^{+0.83}_{-0.42}$
0.6–0.8	$1.37^{+0.53}_{-0.31}$	$1.99^{+0.96}_{-0.50}$	$1.65^{+0.75}_{-0.40}$
0.8–1.0	$3.55^{+1.45}_{-0.82}$	$4.85^{+2.37}_{-1.23}$	–
0.0–1.0	$1.52^{+0.60}_{-0.35}$	$2.20^{+1.06}_{-0.55}$	$1.48^{+0.73}_{-0.38}$

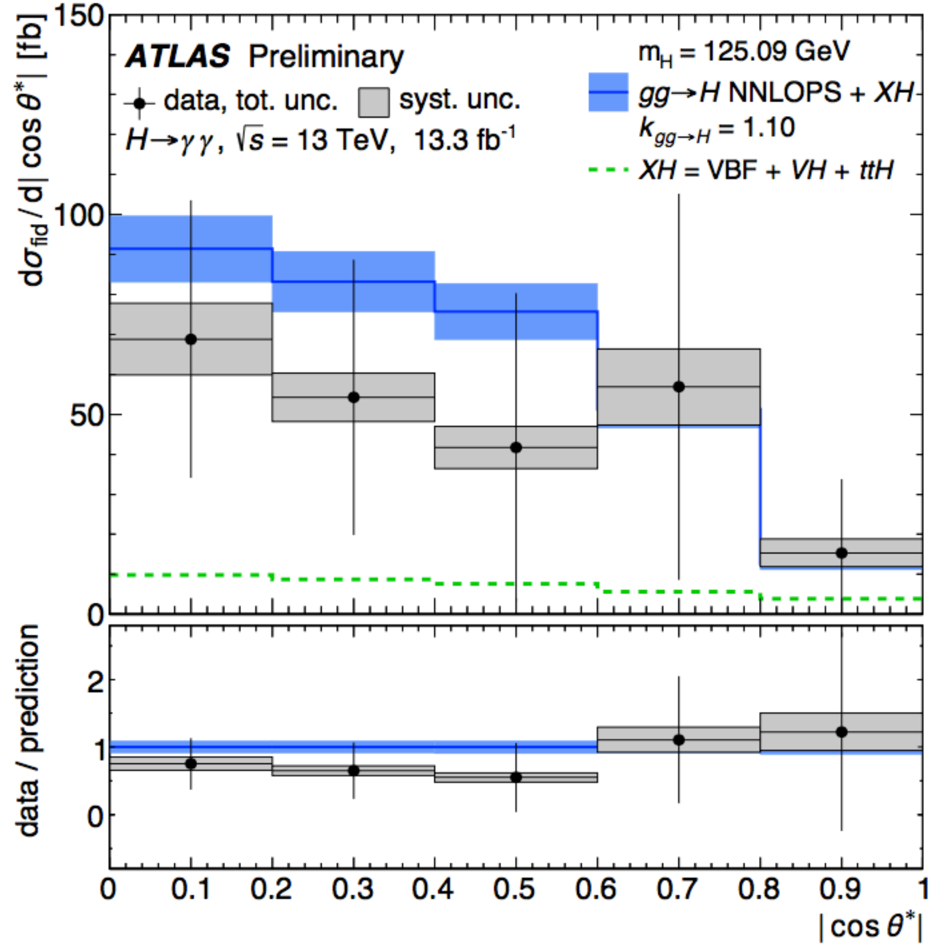


Kinematic features of the interference effect

$\lvert\cos\theta\rvert$	$-\sigma_{\text{int}}/\sigma_{\text{BW}}$ (%)		
	no cuts	p_T^h veto	$\gamma\gamma$ cuts+veto
0.0 − 0.2	$0.87^{+0.34}$	$1.28^{+0.62}$	$1.34^{+0.68}$



We predict data/prediction <1 at low pT and ~1 at high pT



Summary and outlook for $gg \to h \to \gamma\gamma$

We uniquely explore the physics consequences of this strong phase in Higgs physics

We choose the $gg \to h \to \gamma\gamma$ as one example and found the inclusion of this strong phase reduce the signal rate by ~2.% (at NLO); an important ingredient should be included in all LHC Higgs precision programs (global fit, etc.)

This effect could be used as probes to BSM physics, providing information on

- Higgs light quark Yukawas
- Higgs total width
- CPV effect

There are interesting kinematical distributions for the process can be utilized to map out the interference effect

There are many more other interesting channels and physics to explore using this interference effect.

Summary and outlook for $gg \to h \to \gamma\gamma$

We uniquely explore the physics consequences of this strong phase in Higgs physics

We choose the $gg \to h \to \gamma\gamma$ as one example and found the inclusion of this strong phase reduce the signal rate by ~2.% (at NLO); an important ingredient should be included in all LHC Higgs precision programs (global fit, etc.)

This effect could be used as probes to BSM physics, providing information on

- Higgs light quark Yukawas
- Higgs total width
- CPV effect

There are interesting kinematical distributions for the process can be utilized to map out the interference effect

There are many more other interesting channels and physics to explore using this interference effect.

Thank you!

Backup

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

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

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

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

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

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

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,

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

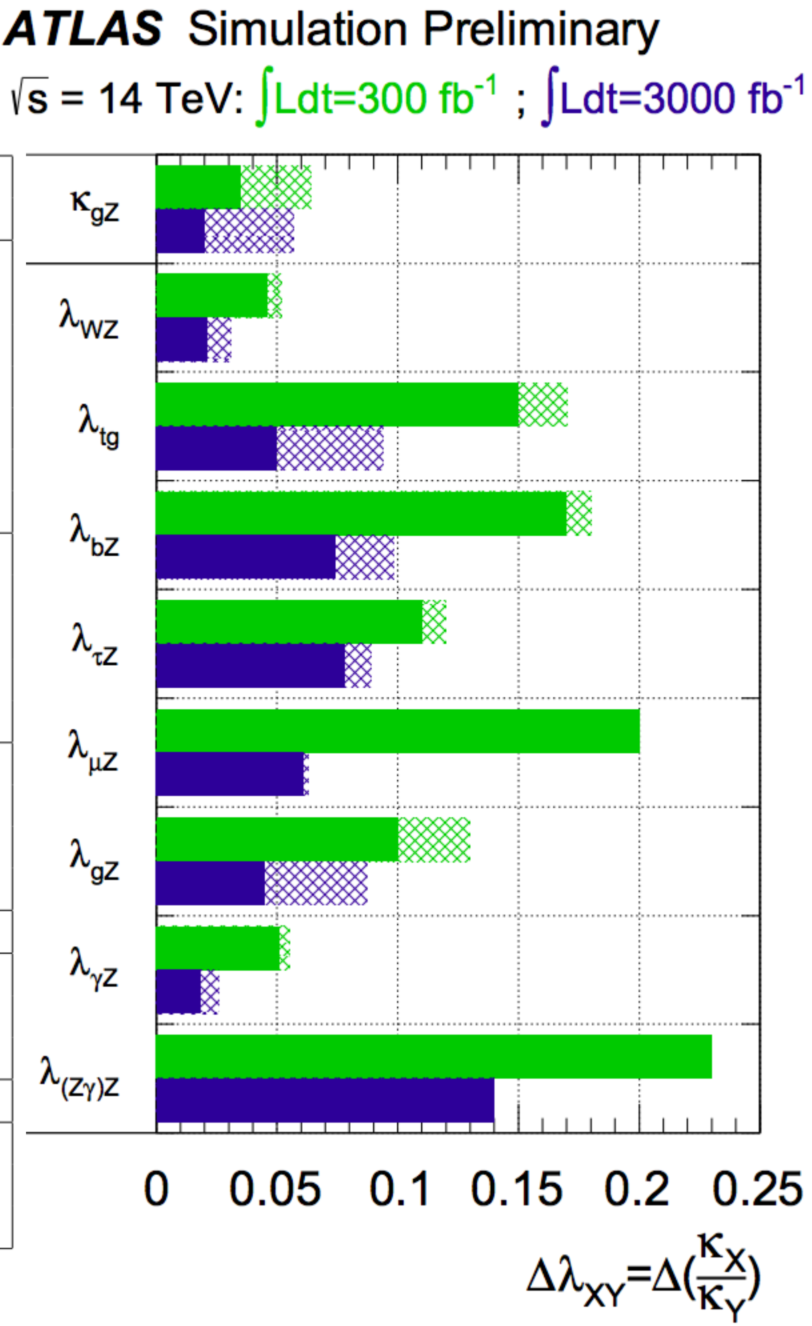
$$\begin{aligned}
\hat{\sigma}^{\rm odd}_{\rm BSM}(\hat{s};\tilde{y}_t)(gg\to S\to t\bar{t}) &= \hat{\sigma}^{\rm odd}_{\rm B.W.}(\hat{s};\tilde{y}_t)+\hat{\sigma}^{\rm odd}_{\rm Int.}(\hat{s};\tilde{y}_t)\\
\frac{d\hat{\sigma}^{\rm odd}_{\rm B.W.}(\hat{s};\tilde{y}_t)}{dz} &= \frac{3\alpha_s^2\hat{s}^2}{4096\pi^3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

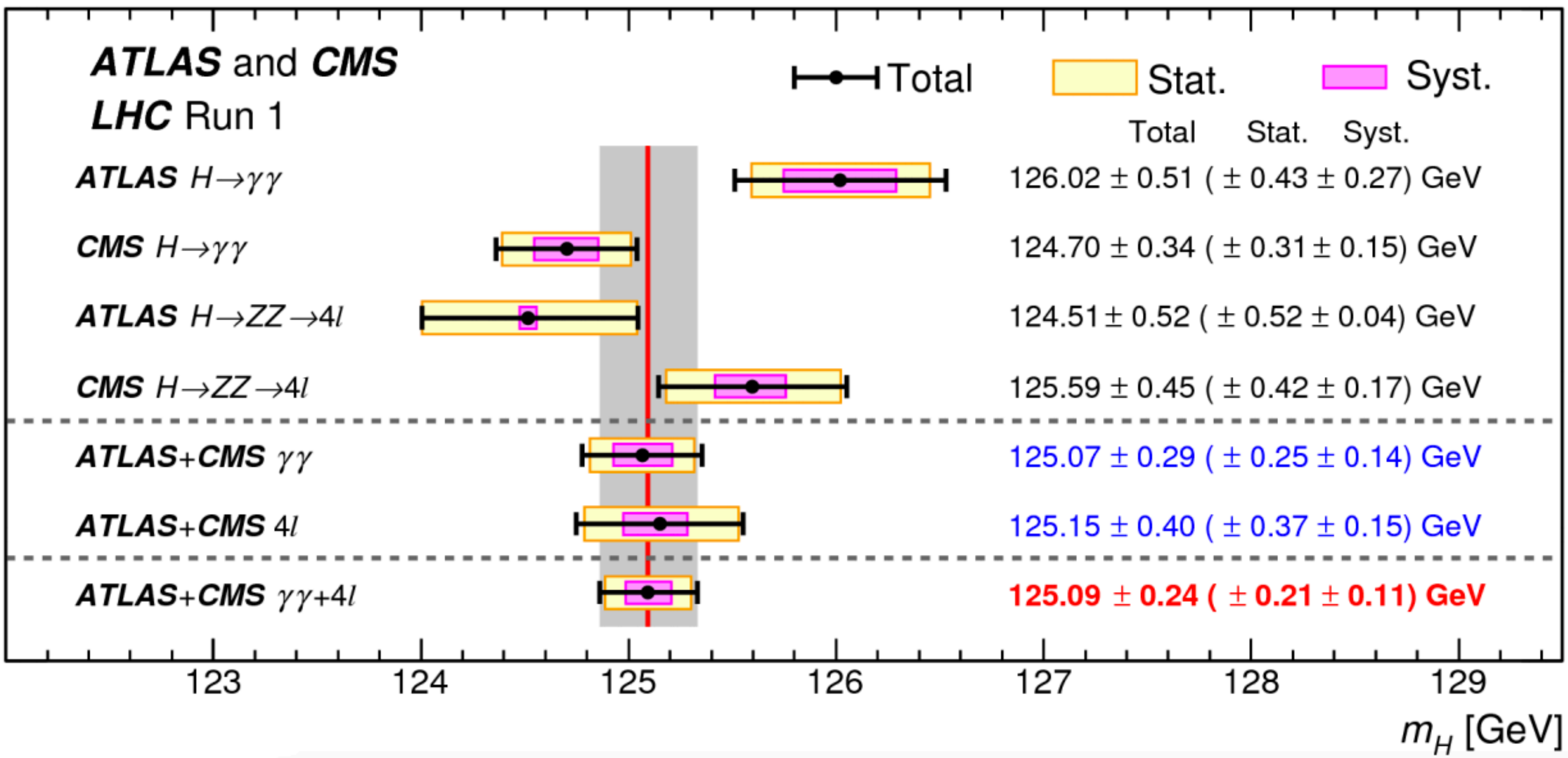
$$\begin{aligned}
\hat{\sigma}^{\rm even}_{\rm BSM}(\hat{s};y_t)(gg\to S\to t\bar{t}) &= \hat{\sigma}^{\rm even}_{\rm B.W.}(\hat{s};y_t)+\hat{\sigma}^{\rm even}_{\rm Int.}(\hat{s};y_t)\\
\frac{d\hat{\sigma}^{\rm even}_{\rm B.W.}(\hat{s};y_t)}{dz} &= \frac{3\alpha_s^2\hat{s}^2}{4096\pi^3 v^2}\beta^3\left|\frac{y_t^2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

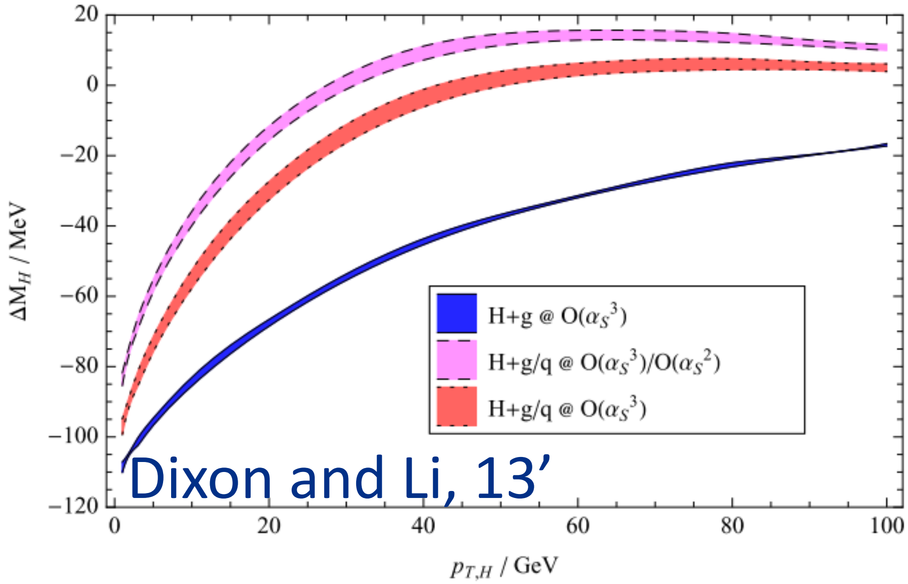
$$\begin{aligned}
\frac{d\sigma^{\rm S_1-S_2}_{\rm Int.}(\hat{s})(gg\to S_1,S_2\to t\bar{t})}{dz} = \frac{3\alpha_s^2\hat{s}^2}{2048\pi^3v^2}\\
{\rm Re}\left[\frac{(y_{t,S_1}y_{t,S_2}|I_{\frac{1}{2}}(\tau_t)|^2+\tilde{y}_{t,S_1}\tilde{y}_{t,S_2}|\tilde{I}_{\frac{1}{2}}(\tau_t)|^2)(\beta^2 y_{t,S_1}y_{t,S_2}+\tilde{y}_{t,S_1}\tilde{y}_{t,S_2})}{(\hat{s}-m_{S_1}^2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

1.ATL-PHYS-PUB-2014-016

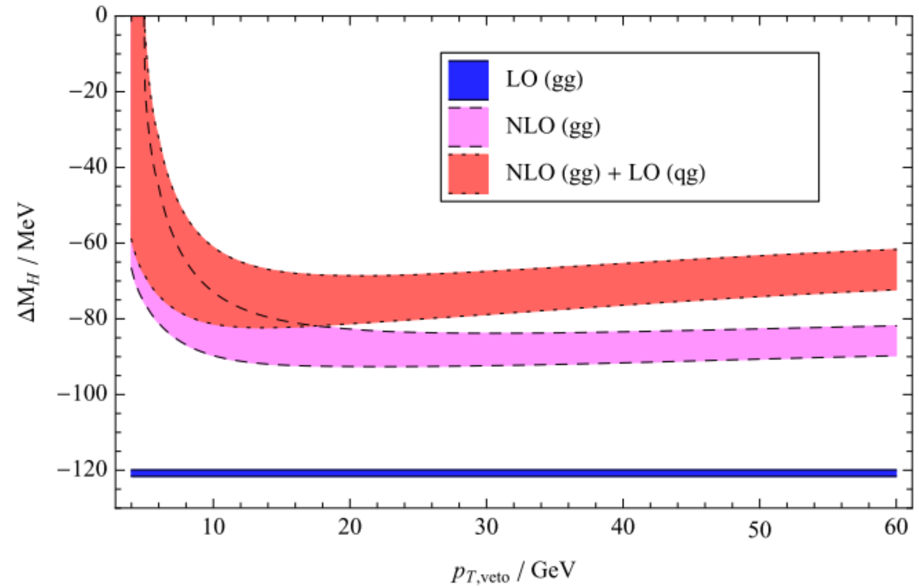
$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \gamma\gamma$ (comb.)	0.13	0.09	0.09	0.04
(0j)	0.19	0.12	0.16	0.05
(1j)	0.27	0.14	0.23	0.05
(VBF-like)	0.47	0.43	0.22	0.15
(WH-like)	0.48	0.48	0.19	0.17
(ZH-like)	0.85	0.85	0.28	0.27
(ttH-like)	0.38	0.36	0.17	0.12
$H \to ZZ$ (comb.)	0.11	0.07	0.09	0.04
(VH-like)	0.35	0.34	0.13	0.12
(ttH-like)	0.49	0.48	0.20	0.16
(VBF-like)	0.36	0.33	0.21	0.16
(ggF-like)	0.12	0.07	0.11	0.04
$H \to WW$ (comb.)	0.13	0.08	0.11	0.05
(0j)	0.18	0.09	0.16	0.05
(1j)	0.30	0.18	0.26	0.10
(VBF-like)	0.21	0.20	0.15	0.09
$H \to Z\gamma$ (incl.)	0.46	0.44	0.30	0.27
$H \to b\bar{b}$ (comb.)	0.26	0.26	0.14	0.12
(WH-like)	0.57	0.56	0.37	0.36
(ZH-like)	0.29	0.29	0.14	0.13
$H \to \tau\tau$ (VBF-like)	0.21	0.18	0.19	0.15
$H \to \mu\mu$ (comb.)	0.39	0.38	0.16	0.12
(incl.)	0.47	0.45	0.18	0.14
(ttH-like)	0.74	0.72	0.27	0.23



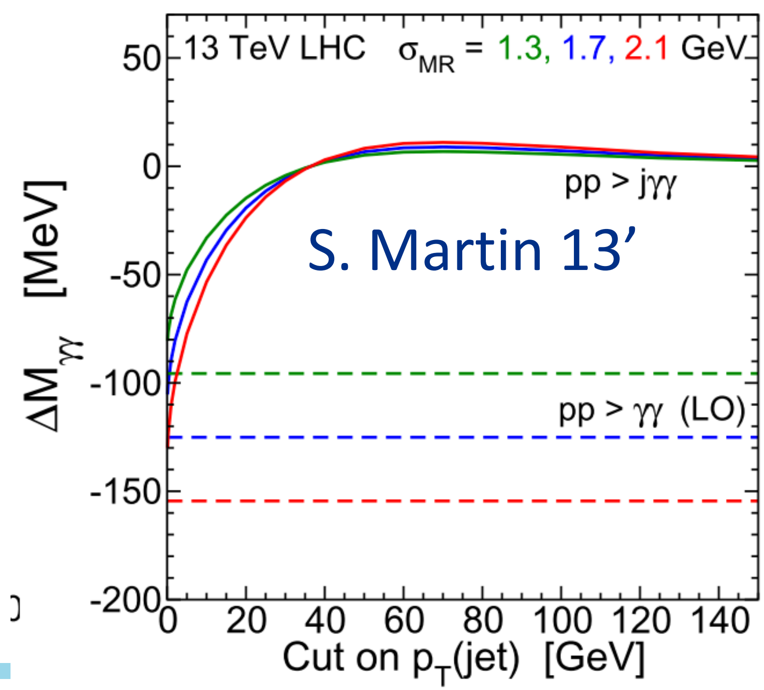

ATLAS and CMS
LHC Run 1
Total
Stat.
Syst.
Total Stat. Syst.
ATLAS H→γγ
126.02 ± 0.51 (± 0.43 ± 0.27) GeV
CMS H→γγ
124.70 ± 0.34 (± 0.31 ± 0.15) GeV
ATLAS H→ZZ→4l
124.51 ± 0.52 (± 0.52 ± 0.04) GeV
CMS H→ZZ→4l
125.59 ± 0.45 (± 0.42 ± 0.17) GeV
ATLAS+CMS γγ
125.07 ± 0.29 (± 0.25 ± 0.14) GeV
ATLAS+CMS 4l
125.15 ± 0.40 (± 0.37 ± 0.15) GeV
ATLAS+CMS γγ+4l
125.09 ± 0.24 (± 0.21 ± 0.11) GeV
123
124
125
126
127
128
129
m_H [GeV]



H+g @ O(α_S^3)
H+g/q @ O(α_S^3)/O(α_S^2)
H+g/q @ O(α_S^3)
Dixon and Li, 13'
ΔM_H / MeV
$p_{T,H}$ / GeV

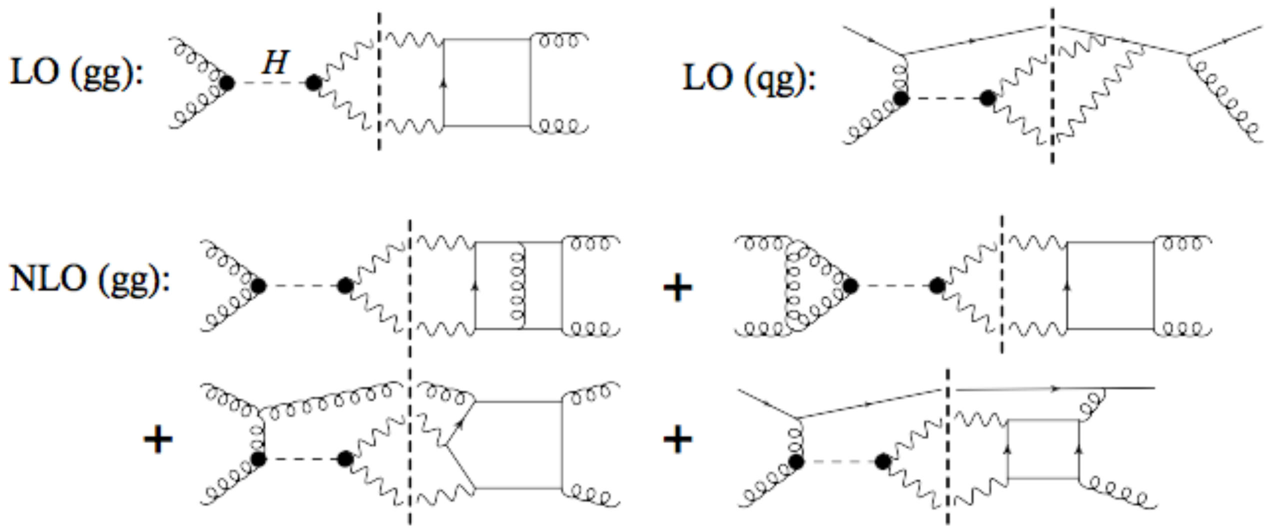


LO (gg)
NLO (gg)
NLO (gg) + LO (qg)
ΔM_H / MeV
$p_{T,\mathrm{veto}}$ / GeV

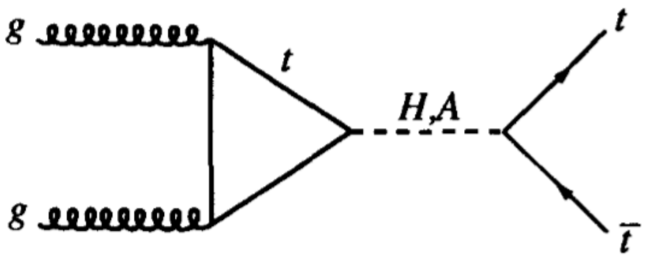


13 TeV LHC σ_{MR} = 1.3, 1.7, 2.1 GeV
pp > jγγ
S. Martin 13'
pp > γγ (LO)
$\Delta M_{\gamma\gamma}$ [MeV]
Cut on p_T(jet) [GeV]

Dots represent point-like interaction, where the phase is ignored.



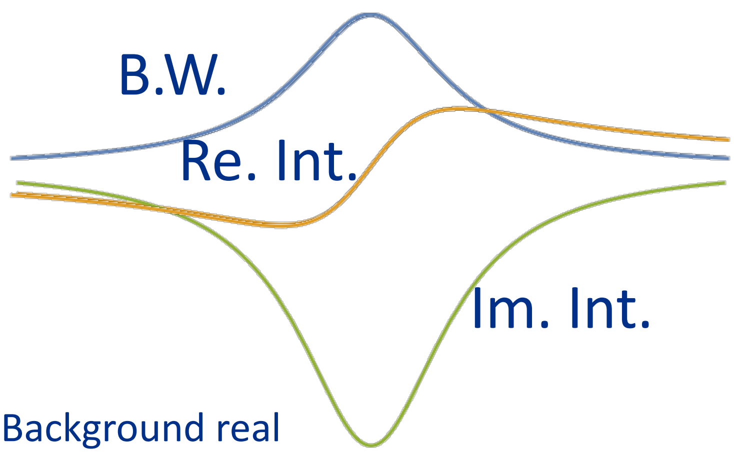
Sketching the interference



$$g_{Sgg}(\hat{s}) = \frac{\alpha_s}{2\sqrt{2}\pi}\frac{y_t^S}{m_t} I_{\frac{1}{2}}(\tau_t)$$

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

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

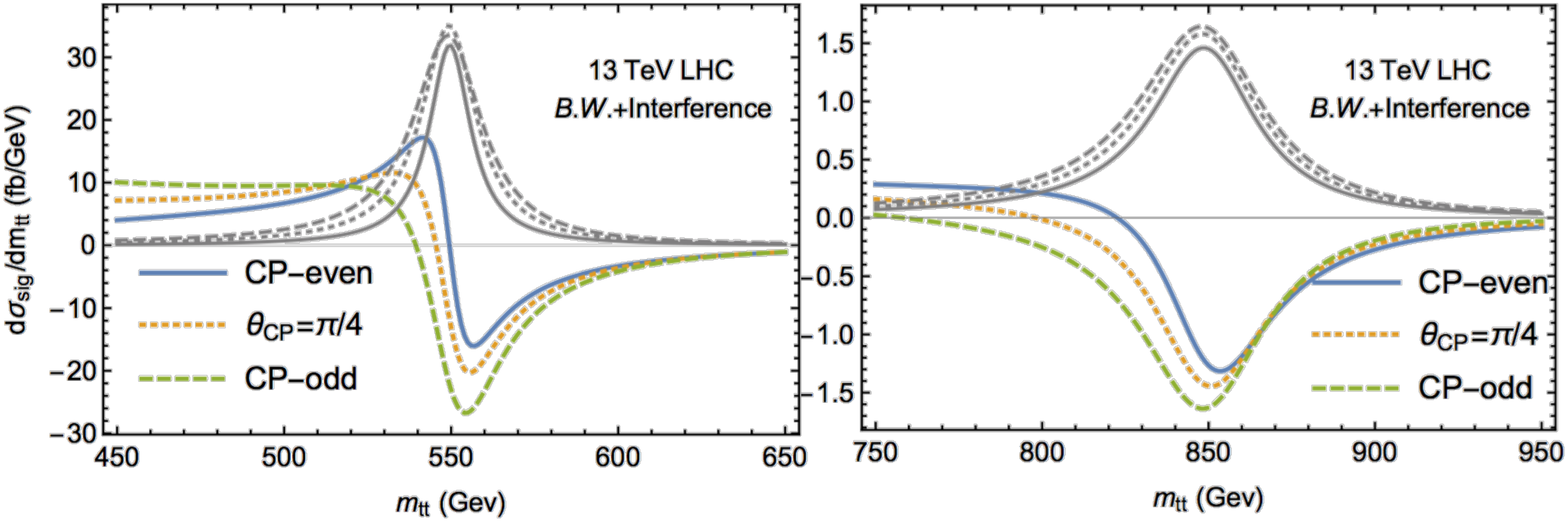


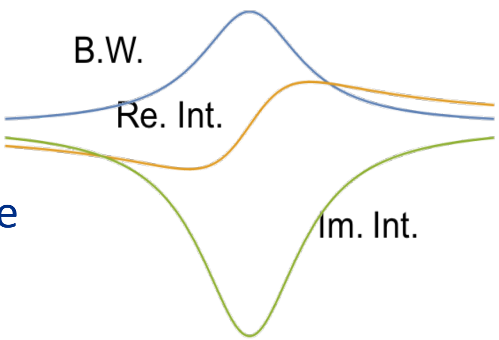
Background real

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)

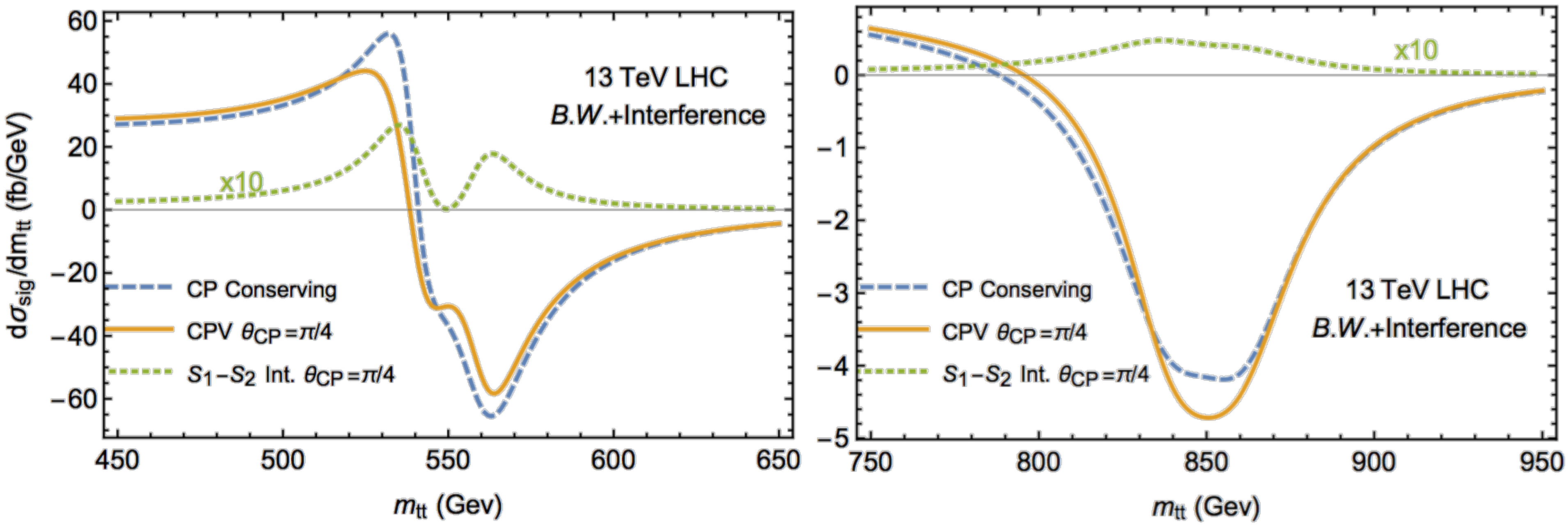
Challenges





- 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.

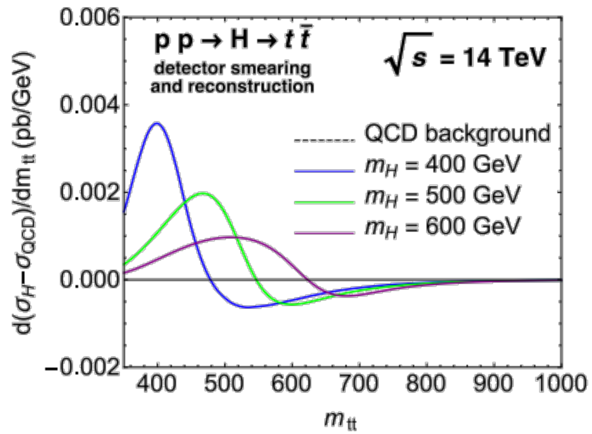
Opportunities—nearly degenerate with CPV

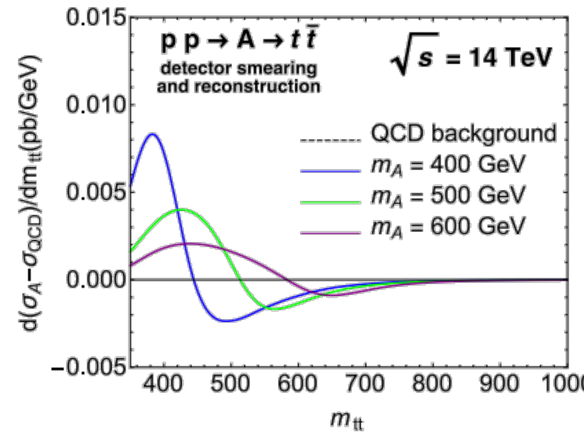


(left panel) 540 and 560 GeV scalars
(right panel) 840 and 860 GeV scalars
The signature—bumps and dips—roughly doubled, increasing the potential sensitivity;
With CPV, new interference between the two heavy nearly degenerate scalars occurs (although the effect is small) but unique.

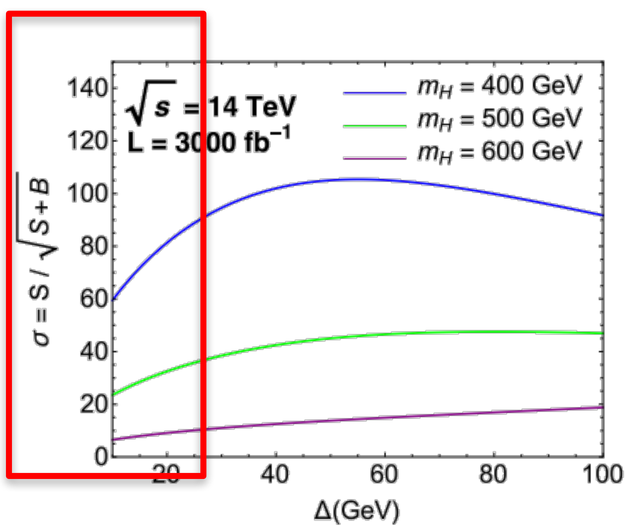
LHC perspectives—Challenges

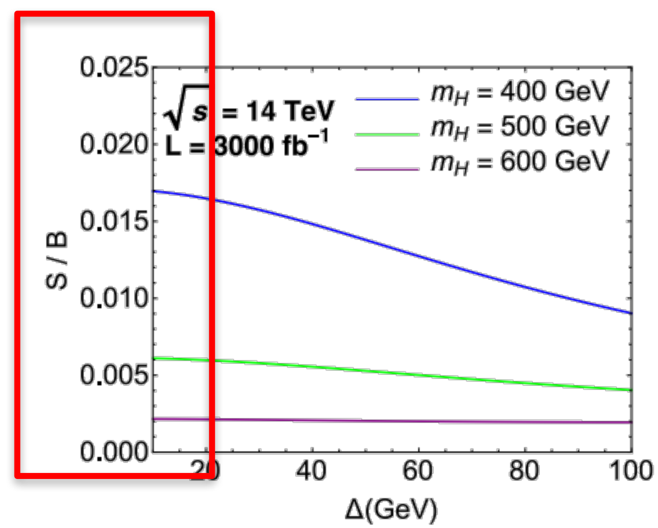
Statistically promising;
Systematically, challenging.





Craig, Draper, Erasmo, Thomas, Zhang '15





Taking only one central bin, ignored shape information