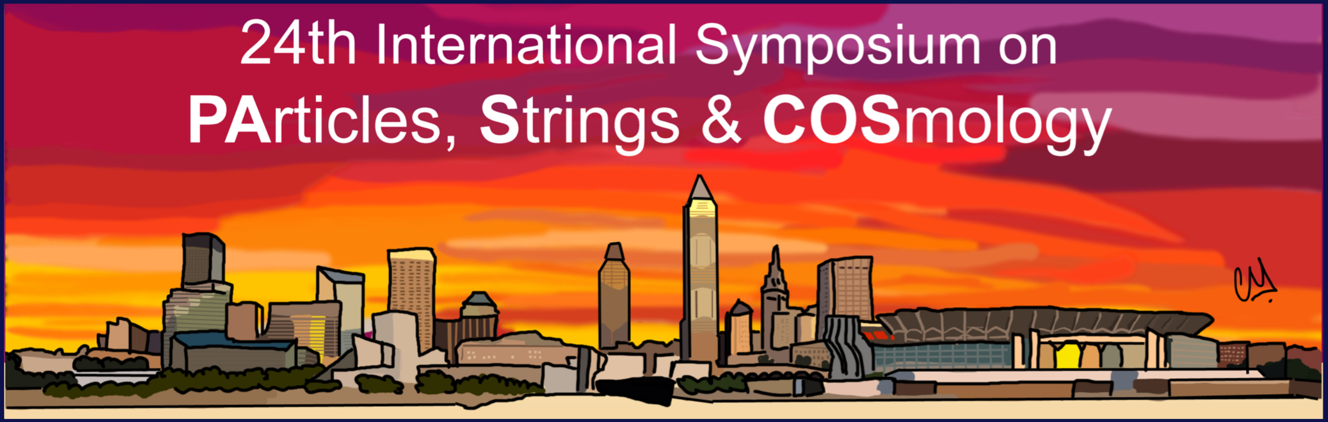
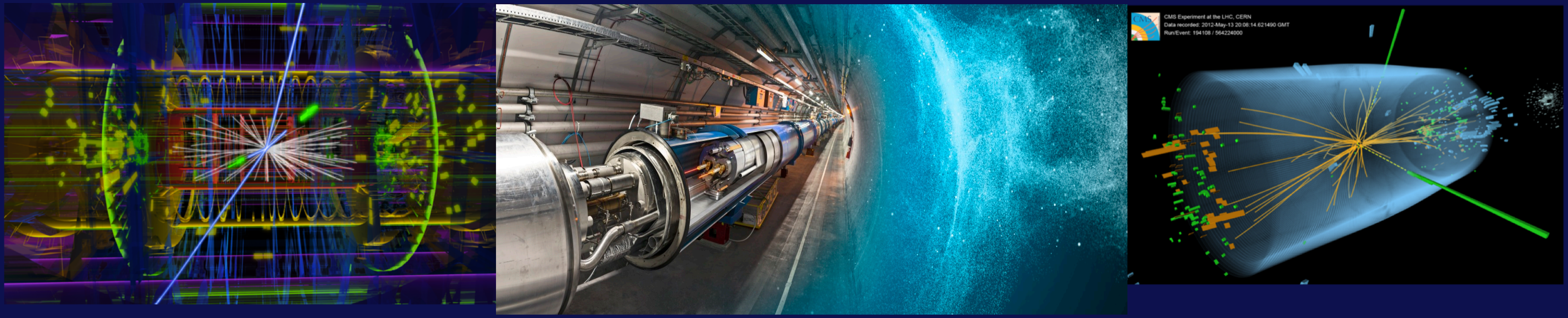
The Higgs Boson as a Tool for Exploration



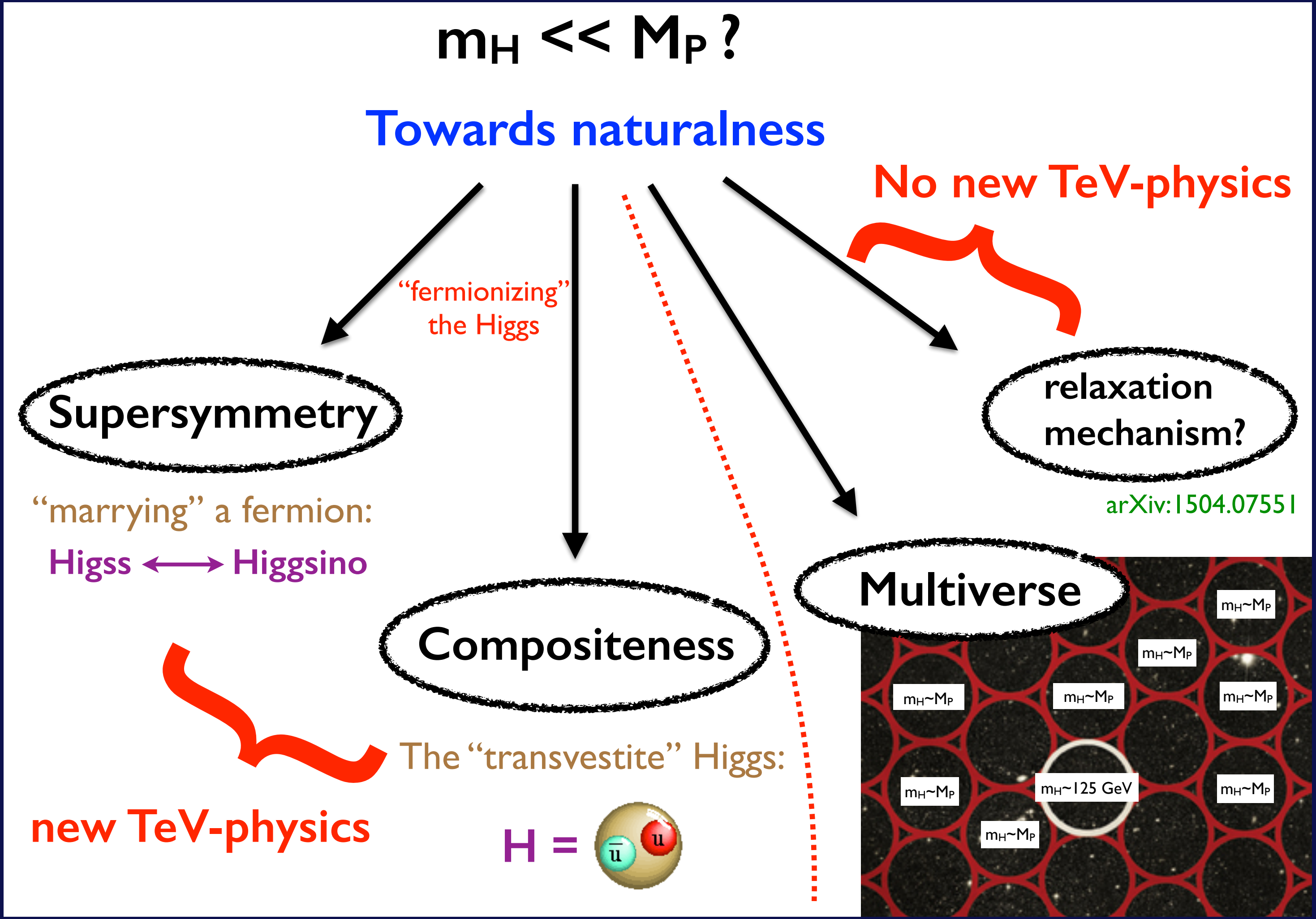


Marcela Carena

Fermilab and UChicago

Case Western Reserve University, Cleveland, June 4, 2018

New Physics Landscape after the Higgs Discovery



$m_H << M_P$?

Towards naturalness

No new TeV-physics

“fermionizing” the Higgs

Supersymmetry

“marrying” a fermion:

Higgs ⟷ Higgsino

Compositeness

The “transvestite” Higgs:

$H =$

new TeV-physics

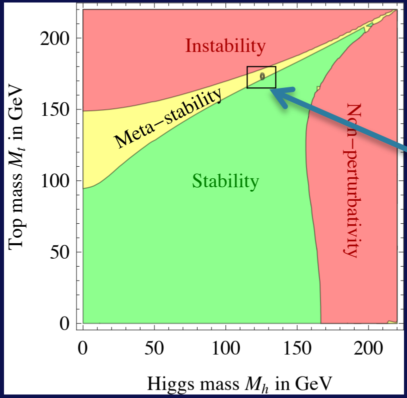
Multiverse

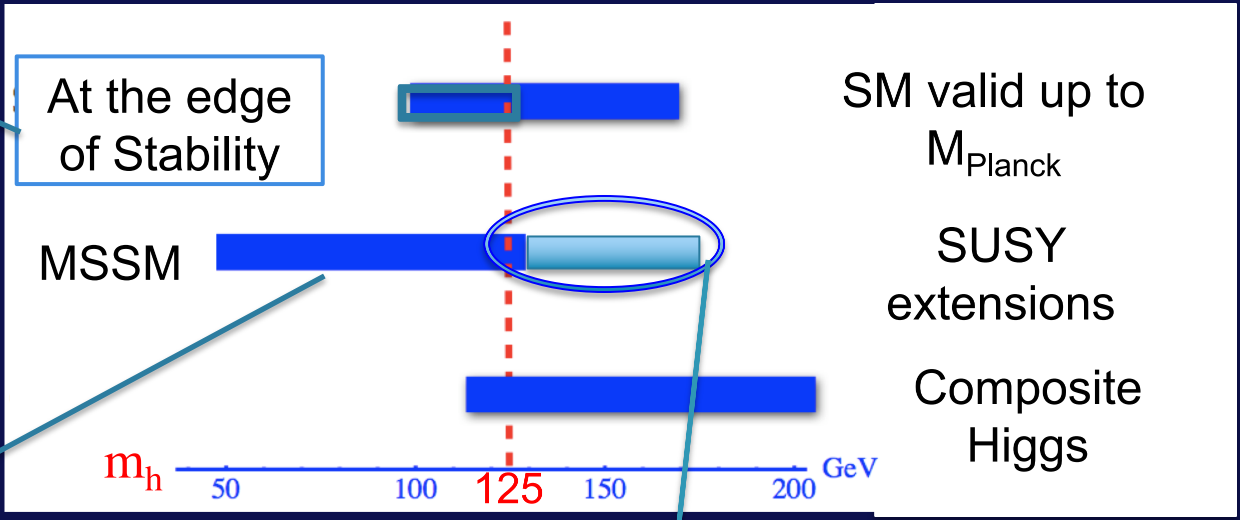
relaxation mechanism?

arXiv:1504.07551

How far are we willing to go?

Under the Higgs lamp-post:





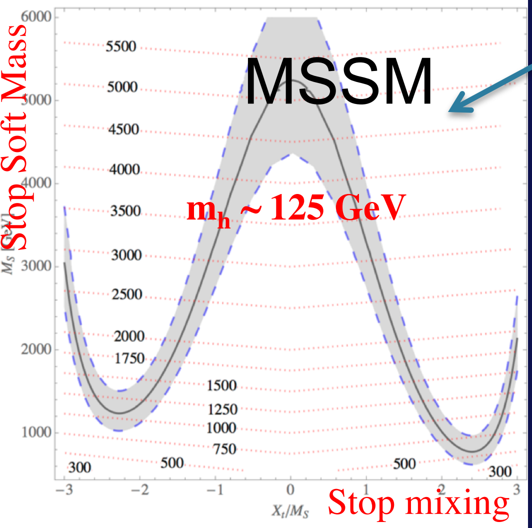
At the edge of Stability

MSSM

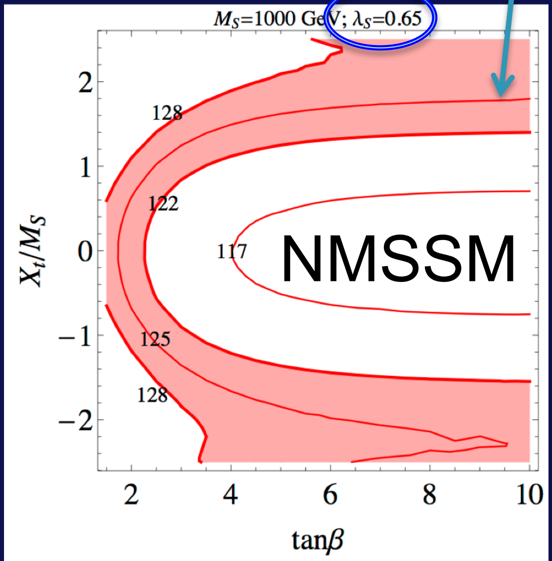
SM valid up to M_{Planck}

SUSY extensions

Composite Higgs



Splitting in stop SUSY breaking mass parameters can accommodate one lighter stop with minimal impact to gluon fusion

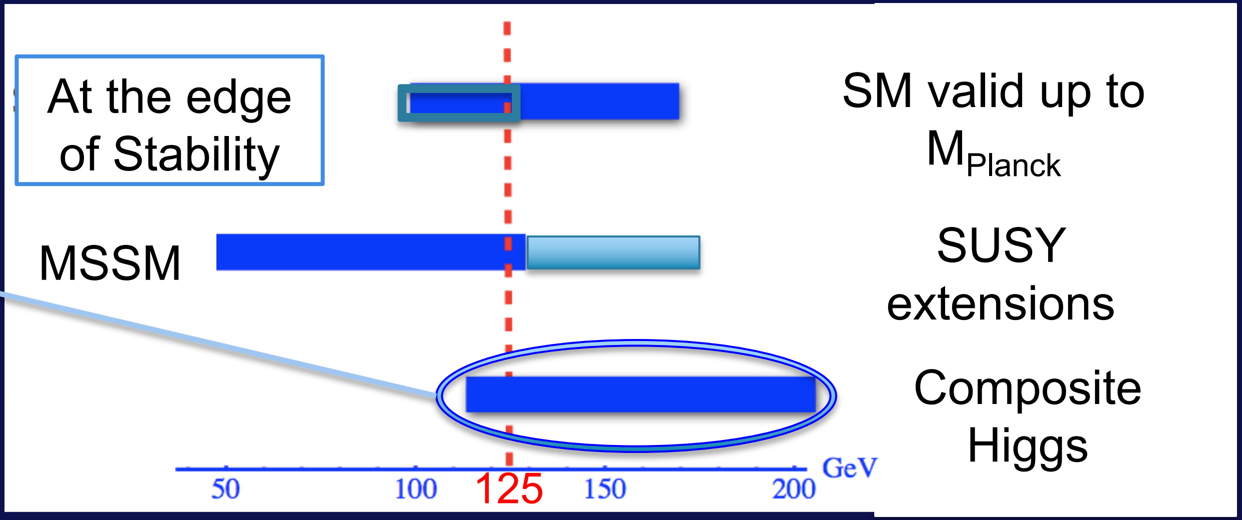


NMSSM + mh ~ 125 GeV: At low tanβ naturally compatible with stops at the electroweak scale, thereby reducing the degree of fine tuning to get EWSB

Under the Higgs lamp-post:

No Higgs above a certain scale, at which the new strong dynamics turns on

➔ dynamical origin of EWSB



New strong resonance masses constrained by EW data and direct searches
Higgs ➔ scalar resonance much lighter that other ones

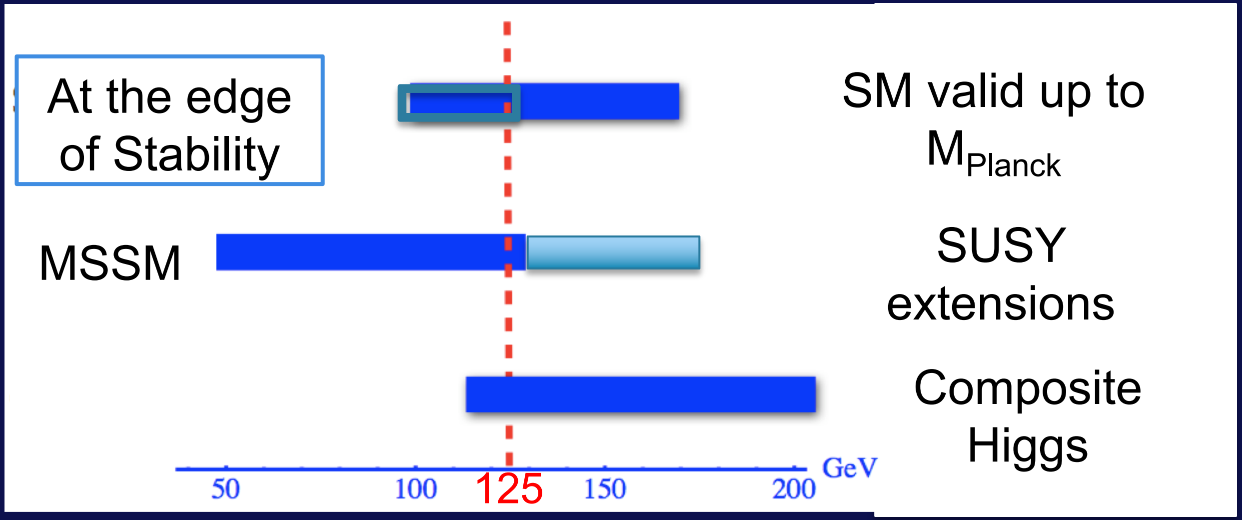
Also in fashion:
Twin Higgs and Mirror Worlds
- Demand a UV completion → Composite Higgs-

Under the Higgs lamp-post:

Composite

or SUSY

extensions



2HDMs or additional Higgs singlets or triplets, more complicated combinations of Higgs multiplets or extended gauge symmetries

Can be appealing to provide a strong first order EW phase transition

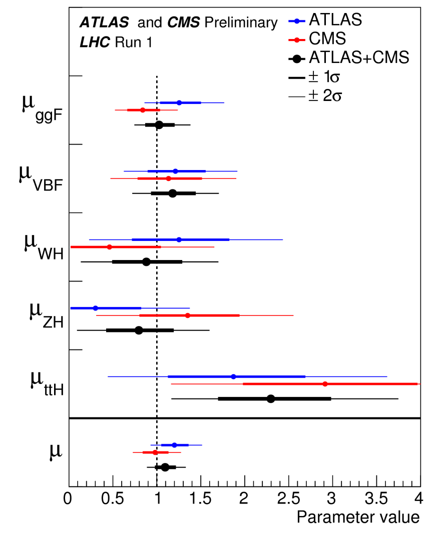
Flavor from the electroweak scale

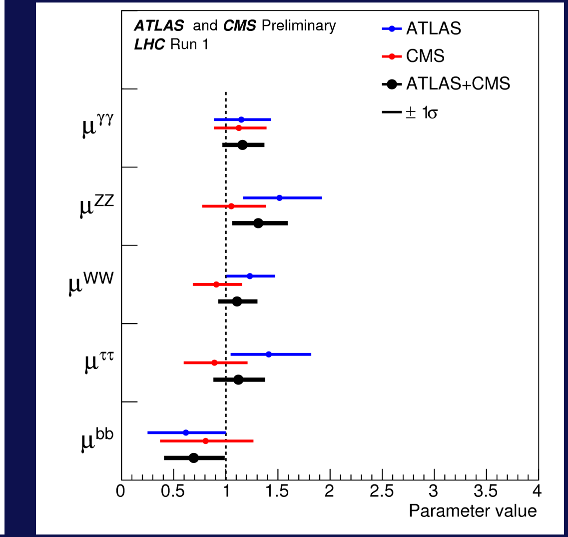
Flavor hierarchies arise from a Froggatt-Nielsen mechanism with two Higgs doublets jointly acting as a flavon

All BSM alternatives can affect Higgs production & decay signal strengths

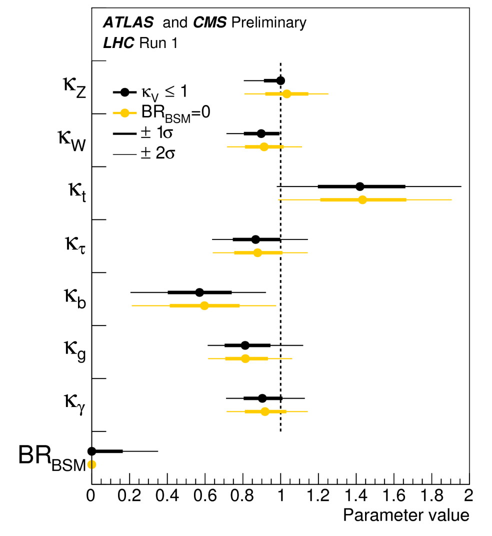
RUN 1 Results

Higgs Properties in good agreement with SM predictions





Assuming no strict correlation between gluon and top couplings

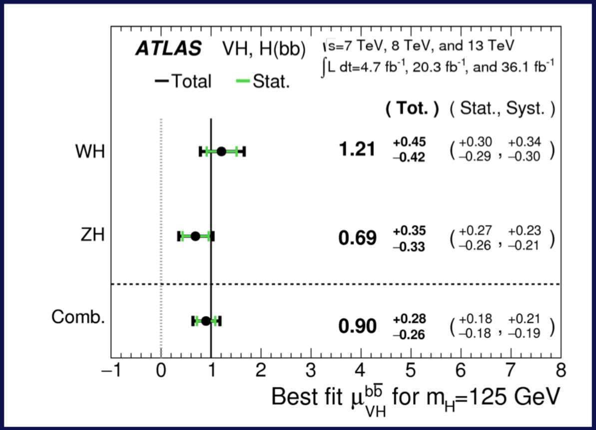


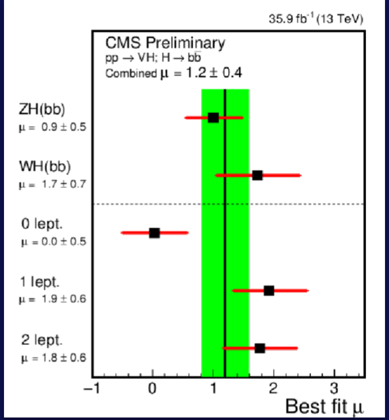
The bottom coupling affects all Higgs BRs in a relevant way (large effect in total width)
Strong interplay with gluon fusion rate (top coupling) and also vector boson fusion and H→ WW/ZZ decays

Direct measurement of bottom & top couplings subject to large uncertainties
Deviations from SM predictions quite possible

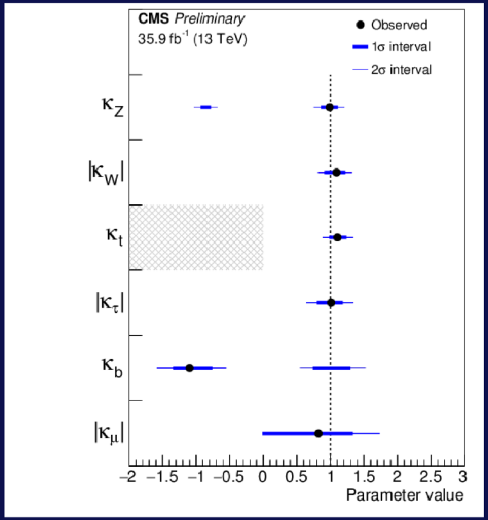
RUN 2 Results

There is evidence of Higgs decaying to bottom quarks



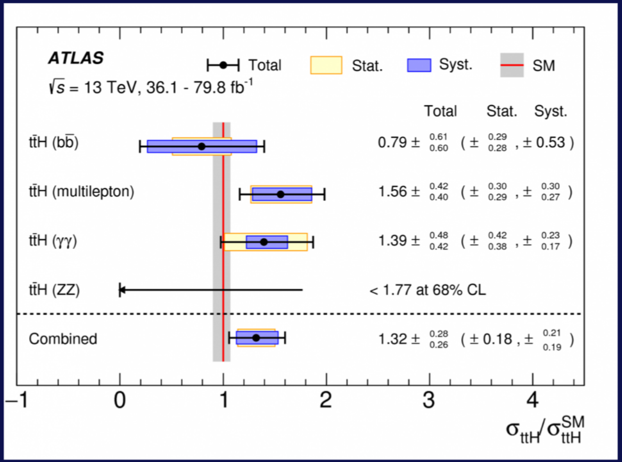


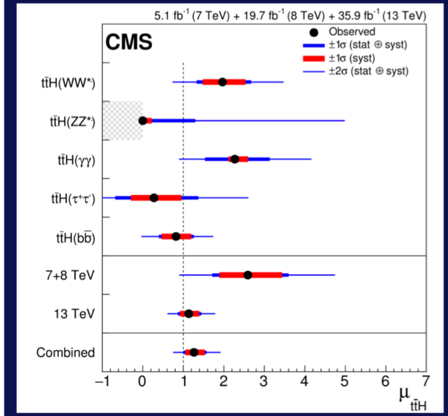
Assuming no strict correlation between gluon and top couplings



Today's CERN press release; tth CMS & ATLAS results

The Higgs boson reveals its affinity for the top quark





Consistency with SM results

Errors still admit deviations of a few tens of percent from the SM results

HL- LHC : precision on most relevant couplings will be better than/about 10%

Data on SM-like Higgs signal strengths ➔Alignment

For a general 2HDM (H_1, H_2), **the couplings of h/H to V = W,Z are**

$$\mathbf{h} = -\sin\alpha\, \mathbf{H_1^0} + \cos\alpha\, \mathbf{H_2^0} \qquad \mathrm{HVV} = (\mathrm{hVV})^{\mathrm{SM}} \cos(\beta - \alpha)$$

$$\mathbf{H} = \cos\alpha\, \mathbf{H_1^0} + \sin\alpha\, \mathbf{H_2^0} \qquad \mathbf{hVV} = (\mathbf{hVV})^{\mathrm{SM}} \sin(\beta - \alpha)$$

In a 2HDM type II (e.g. MSSM), H_1 couples to down-quarks and charged leptons, while H_2 couples to up-quarks. **$\langle H_i \rangle = v_i$ tan $\beta = v_2/v_1$**

$$\mathbf{g_{hdd(hll)}} = \frac{\mathbf{m_{d(l)}}}{\mathbf{v}} \frac{(-\sin\alpha)}{\cos\beta} \qquad \mathbf{g_{Hdd(Hll)}} = \frac{\mathbf{m_{d(l)}}}{\mathbf{v}} \frac{\cos\alpha}{\cos\beta} \qquad \mathbf{g_{huu}} = \frac{\mathbf{m_{uu}}}{\mathbf{v}} \frac{\cos\alpha}{\sin\beta} \qquad \mathbf{g_{Huu}} = \frac{\mathbf{m_{u}}}{\mathbf{v}} \frac{\sin\alpha}{\sin\beta}$$

In 2HDM type I, all fermions couple to H_2

If the mixing in the CP-even sector yields cos (β-α) = 0 ➔ cosα = sinβ

The lightest Higgs coupling to fermions and gauge bosons is SM-like.

This situation is called ALIGNMENT

Gunion and Haber ’03

H and A couplings scale like 1/ tanβ with the exception of the down-quark/lepton couplings enhanced by tanβ in Type II (SUSY)

Alignment Conditions in General 2HDMs

General 2HDM
Higgs potential

$$\begin{aligned} V = {} & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} , \end{aligned}$$

Minimization conditions define m_A, m_{H+} and $m_{h/H}$ in terms of quartic couplings, one mass parameter and tanβ

Eigenstate Eq.

$$\underbrace{\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}}_{\approx 0 \ \rightarrow\ \cos(\beta-\alpha) = 0} = -\frac{v^2}{m_A^2} \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} + \frac{m_h^2}{m_A^2} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}$$

Alignment occurs for **large values of m_A → Decoupling OR**

specific conditions independent of M_A → Alignment without Decoupling

If no CP violation in the Higgs sector

Valid for any 2HDM

$$\begin{aligned} & (m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2)t_\beta^2 = v^2(3\lambda_6 t_\beta + \lambda_7 t_\beta^3) , \\ & (m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2)t_\beta^{-2} = v^2(3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3}) \end{aligned}$$

Craig, Galloway,Thomas’13 M.C, Low, Shah, Wagner ‘13

Departures from Alignment (Type II 2HDM)

- Alignment might only be partially realized, useful to study effects of small departures
- It is customary to parametrize departures from alignment by a Taylor exp. in cos (β-α) which defines deviations from Higgs-WW/ZZ couplings

BUT Higgs –bottom coupling is controlled by **$\eta = \cos_{\beta-\alpha}\, t_\beta$**

At leading order in η

$$c_{\beta-\alpha} = t_\beta^{-1}\eta\ , \qquad s_{\beta-\alpha} = \sqrt{1 - t_\beta^{-2}\eta^2}$$

$$\begin{aligned} g_{hVV} &\approx \left(1 - \frac{1}{2} t_\beta^{-2}\eta^2\right) g_V \\ g_{hdd} &\approx (1-\eta)\, g_f\ , \\ g_{huu} &\approx (1 + t_\beta^{-2}\eta)\, g_f\ , \end{aligned}$$

The couplings to down fermions are not only the ones that dominate the Higgs width but also tend to be the ones that differ the most from the SM ones

In the MSSM for moderate to sizeable t_β

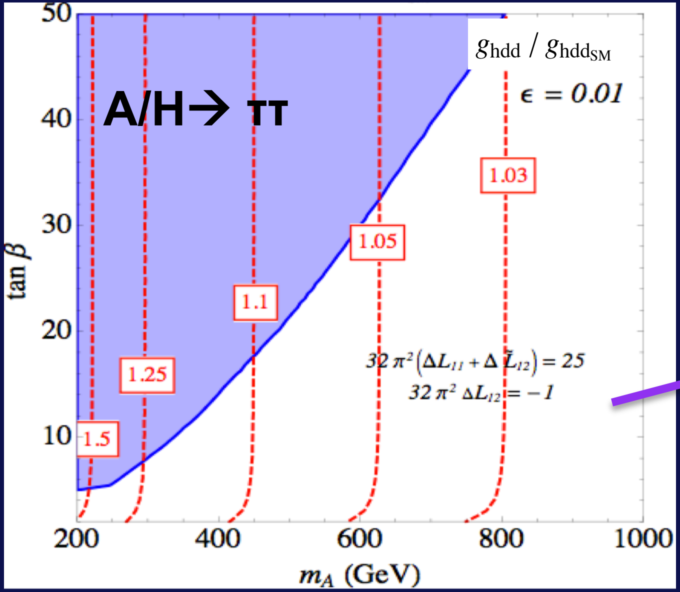
$$t_\beta\, c_{\beta-\alpha} \simeq \frac{-1}{m_H^2 - m_h^2}\left[m_h^2 + m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2 M_S^2}\left\{A_t \mu t_\beta\left(1 - \frac{A_t^2}{6M_S^2}\right) - \mu^2\left(1 - \frac{A_t^2}{2M_S^2}\right)\right\}\right]$$

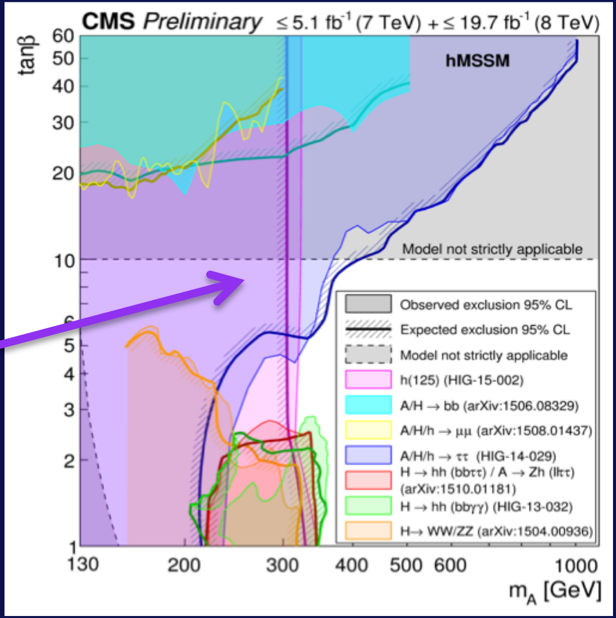
For small departures from alignment, η can be determined as a function of the quartic couplings and the Higgs masses

Interpretation of precision Higgs measurements on A/H searches strongly dependent on the proximity to Alignment without decoupling

Small μ as analyzed by ATLAS/CMS ($\lambda_{6,7} \propto \mu\, A_t \simeq 0$ => No Alignment)

Bottom coupling in the MSSM





$$t_\beta\, c_{\beta-\alpha} \simeq \frac{-1}{m_H^2 - m_h^2}\left[m_h^2 + m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2 M_S^2}\left\{A_t \mu t_\beta \left(1 - \frac{A_t^2}{6M_S^2}\right) - \mu^2\left(1 - \frac{A_t^2}{2M_S^2}\right)\right\}\right]$$

For moderate to large tanβ and small μ

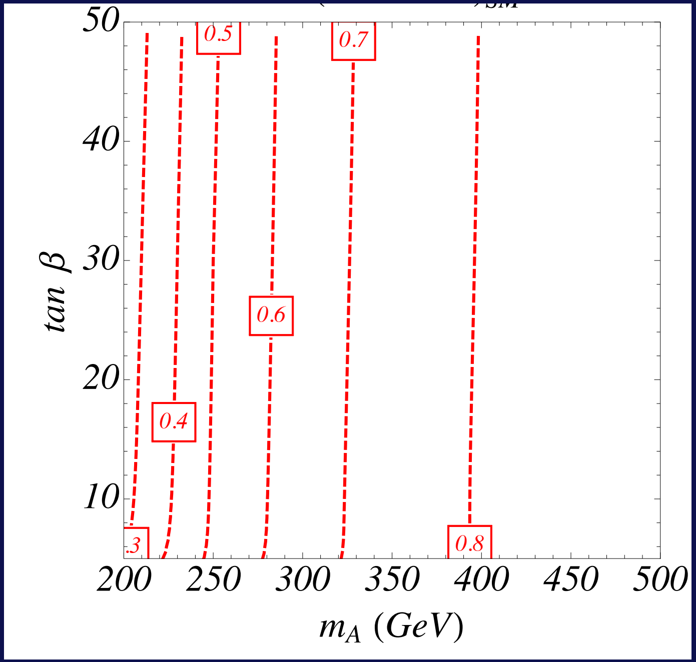
➔ no dependence on tanβ or on the stop mixing

➔ All vector boson BR's suppressed by enhancement of bottom decay width

Interpretation of precision Higgs measurements on A/H searches strongly correlated to the proximity to Alignment without decoupling

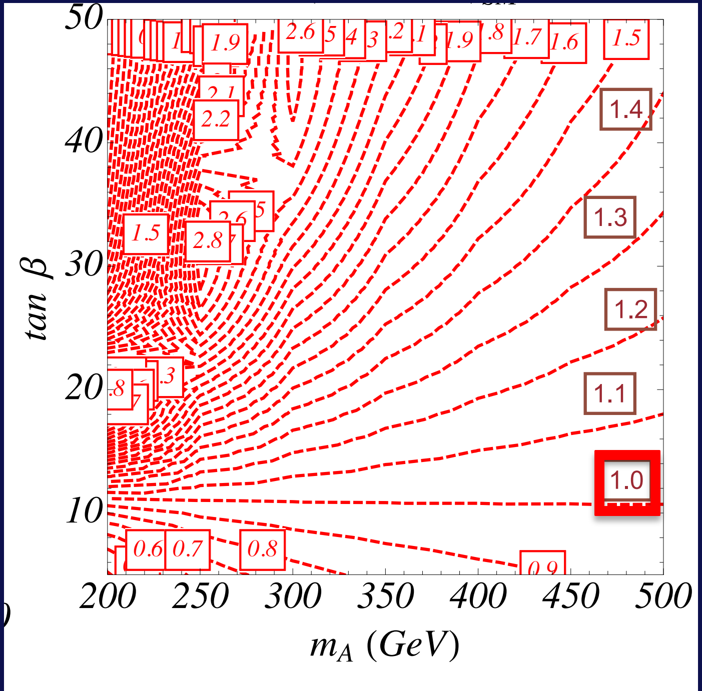
Higgs decays into gauge bosons mostly determined by bottom decay width

Small μ (no Alignment)



$$\frac{BR\,(h \to WW)}{BR\,(h \to WW)_{SM}}$$

Sizeable μ ~ 2 M_{SUSY} (Alignment)



CP-odd Higgs masses of order 200 GeV and tanβ ~10 are allowed in the alignment case, but alignment is in tension with naturalness in the MSSM

M.C., I. Low, N. Shah, Wagner'13

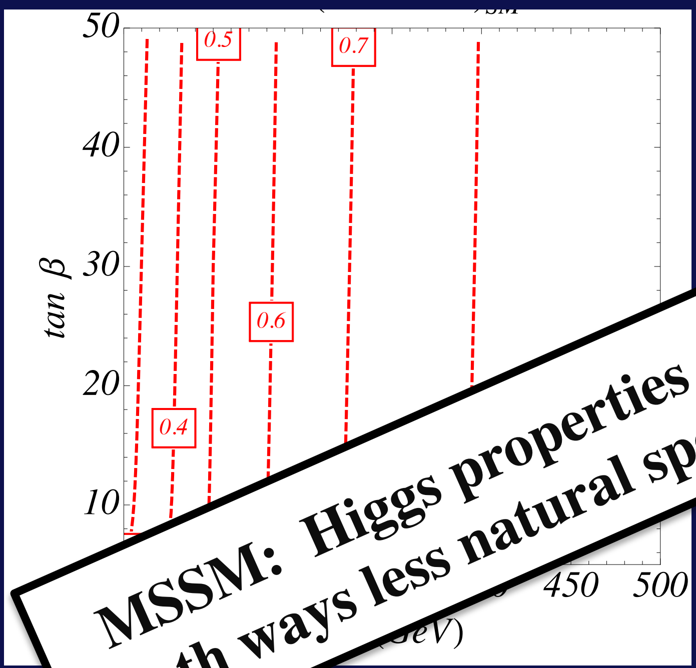
e.g. Tauphobic Benchmark MC, Heinemeyer, Stal, Wagner, Weiglein'14

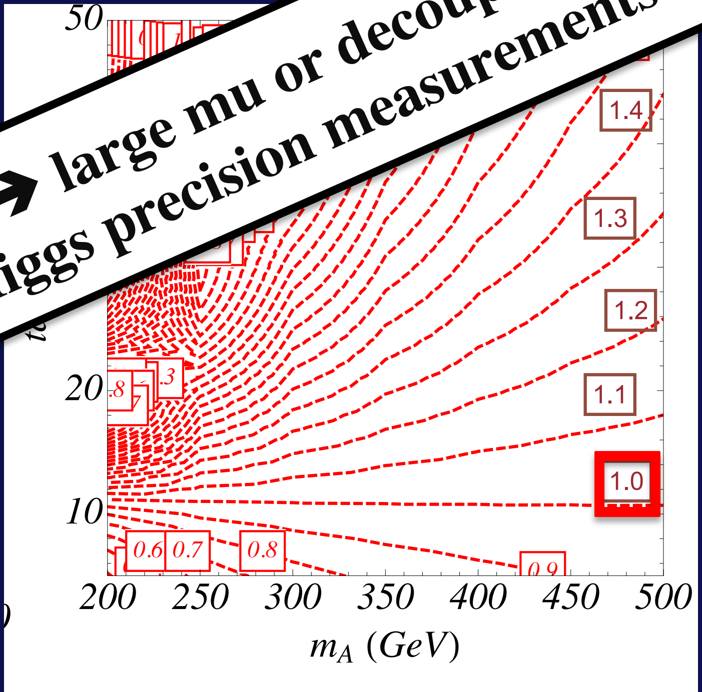
Interpretation of precision Higgs measurements on A/H searches strongly correlated to the proximity to Alignment without decoupling

Higgs decays into gauge bosons mostly determined by bottom decay width

Small μ (no Alignment)

Sizeable $\mu \sim 2 M_{SUS}$





MSSM: Higgs properties close to SM-like ➔ large mu or decoupling

Both ways less natural spectra just from Higgs precision measurements

CP-odd Higgs masses of order 200 GeV and tanβ ~10 are allowed in the alignment case, but alignment is in tension with naturalness in the MSSM

M.C., I. Low, N. Shah, Wagner'13

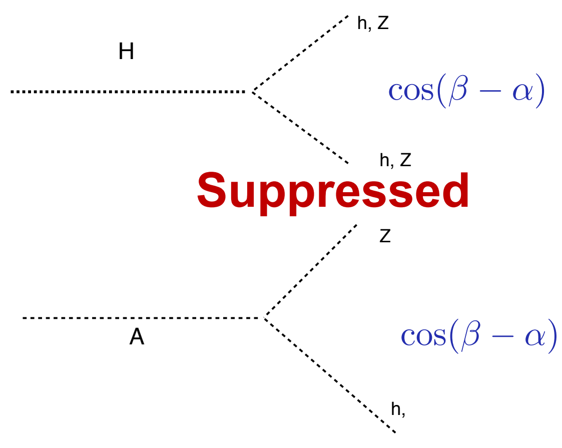
e.g. Tauphobic Benchmark MC, Heinemeyer, Stal, Wagner, Weiglein'14

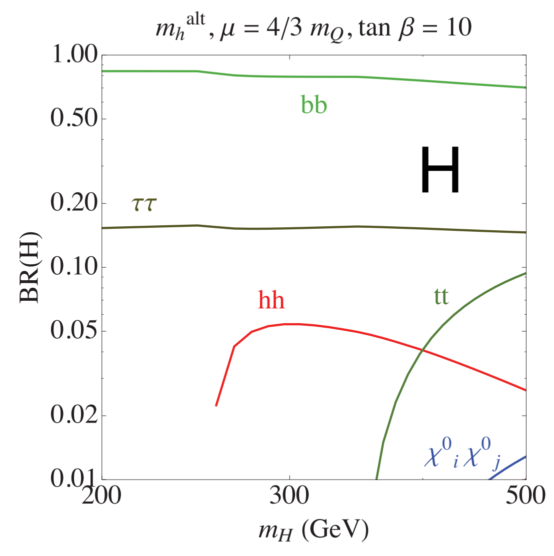
Heavy Higgs Bosons: A variety of decay Branching Ratios

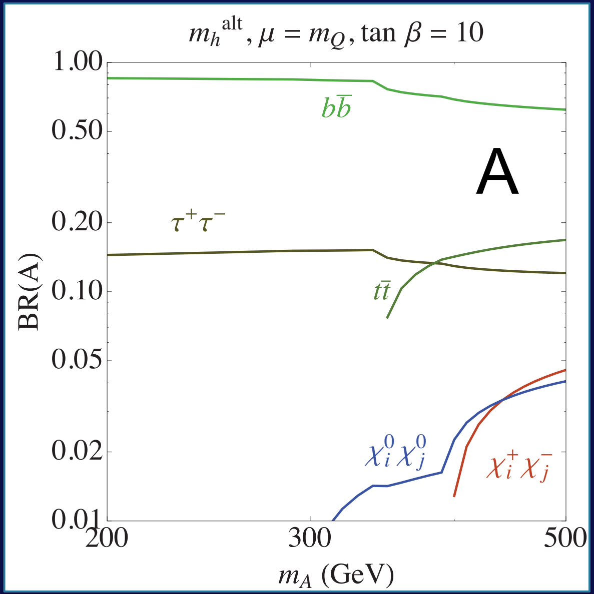
Craig, Galloway, Thomas'13; Su et al. '14, '15; M.C, Haber, Low, Shah, Wagner.'14

Depending on the values of μ and tanβ different search strategies must be applied

Alignment







Sizeable tanβ ➔ very close to alignment, dominant bottom and tau decays;

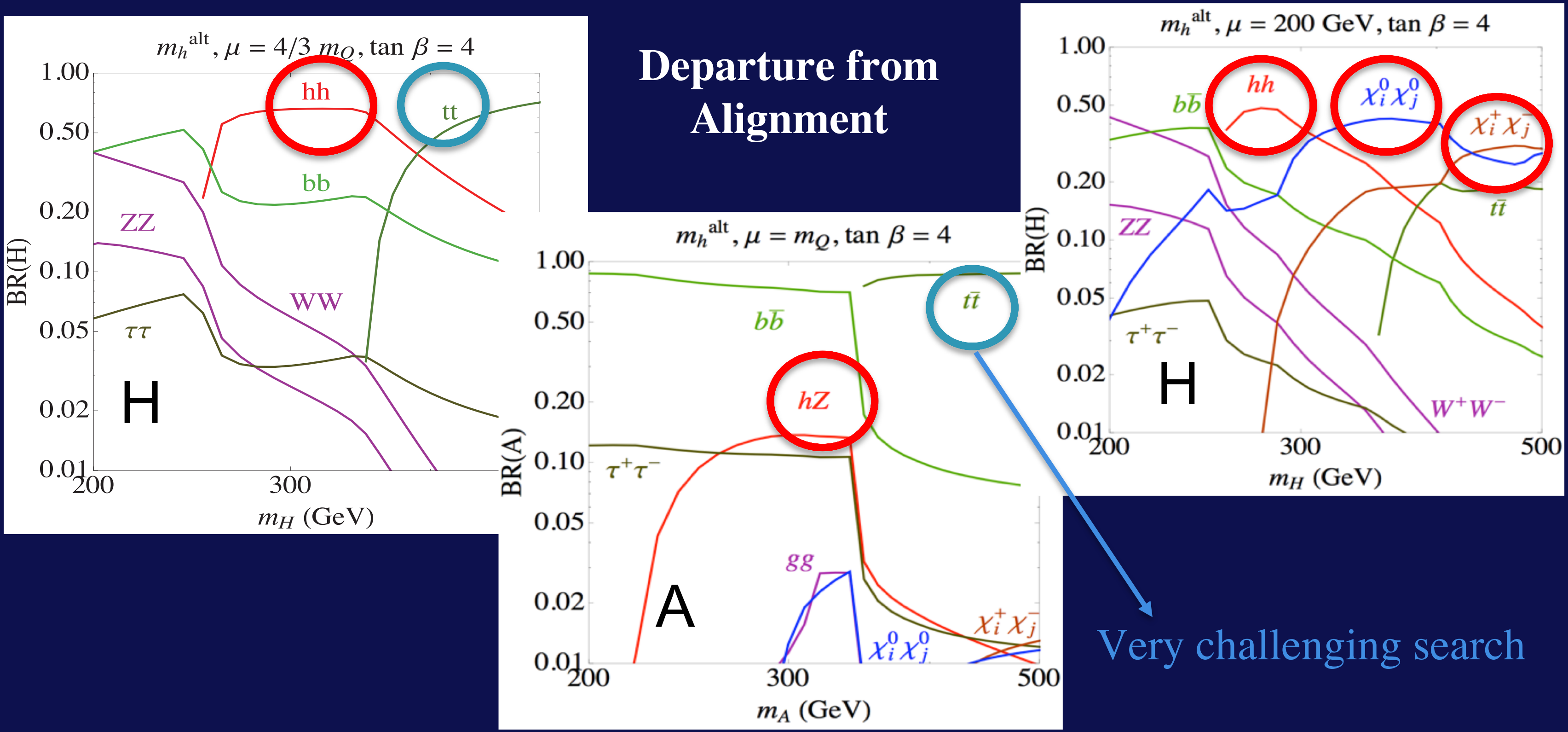
while $g_{Hhh} \simeq g_{HWW} \simeq g_{HZZ} \simeq g_{AhZ} \simeq 0$

Production mainly via large bottom couplings: bbH

Heavy Higgs Bosons: A variety of decay Branching Ratios

Craig, Galloway, Thomas'13; Su et al. '14, '15; M.C, Haber, Low, Shah, Wagner.'14

Depending on the values of μ & tanβ different search strategies apply



Departure from Alignment

Very challenging search

Smaller tanβ ➔ some departure from alignment,

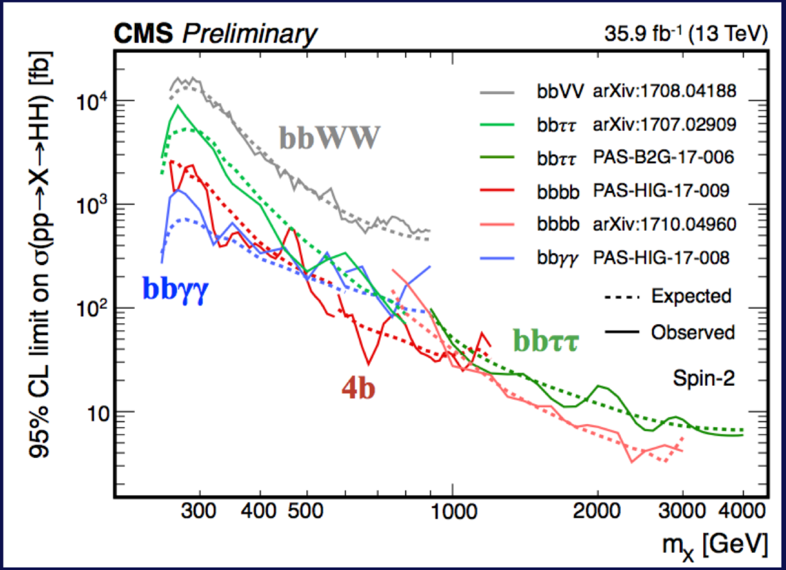
H→ hh, WW, ZZ and tt (also (A ➔ hZ, tt) become relevant.

Production mainly via top loops in gluon fusion

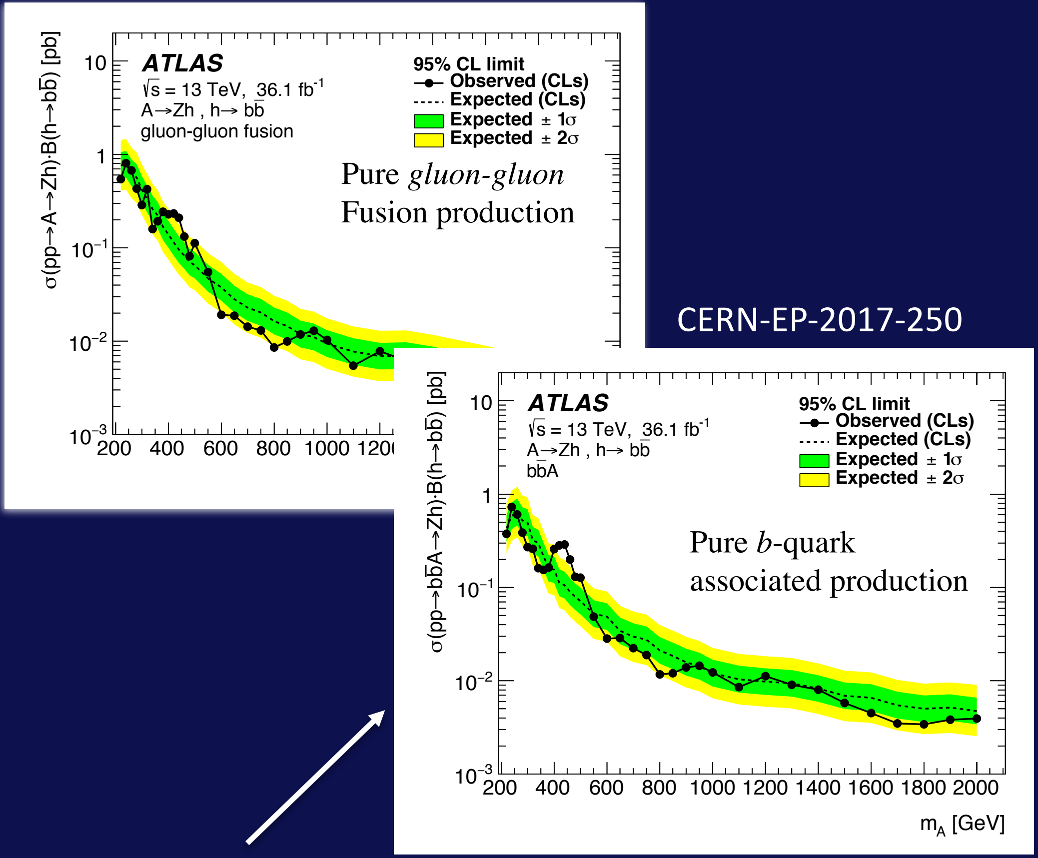
If low μ, then chargino and neutralino channels open up (impact on H/A → **ττ**)

Ongoing A/H boson searches at LHC

CMS summary on H→hh searches



ATLAS, with A → Zh and h → bb



CERN-EP-2017-250

- Mild excess of events is observed around 440 GeV, mainly driven by the di-muon channel in the resolved category with 3+ *b*-tags.
- Local significance of this excess with respect to the background-only hypothesis is 3.6 σ.
- Global significance, accounting for the look-elsewhere effect is estimated to be 2.4 σ.

Complementarity between Higgs precision and A/H Searches

All other 3 Higgs bosons may be heavy ~ TeV range ~ (Decoupling)
Or as light as a few hundred GeV (Alignment)

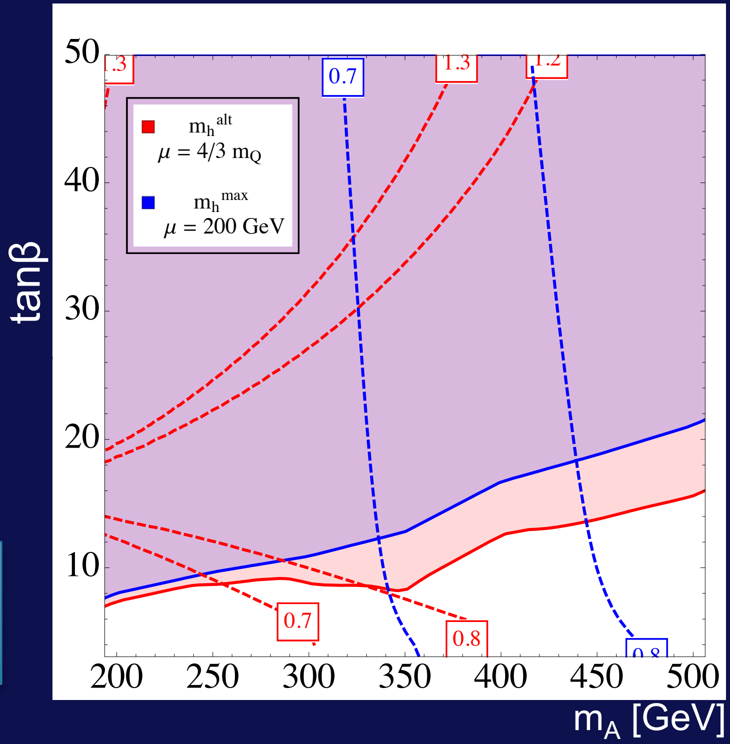
Direct A/H → ττ searches (shaded)
Indirect from h → VV measurements (dashed)

For Sizeable μ, alignment weakens limits from precision measurements (dashed red lines), and direct detection (red lines) is more relevant.

For smaller μ, departure from alignment implies limits from precision measurements (dashed blue) is more relevant

Hence, bounds on m_A are dependent on the scenario. at present are weaker for larger μ

M.C, Low, Shah, Wagner+ Haber



A modest improvement of direct search limits would be able to close the wedge, **below top pair decay threshold**

Similar effects in Extensions of the MSSM

e.g. additional SM singlets or triplets or models with enhanced weak gauge symmetries

Naturalness and the Alignment in the NMSSM

M.C, Haber, Low, Shah, Wagner.’15   Also Kang, Li, Liu, Shu’13; Agashe, Cui, Franceschini ’13

Superpotential $\lambda\, S\, H_u H_d \rightarrow \mu_{\rm eff} = \lambda \langle S \rangle$

- Well known additional contributions to m_h

$$m_h^2 \simeq \lambda^2 \frac{v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}$$

- Less well known:
  sizeable contributions to the mixing between MSSM CP-even eigenstates

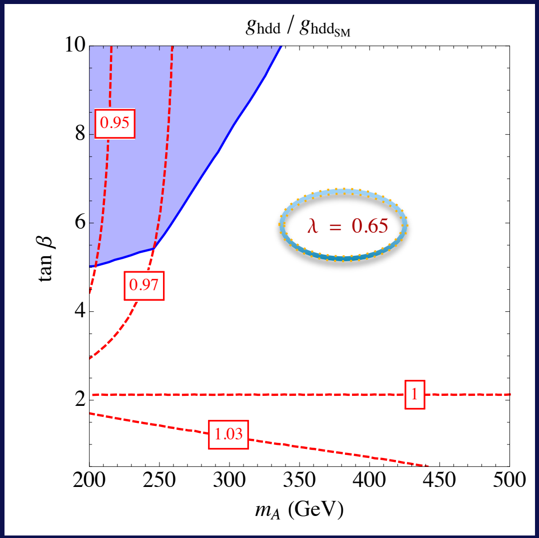
$$M_S^2(1,2) \simeq \frac{1}{\tan\beta}\left(m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2\beta + \delta_{\tilde{t}}\right)$$

Last term from MSSM; small for moderate/small μA_t and small tanβ

Alignment leads to λ in the restricted range 0.62 to 0.75, in agreement with perturbativity up to the GUT scale

$$\lambda^2_{\rm alt} = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2\beta}$$

Higgs-Bottom coupling in the NMSSM



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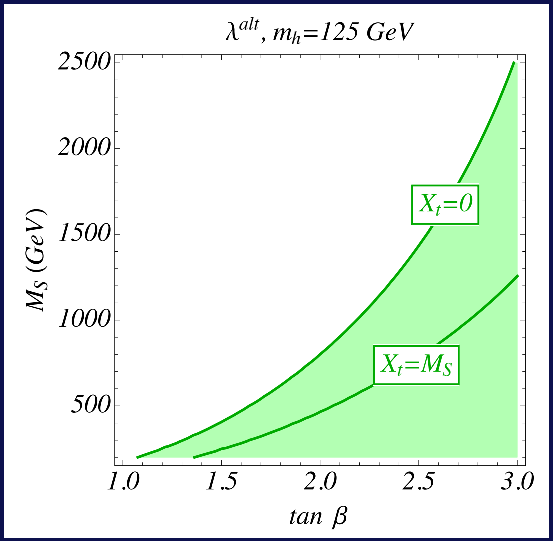


Alignment in the doublet Higgs sector of the NMSSM allows for light stops with moderate mixing

Aligning the Singlet

For a singlet at LHC reach, precision Higgs data demands high degree of alignment.

The mixing mass matrix element between the singlet and the SM-like Higgs is

$$M_S^2(1,3) \simeq 2\lambda v\mu \left(1 - \frac{m_A^2 \sin^2 2\beta}{4\mu^2} - \frac{\kappa \sin 2\beta}{2\lambda}\right)$$

Needs to vanish in alignment

For tanβ < 3, λ ~ 0.65 and κ in the perturbative regime, small mixing in the Higgs sector implies that m_A and μ are correlated

$$M_A \sim \frac{2|\mu|}{s_{2\beta}}$$

$$\boxed{\mathbf{m_A} \approx \frac{\mathbf{2}|\mu|}{\mathbf{sin2}\beta}}$$

Unlike the MSSM, alignment without decoupling implies small μ, hence, again alignment and naturalness come together in a beautifully in the NMSSM

Moreover, this ensures also that all parameters are small and the CP-even and CP-odd singlets and singlino become self consistently light

$$\mathbf{m_{\tilde{S}}} = \mathbf{2}\mu\frac{\kappa}{\lambda}$$

of interest for Dark Matter

NMSSM properties close to Alignment

Singlet spectra and decays

- Heavier CP-even Higgs can decay to lighter ones: $2\,m_{hs} < M_H$
- CP-even light scalar, $h_{S,}$ mainly decays to bb and WW ;
- CP odd light scalar, $a_{S,}$ mainly decays to bb
- Anti-correlation between singlet –like CP-even and CP-odd masses

doublet-like A and H decays:

-- **A/H decay significantly into top pairs; BRs ~ 20% to 80% (dep. on tanβ)**

decays may be depleted by decays into charginos/neutralinos (10% to 50%)

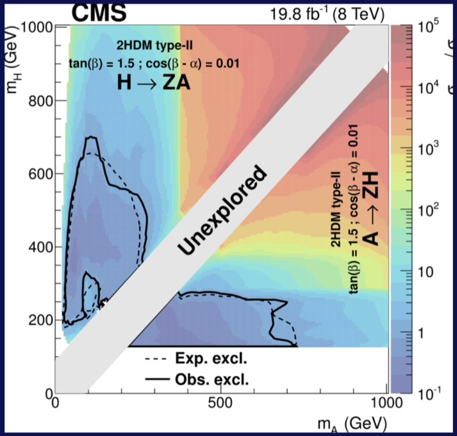
-- Other relevant decays: H → hh_S and A → Zh_S (20% to 50%, dep on mass)

H → hh and A → hZ decays strongly suppressed due to alignment

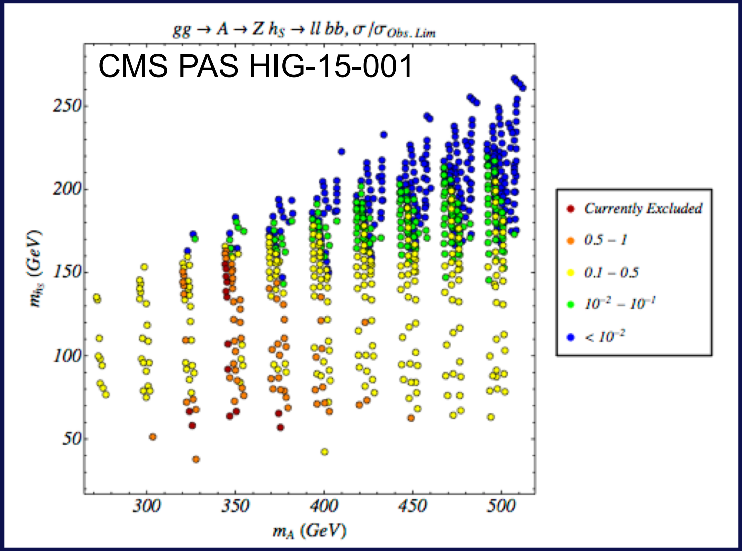
Others: H →hs hs; H→As Z; A→As hs; A→As h of order 10% or below

Ongoing searches at the LHC are probing exotic Higgs decays

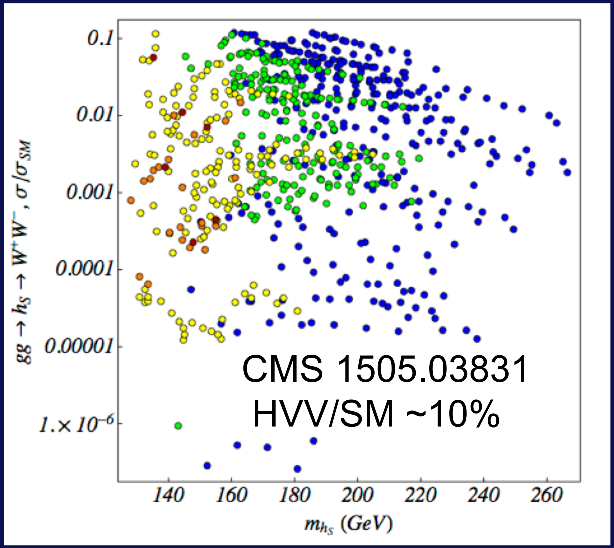
- Complementarity between gg → A → Z h_S → ll bb and gg → h_S → WW searches



CMS-PAS-HIG-15-001



CMS PAS HIG-15-001



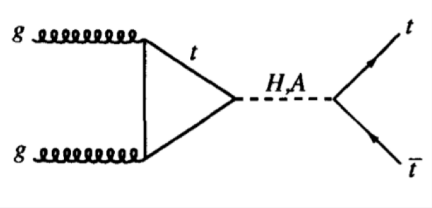
CMS 1505.03831
HVV/SM ~10%

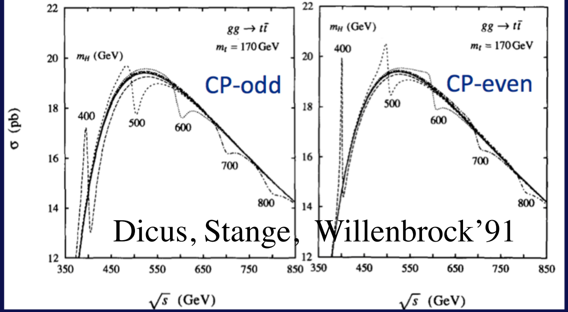
- **Promising H → h h_S channels with h_S → bb or WW (4b's or bb WW)**
- **Searches for H → ZA or A → ZH should replace Z by h_{125} (Di-scalar Searches)**
- Channels with missing energy: A → h a_s; H → Z a_s with a_s → Dark Matter

The challenging A/H ➔ tt channel: Interference effects

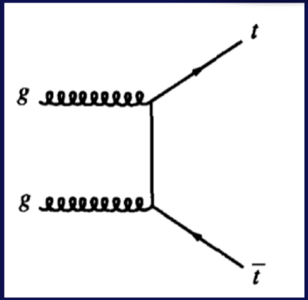
LHC is a top factory but challenges lie in the interference effect.

See Zhen Liu’s Talk





Dicus, Stange, Willenbrock’91

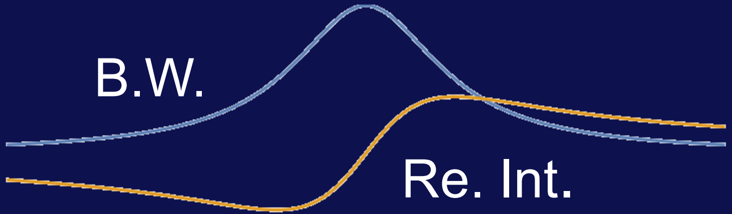


$$A_{sig} = c_{sig} \frac{\hat{s}}{\hat{s} - m^2 + i\,\Gamma m} = c_{sig}\, \mathrm{P}(\hat{s})$$

$$A_{bkg} = c_{bkg} \text{ (slowing varying function of } \hat{s}\text{)}$$

$$|A|^2 = \left|A_{sig} + A_{bkg}\right|^2 = \left|A_{sig}\right|^2 + \left|A_{bkg}\right|^2 + 2Re\left[A_{sig} A^*_{bkg}\right]$$

$$= B.W. + BKG + \underbrace{2Re\left[c_{sig} c^*_{bkg}\right] \boldsymbol{Re[P(\hat{s})]}}_{\mathrm{R_{int}}} + 2Im\left[c_{sig} c^*_{bkg}\right] \boldsymbol{Im[P(\hat{s})]}$$



$$\boldsymbol{Re[P(\hat{s})]} = \frac{\hat{s}(\hat{s} - m^2)}{(\hat{s} - m^2)^2 + \Gamma^2 m^2}$$

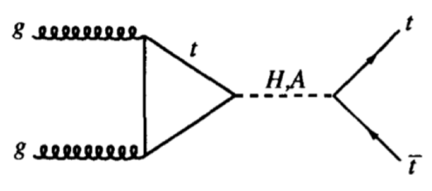
$$\boldsymbol{Im[P(\hat{s})]} = \frac{-i\,\hat{s}\,\Gamma m}{(\hat{s} - m^2)^2 + \Gamma^2 m^2}$$

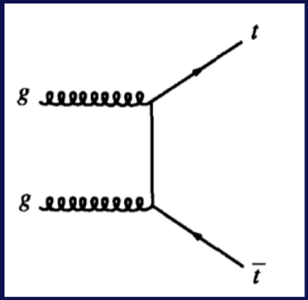
- Background real
- Re. Int.– from the real part of the propagator:

at parton level no contribution to the rate
➔ shift the mass peak. [When convoluting with PDF, may generate residual contribution to signal rate]

The challenging A/H ➔ tt channel: Interference effects

LHC is a top factory ➔ good statistics but challenges lie in the interference effect.





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

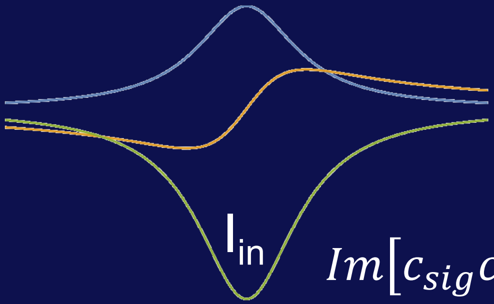
$A_{bkg} = c_{bkg}$ (slowing varying function of $\hat{s}$)

$$|A|^2 = \left|A_{sig}+A_{bkg}\right|^2 = \left|A_{sig}\right|^2 + \left|A_{bkg}\right|^2 + 2Re\left[A_{sig}A^*_{bkg}\right]$$

$$= B.W. + BKG + 2Re\left[c_{sig}c^*_{bkg}\right]\boldsymbol{Re[P(\hat{s})]} + \underbrace{2Im\left[c_{sig}c^*_{bkg}\right]\boldsymbol{Im[P(\hat{s})]}}_{\mathrm{I_{int}}}$$

$$\boldsymbol{Re[P(\hat{s})]} = \frac{\hat{s}(\hat{s}-m^2)}{(\hat{s}-m^2)^2+\Gamma^2 m^2}$$

$$\boldsymbol{Im[P(\hat{s})]} = \frac{-i\,\hat{s}\,\Gamma m}{(\hat{s}-m^2)^2+\Gamma^2 m^2}$$

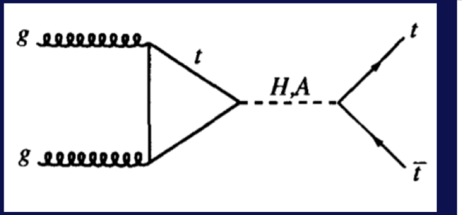


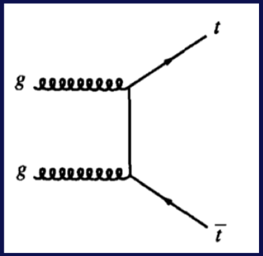
Im. Int.–from the imaginary part of propagator

$$Im\left[c_{sig}c^*_{bkg}\right] = |\mathrm{c_{sig}}||\mathrm{c^*_{bkg}}|\sin(\delta_{sig}-\delta_{bkg})$$

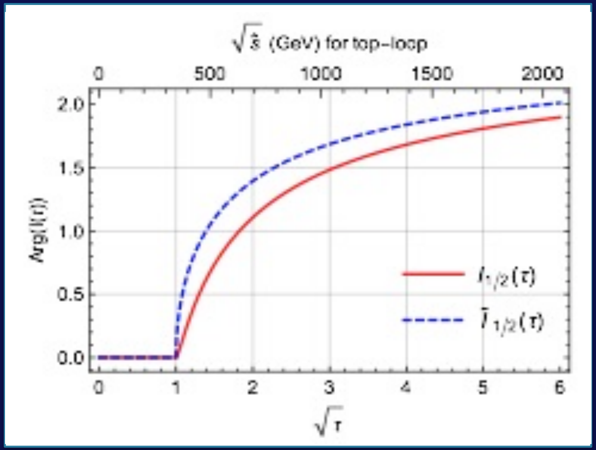
When phase $\delta_{sig}-\delta_{bkg}$ (strong phase) is none-zero, there is a new interference effect that cannot be neglected, no matter how narrow is the resonance

The challenging A/H → tt channel: Interference effects

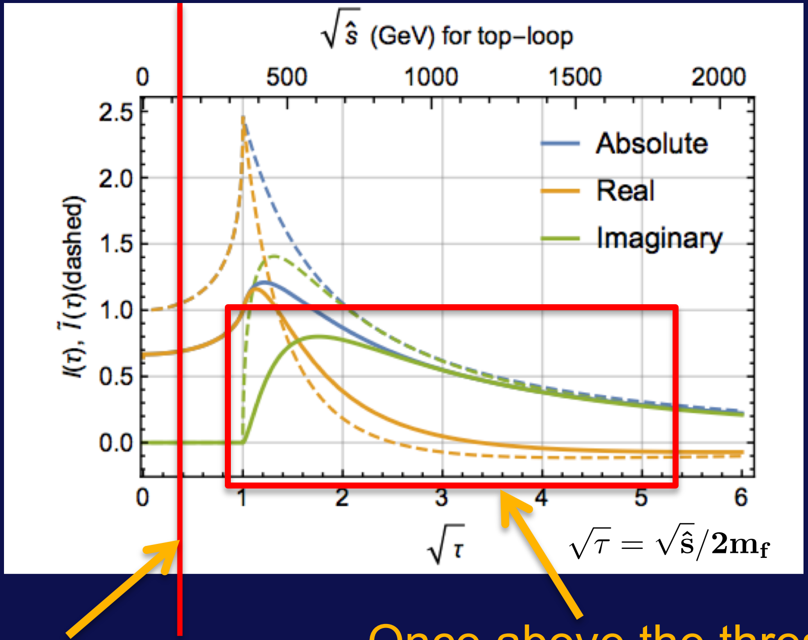




Phase of the loop function



Triangle loop function



SM Higgs
real & slowly varying

Once above the threshold, imaginary piece increases and real piece decreases.

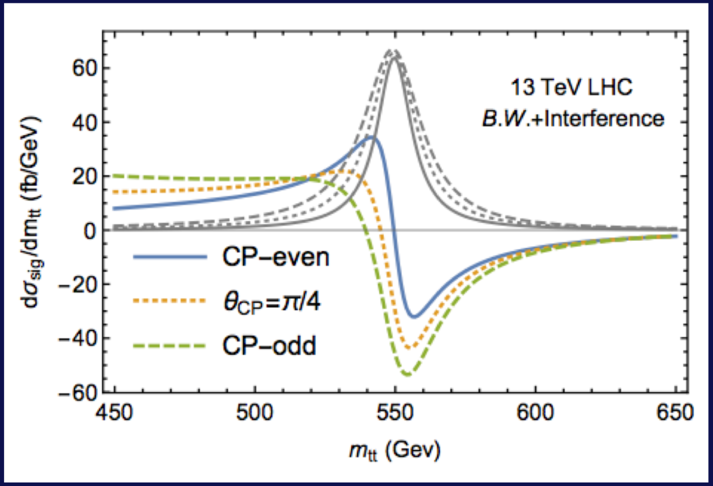
Background real

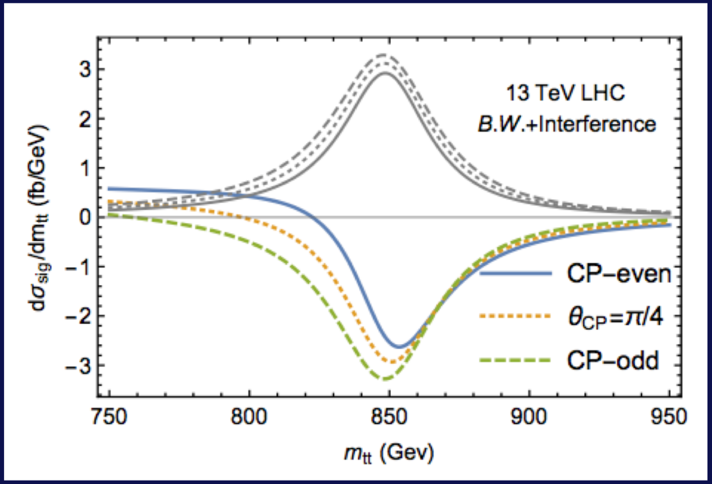
Real Interference from the real part of the propagator and real part of loop function (shifts the mass peak; no contribution to the signal rate besides residual effect of PDF's)

Im. Interference from the imaginary part of propagator with imaginary part of loop function (rare case, changes signal rate)

Special Line-shapes examples with one (pseudo) scalar

BSM line-shapes for various CP phase eigenstates
for heavy scalar masses at 550 GeV and 850 GeV



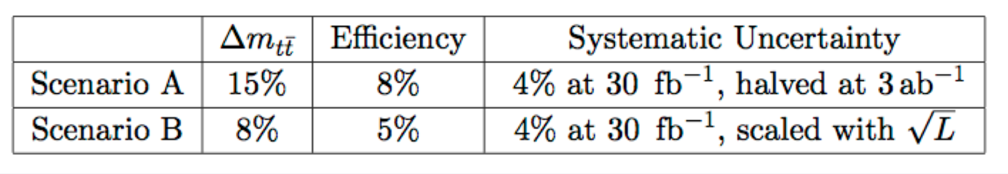


Searches not designed/optimized for
bump-dip/ dip structure.
Smearing effects flatten the dips and bumps,
making it harder.

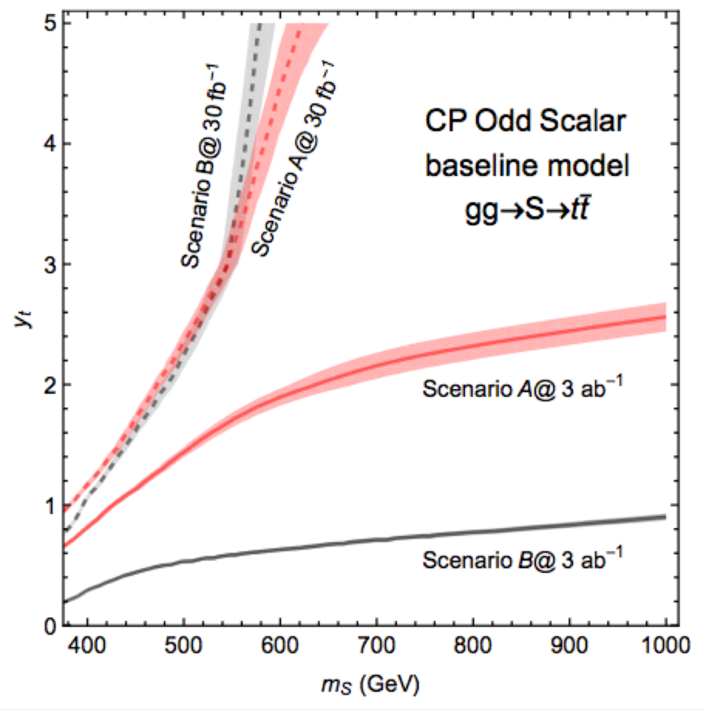
Impact of interference effect in A/H → tt at the LHC

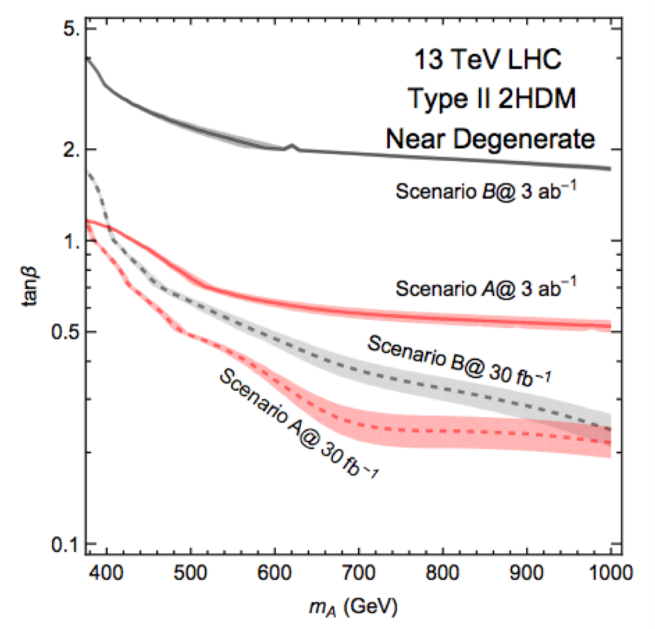
Projections for A/H → tt in Type II 2HDM

M.C., Liu ‘16

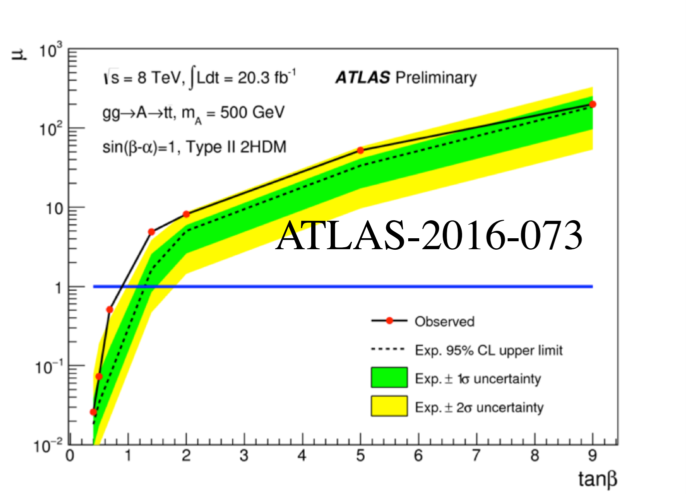


	$\Delta m_{t\bar{t}}$	Efficiency	Systematic Uncertainty
Scenario A	15%	8%	4% at 30 fb^{-1}, halved at 3 ab^{-1}
Scenario B	8%	5%	4% at 30 fb^{-1}, scaled with $\sqrt{L}$





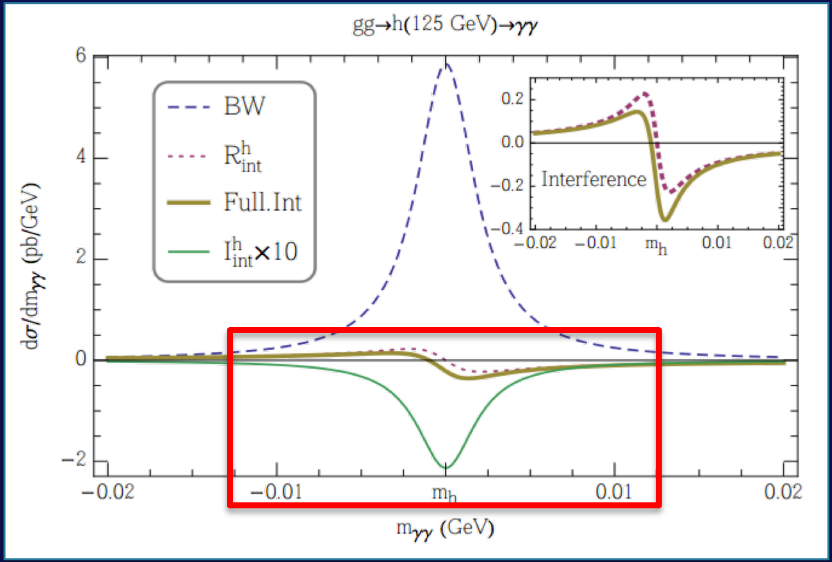
First interference studies at ATLAS



ATLAS-2016-073

Interference effects can affect Higgs LHC interpretations

Novel probe of Higgs total width & sensitivity to new physics from $gg \rightarrow h \rightarrow \gamma\gamma$

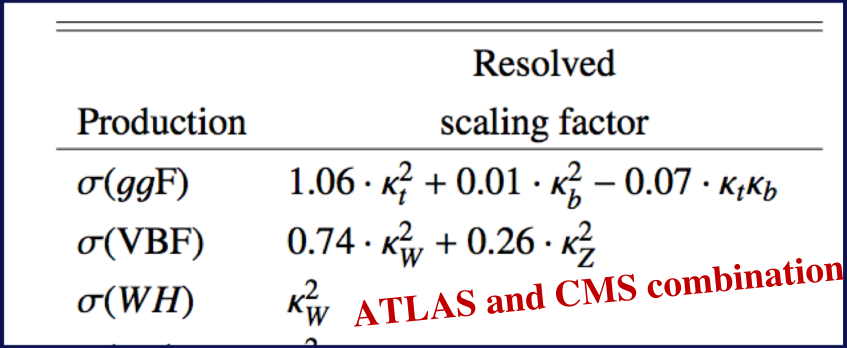


See Zhen Liu's Talk

Averaging over helicity amplitudes and polar angles, one can calculate this interference between signal & background

$$Im = |c_{sig}||c^*_{bkg}|\sin(\delta_{sig} - \delta_{bkg})$$

Interference from the strong phase changes SM rate by $\sim -2.\%$



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

ATLAS and CMS combination

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

Sensitivity to Higgs Width from gg → h → γγ on-shell rate

Interference & Breit-Wigner terms have different dependence on the Higgs boson total width

$$\sigma \propto \frac{|F_{gg}|^2|F_{\gamma\gamma}|^2}{\Gamma_h m_h}\left(1+\frac{2m_h\Gamma_h|A_{\rm bkg}|\sin\delta_s}{|F_{gg}||F_{\gamma\gamma}|}\right) \longrightarrow \sigma = \sigma_{\rm BW}(1+\sigma_{\rm int}/\sigma_{\rm BW}).$$

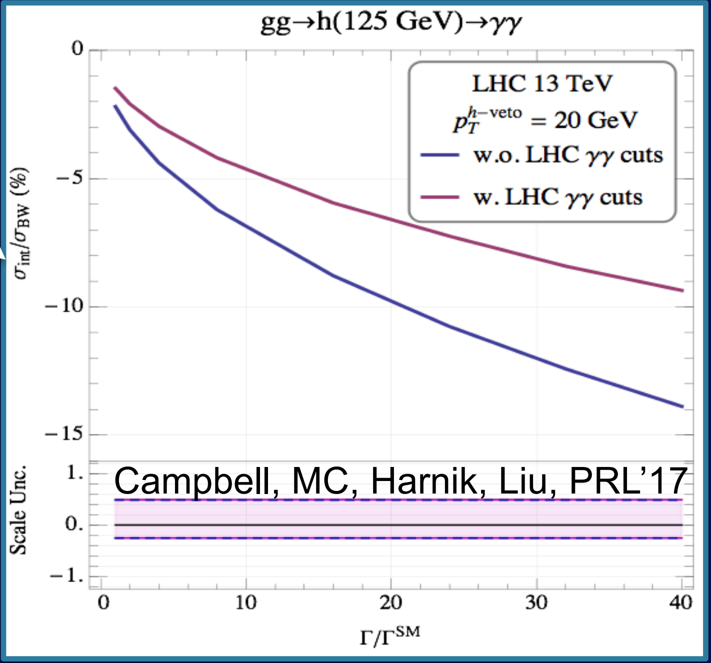
In the extreme case where observed Higgs couplings increase by factor f, and Higgs total width by factor f^4 ➔ All on-shell cross sections remain the same as SM predictions

In gg → h → γγ , the presence of the interference term lifts the degeneracy

$$\sigma = \sigma^{\rm SM}_{\rm BW}\left(1+\frac{\sigma^{\rm SM}_{\rm int}}{\sigma^{\rm SM}_{\rm BW}}\sqrt{\frac{\Gamma_h}{\Gamma_h^{\rm SM}}}\right) \simeq \sigma^{\rm SM}_{\rm BW}\left(1-2\%\sqrt{\frac{\Gamma_h}{\Gamma_h^{\rm SM}}}\right)$$

Unique piece that does not depend on total width

- Similar to off-shell ZZ/WW measurement;
- Negligible dependence on coupling at different scales (unlike the off-shell measurements).



Campbell, MC, Harnik, Liu, PRL'17

Suppose HL-LHC will measure this effect (e.g., the ratio of σγγ/σ4l) to 4%, it will constrain Higgs total width to ~14 times SM value

The large scale uncertainty calls for improvement of the QCD background beyond NLO.

Differential distributions can help improve on the width information!

Interference Effects in Di-Higgs Production: gg → S → HH

Models with additional singlets open a door for strong first order phase transitions

Singlet extension of the SM can serve as a benchmark, challenging to test at colliders

- Consider case of Spontaneous Z_2 breaking
- Find that interference effect can enhance di-Higgs production up to 40%, improving LHC

$$V(s,\phi) = -\mu^2\phi^\dagger\phi - \frac{1}{2}\mu_s^2 s^2 + \lambda(\phi^\dagger\phi)^2 + \frac{\lambda_s}{4}s^4 + \frac{\lambda_{s\phi}}{2}s^2\phi^\dagger\phi,$$

spontaneous symmetry breaking defines μ^2 and μ^2_S in terms of the original quartic couplings & the vevs

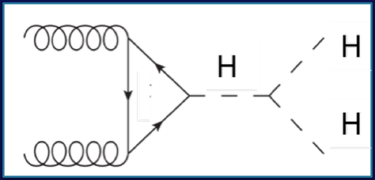
Parameters in the potential can be traded by

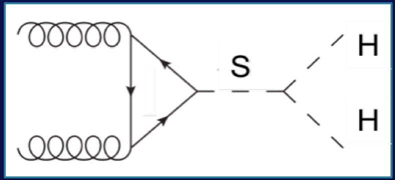
m_H =125 GeV, v=246 GeV

m_S, $\tan_\beta(\equiv v_s/v)$, $\sin\theta$,

Besides singlet-doublet mixing governed by $\sin\theta$, di-Higgs final states are characterized by two trilinear coupling:

$$L \supset \lambda_{HHH}H^3 + \lambda_{SHH}SH^2.$$





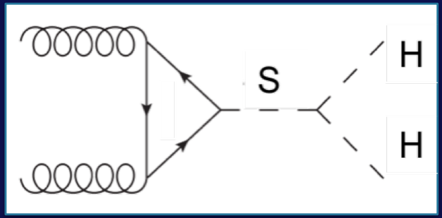
$$\lambda_{HHH} = -\frac{m_H^2}{2\tan\beta\; v}\left(\tan\beta\cos^3\theta - \sin^3\theta\right),$$

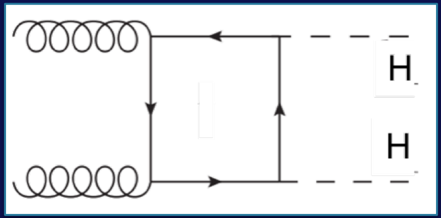
$$\lambda_{SHH} = -\frac{m_H^2}{2\tan\beta\; v}\sin 2\theta(\tan\beta\;\cos\theta + \sin\theta)(1 + \frac{m_S^2}{2m_H^2}).$$

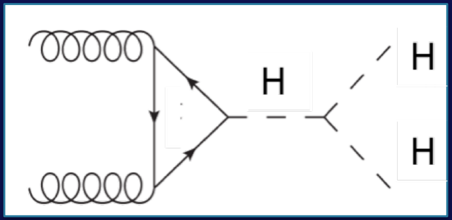
Interference Effects in Di-Higgs Production: gg → S → hh

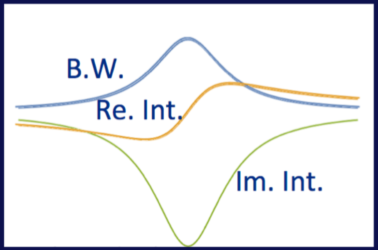
Models with additional singlets open a door for a strong first order phase transition

Singlet extension of the SM can serve as a benchmark, challenging to test at colliders





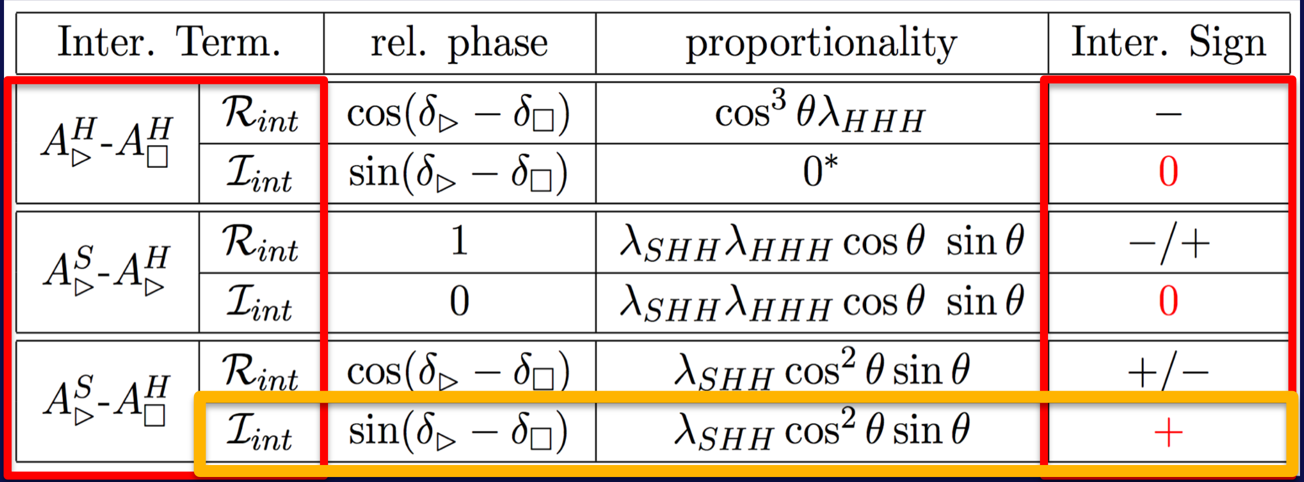




$$A^S_\Delta = A_{gg-S\to hh} = c_\Delta \frac{\hat{s}}{\hat{s} - m^2 + i\,\Gamma m}$$

$$A^H_\Box = A_{gg\to hh} = c_\Box \text{(slowing varying function of } \hat{s}\text{)}$$

$$A^H_\Delta = A_{gg\to h^*\to hh} = c'_\Delta \text{ (slowing varying function of } \hat{s}\text{)}$$



Inter. Term.		rel. phase	proportionality	Inter. Sign
$A^H_\triangleright$-$A^H_\Box$	$\mathcal{R}_{int}$	$\cos(\delta_\triangleright - \delta_\Box)$	$\cos^3\theta\lambda_{HHH}$	$-$
	$\mathcal{I}_{int}$	$\sin(\delta_\triangleright - \delta_\Box)$	0^*	0
$A^S_\triangleright$-$A^H_\triangleright$	$\mathcal{R}_{int}$	1	$\lambda_{SHH}\lambda_{HHH}\cos\theta\ \sin\theta$	$-/+$
	$\mathcal{I}_{int}$	0	$\lambda_{SHH}\lambda_{HHH}\cos\theta\ \sin\theta$	0
$A^S_\triangleright$-$A^H_\Box$	$\mathcal{R}_{int}$	$\cos(\delta_\triangleright - \delta_\Box)$	$\lambda_{SHH}\cos^2\theta\sin\theta$	$+/-$
	$\mathcal{I}_{int}$	$\sin(\delta_\triangleright - \delta_\Box)$	$\lambda_{SHH}\cos^2\theta\sin\theta$	$+$

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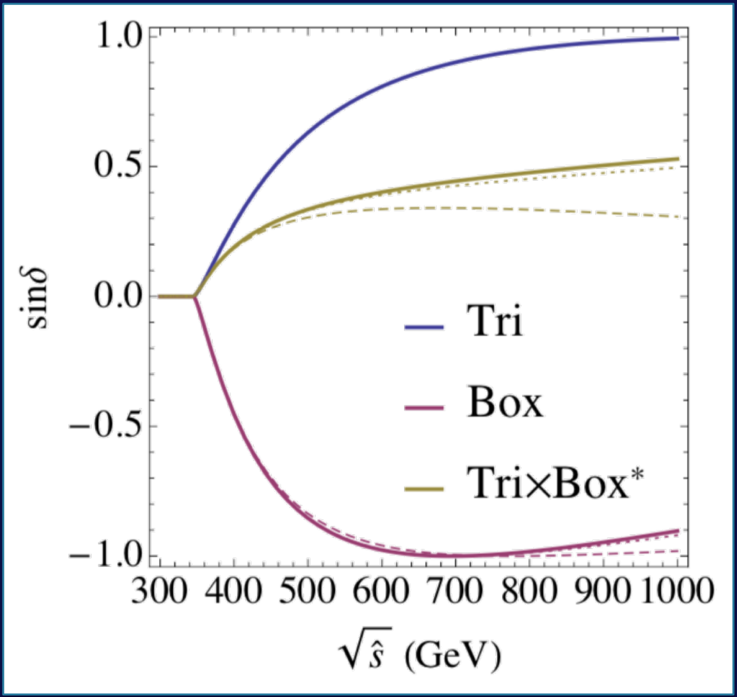
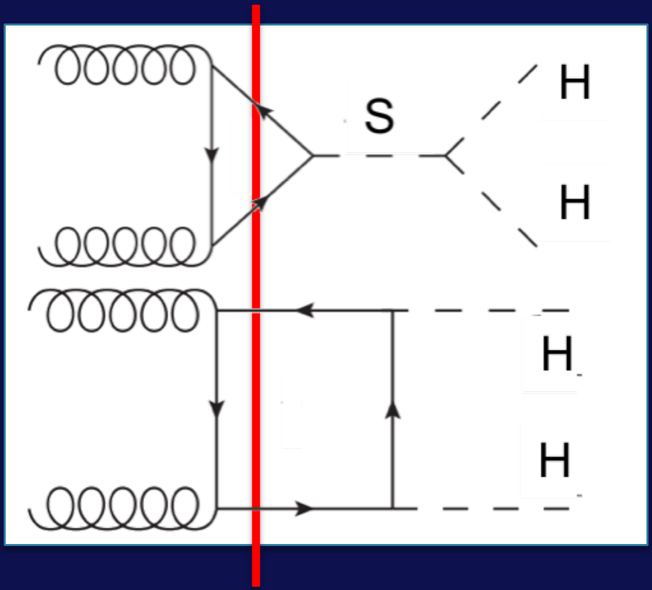
Strong phase in the loop functions

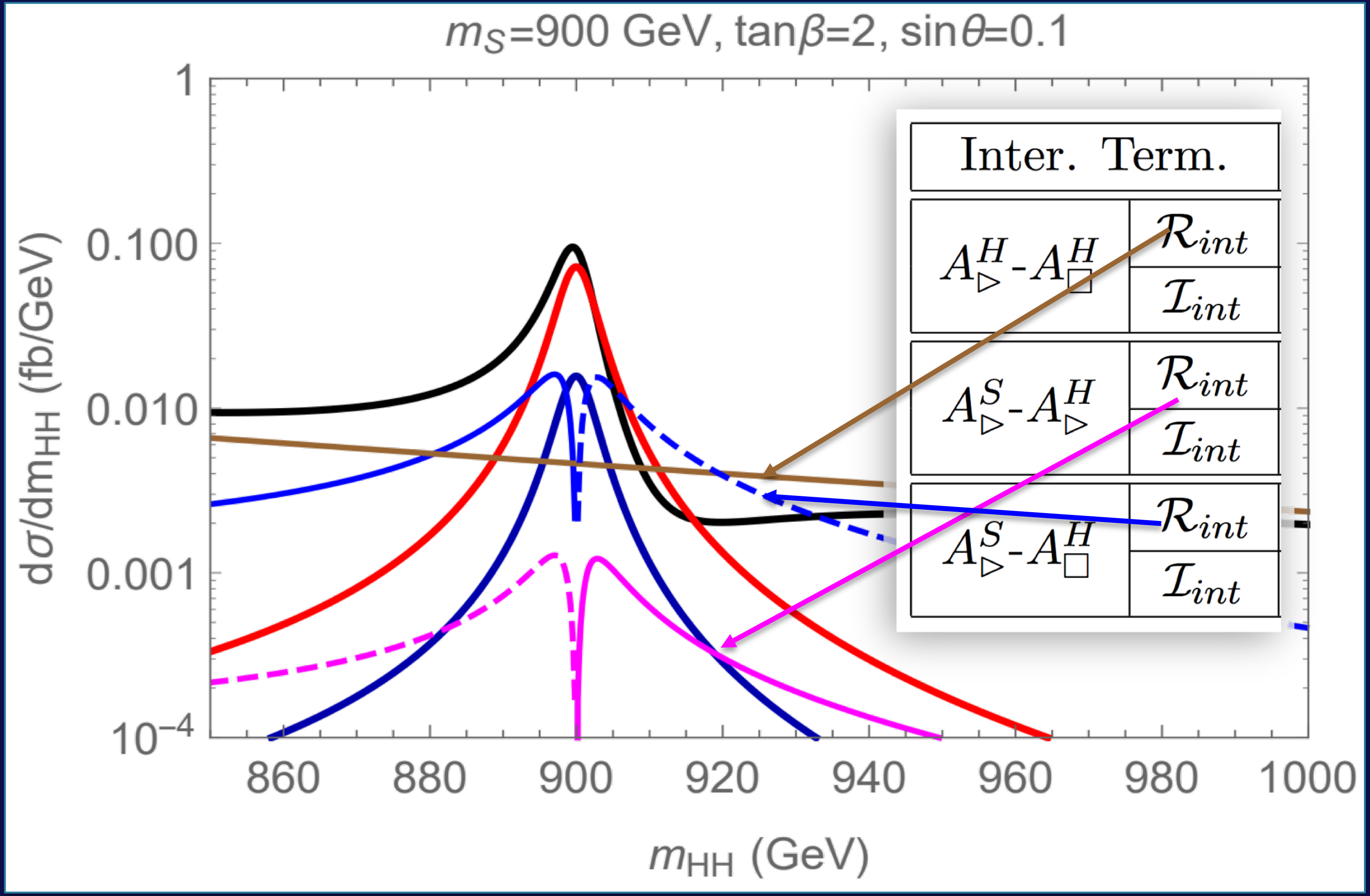




The solid, dotted, and dashed curves correspond to scattering angles of 0, 0.5 and 1, respectively

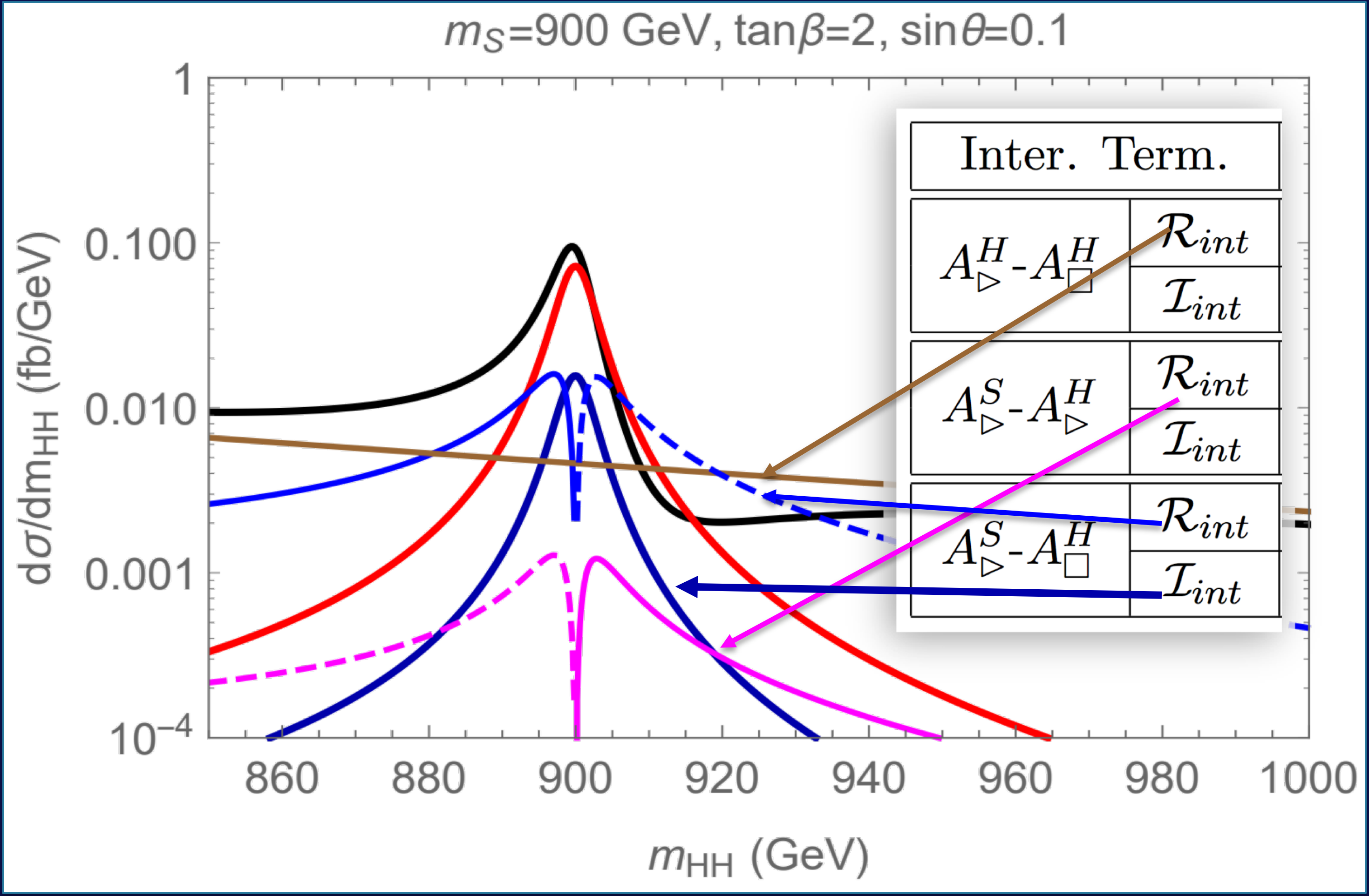
Relative strong phase (yellow curve) allows for a non-vanishing interference effect between the singlet resonance diagram and the SM box diagram.

Interference Line shape



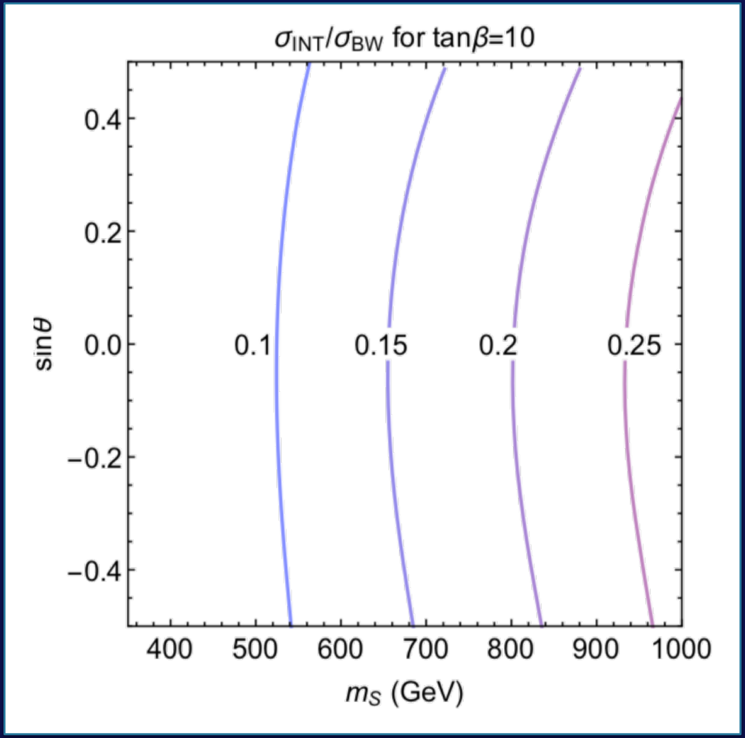
Logarithmic to see other components;
Dashed represent destructive interference;
Dark blue, unique on-shell constructive interference

Interference Line shape



Logarithmic to see other components;
Dashed represent destructive interference;
Dark blue, unique on-shell constructive interference

Relevance of the on-shell interference

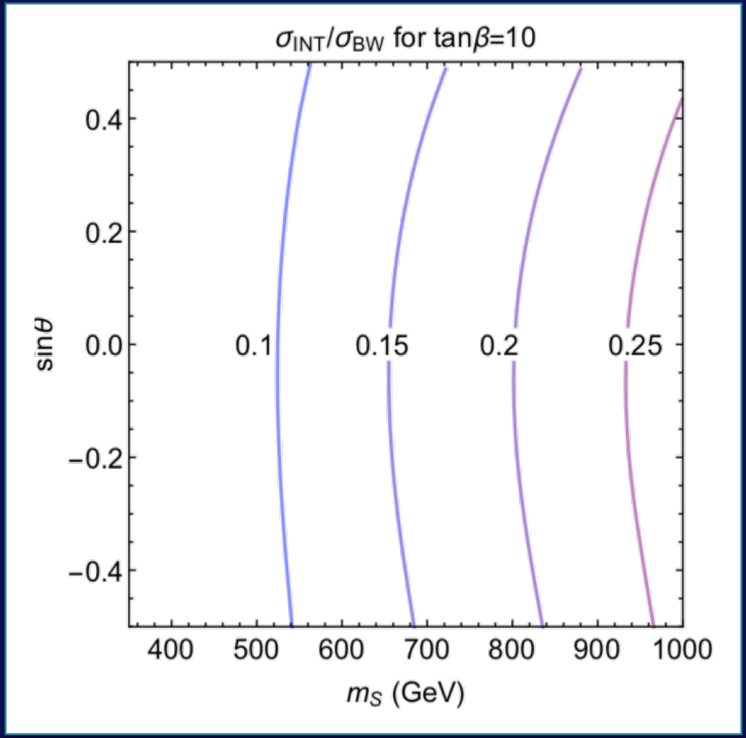


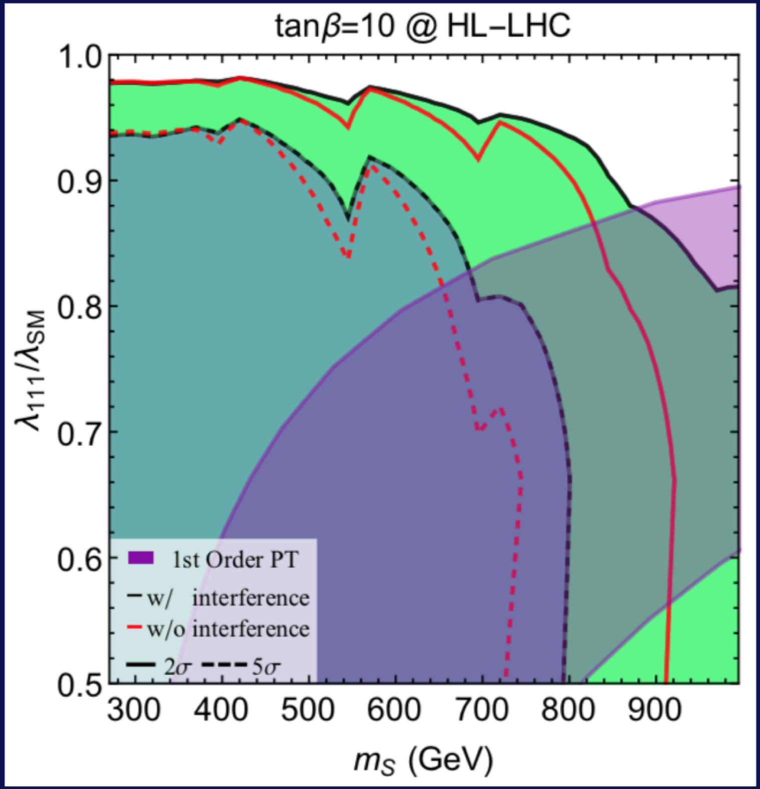
Relative size of the on-shell interference effect w.r.t. the resonant BW signal, averaged over scattering angle [-0.5,0.5]

For different parameters, it could be up to 40% below 1 TeV or increase even further for heavier singlet masses.

Interference effect could play an important role in the pheno and further determination of model parameters if the heavy scalar is discovered.

Relevance of the on-shell interference





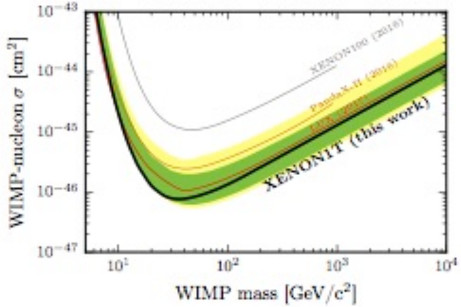
Based on the pp → HH → bbγγ, analysis [arXiv:1502.00539] we perform a differential analysis of the lineshapes:

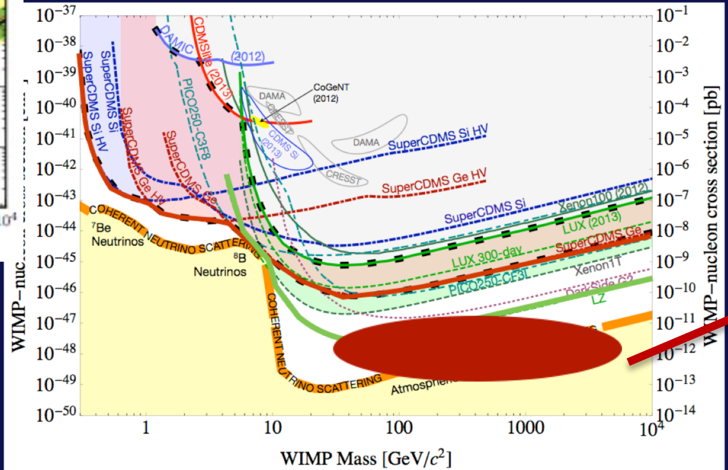
M.C. Z. Liu and M. Riembau. ‘18

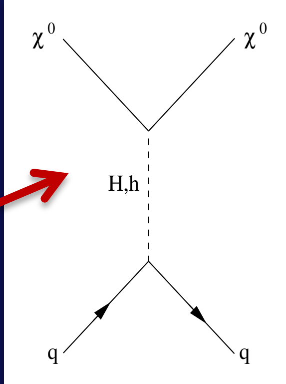
- Black/red lines, w/wo interference effect;
- Purple shaded region, 1st Order Phase Transition (FOPT) through an EFT analysis
- Correct inclusion of the interference effect extends the sensitivity in FOPT region

Dark Matter Direct Detection

Starting to probe the Higgs portal







Close to Alignment (MSSM)

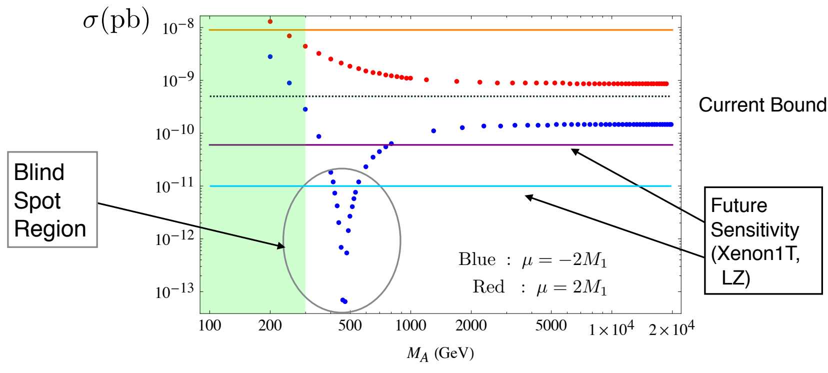
$$\sigma_p^{SI} \sim \left[(F_d^{(p)}+F_u^{(p)})(m_\chi+\mu\sin 2\beta)\frac{1}{m_h^2}+\mu\tan\beta\cos 2\beta(-F_d^{(p)}+F_u^{(p)}/\tan^2\beta)\frac{1}{m_H^2}\right]^2$$

$$\boxed{2\,(m_\chi+\mu\sin 2\beta)\frac{1}{m_h^2}\simeq -\,\mu\tan\beta\frac{1}{m_H^2}}$$

Destructive interference between h and H contributions for negative values of μ (cos2β negative)

Still room for a SUSY WIMP miracle

Huang, Wagner, '15



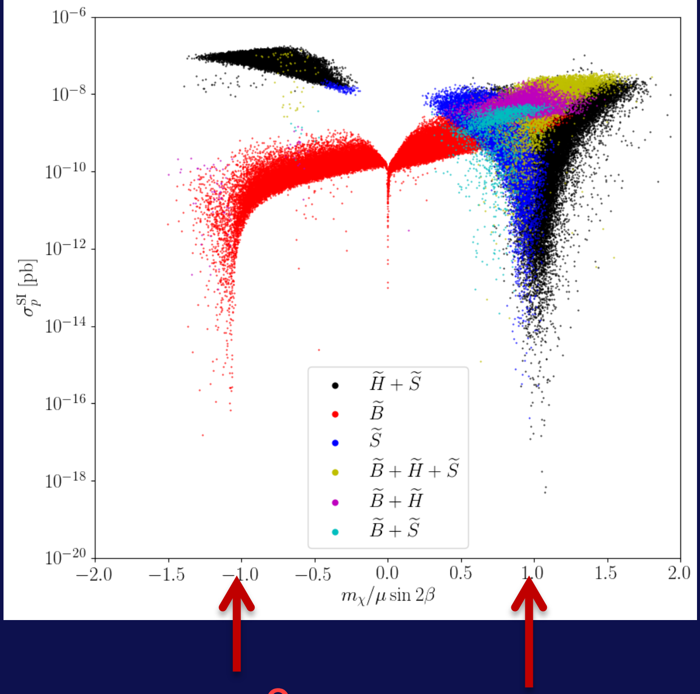
Blind Spots in Direct DM detection in the NMSSM

Possible to have a three way cancellation between the hs, h and H contributions

$$\sigma_{SI} \propto \left\{ \left(\frac{2}{t_\beta} - \frac{m_\chi}{\mu}\right)\frac{2\,t_\beta}{m_h^2} + \frac{t_\beta}{m_H^2} + \frac{1}{m_{h_S}^2}\left(2\,S_{h,s} + \frac{\lambda\, v}{\mu}\right)\left[\frac{\lambda\, v}{\mu^2}\, m_\chi + S_{h,s}\left(\frac{2}{t_\beta} - \frac{m_\chi}{\mu}\right) + \frac{\kappa\,\mu}{\lambda^2\, v}\right]\right\}^2 .$$

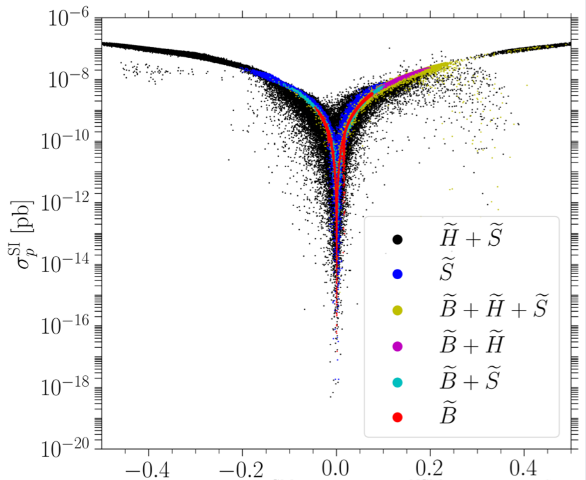
$$S_{h,s} \approx \frac{-2\lambda v \mu \epsilon}{(m_h^2 - m_{h_S}^2)}$$

Cheung, Papucci, Sanford, Shah, Zurek '14



μ < 0

μ > 0



Higgs Mixing Effects:
Couplings to the 125 GeV Higgs tend to be suppressed close to the blind spots. However, they remain relevant in the singlino region, denoting the presence of relevant interferences

A SM-like Higgs would have couplings that vanish when $m_\chi = \pm\mu \sin(2\beta)$. The plus and minus signs correspond to the cases in which the neutralino is Bino-Higgsino or Singlino-Higgsino admixtures.

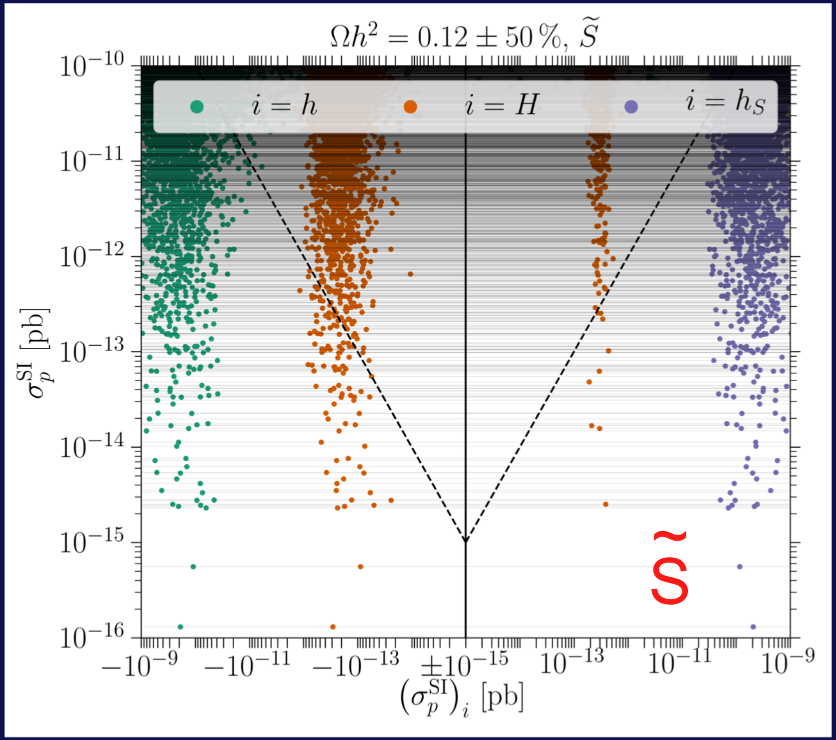
assumed 50% composition

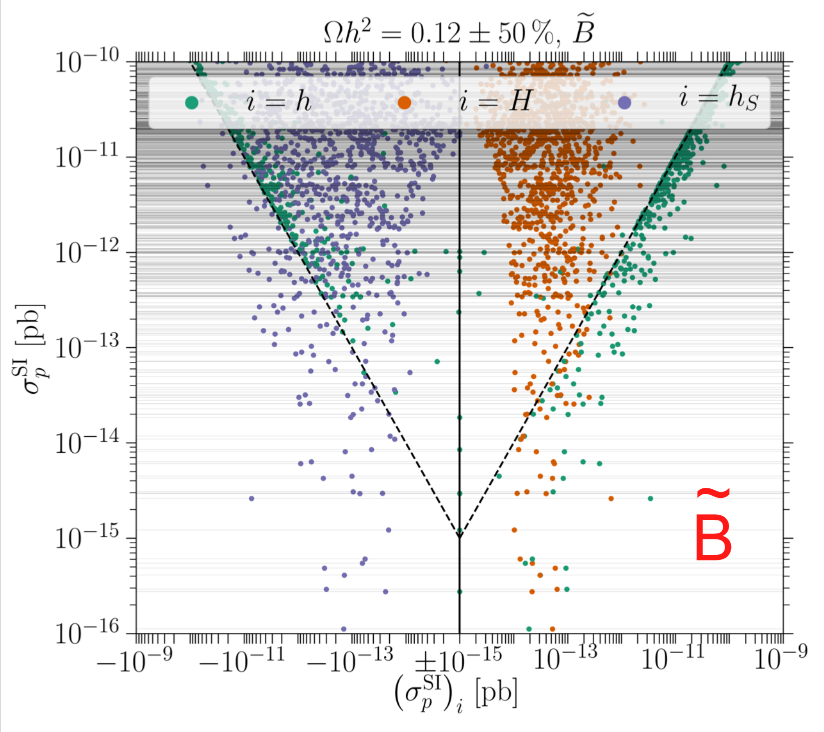
Baum, M.C. Shah, Wagner '18

NMSSM opens up new possibilities

Contributions to SI XS of the different (scalar) Higgs bosons

and sign of the different scalar contributions to the SI cross section.





Mostly singlinos: coupling to Higgs larger than for Bino ➔ SM-like Higgs coupling close to blind spot and destructive interference with singlet and non-SM CP even doublet needed
Thermal Relic can be obtained via Z (G) annih.

Mostly Binos: SM-like Higgs provides the dominant contribution.
NEW Bino well-tempered region, with small couplings to Higgs and proximity to blind spot
Thermal Relic density via resonant Z, Higgs annih, or co-annihilation of bino with singlino

Outlook

The 125 GeV Higgs

- Higgs Precision measurements call for a significant degree of alignment, with important implications for additional Higgs bosons searches & Dark Matter

Minimal SUSY (MSSM)

- Alignment in the Higgs sector calls for a heavy spectrum (sizeable mu or heavy M_A
- DM well tempered, Bino-Higgsino region: SI direct detection requires blind spots with relatively light additional Higgs masses
- Some departure from Alignment → A/H decays into WW.ZZ, hh, tops, (Ewkinos)

Singlet SUSY extensions (NMSSM)

- Necessary degree of alignment without decoupling is tied to a light Higgsino, Singlino and singlet Higgs sector, and allows for lighter stops with moderate mixing.
- Good for achieving the 125 GeV Higgs and compatible with perturbavity up to M_{GUT}
- New search channels for A/H decaying to scalars and gauge bosons (not explored)
- New well-tempered Bino-Higgsino region with blind spots for SI Direct detection

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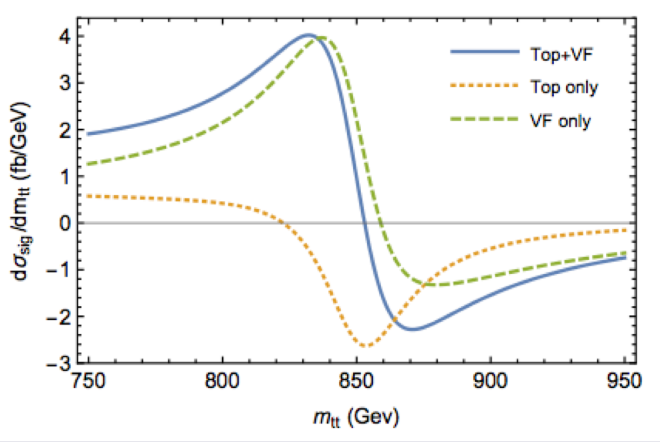
Phase shift between SM and new physics can have important implications

- Provide novel on-shell info on Higgs total width & light quark Higgs couplings
- Enhance LHC sensitivity to simple models with a strong FOPT
- Needed in performing scalar resonant searches above the top threshold

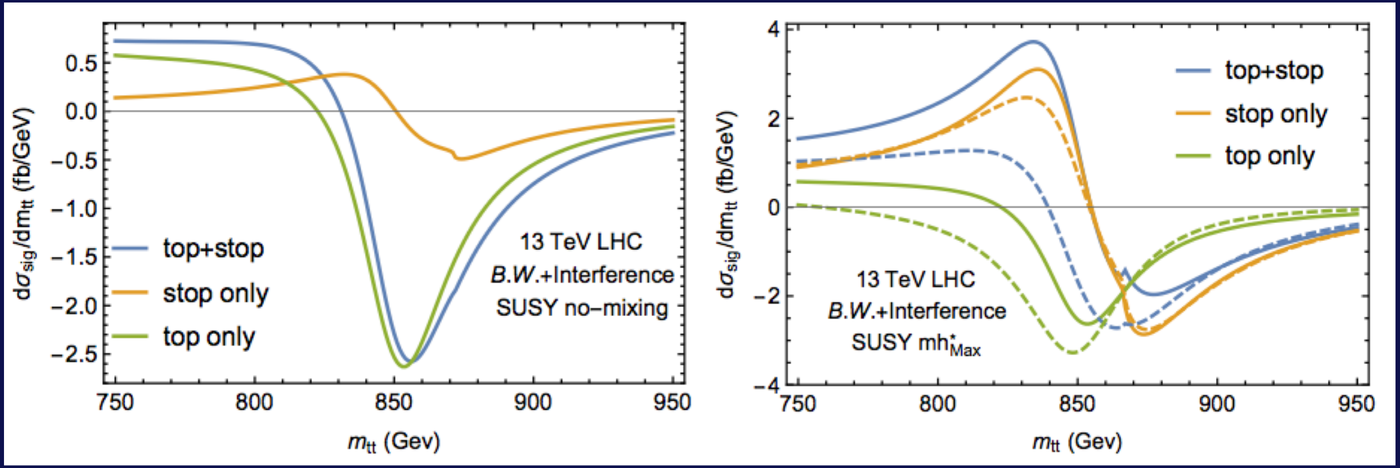
Extras

Special Line-shapes examples with additional BSM particles

Vector-like quarks in loop function:
Real, hence no destructive interference

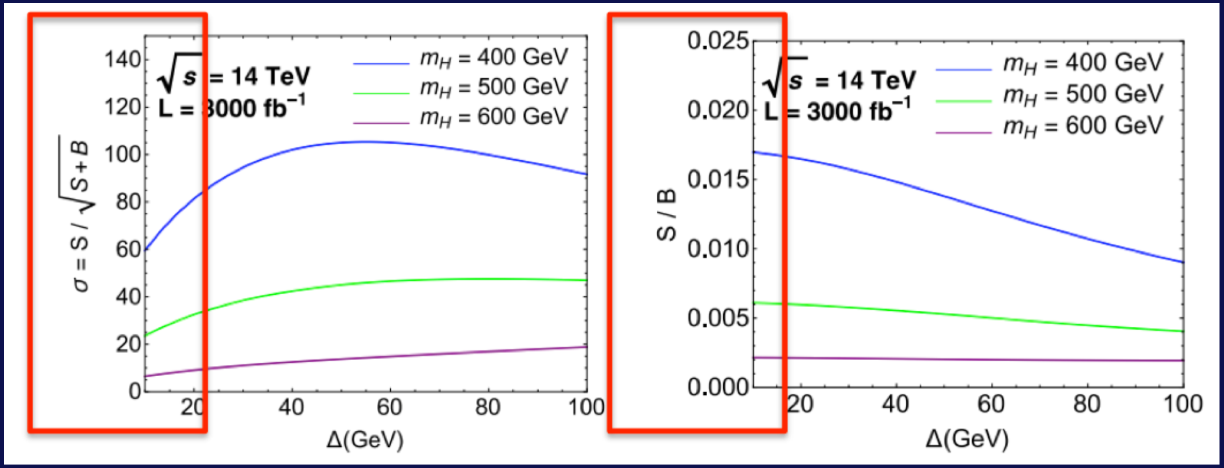


Stops in the loop function:
Zero L-R stop mixing → small interference (dip-bump structure), top quark dip structure prevails
Large L-R mixing → dominant contribution, dip-bump structure prevails



The challenging A/H ➔ tt channel: Systematic Uncertainties

Searches not designed/optimized for bump-dip/ dip structures
Smearing effects flatten the dips and bumps, making it harder

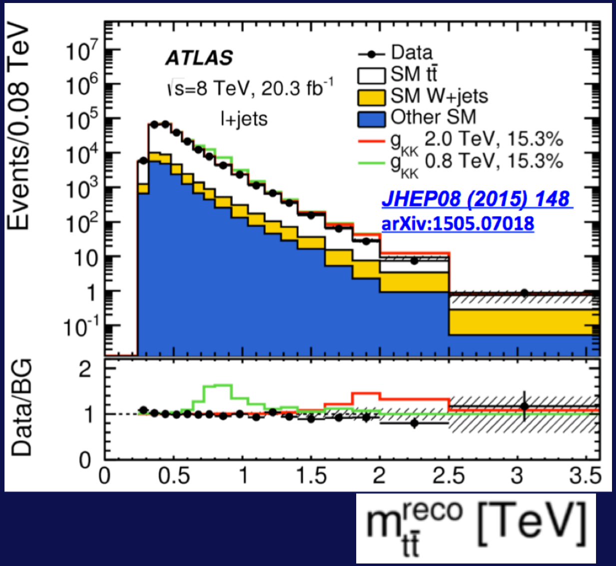


After detector smearing
and reconstruction:

Statistically promising
Systematically challenging

Craig et al ‘15

Using Atlas
8 TeV Analysis



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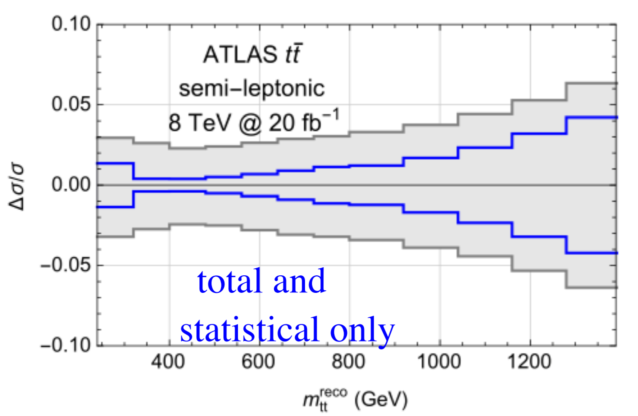
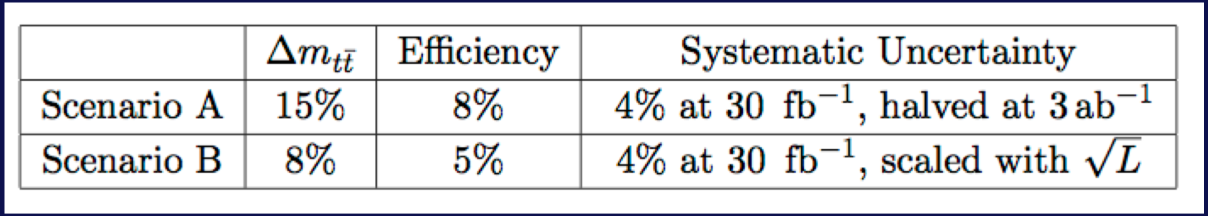
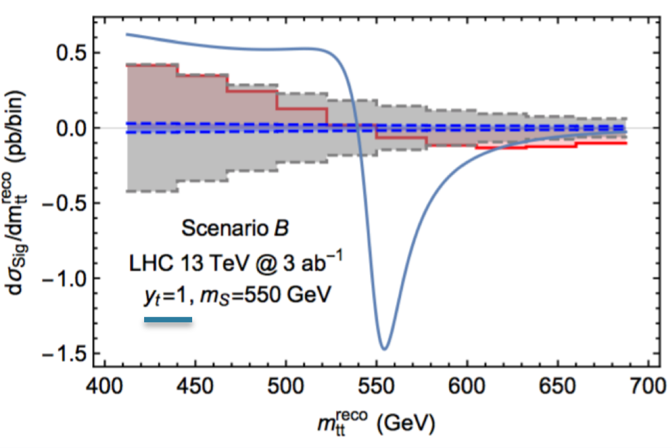


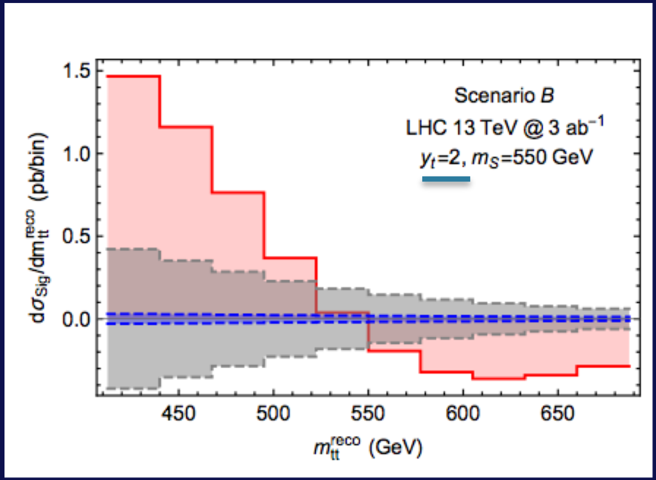
Prospects for searches in A/H→ tt : Benchmark Studies

Performance parameters



	$\Delta m_{t\bar{t}}$	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 line: the signal line-shape before smearing

Red bins: signal after smearing and binning

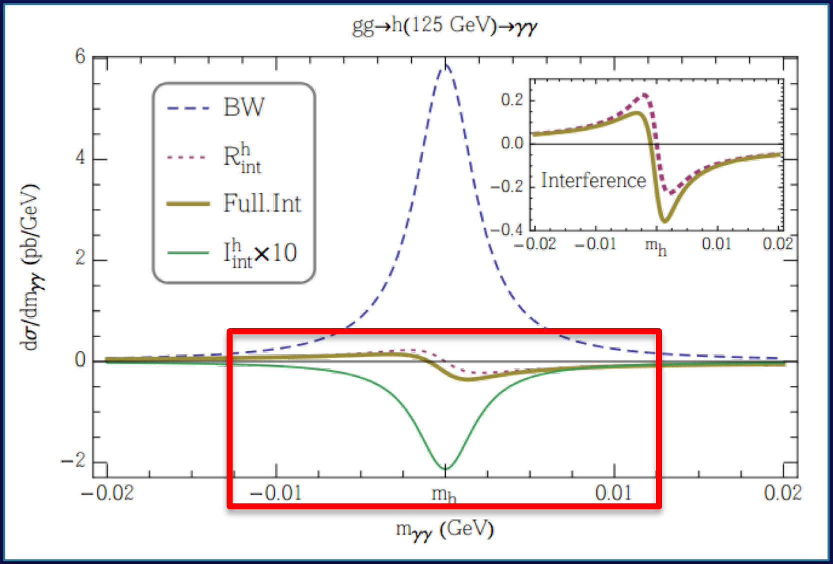
Blue and gray histograms: background statistical and uncertainties after smearing & binning

M.C., Liu'16

These studies are important for any new heavy scalar that couples to top pairs

Interference effects can affect Higgs LHC interpretations

Novel probe of Higgs total width & sensitivity to new physics from $gg \to h \to \gamma\gamma$



$$\begin{aligned}|\mathcal{M}_h|^2 &= |A_h + A_{\rm bkg}|^2 - |A_{\rm bkg}|^2 \\ &= |A_h|^2 + 2\,{\rm Re}\left[A_h A^*_{\rm bkg}\right]\end{aligned}$$

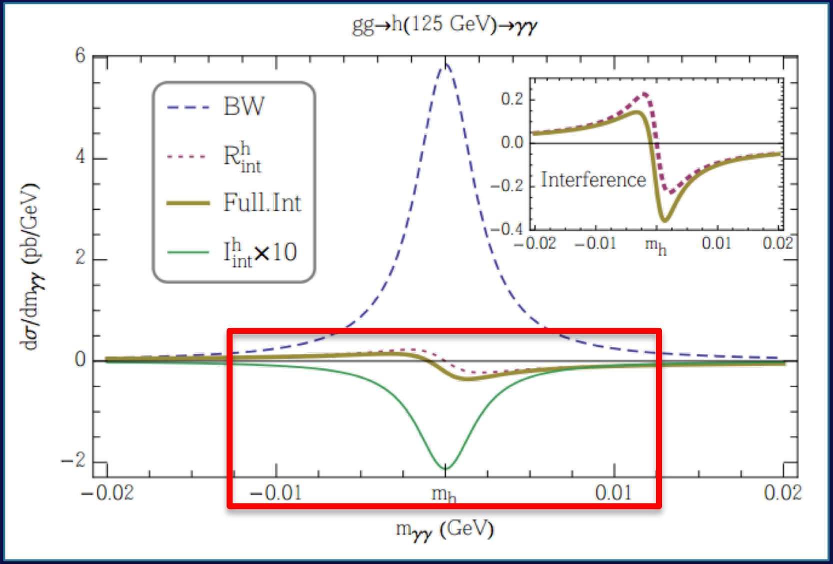
$$|\mathcal{M}_h|^2_{\rm int} \equiv 2\,{\rm Re}[A_h A^*_{\rm bkg}] = \frac{2|A_{\rm bkg}||F_{gg}||F_{\gamma\gamma}|}{(\hat{s}-m_h^2)^2+\Gamma_h^2 m_h^2} \times \left[(\hat{s}-m_h^2)\cos(\delta_{\rm bkg}-\delta_h) + m_h\Gamma_h\sin(\delta_{\rm bkg}-\delta_h)\right],$$

$$\delta_h = \arg[F_{gg}] + \arg[F_{\gamma\gamma}]$$

$$\delta_{\rm bkg} = \arg[A_{\rm bkg}]$$

Interference effects can affect Higgs LHC interpretations

Novel probe of Higgs total width & sensitivity to new physics from $gg \to h \to \gamma\gamma$



$$
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&= |A_h|^2 + 2\,{\rm Re}\left[A_h A^*_{\rm bkg}\right]
\end{aligned}
$$

$$
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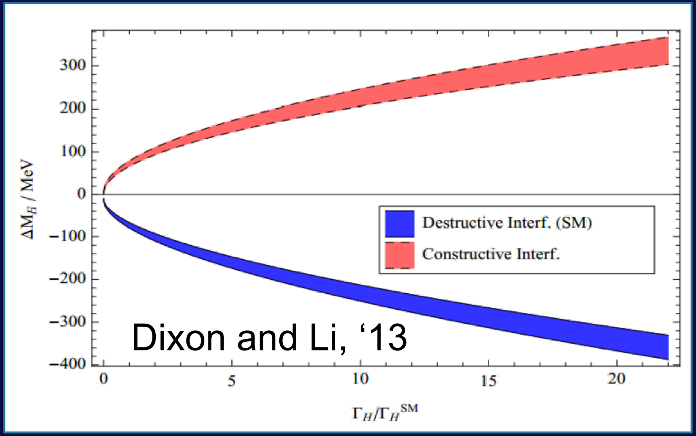
$$

$$
\times\left[(\hat{s}-m_h^2)\cos(\delta_{\rm bkg}-\delta_h) + m_h\Gamma_h\sin(\delta_{\rm bkg}-\delta_h)\right]
$$

$$
\delta_h = \arg[F_{gg}] + \arg[F_{\gamma\gamma}]
$$

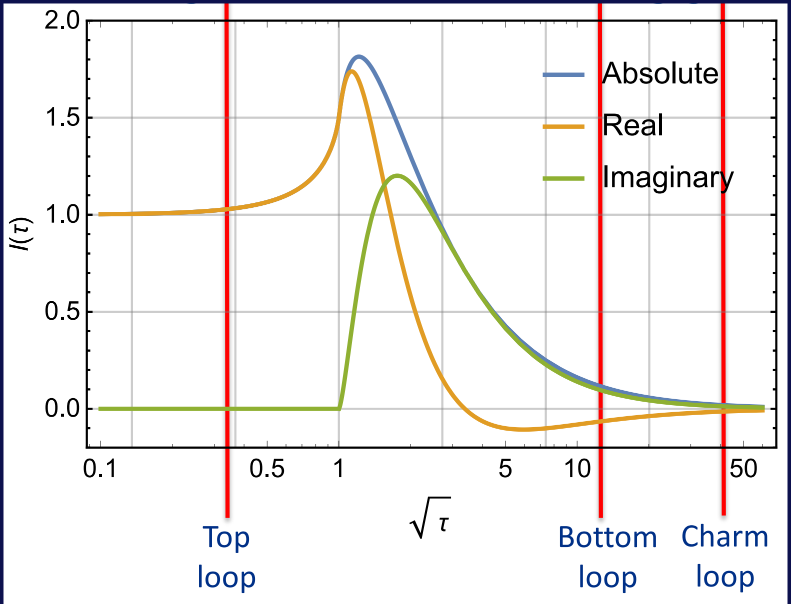
$$
\delta_{\rm bkg} = \arg[A_{\rm bkg}]
$$

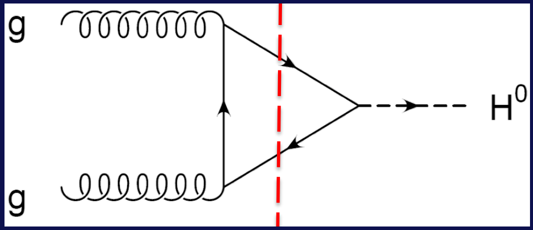
Much work done computing the shift in the di-photon mass peak from R_h^{int}



Dixon and Li, '13

Strong Phase in SM Higgs gluon fusion production





- 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 $-0.004 + 0.002i$

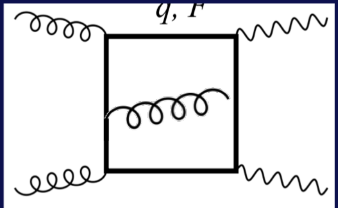
The signal amplitude also contains a strong phase, mainly due to bottom quark loops.

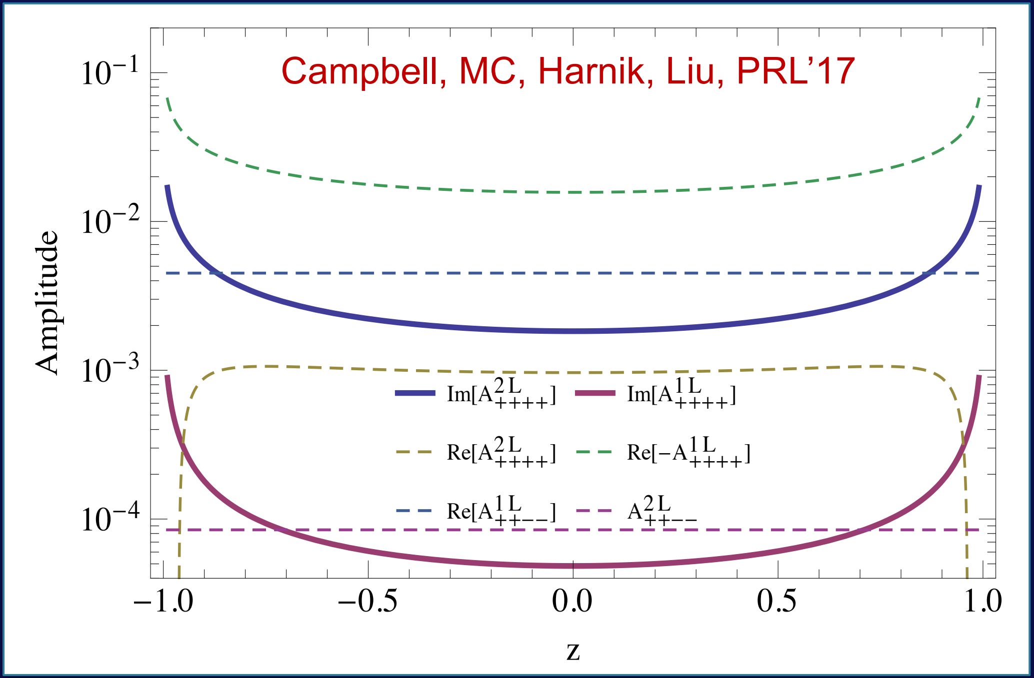
The gluon-gluon-Higgs vertex is reduced by an opposite-sign strong phase from the photon-photon- Higgs vertex.

$$\boxed{\delta_h \equiv \arg(F_{gg}F_{\gamma\gamma}) = \pi + 0.036.}$$

Phase from interfering background

Interfering background are from SM box diagram of gg→ γγ
The overall sizes of different helicity amplitudes are




Campbell, MC, Harnik, Liu, PRL’17

- Angular dependence
- $A_{++++} = A_{----}$ and dominant

- Imaginary part dominated by the 2-loop amplitude.

After summing over helicities and integrating over z, the averaged background phase

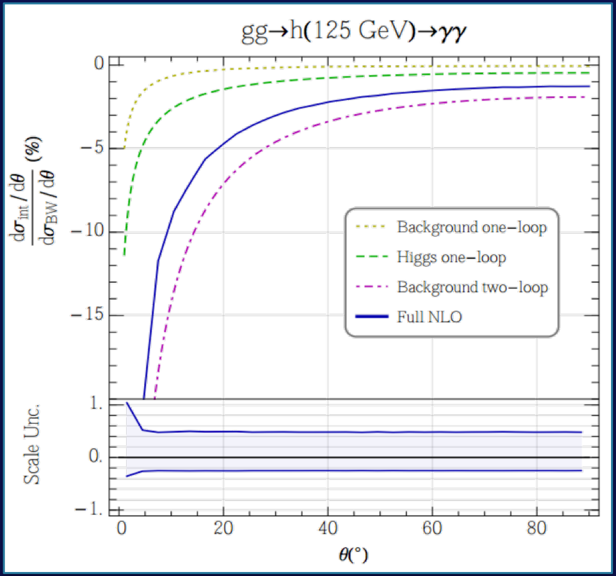
δ_{bgd} = -0.205

becomes the main source of for the Imaginary induced part of the interference

The amplitudes are shown as a function of the cosine of the outgoing photon polar angle with respect to the beam direction, z ≡ cosθ, in the collision center of mass frame.

Kinematic features of Interference effects

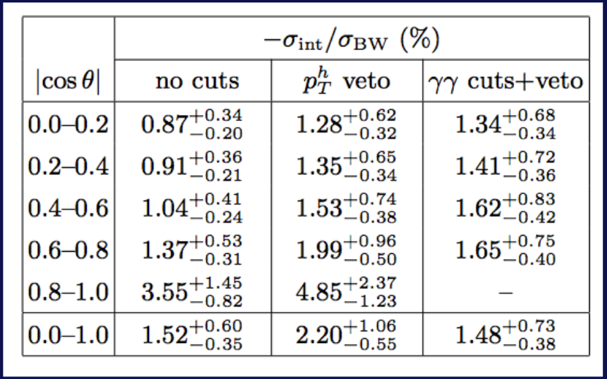
Photon scattering angle in the di-photon rest frame and a veto on the Higgs boson p_T as complementary tools to explore interference effects



Angular Distribution

- Interference effects larger in forward direction, driven by background amplitude kinematics;
- Interference effects ~0.5% at LO
- Interference effects increases to ~2% at NLO, driven by 2-loop amplitude's large imaginary part

Differential distributions can help to map out interference effects, and improve on the width information!



$\lvert\cos\theta\rvert$	$-\sigma_{\rm int}/\sigma_{\rm BW}$ (%)		
	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	$1.52^{+0.60}_{-0.35}$	$2.20^{+1.06}_{-0.55}$	$1.48^{+0.73}_{-0.38}$