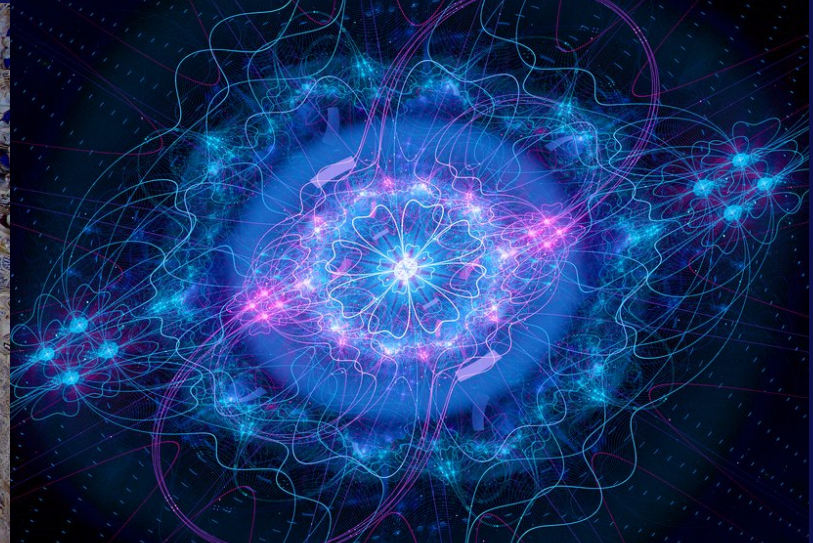


New Physics Opportunities in Higgs Searches

Planck 2019

22nd International Conference
From the Planck scale to the Electroweak scale
3 – 7 June 2019, Granada, Spain

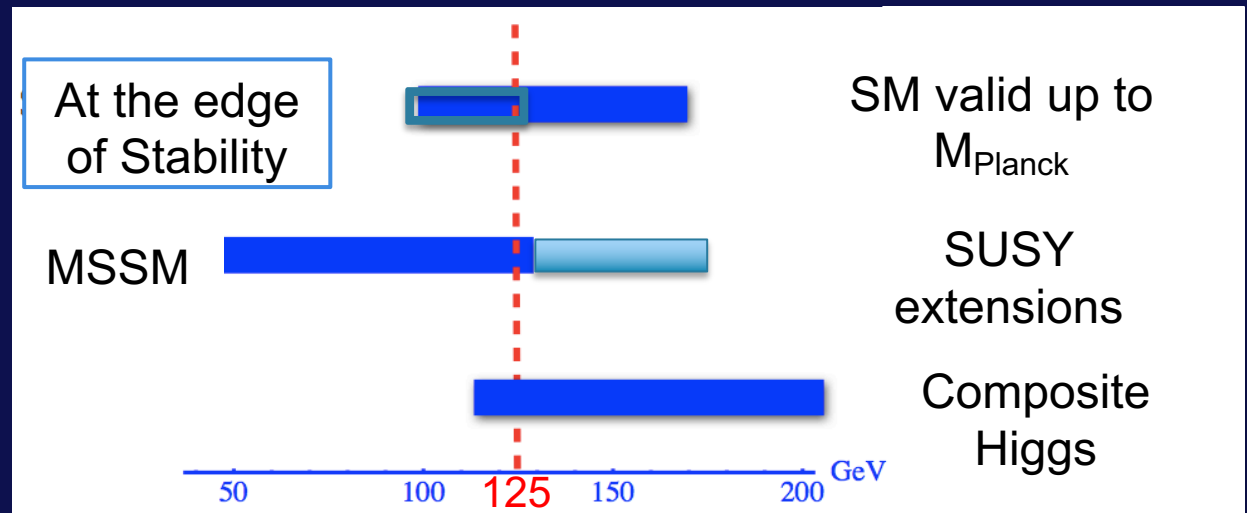


Marcela Carena

Fermilab and UChicago

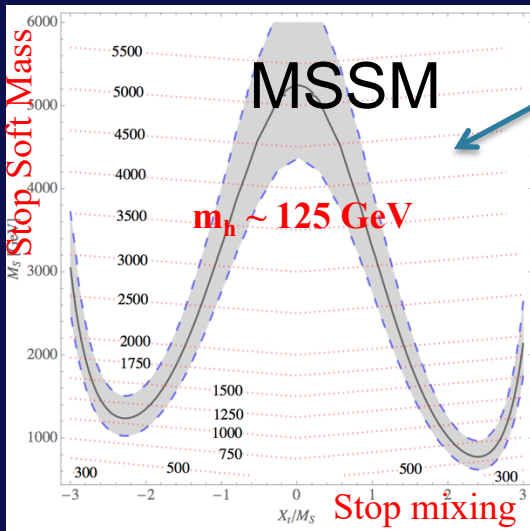
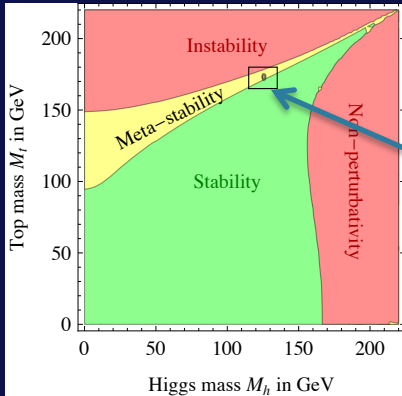
Granada, Spain, June 7, 2019

Under the Higgs lamp-post:



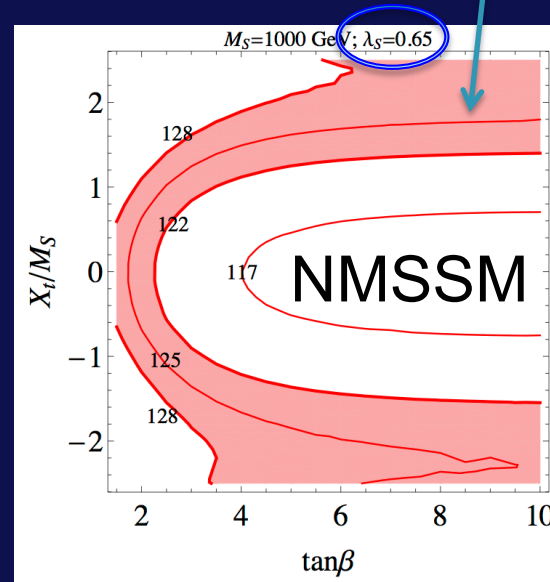
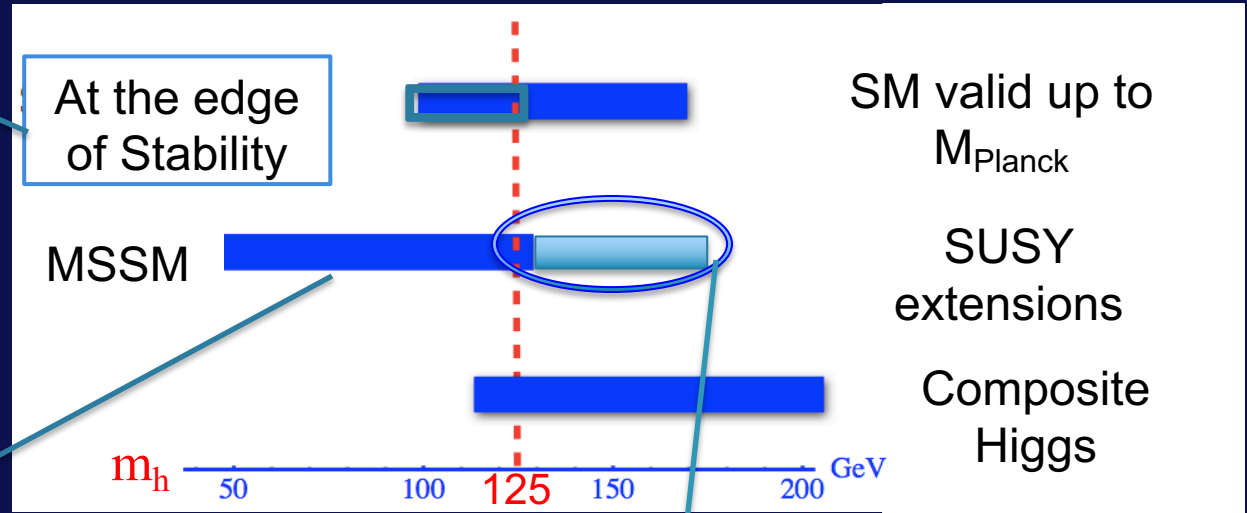
Riotto's talk

Under the Higgs lamp-post:



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

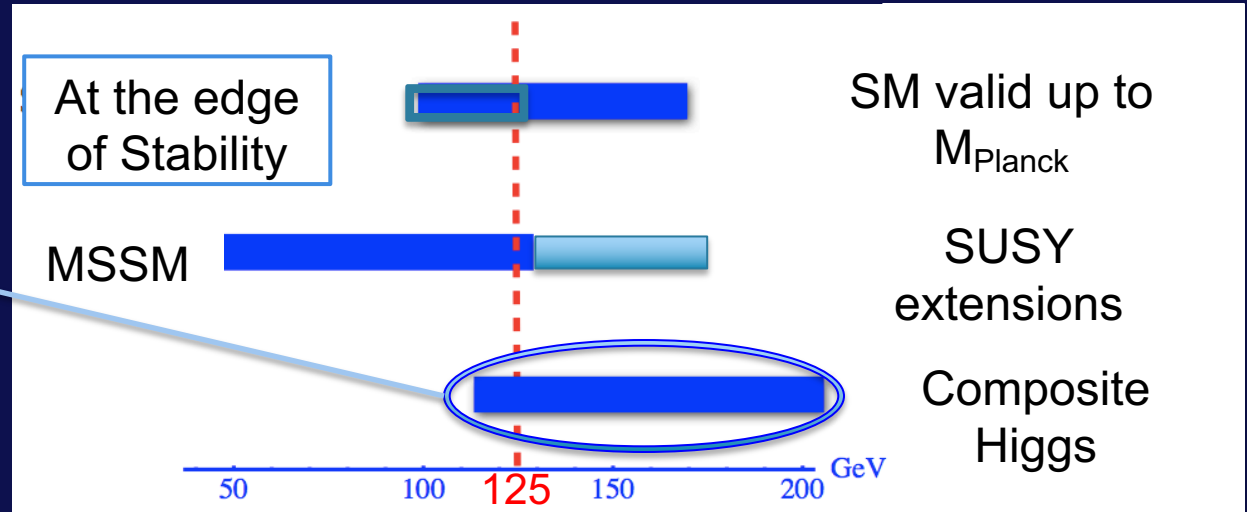
see also Weiglein's talk



NMSSM + $m_h \sim 125$ GeV:
At low $\tan\beta$
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 than the other ones

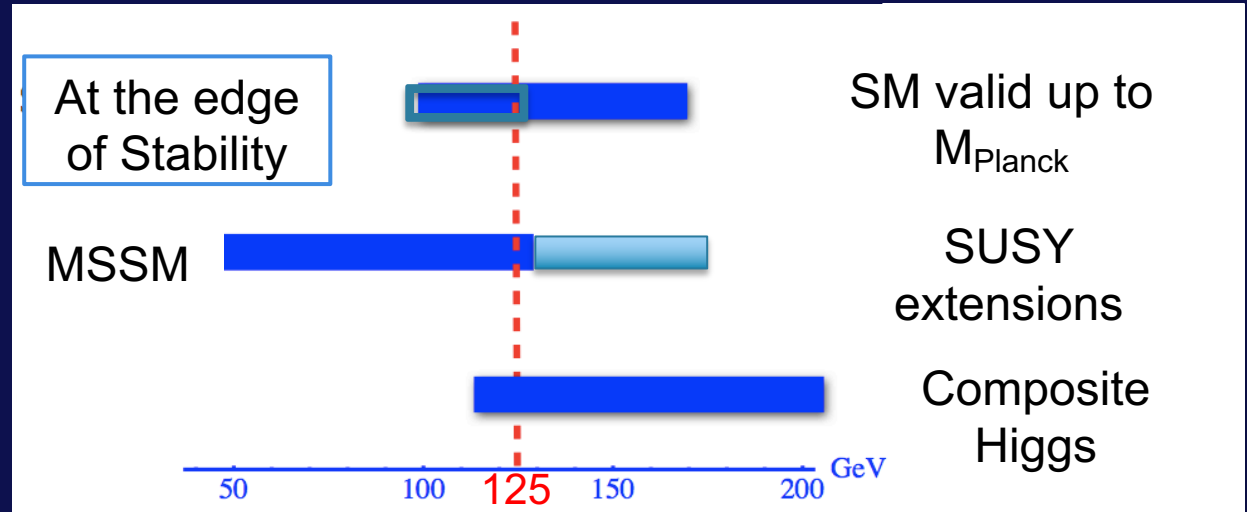
Also: Twin Higgs and Mirror Worlds

- Demand a UV completion → Composite Higgs-



Under the Higgs lamp-post:

**Composite
or SUSY
extensions**



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

- Can be appealing to provide a strong first order EW phase transition
- Can generate flavor hierarchies a la Frogatt-Nielsen with 2 Higgs doublets jointly acting as a flavon
- Can relate enhanced light fermion Yukawas to enhanced di-Higgs signals

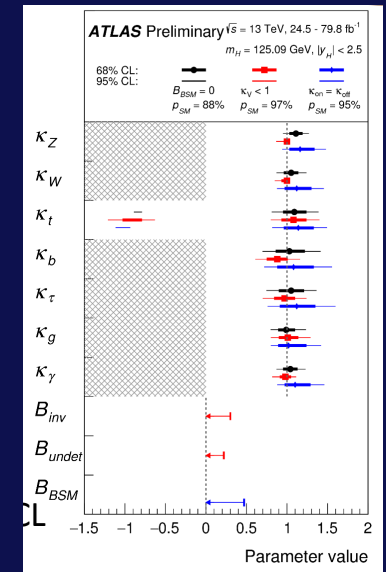
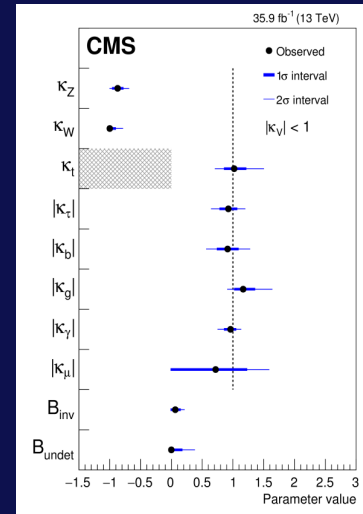
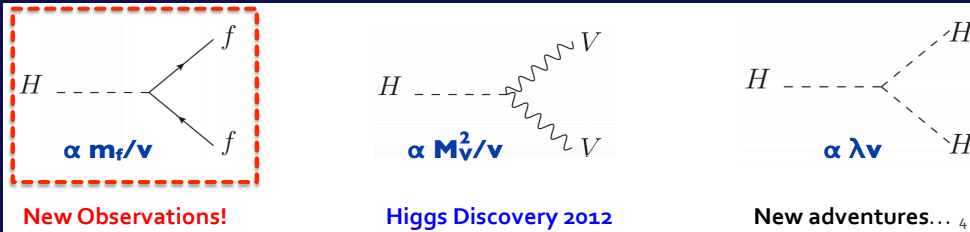
All BSM alternatives can affect Higgs production & decay signal strengths

ATLAS and CMS Higgs results

Run-II headlines: observations with the 3rd generation fermions!

Assuming no strict correlation between gluon & top couplings \implies consistency with SM

Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 \pm 0.35	1.01 \pm 0.20	1.32 \pm 0.27
CMS	Exp. Sig.	5.9 σ	5.5 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.6 σ	5.2 σ
	mu	1.09 \pm 0.27	1.04 \pm 0.20	1.26 \pm 0.26
Paper References		PRD 99 (2019) 072001 PLB 779 (2018) 283	PLB 786 (2018) 59 PRL 121 (2018) 121801	PLB 784 (2018) 173 PRL 120 (2018) 231801



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

HL-LHC (3 ab⁻¹ @ 14TeV): expected ~ 2-4% precision for most 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 \rightarrow WW/ZZ decays

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

$$\begin{aligned} h &= -\sin \alpha H_1^0 + \cos \alpha H_2^0 & HVV &= (hVV)^{\text{SM}} \cos(\beta - \alpha) \\ H &= \cos \alpha H_1^0 + \sin \alpha H_2^0 & hVV &= (hVV)^{\text{SM}} \sin(\beta - \alpha) \end{aligned}$$

In a 2HDM type II (e.g. MSSM), H_1 couples to down-quarks and charged leptons, while H_2 couples to up-quarks.

$$\langle H_i \rangle = v_i \quad \tan \beta = v_2/v_1$$

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

In 2HDM type I, all fermions couple to H_2

If the mixing in the CP-even sector yields $\cos(\beta - \alpha) = 0 \rightarrow \cos \alpha = \sin \beta$
 The lightest Higgs coupling to fermions and gauge bosons is SM-like.

This situation is called ALIGNMENT

Gunion, Haber '03

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

Alignment Conditions in General 2HDMs

General 2HDM
Higgs potential

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

Minimization conditions define m_A , m_{H^\pm} and $m_{h/H}$ in terms of quartic couplings, one mass parameter and $\tan\beta$

Eigenstate Eq.

$$\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} = -\frac{v^2}{m_A^2} \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} + \frac{m_h^2}{m_A^2} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}$$

$$\approx 0 \rightarrow \cos(\beta - \alpha) = 0$$

Alignment occurs for large values of $m_A \rightarrow$ Decoupling OR
specific conditions independent of $M_A \rightarrow$ Alignment without Decoupling

If no CP violation in the Higgs sector

Valid for any 2HDM

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

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 $\cos(\beta-\alpha)$ 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

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

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

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**

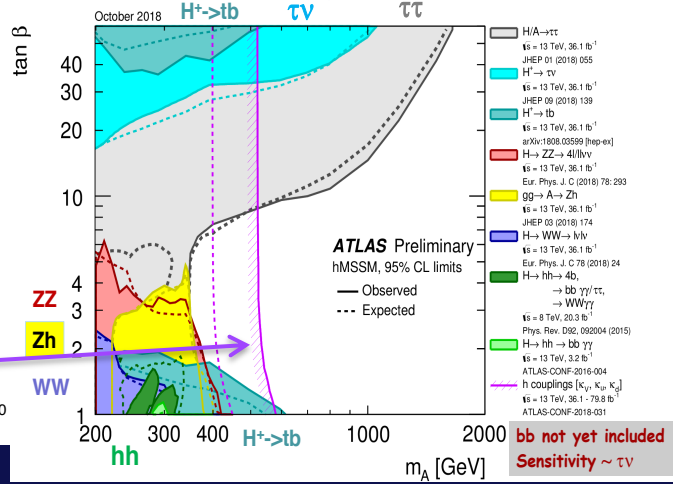
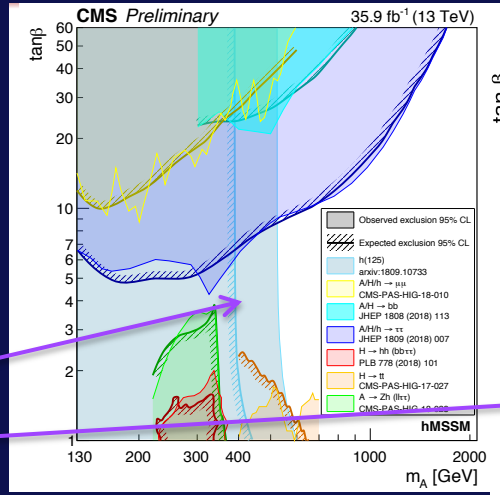
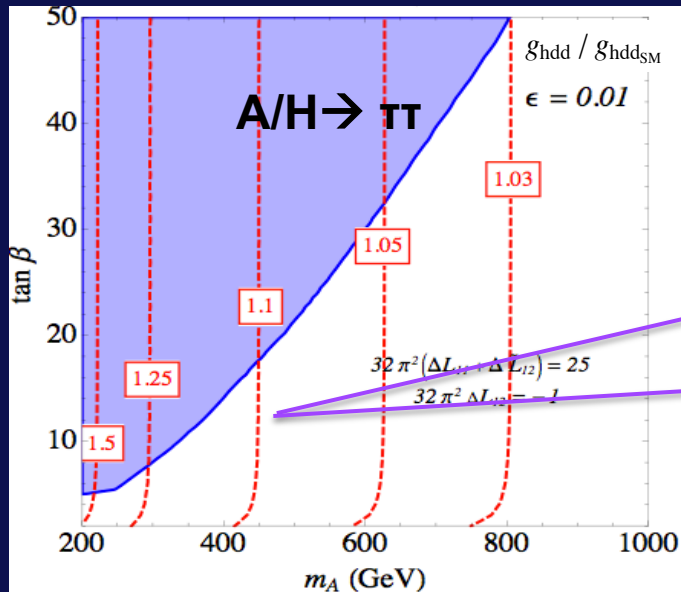
$$t_\beta c_{\beta-\alpha} \simeq \frac{-1}{m_H^2 - m_h^2} \left[m_h^2 + m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2 M_S^2} \left\{ A_t \mu t_\beta \left(1 - \frac{A_t^2}{6M_S^2}\right) - \mu^2 \left(1 - \frac{A_t^2}{2M_S^2}\right) \right\} \right]$$

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 ($\lambda_{6,7} \propto \mu A_t \simeq 0 \Rightarrow$ No Alignment)

Bottom coupling in the MSSM



hMSSM scenario not applicable for small $\tan \beta$ ($\sim \tan \beta < 3$)

(see also Weiglein's talk)

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

For moderate to large $\tan \beta$ and small μ

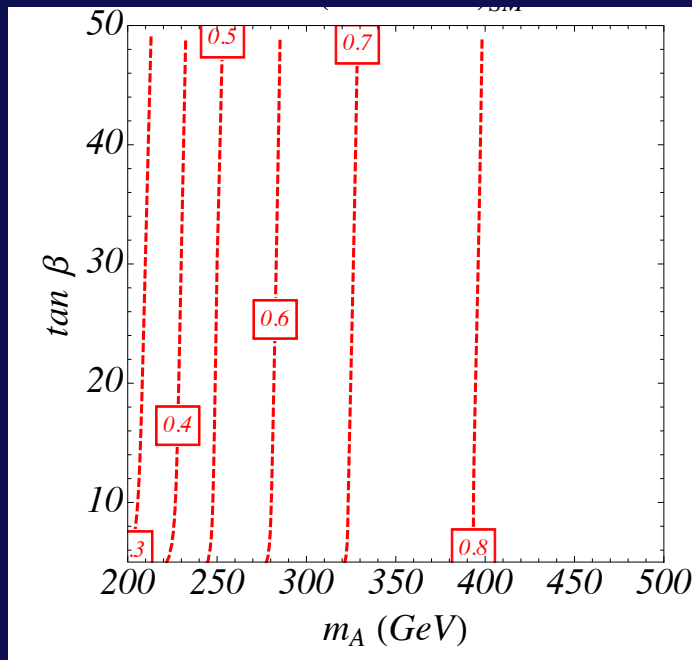
\rightarrow no dependence on $\tan \beta$ or on the stop mixing

\rightarrow 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

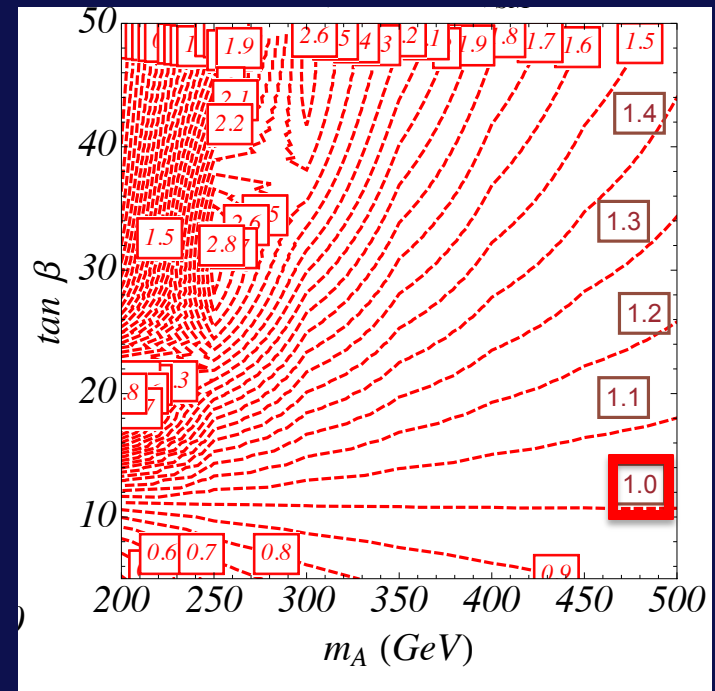
Higgs decays into gauge bosons mostly determined by bottom decay width

Small μ (no Alignment)



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

Sizeable $\mu \sim 2 M_{SUSY}$ (Alignment)

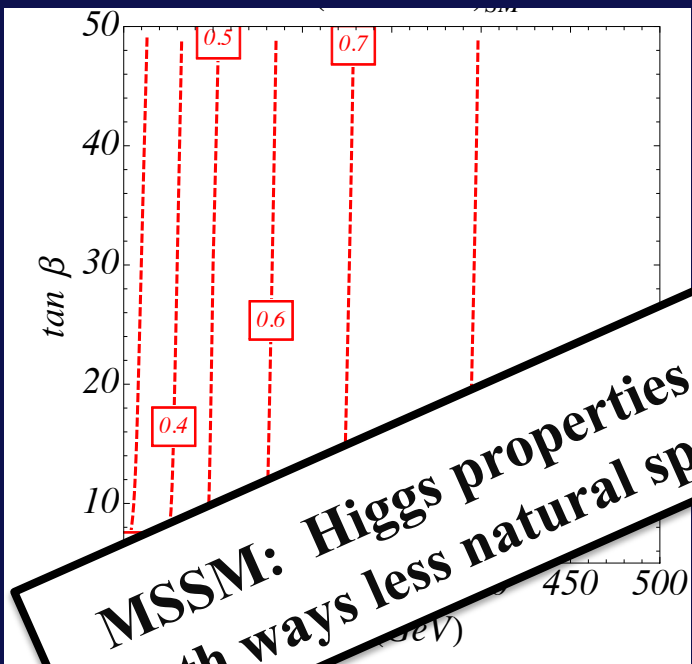


CP-odd Higgs masses of order 200 GeV and $\tan\beta \sim 10$ are allowed in the alignment case, but alignment is in tension with naturalness in the MSSM

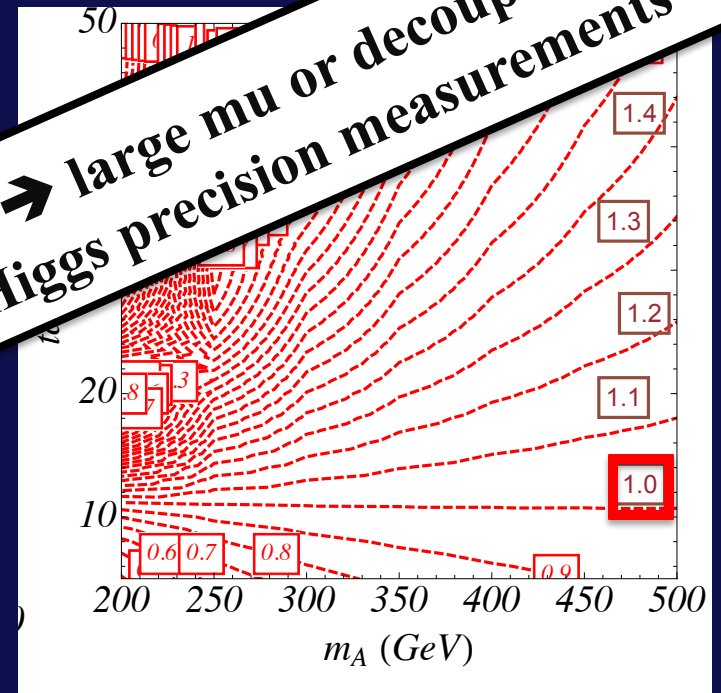
Interpretation of precision Higgs measurements on A/H searches strongly correlated to the proximity to Alignment without decoupling

Higgs decays into gauge bosons mostly determined by bottom decay width

Small μ (no Alignment)



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



MSSM: Higgs properties close to SM-like \rightarrow large μ or decoupling
Both ways less natural spectra just from Higgs precision measurements

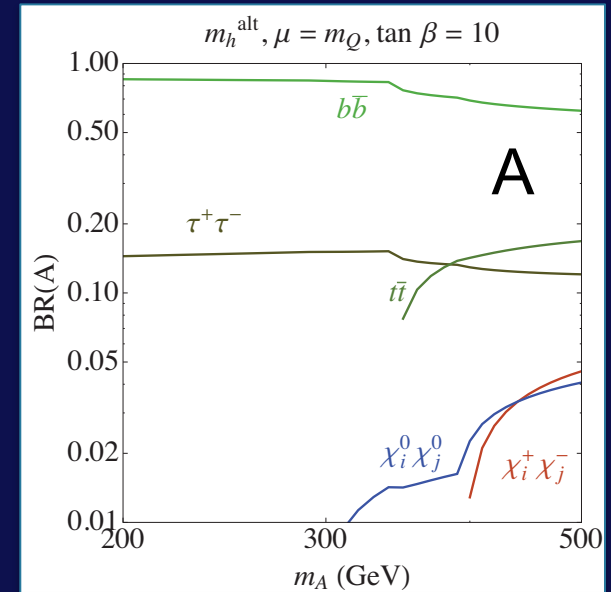
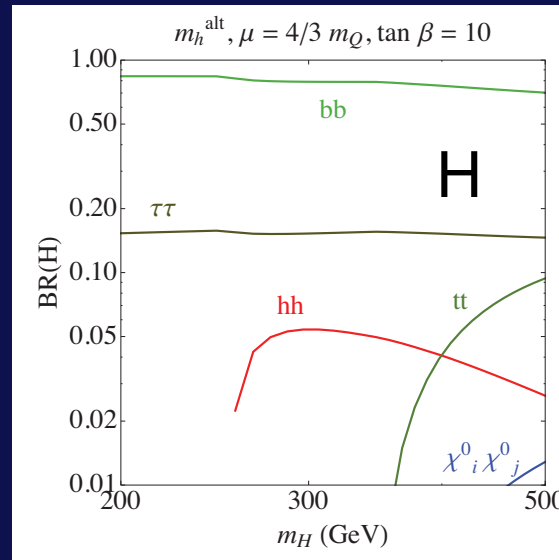
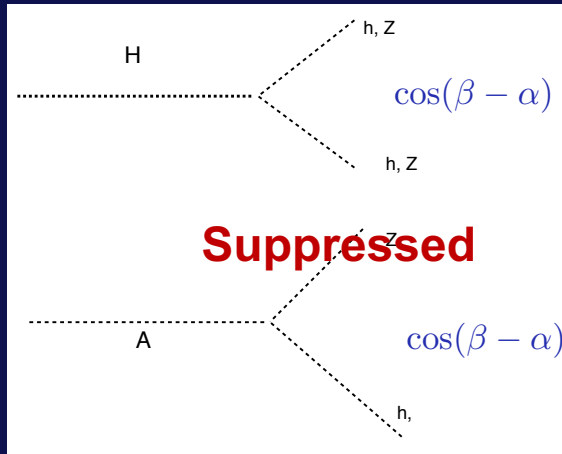
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Heavy Higgs Bosons: A variety of decay Branching Ratios

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

Depending on the values of μ and $\tan\beta$ different search strategies must be applied

Alignment



Sizeable $\tan\beta \rightarrow$ very close to alignment, dominant bottom and tau decays;

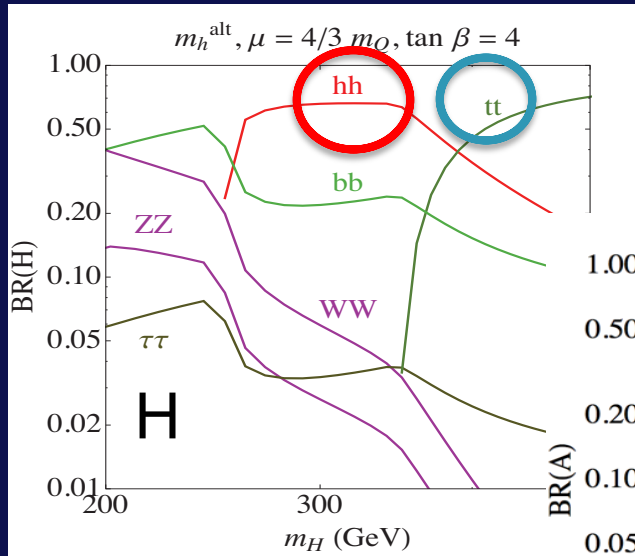
while $g_{Hhh} \simeq g_{HWW} \simeq g_{HZZ} \simeq g_{Ahz} \simeq 0$

Production mainly via large bottom couplings: bbH

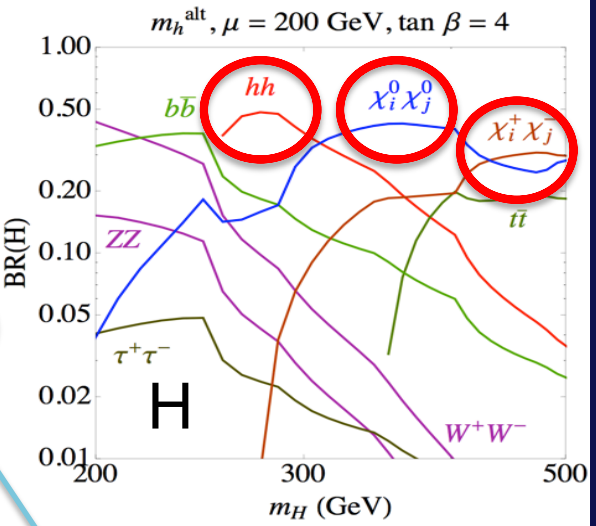
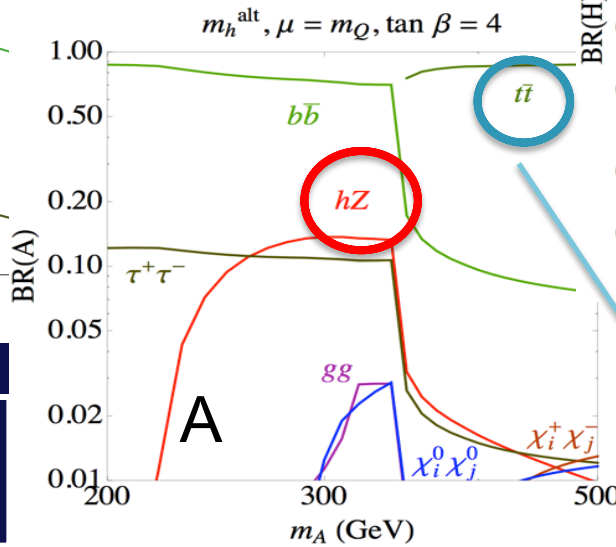
Heavy Higgs Bosons: A variety of decay Branching Ratios

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Depending on the values of μ and $\tan\beta$ different search strategies must be applied



Departure from Alignment



Precision Higgs constraints become important

Very challenging search

Smaller $\tan\beta \rightarrow$ some departure from alignment,

$H \rightarrow hh, WW, ZZ$ and tt (also $A \rightarrow hZ, tt$) become relevant.

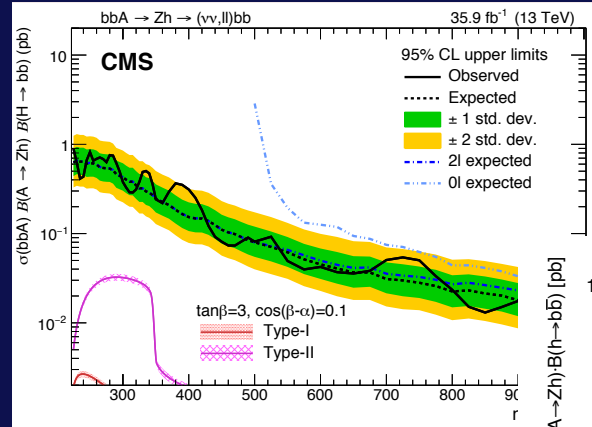
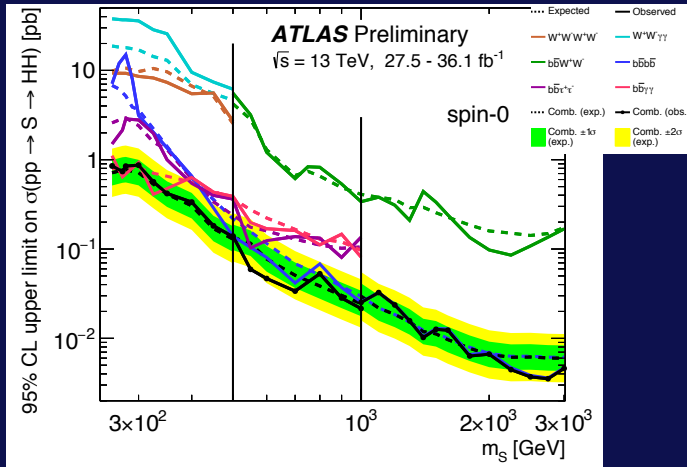
Production mainly via top loops in gluon fusion

If low μ , then chargino and neutralino channels open up (impact on $H/A \rightarrow \tau\tau$)

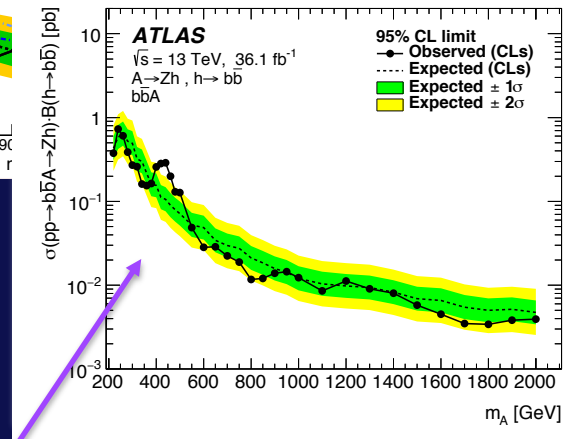
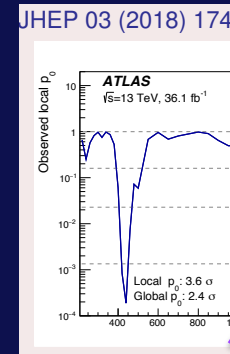
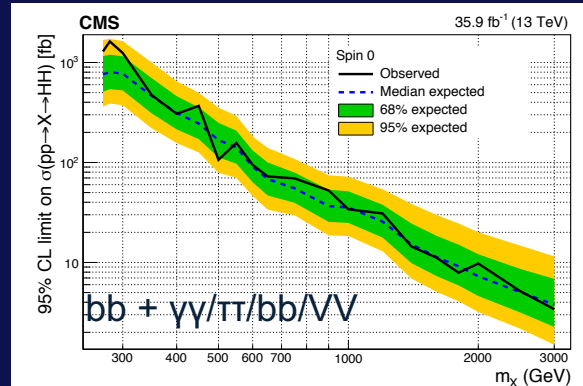
Many ongoing A/H boson searches at LHC

CMS summary on $H \rightarrow hh$ searches

ATLAS/CMS, with $A \rightarrow Zh$ and $h \rightarrow bb$



From b -quark Associated production



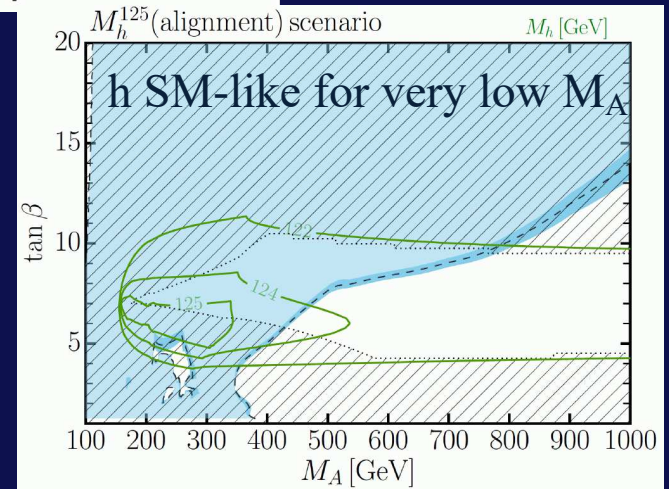
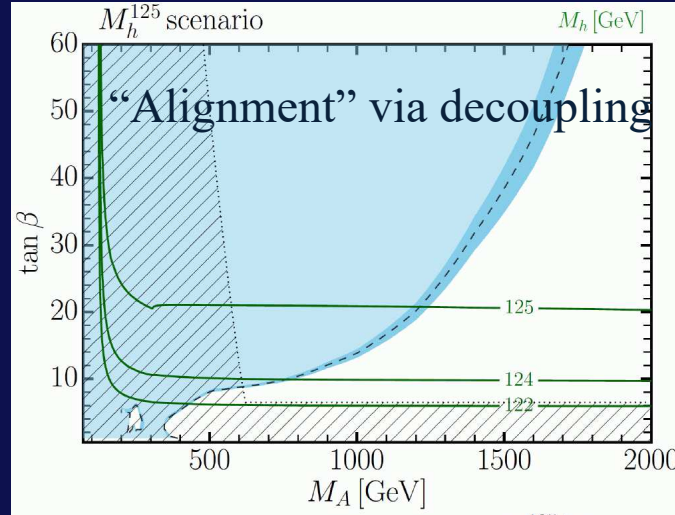
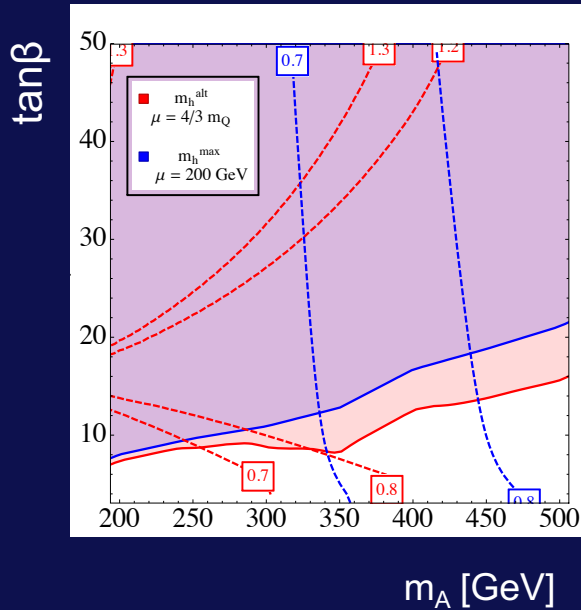
- **Resonant Production**
Upper limit between 4 fb and 1 to 2 pb

- Mild excess of events is observed around 440 GeV, mainly 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

Strength of direct & indirect searches vary importantly depending on parameter space

M.C, Low, Shah, Wagner + Haber



e. g. New benchmarks

Weiglein's talk

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 $\lambda S H_u H_d \rightarrow \mu_{\text{eff}} = \lambda \langle S \rangle$

- Well known additional contributions to m_h
- Less known: sizeable contributions to the mixing between MSSM CP-even eigenstates

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

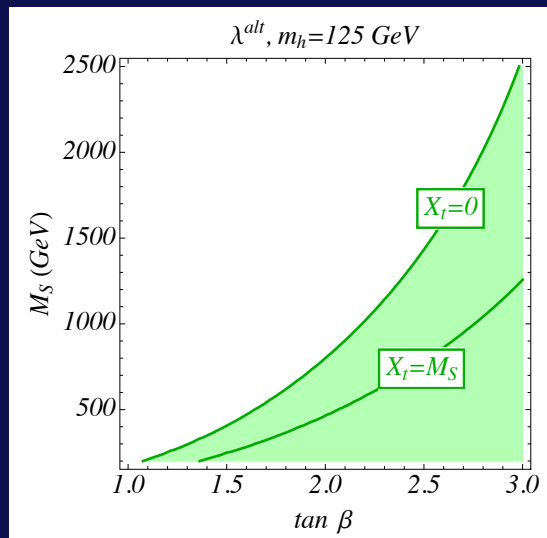
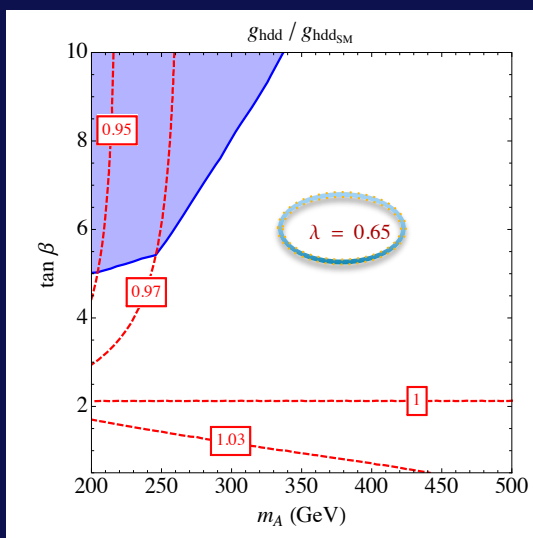
$$M_S^2(1, 2) \simeq \frac{1}{\tan \beta} (m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2 \beta + \delta_{\tilde{t}})$$

Last term from MSSM; small for moderate/small μ_{A_t} and small $\tan\beta$

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

$$\lambda_{\text{alt}}^2 = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2 \beta}$$

Higgs-Bottom coupling in the NMSSM



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

$$M_S^2(1,3) \simeq 2\lambda v\mu \left(1 - \frac{m_A^2 \sin^2 2\beta}{4\mu^2} - \frac{\kappa \sin 2\beta}{2\lambda} \right) \quad \text{Needs to vanish in alignment}$$

For $\tan\beta < 3$, $\lambda \sim 0.65$ and κ in the perturbative regime, small mixing in the Higgs sector implies that m_A and μ are correlated

$$m_A \approx \frac{2|\mu|}{\sin 2\beta}$$

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

$$m_{\tilde{g}} = 2\mu \frac{\kappa}{\lambda} \quad \text{of interest for Dark Matter}$$

NMSSM properties close to Alignment

Singlet spectra and decays (to SM via mixing with doublet or invisibly to DM)

- Heavier CP-even Higgs can decay to lighter ones: $2 m_{h_s} < M_H$
- 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 $\sim 20\%$ to 80% (dep. on $\tan\beta$)
decays may be depleted by decays into charginos/neutralinos (10% to 50%)

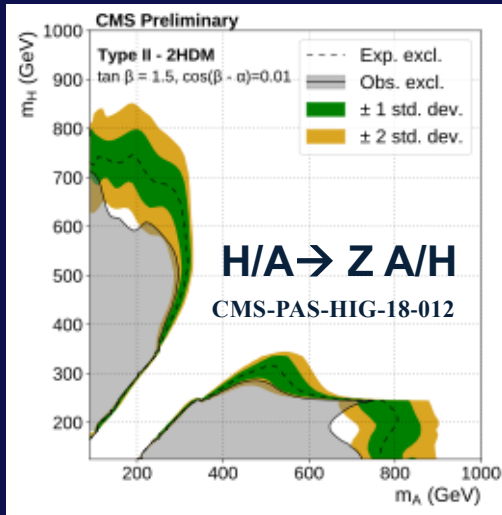
-- Other relevant decays: $H \rightarrow hh_s$ and $A \rightarrow Zh_s$ (20% to 50%, dep on mass)

$H \rightarrow hh$ and $A \rightarrow hZ$ decays strongly suppressed due to alignment

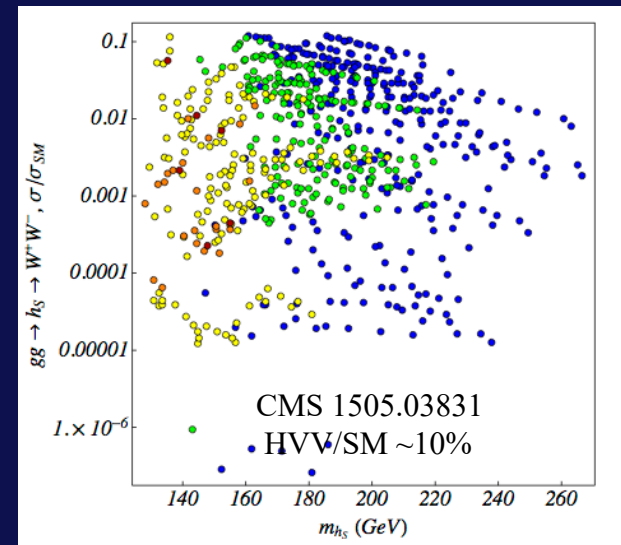
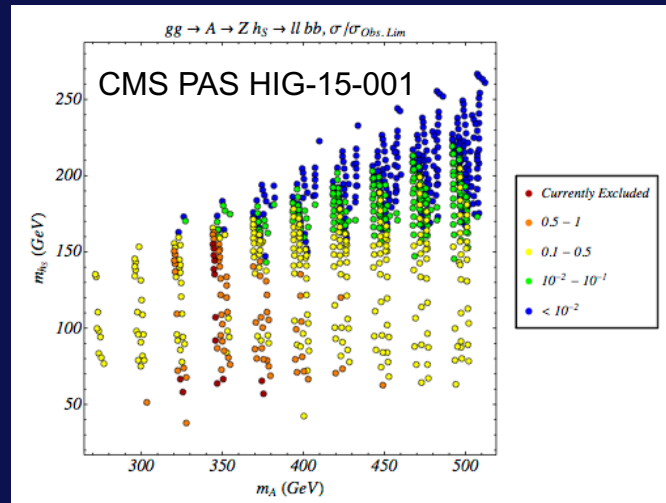
Others: $H \rightarrow h_s h_s$; $H \rightarrow A_s Z$; $A \rightarrow A_s h_s$; $A \rightarrow A_s h$ of order 10% or below

Ongoing searches at the LHC are probing exotic Higgs decays

- Complementarity between $gg \rightarrow A \rightarrow Z h_S \rightarrow ll bb$ and $gg \rightarrow h_S \rightarrow WW$ searches



Observed exclusion CMS-PAS-HIG-18-012 similar to CMS-PAS-HIG-15-001 result

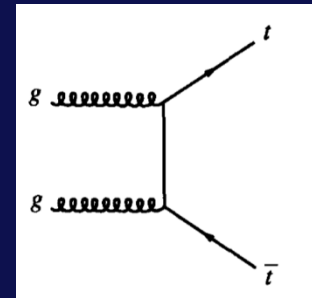
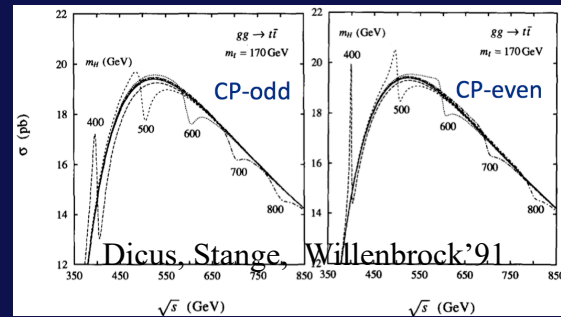
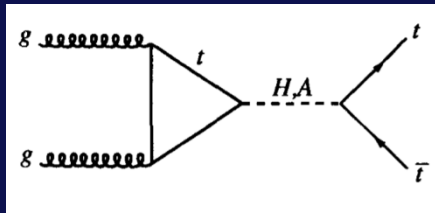


For $M > 200$ GeV also CMS-PAS-HIG-17-033

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

The challenging A/H → tt channel: Interference effects

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



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

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

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

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

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

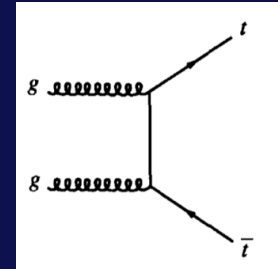
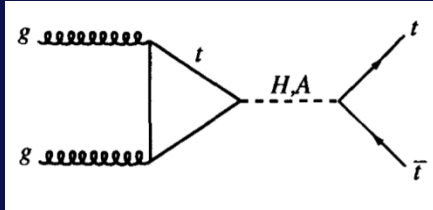
$$\text{Im}[P(\hat{s})] = \frac{-i \hat{s} \Gamma m}{(\hat{s} - m^2)^2 + \Gamma^2 m^2}$$

- 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 \rightarrow tt channel: Interference effects

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



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

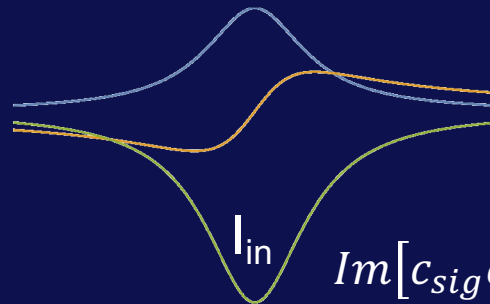
$$A_{bkg} = c_{bkg} \text{ (slowly varying function of } \hat{s})$$

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

$$= B.W. + BKG + 2\text{Re}[c_{sig}c_{bkg}^*] \text{Re}[P(\hat{s})] + 2\text{Im}[c_{sig}c_{bkg}^*] \text{Im}[P(\hat{s})]$$

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

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

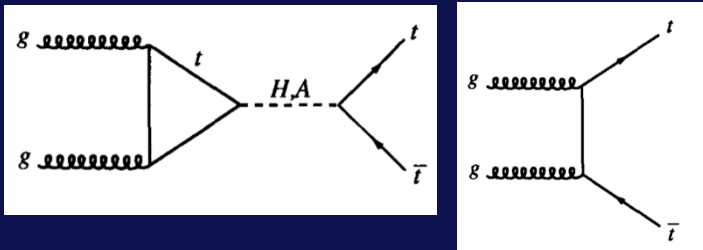


Im. Int.—from the imaginary part of propagator

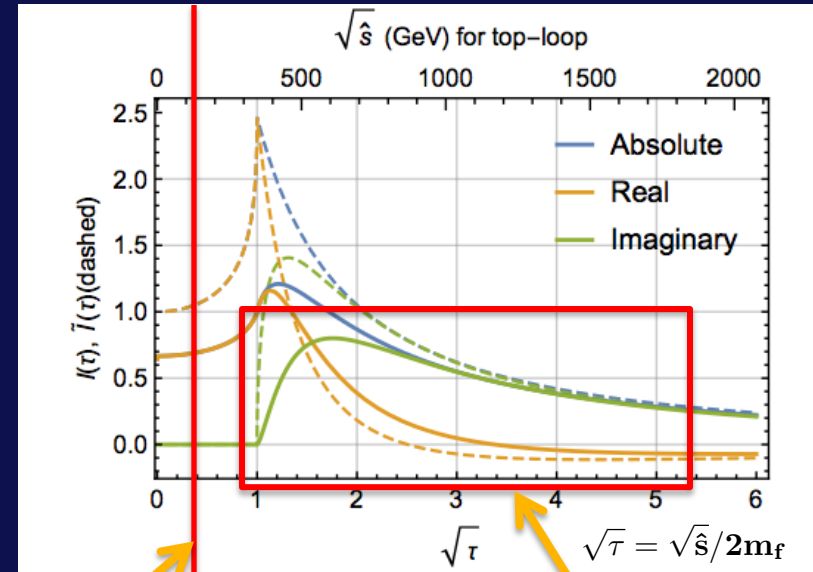
$$\text{Im}[c_{sig}c_{bkg}^*] = |c_{sig}| |c_{bkg}^*| \sin(\delta_{sig} - \delta_{bkg})$$

When **phase** $\delta_{sig} - \delta_{bkg}$ (strong phase) is non-zero, there is a new interference effect that cannot be neglected, no matter how narrow is the resonance

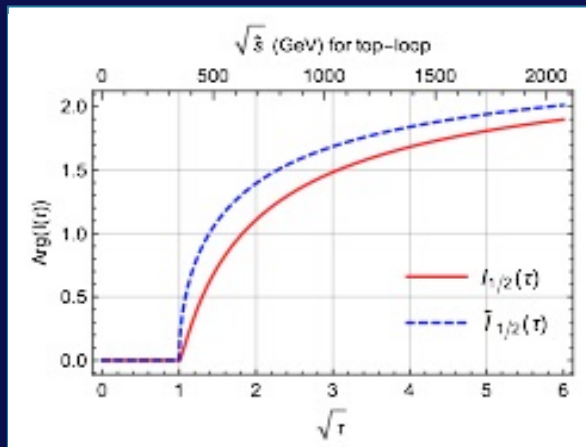
The challenging A/H \rightarrow tt channel: Interference effects



Triangle loop function



Phase of the loop function



SM Higgs
real & slowly varying

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

Background real

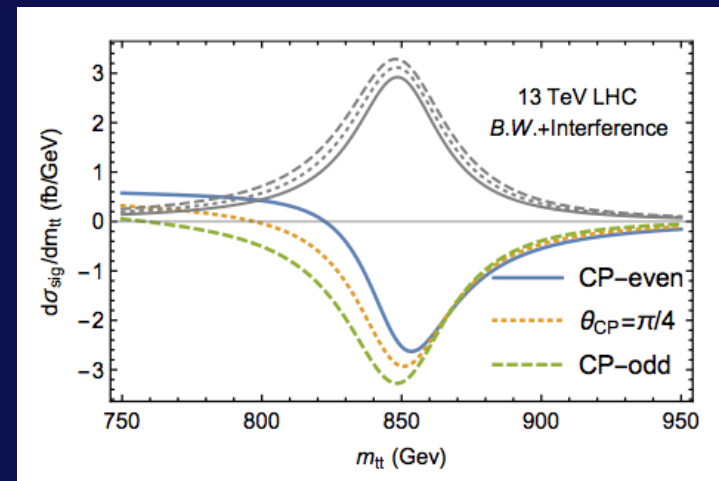
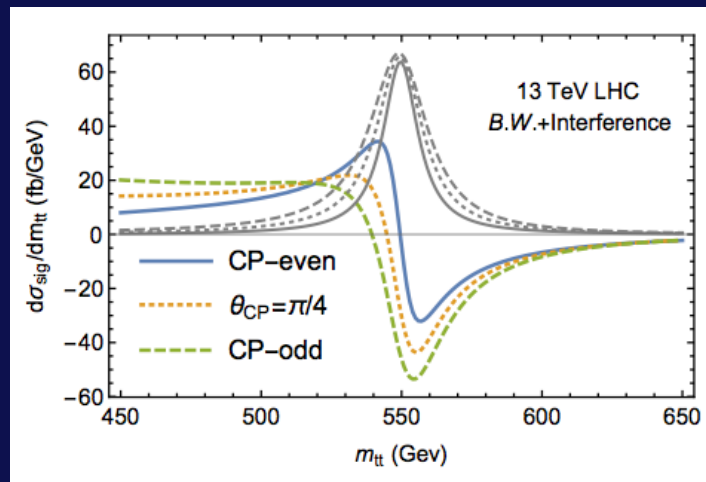
Real Interference from the real part of the propagator and real part of loop function
(shifts the mass peak; no contribution to the signal rate besides residual effect of PDF's)

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

M.C., Liu '16

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.

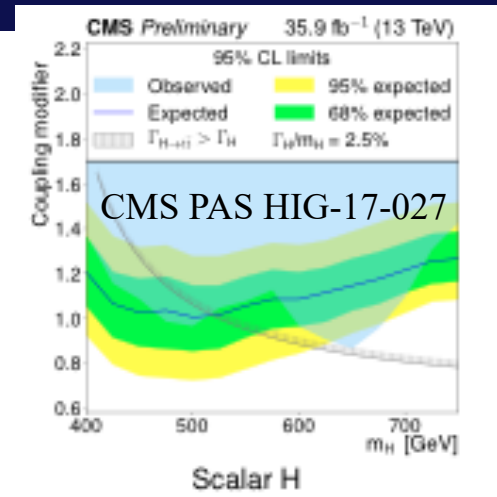
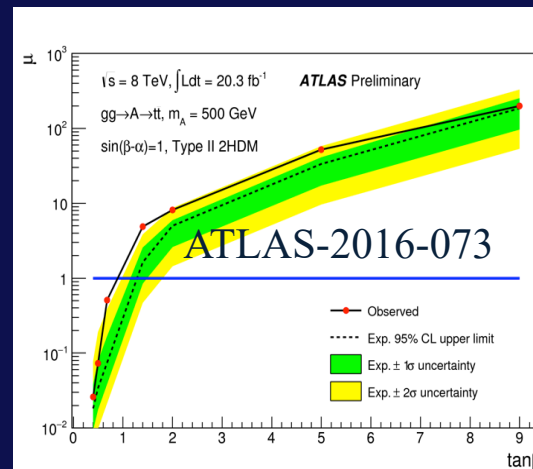
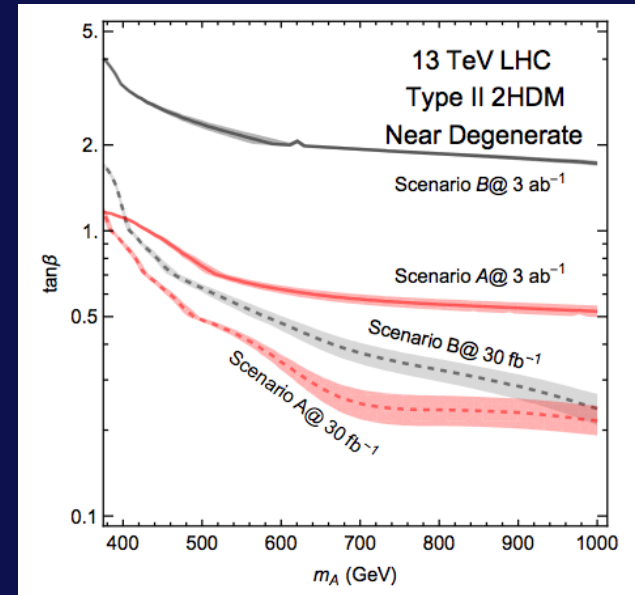
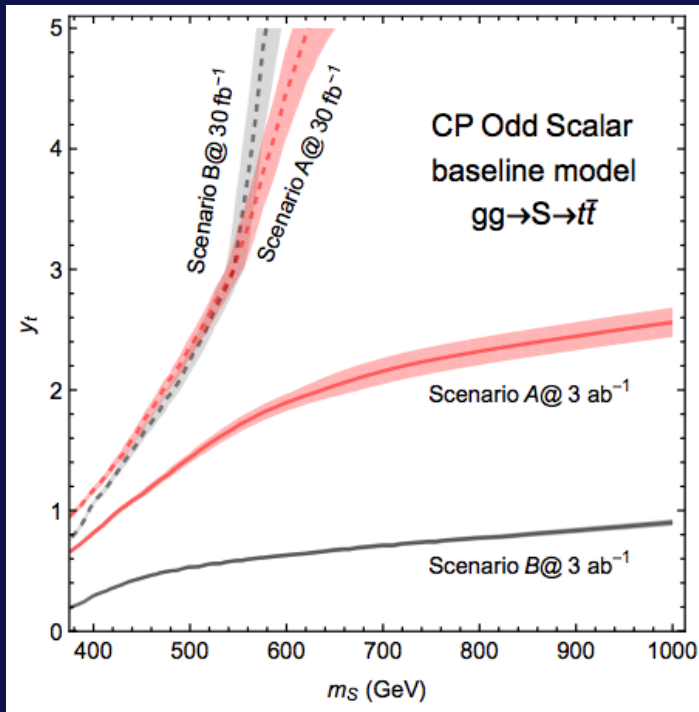
Smearing effects flatten the dips and
bumps, making it harder.

Impact of interference effect in $A/H \rightarrow t\bar{t}$ at the LHC

Projections for $A/H \rightarrow t\bar{t}$ 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 and CMS @ SUSY2019

Interference Effects in Di-Higgs Production: $gg \rightarrow S \rightarrow hh$

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 reach

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

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

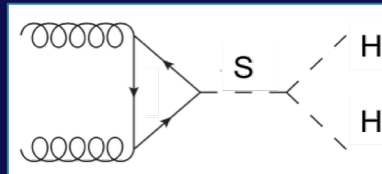
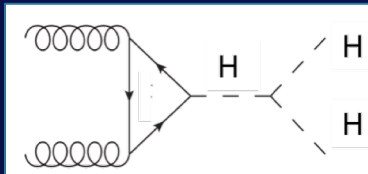
Parameters in the potential can be traded by

$$m_H = 125 \text{ GeV}, v = 246 \text{ GeV}$$

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

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

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



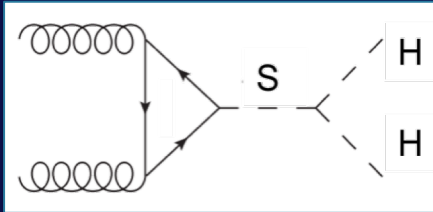
$$\lambda_{HHH} = -\frac{m_H^2}{2 \tan\beta v} (\tan\beta \cos^3\theta - \sin^3\theta),$$

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

Interference Effects in Di-Higgs Production: $gg \rightarrow S \rightarrow hh$

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

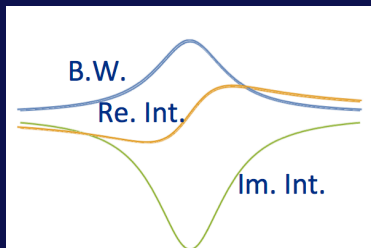
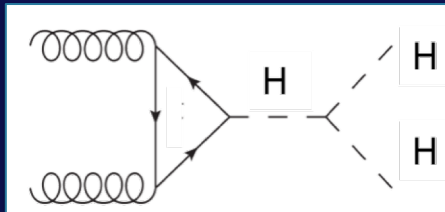
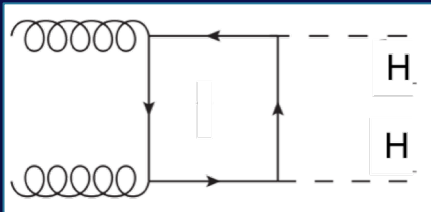
Singlet extension of the SM can serve as a benchmark, challenging to test at colliders



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

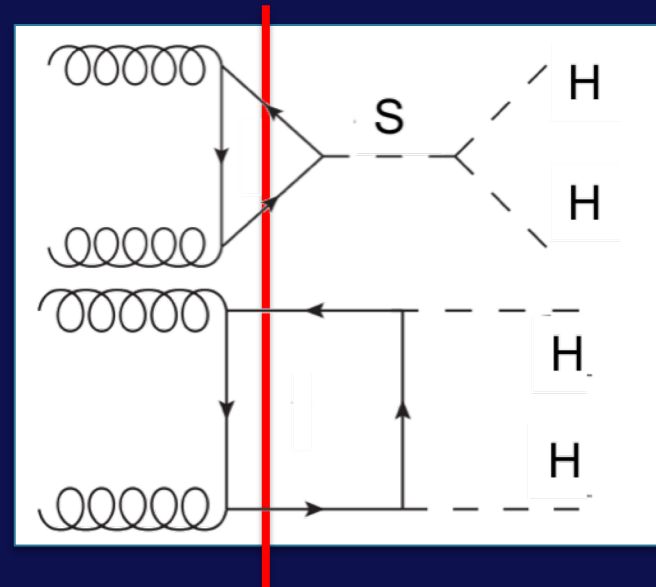
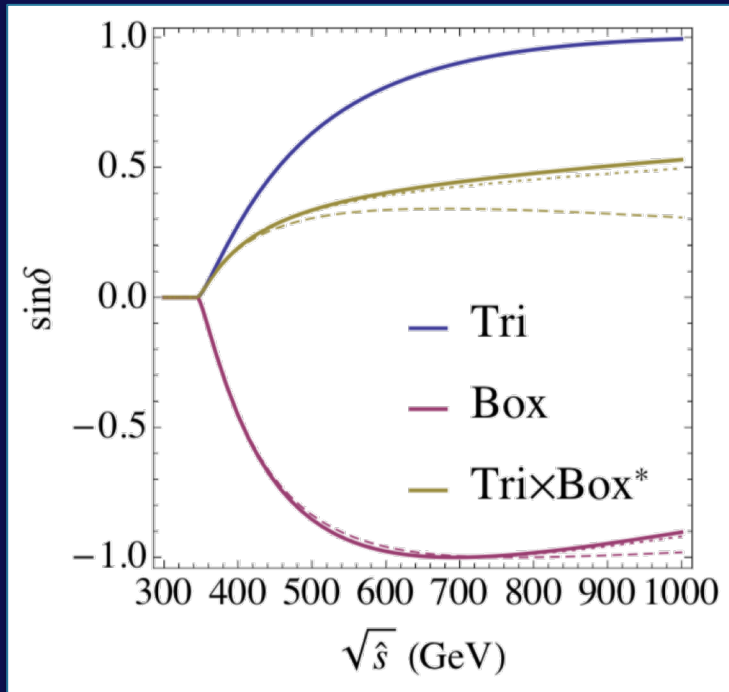
$$A_{\square}^H = A_{gg \rightarrow hh} = c_{\square} (\text{slowing varying function of } \hat{s})$$

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



Inter. Term.		rel. phase	proportionality	Inter. Sign
$A_{\triangleright}^H - A_{\square}^H$	\mathcal{R}_{int}	$\cos(\delta_{\triangleright} - \delta_{\square})$	$\cos^3 \theta \lambda_{HHH}$	-
	\mathcal{I}_{int}	$\sin(\delta_{\triangleright} - \delta_{\square})$	0^*	0
$A_{\triangleright}^S - A_{\square}^H$	\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
$A_{\triangleright}^S - A_{\square}^H$	\mathcal{R}_{int}	$\cos(\delta_{\triangleright} - \delta_{\square})$	$\lambda_{SHH} \cos^2 \theta \sin \theta$	+/-
	\mathcal{I}_{int}	$\sin(\delta_{\triangleright} - \delta_{\square})$	$\lambda_{SHH} \cos^2 \theta \sin \theta$	+

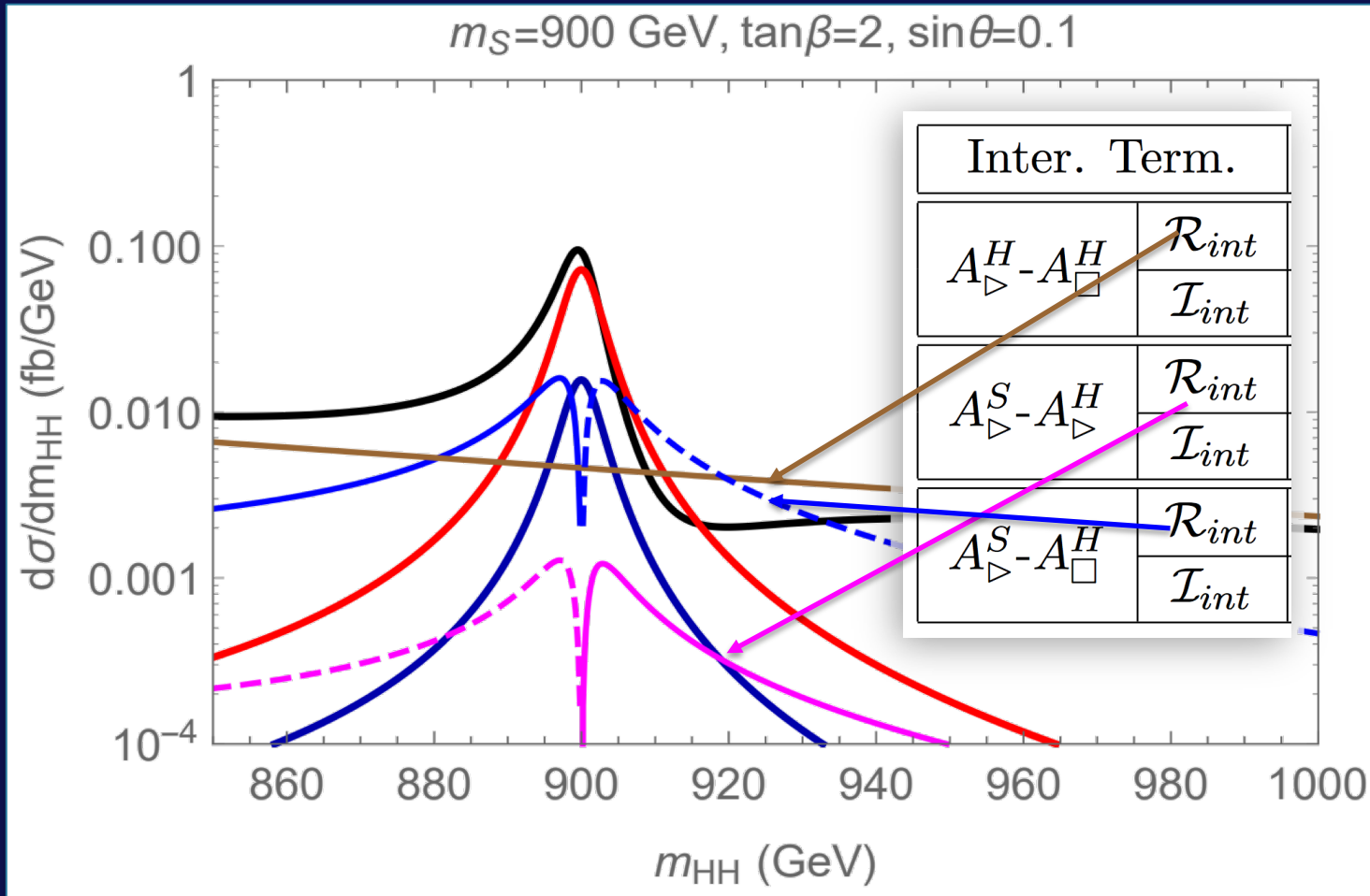
Strong phase in the loop functions



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

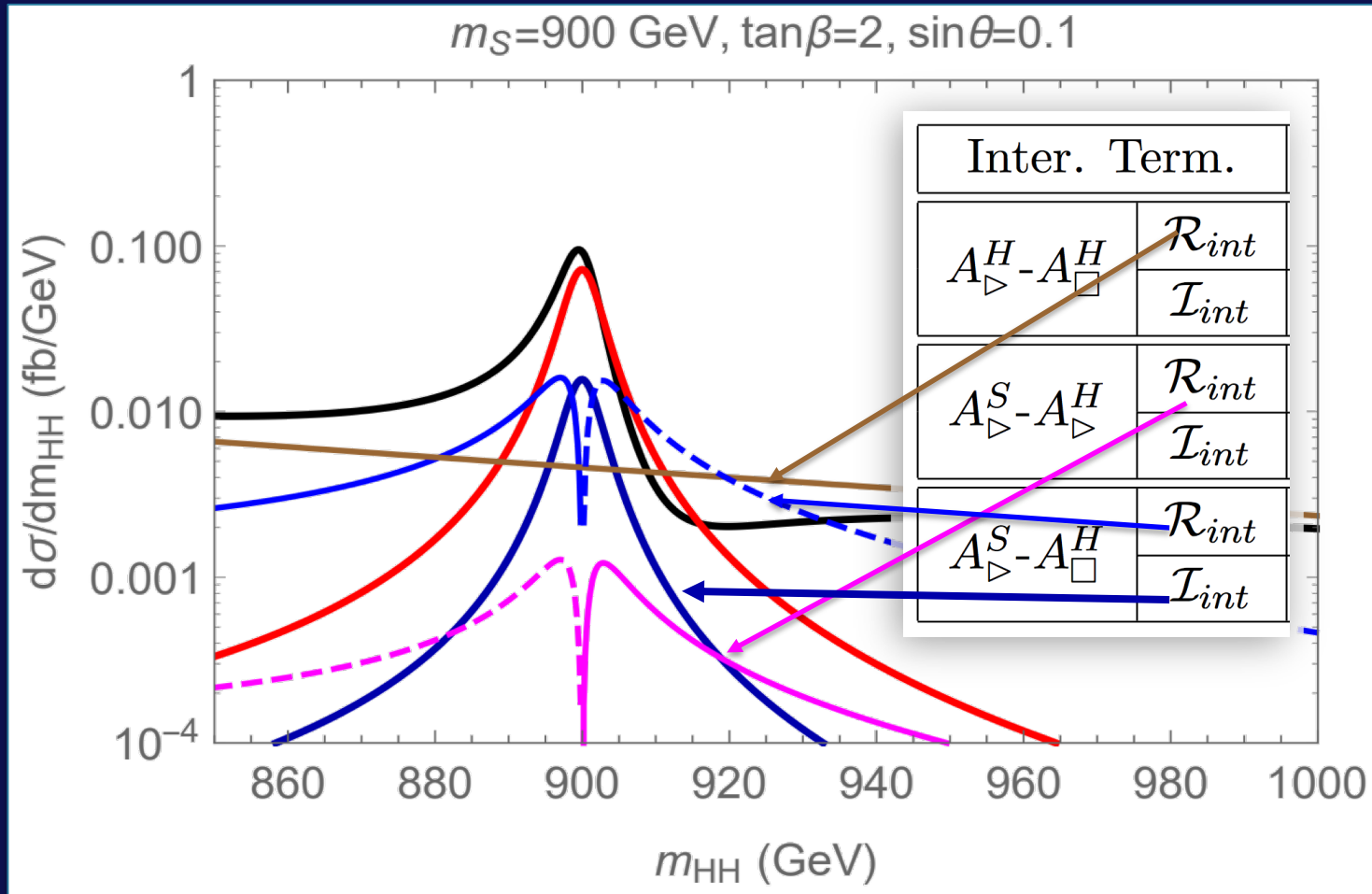
Relative strong phase (yellow curve) allows for a non-vanishing interference effect between the singlet resonance diagram and the SM box diagram.

Interference Line shape



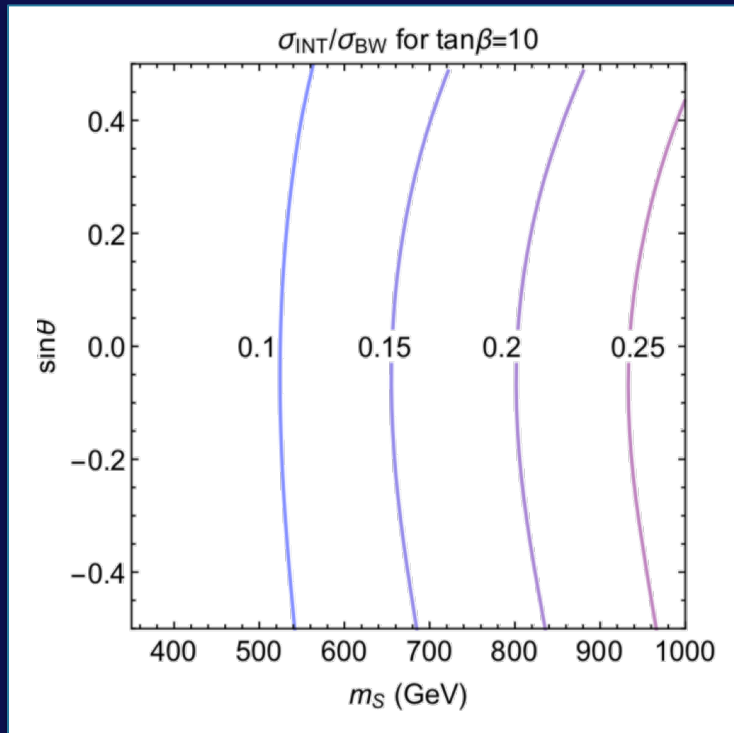
Logarithmic to see other components;
 Dashed represent destructive interference;
Dark blue, unique on-shell constructive interference

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

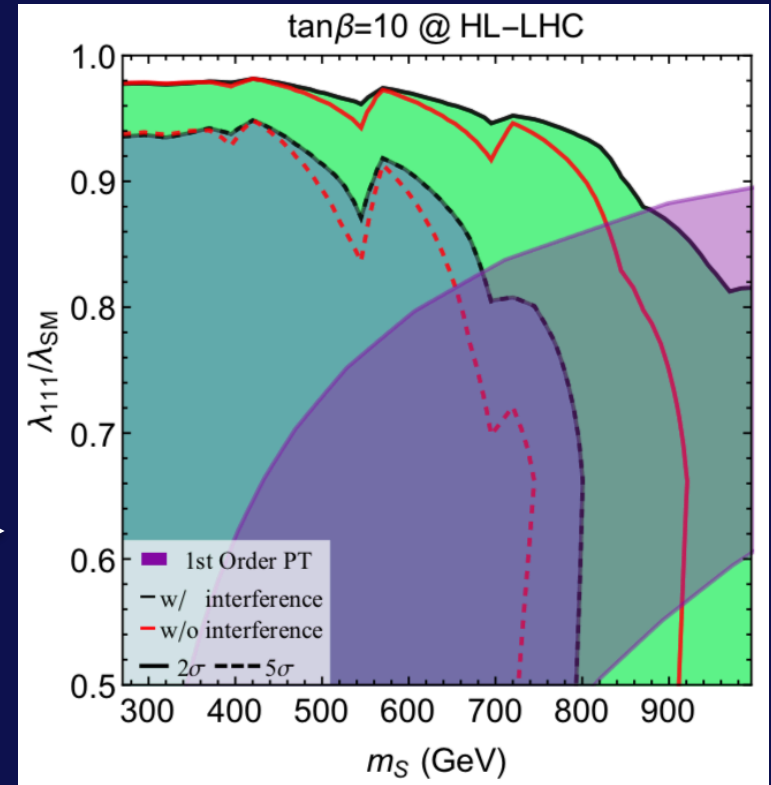
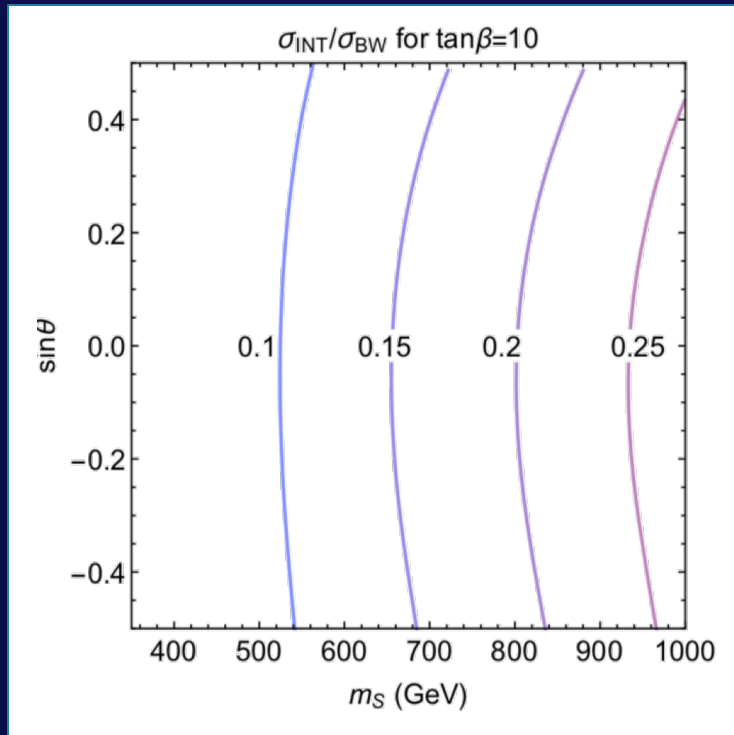


Relative size of the on-shell interference effect w.r.t. the resonant BW signal, averaged over scattering angle $[-0.5,0.5]$

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 $pp \rightarrow HH \rightarrow bb\gamma\gamma$, analysis [arXiv:1502.00539] we perform a differential analysis of the lineshapes:

M.C. Z. Liu and M. Riemann. '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

Di-Higgs Production as a signal of Enhanced Yukawa couplings

Bauer, MC, Carmona (1801.00363)

Correlation between enhanced Higgs-fermion couplings and di-Higgs production in 2HDM w/ flavour symmetry (2HDFM)

$$\mathcal{L}_Y^I \ni y_{ij}^u \left(\frac{\phi_1 \phi_2}{\Lambda^2} \right)^{n_{u_{ij}}} \bar{Q}_i \phi_1 u_j + y_{ij}^d \left(\frac{\phi_1^\dagger \phi_2^\dagger}{\Lambda^2} \right)^{n_{d_{ij}}} \bar{Q}_i \tilde{\phi}_1 d_j + y_{ij}^\ell \left(\frac{\phi_1^\dagger \phi_2^\dagger}{\Lambda^2} \right)^{n_{\ell_{ij}}} \bar{L}_i \tilde{\phi}_1 \ell_j + h.c. ,$$

$$g_{\varphi f L_i f R_i} = \kappa_{f_i}^\varphi \frac{m_{f_i}}{v} = \left(g_{f_i}^\varphi(\alpha, \beta) + n_{f_i} f^\varphi(\alpha, \beta) \right) \frac{m_{f_i}}{v} .$$

$$g_{Hhh} = \frac{c_{\beta-\alpha}}{v} \left[(1 - f^h(\alpha, \beta) s_{\beta-\alpha}) (3M_A^2 - 2m_h^2 - M_H^2) - M_A^2 \right] \quad (1)$$

$$g_{hhh} = -\frac{3}{v} \left[f^h(\alpha, \beta) c_{\beta-\alpha}^2 (m_h^2 - M_A^2) + m_h^2 s_{\beta-\alpha} \right]$$

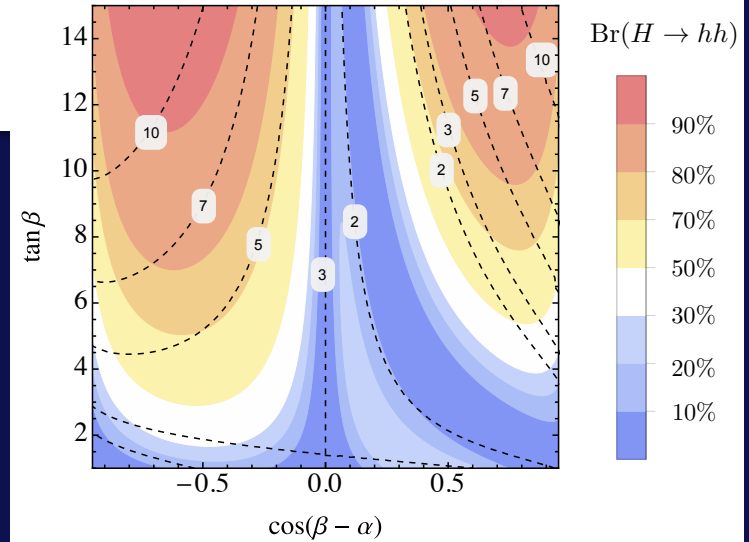


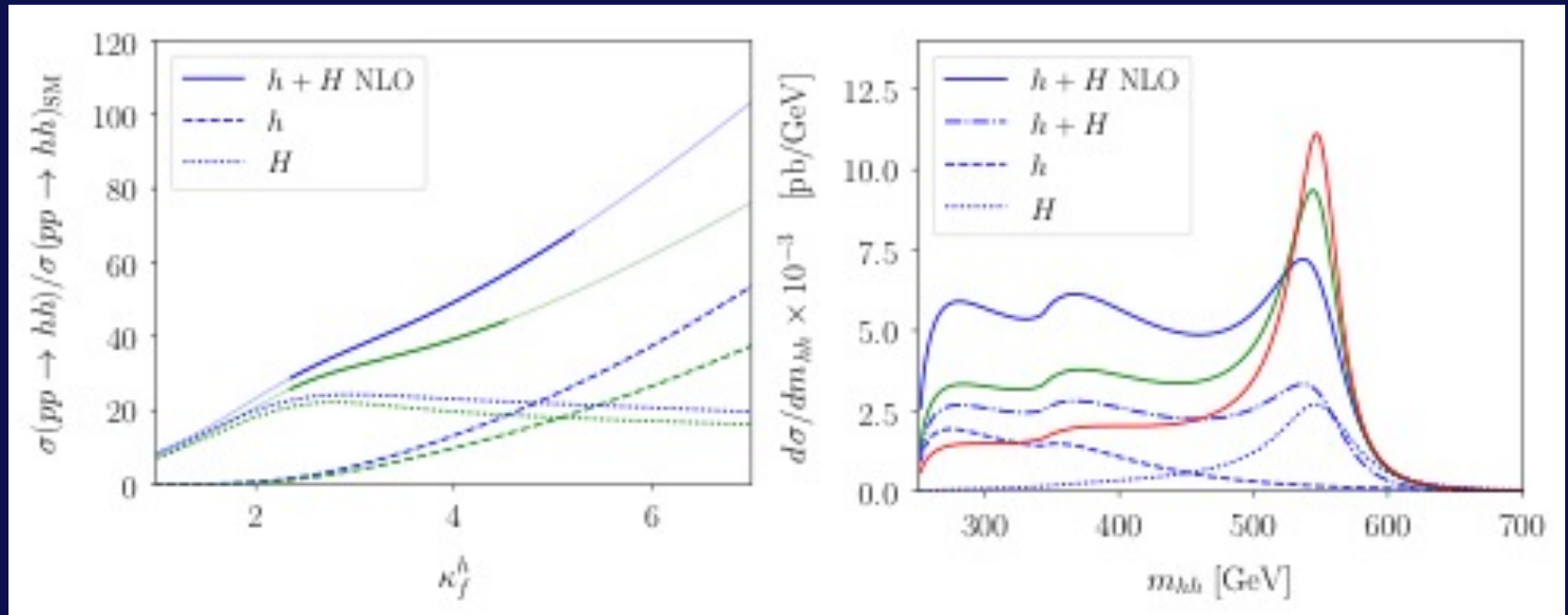
FIG. 1: The color coding shows the dependence of $\text{Br}(H \rightarrow hh)$ on $c_{\beta-\alpha}$ and t_β for $M_H = M_{H^\pm} = 550$ GeV, $M_A = 450$ GeV. The dashed contours correspond to constant $|\kappa_f^h|$ for $n_f = 1$.

Di-Higgs Production as a signal of Enhanced Yukawa couplings

Bauer, MC, Carmona (1801.00363)

Correlation between enhanced Higgs-fermion couplings and di-Higgs production in 2HDM w/ flavour symmetry

Visible in resonant & non-resonant, dedicated LHC searches

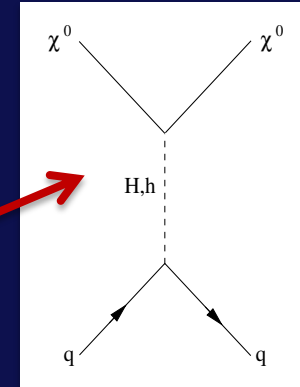
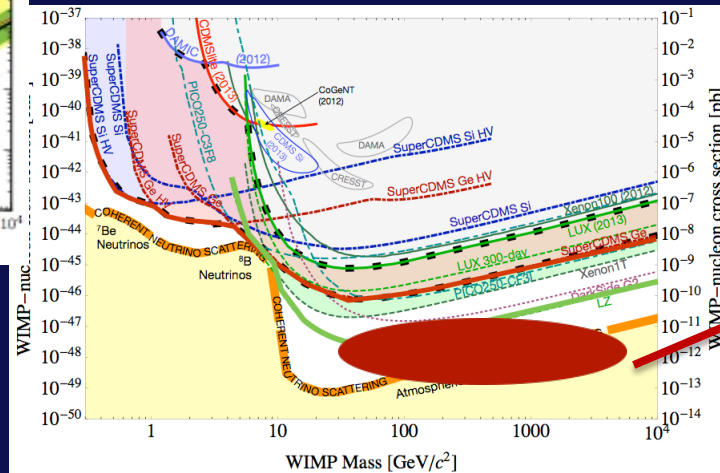
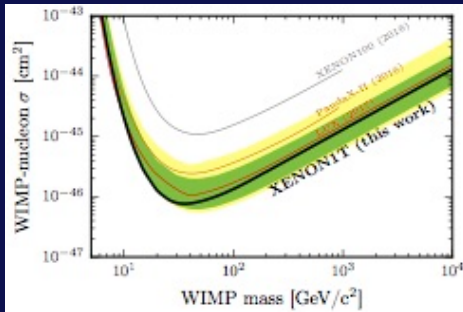


Cross section for Higgs pair production in units of the SM prediction as a function of κ_{hf} for $c(\beta-\alpha) = -0.45$ (-0.4) and $M_H = M_{H^\pm} = 550$ GeV, $M_A = 450$ GeV in blue (green) at $\sqrt{s} = 13$ TeV

Invariant mass distribution for the different contributions to the signal with $c(\beta-\alpha) = -0.45$ and $\kappa_{hf} = 5$ (blue), $\kappa_{hf} = 4$ (green) and $\kappa_{hf} = 3$ (red) at $\sqrt{s} = 13$ TeV, respectively.

Dark Matter Direct Detection

Starting to probe the Higgs portal



Close to Alignment (MSSM)

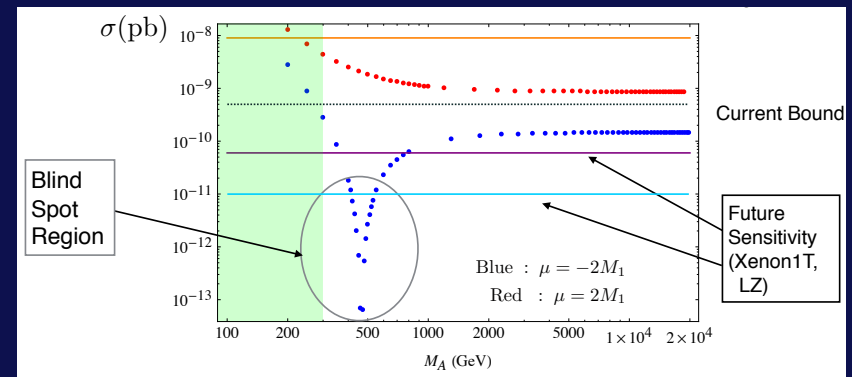
$$\sigma_p^{SI} \sim \left[(F_d^{(p)} + F_u^{(p)})(m_\chi + \mu \sin 2\beta) \frac{1}{m_h^2} + \mu \tan \beta \cos 2\beta (-F_d^{(p)} + F_u^{(p)}/\tan^2 \beta) \frac{1}{m_H^2} \right]^2$$

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

Destructive interference between h and H contributions for negative values of μ ($\cos 2\beta$ negative)

Still room for a SUSY WIMP miracle

Huang, Wagner, '15



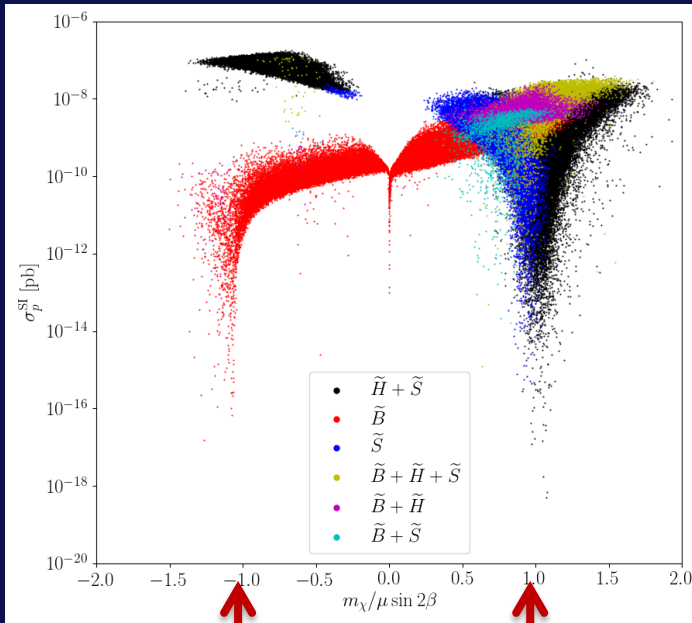
Blind Spots in Direct DM detection in the NMSSM

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

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

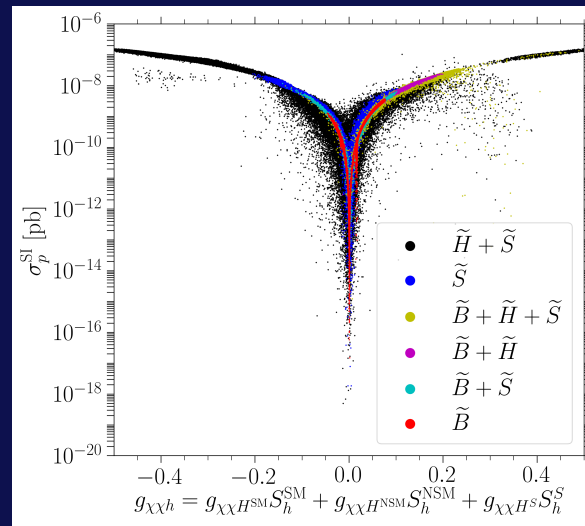
$$S_{h,s} \approx \frac{-2\lambda v \mu \epsilon}{(m_h^2 - m_{h_s}^2)}$$

Cheung, Papucci, Sanford, Shah, Zurek '14



$\mu < 0$

$\mu > 0$



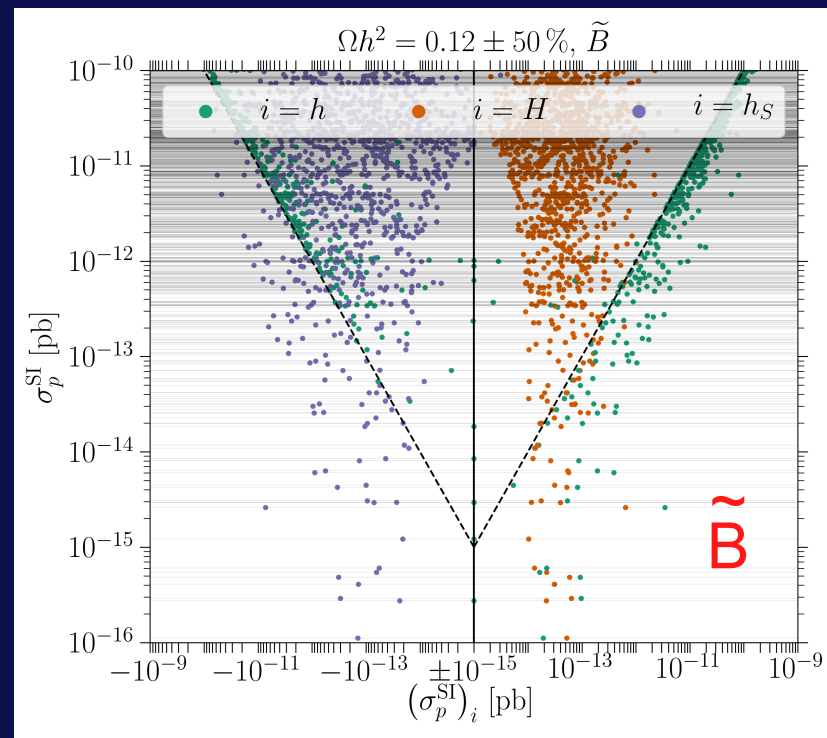
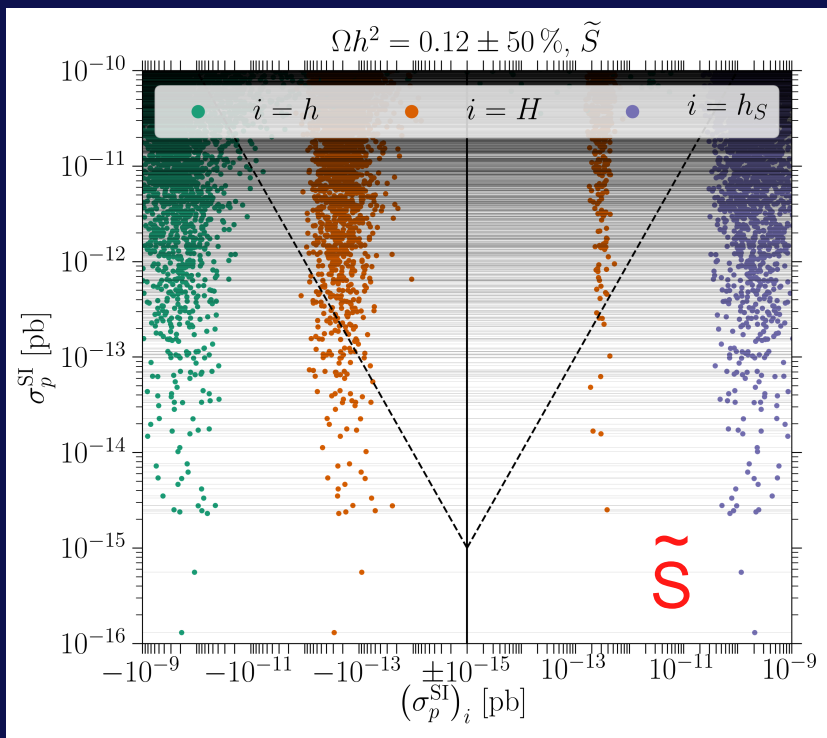
Higgs Mixing Effects:
Couplings to the 125 GeV Higgs tend to be suppressed close to the blind spots. However, they remain relevant in the singlino region, denoting the presence of relevant interferences

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.

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 singlino: coupling to Higgs larger than for Bino \rightarrow SM-like Higgs coupling close to blind spot plus destructive interference with singlet 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 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
- Complementarity between new Higgs searches and Higgs precision measurements

Singlet SUSY extensions (NMSSM)

- Necessary degree of alignment tied to a light Higgsino, Singlino and singlet Higgs sector - allows for lighter stops with moderate mixing.
- Good for achieving the 125 GeV Higgs and compatible with perturbativity up to M_{GUT}
- Unexplored search channels for A/H decaying to di-scalars and gauge bosons

Dark Matter

- Well tempered, Bino-Higgsino regions with blind spots for SI Direct detection

Phase shift between SM and new physics can have important implications

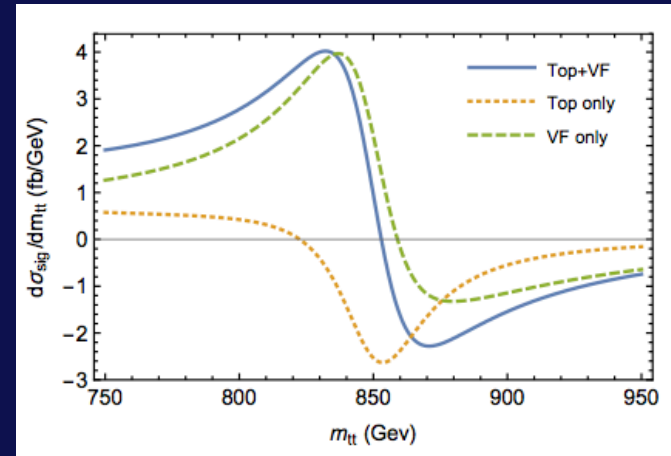
- Novel on-shell info on Higgs total width & light quark Higgs couplings
- Enhance LHC sensitivity to simple models with a strong FOPT
- Needed in scalar resonant searches above the top threshold

Extras

Special Line-shapes examples with additional BSM particles

M.C., Liu '16

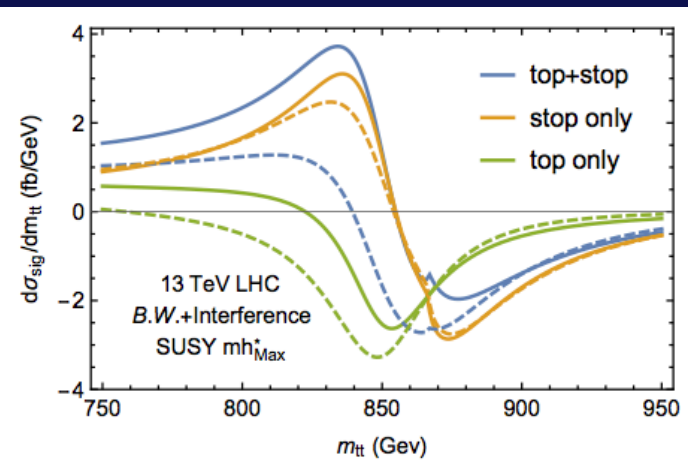
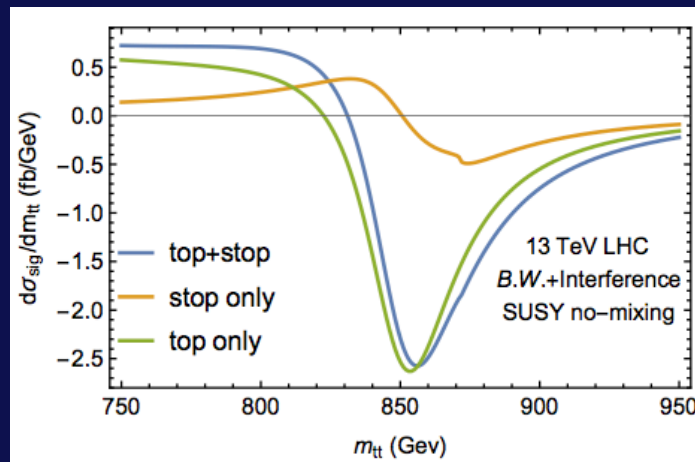
Vector-like quarks in loop function:
Real, hence no destructive interference



Stops in the loop function:

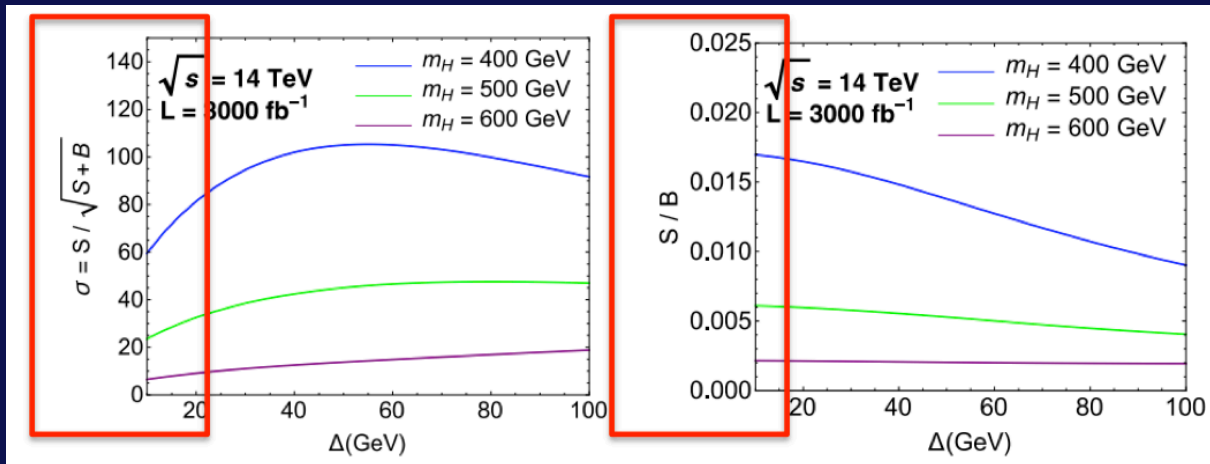
Zero L-R stop mixing \rightarrow small interference (dip-bump structure), top quark dip structure prevails

Large L-R mixing \rightarrow dominant contribution, dip-bump structure prevails



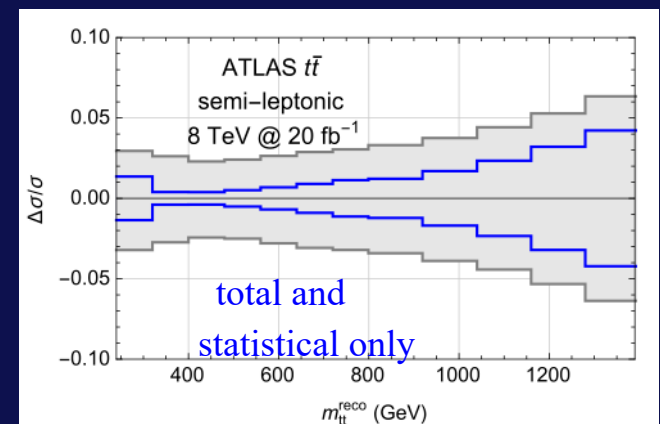
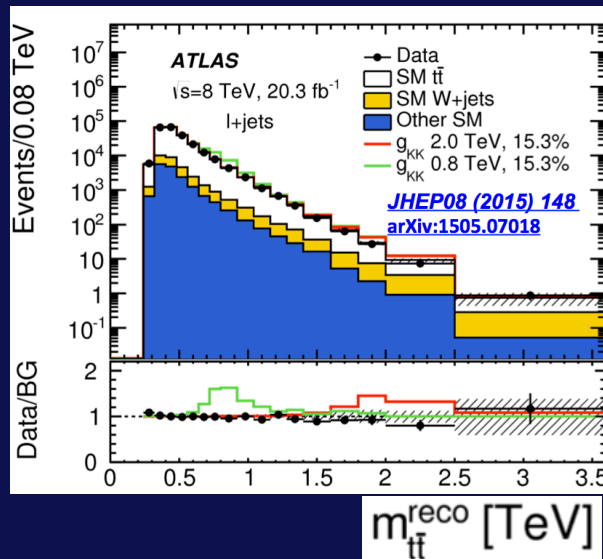
The challenging A/H \rightarrow tt channel: Systematic Uncertainties

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

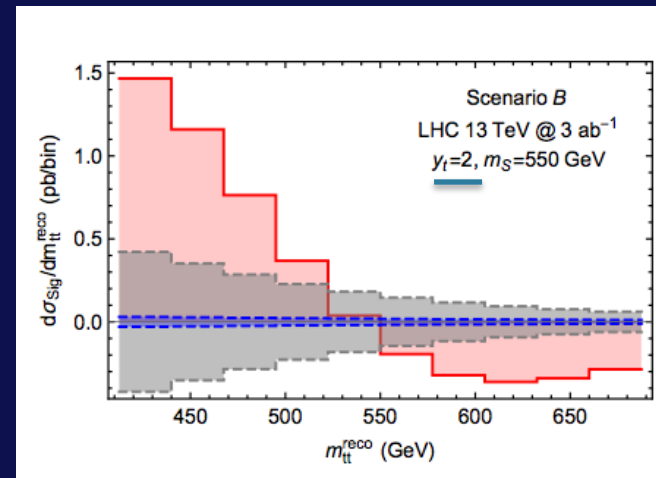
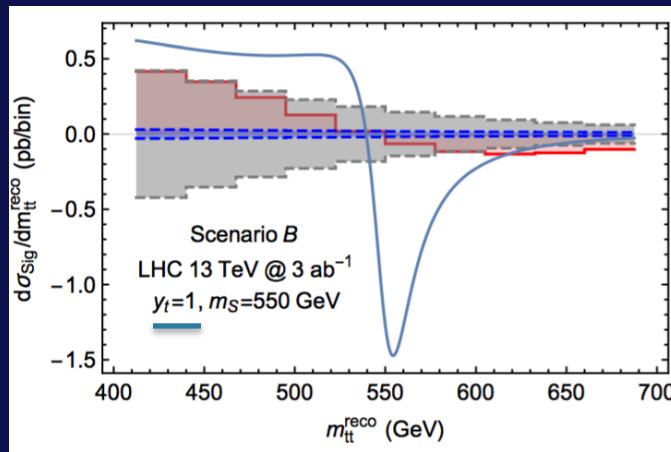
Using Atlas 8 TeV Analysis



Prospects for searches in $A/H \rightarrow tt$: 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

Two Higgs Doublet models and a Theory of Flavor

- The Froggatt Nielsen mechanism: Effective Yukawa coupling

$$\mathcal{L}_{\text{Yuk}} = y_t \bar{Q}_L \tilde{H} t_R + y_b \left(\frac{S}{\Lambda} \right)^{n_b} \bar{Q}_L H b_R + \dots$$

$$m_t = y_t \frac{v}{\sqrt{2}} \quad m_b = y_b \frac{v}{\sqrt{2}} \left(\frac{f}{\Lambda} \right)^{n_b}$$

$$y_{\text{eff}} = \epsilon^n y \quad \epsilon = f/\Lambda \quad \text{Issue: Scales undetermined}$$

- New scalar singlet S obtains a vev: $\langle S \rangle = f$

- Quarks & scalars are charged under a global $U(1)_F$ flavor symmetry

$$n_b a_S = a_{Q_L} - a_H - a_{b_R}$$

- Lighter quarks, more S insertions

- How to define the scales? Can the Higgs play the role of the Flavon?

$$y_b \left(\frac{S}{\Lambda} \right)^{n_b} \bar{Q}_L H b_R \rightarrow y_b \left(\frac{H^\dagger H}{\Lambda^2} \right)^{n_b} \bar{Q}_L H b_R$$

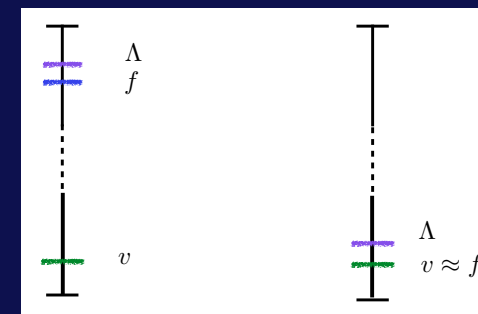
$$\epsilon = v^2/2\Lambda^2 \equiv m_b/m_t \rightarrow \Lambda \approx (5 - 6)v$$

Babu '03, Giudice-Lebedev '08

Flavor Scale fixed by EW scale

Two Main Problems

- The flavon is a flavor singlet
- The Higgs coupling to Bottom quarks is too large
 $g_{hbb} \propto 3 m_b/v$



A Flavoured Higgs Sector

Bauer, MC, Gemmler '15

2HDFM with different flavor charges a_u and a_d for H_u and H_d , respectively.

Type II: $y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H b_R \rightarrow y_b \left(\frac{H_u H_d}{\Lambda^2}\right)^{n_b} \bar{Q}_L H_d b_R$ (Type II for $n_b \rightarrow 0$)

Type I: $y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H b_R \rightarrow \tilde{y}_b \left(\frac{H_u^\dagger H_d^\dagger}{\Lambda^2}\right)^{n_b} \bar{Q}_L \tilde{H}_u b_R$ (Type I for $n_b \rightarrow 0$)

With effective Yukawa coupling: $y_i^{\text{eff}} = \left(\frac{v_u v_d}{2\Lambda^2}\right)^{n_i} y_i$

$$v^2 = v_u^2 + v_d^2$$

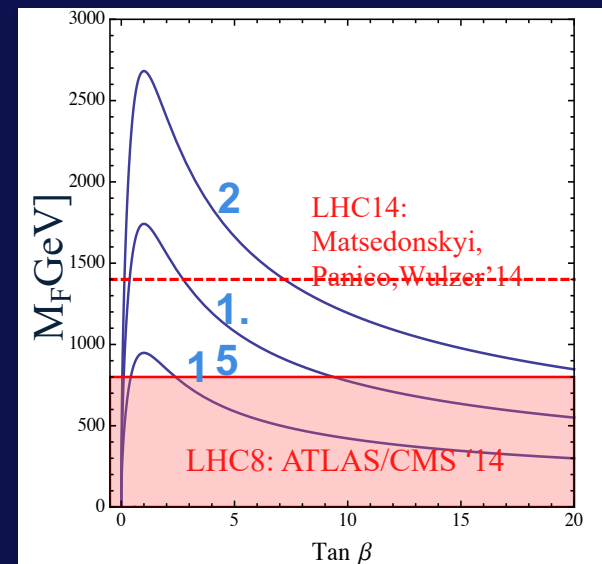
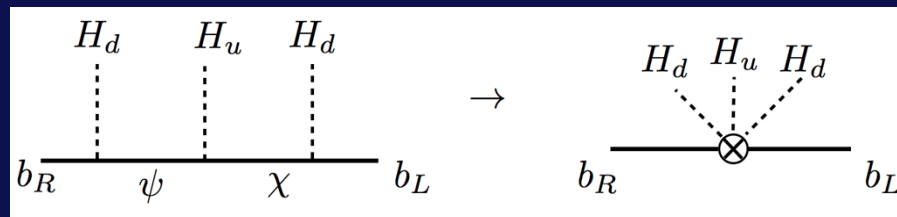
$$\tan \beta = v_u / v_d$$

And suppression factor $\epsilon = v_u v_d / 2\Lambda^2 \equiv m_b / m_t \rightarrow \Lambda \approx (5 - 6)v \left(\frac{\tan \beta}{1 + \tan^2 \beta}\right)^{1/2}$

The value of $\Lambda \sim 4v \sim 1\text{TeV}$ (max. for $\tan \beta = 1$) can be slightly larger depending on UV completion

$$\bar{M} \equiv \sqrt{M_\eta M_\psi}$$

$$\bar{y} = (y_1 y_2 y_3)^{1/3}$$



Lightest (SM-like) Higgs bosons couplings

- Flavor Structure by fixing flavor charges

$$m_t \approx \frac{v_u}{\sqrt{2}}, \quad \frac{m_b}{m_t} \approx \frac{m_c}{m_t} \approx \varepsilon^1, \quad \frac{m_s}{m_t} \approx \varepsilon^2, \quad \frac{m_d}{m_t} \approx \frac{m_u}{m_t} \approx \varepsilon^3$$

$$V_a^{12} = 1, \quad V_a^{13} = V_a^{23} = \varepsilon$$

$$V_b^{12} = V_b^{13} = V_b^{23} = 1$$

- Couplings re-scaled

$$g_{hVV} = \kappa_V g_{hVV}^{\text{SM}} \quad g_{hff} = \kappa_f g_{hff}^{\text{SM}}$$

- Higgs couplings to gauge bosons (top quark) as in 2HDM (type II) :

$$\kappa_V = \sin(\beta - \alpha)$$

$$\kappa_t = \frac{\cos(\beta - \alpha)}{\tan \beta} + \sin(\beta - \alpha)$$

Higgs Production (at leading order) equivalent to a 2HDM type II

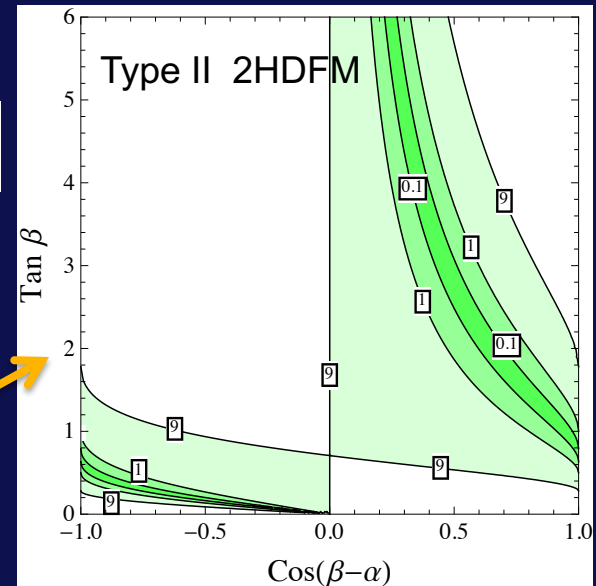
- Higgs coupling to the bottom (& charm) quarks

$$\kappa_b = 3 \sin(\beta - \alpha) + \cos(\beta - \alpha) \left(\frac{1}{\tan \beta} - 2 \tan \beta \right)$$

$$\kappa_c = 3 s_{\beta-\alpha} + c_{\beta-\alpha} \left(\frac{2}{t_\beta} - t_\beta \right)$$

VERY DIFFERENT BEHAVIOUR

- Values of order one or below for sizeable values of $c_{\beta-\alpha}$
- Two acceptable branches with positive and negative values of the bottom Yukawa coupling



Two Higgs Doublet models and a Theory of Flavor (2HDFM)

Bauer, MC, Gemmler '15, '16

A Flavored Higgs Sector with different flavor charges a_u and a_d for H_u and H_d ,
that jointly act as the flavon of the Froggatt-Nielsen Mechanism
→ generating effective Yukawa couplings

Many interesting, measurable effects can probe this idea

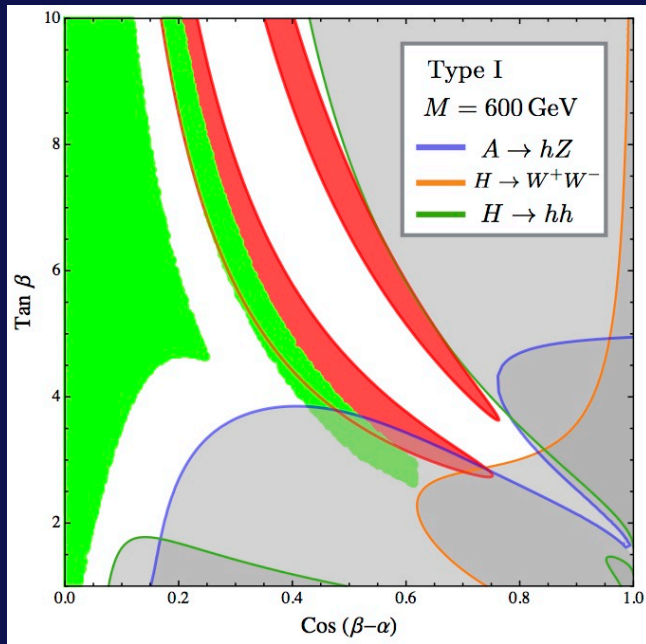
Modified quark-Higgs couplings ↔ Precision measurements/Global Higgs Fit

FCNCs at tree-level ↔ Numerous Flavor constraints

Direct collider probes of heavy scalars ↔ ATLAS and CMS searches

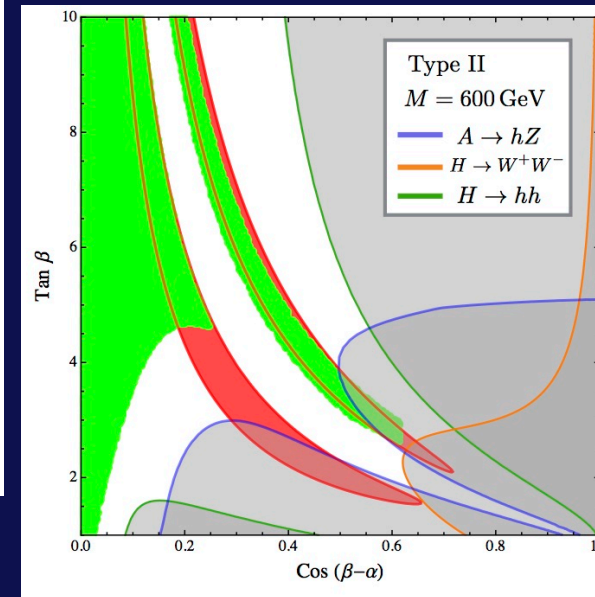
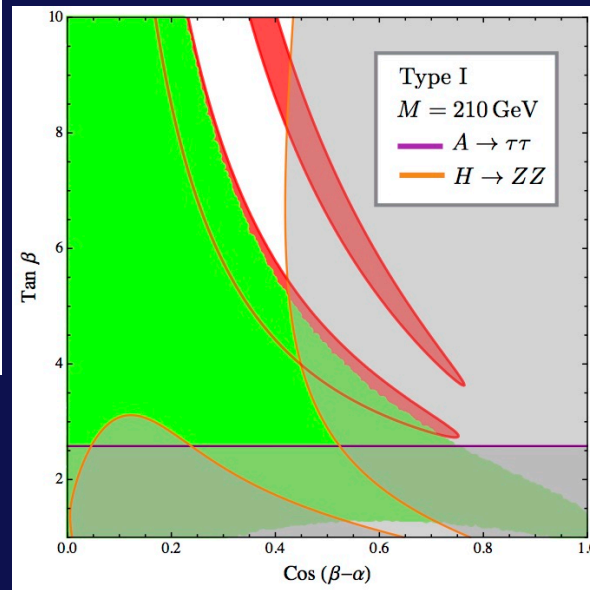
Benchmark scenarios to probe the model

A predictive model with new Physics at LHC reach allowed regions beyond those in a 2HDM type I or II



Red bands: allowed region at the 95% CL from the Higgs signal strengths at ATLAS/CMS - ICHEP 2016 results

The green area highlights the allowed region from EW precision observables, perturbativity and unitarity constraints



Flavor physics:
 ϵ_K , Mixing in B_d and B_s
 system, $b \rightarrow s \gamma$
 Compatible with cancellations
 in the 5 % level at most

Great possibilities for direct collider searches !

Additional Higgs Bosons should be below 700 GeV + TeV vector-like fermions