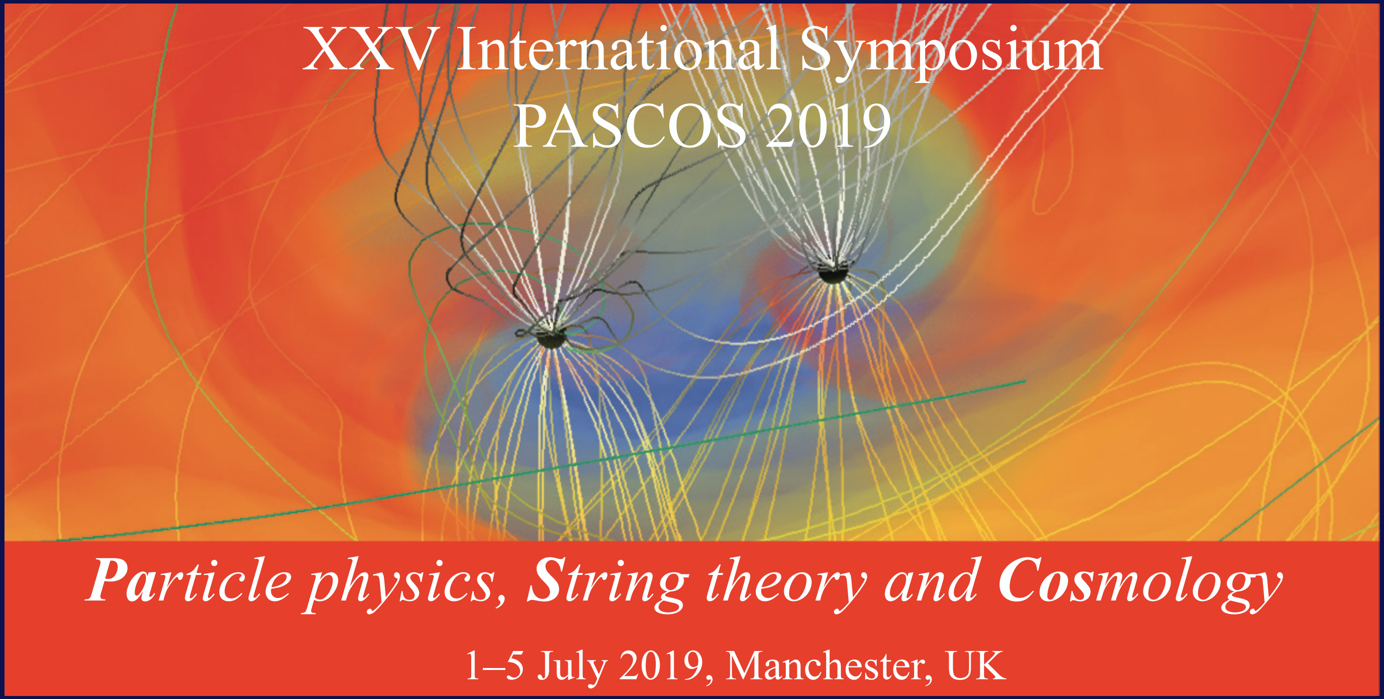
New Physics Opportunities in Higgs Searches

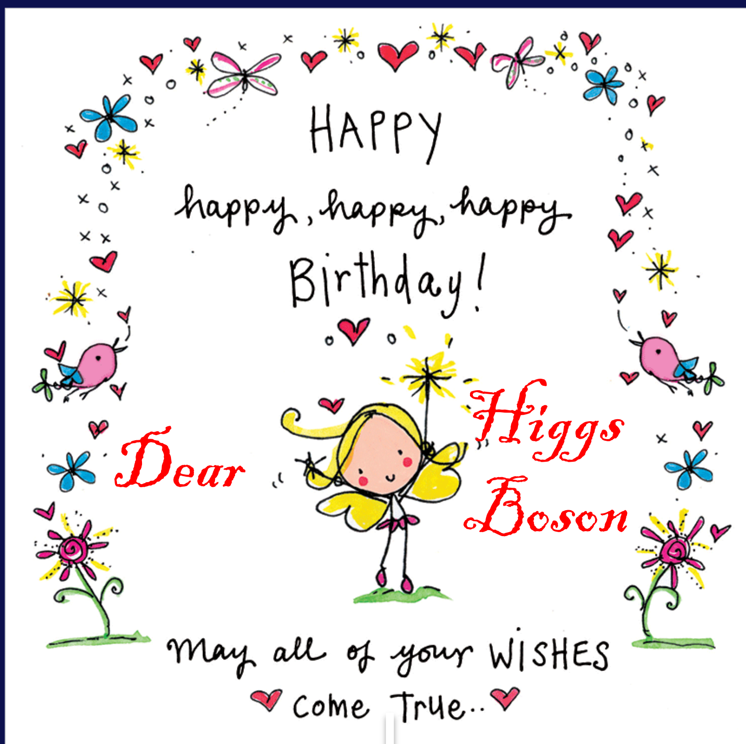


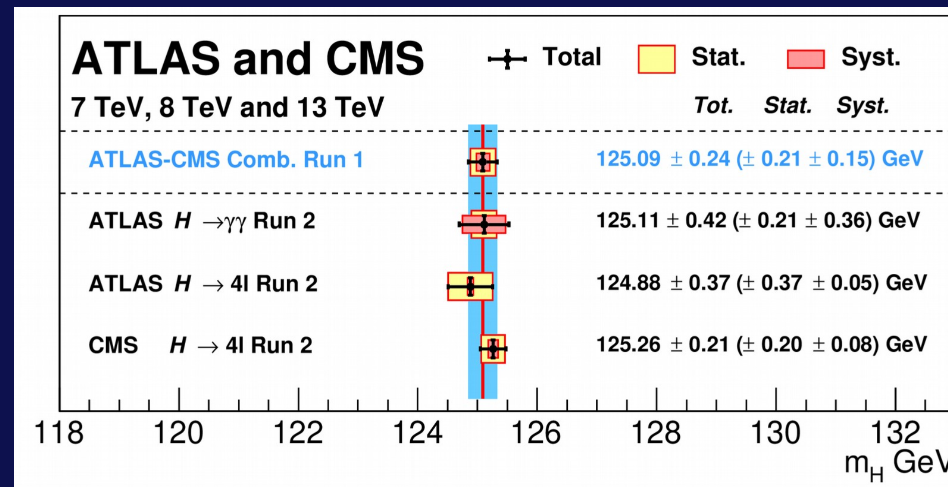
Marcela Carena

Fermilab and UChicago

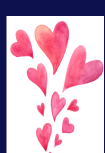
University of Manchester, July 4, 2019

The Higgs turns 7!





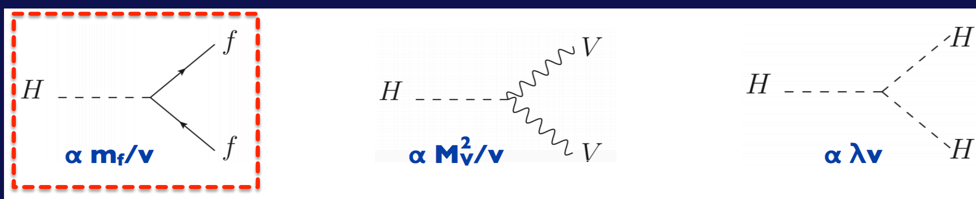
Andrey Pozdnyakov's talk

 Some Departure from Standard Model properties 

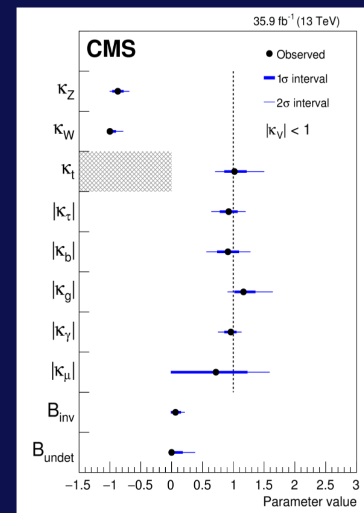
ATLAS and CMS Higgs results

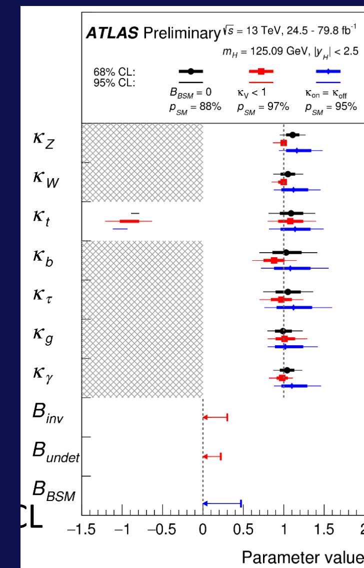
Run-II headlines: observations with the 3rd generation fermions!

Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4σ	5.5σ	5.1σ
	Obs. Sig.	6.4σ	5.4σ	6.3σ
	mu	1.09±0.35	1.01±0.20	1.32±0.27
CMS	Exp. Sig.	5.9σ	5.5σ	4.2σ
	Obs. Sig.	5.9σ	5.6σ	5.2σ
	mu	1.09±0.27	1.04±0.20	1.26±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



Assuming no strict correlation between gluon & top couplings ==> consistency with SM



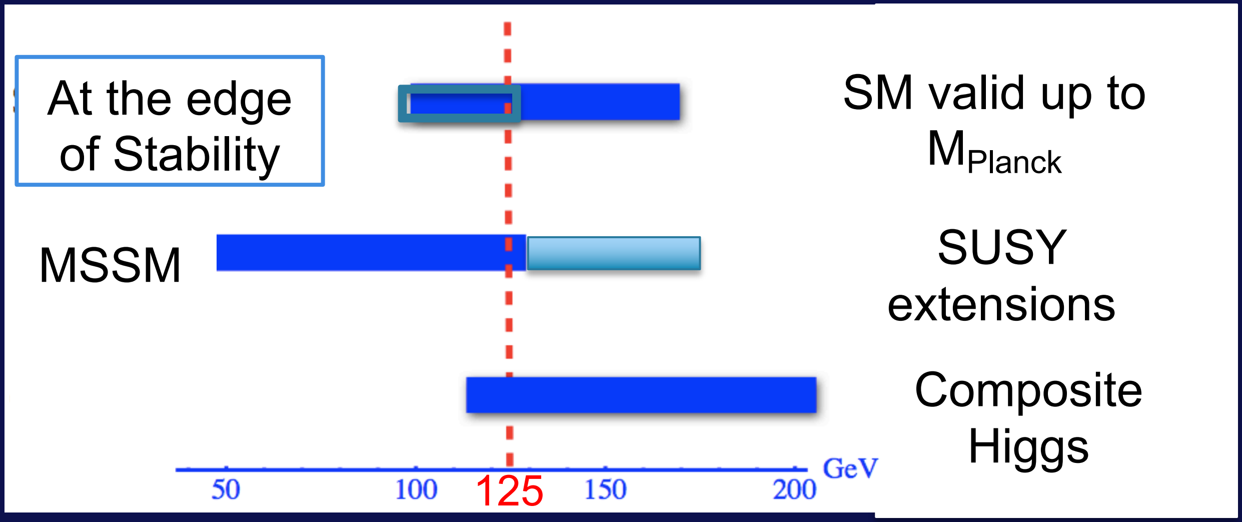


Errors still admit deviations of a few tens of percent from the SM results

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→ WW/ZZ decays

Under the Higgs lamp-post:



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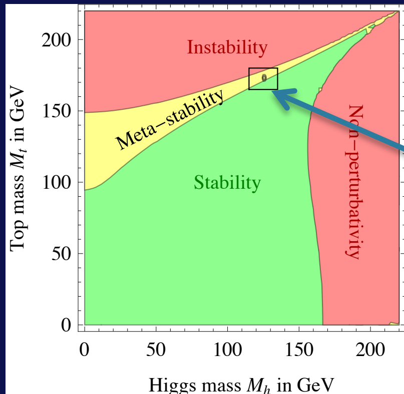
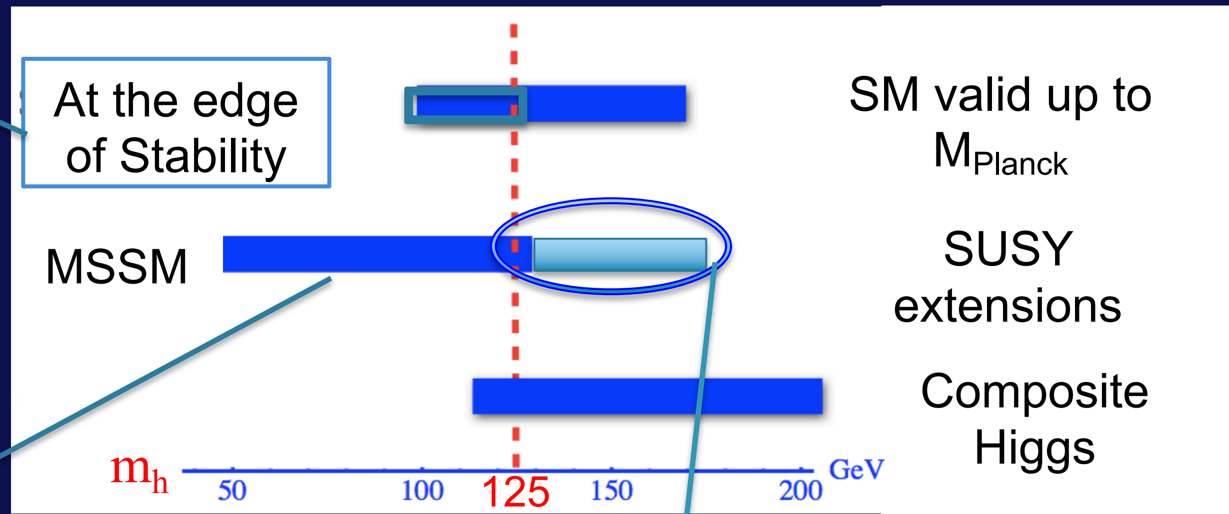
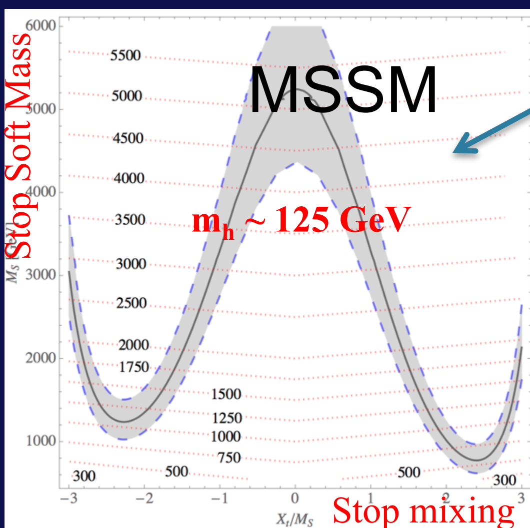
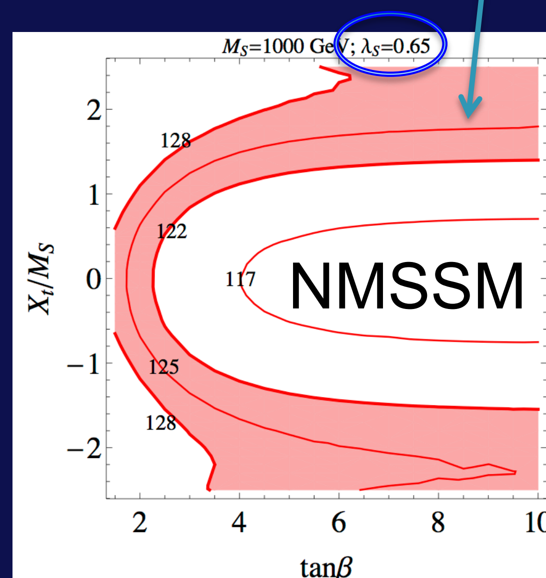






Splitting in stop SUSY breaking mass parameters can accommodate one lighter stop with minimal impact to gluon fusion

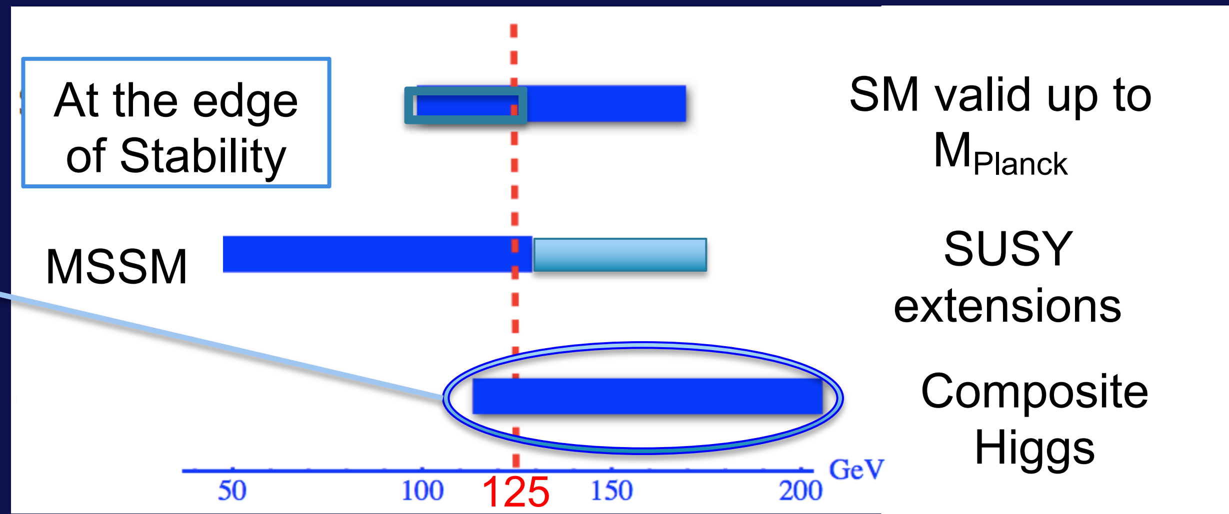


NMSSM + mh ~ 125 GeV: At low tanβ naturally compatible with stops at the electroweak scale, thereby reducing the degree of fine tuning to get EWSB

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

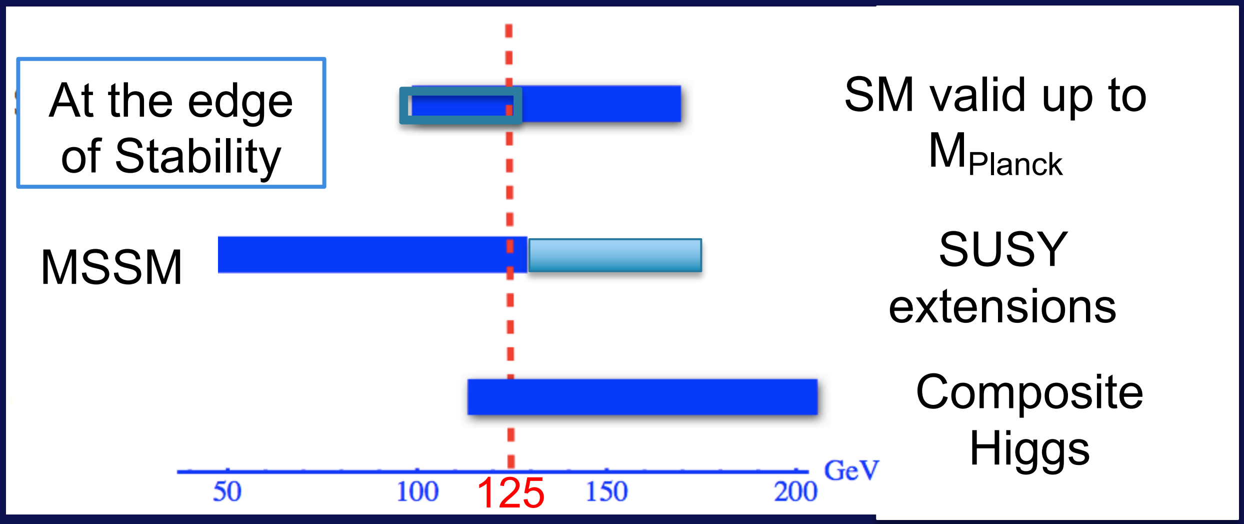
Higgs ➔ scalar resonance much lighter than the other ones

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

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**

$$\mathbf{h} = -\sin\alpha\,\mathbf{H_1^0} + \cos\alpha\,\mathbf{H_2^0}$$
$$\mathbf{H} = \cos\alpha\,\mathbf{H_1^0} + \sin\alpha\,\mathbf{H_2^0}$$

$$\mathbf{HVV} = (\mathbf{hVV})^{\mathbf{SM}}\cos(\beta-\alpha)$$
$$\mathbf{hVV} = (\mathbf{hVV})^{\mathbf{SM}}\sin(\beta-\alpha)$$

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 β = 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, 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

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

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

Eigenstate Eq.

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

≈ 0 ➔ cos (β-α) = 0

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

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

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

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

$$g_{hVV} \approx \left(1 - \frac{1}{2} t_\beta^{-2}\eta^2\right) g_V$$

$$g_{hdd} \approx (1-\eta)\, g_f \,,$$

$$g_{huu} \approx (1 + t_\beta^{-2}\eta)\, g_f \,,$$

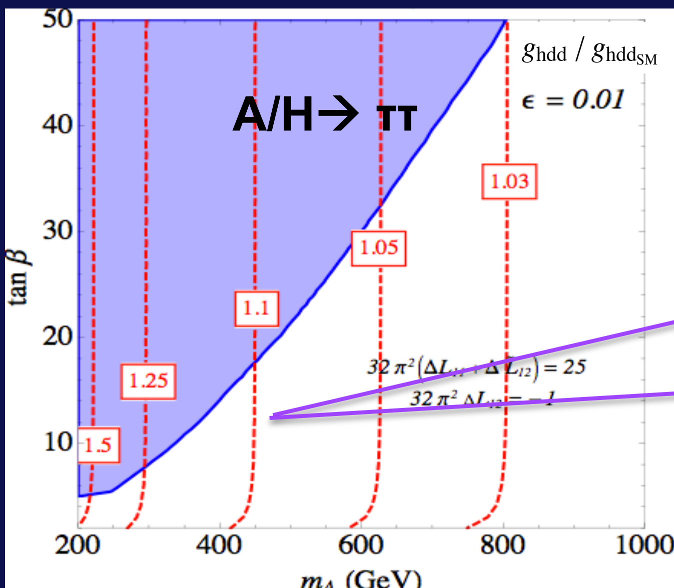
The couplings to down fermions are not only the ones that dominate the Higgs width but also tend to be the ones that differ the most from the SM ones

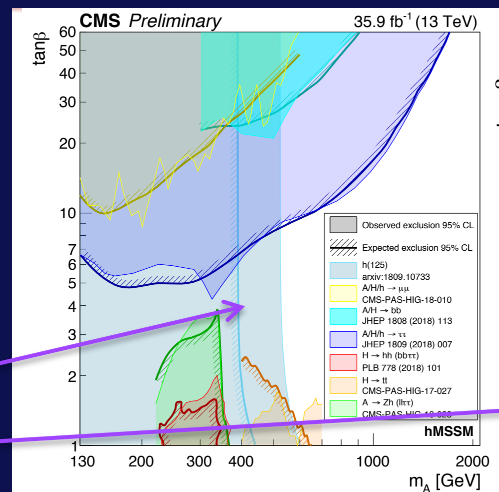
For small departures from alignment, η can be determined as a function of the quartic couplings and the Higgs masses

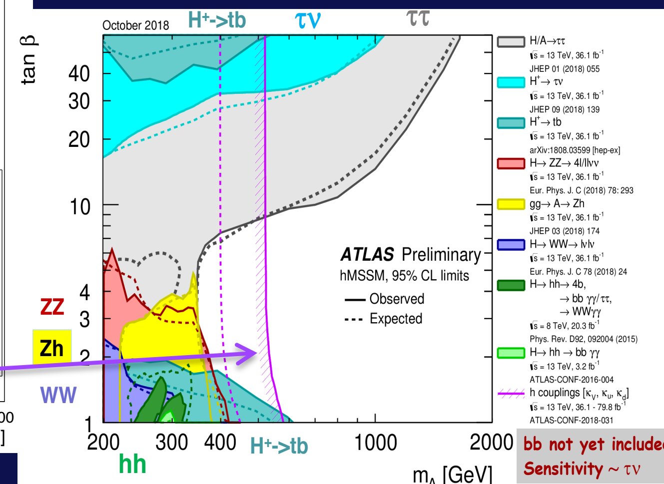
Interpretation of precision Higgs measurements on A/H searches strongly dependent on the proximity to Alignment without decoupling

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

Bottom coupling in the MSSM







hMSSM scenario not applicable for small tan β (~ tan β < 3)

e.g. 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 moderate to large tanβ and small μ

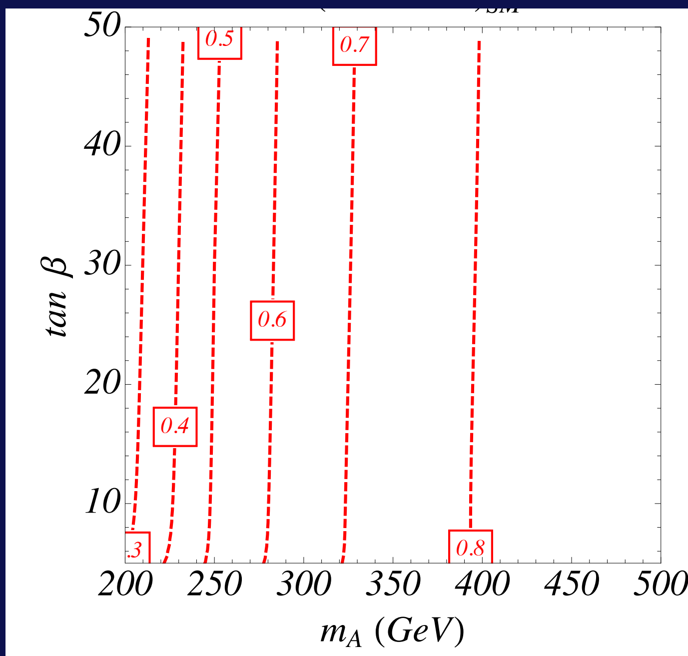
➔ no dependence on tanβ or on the stop mixing

➔ 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

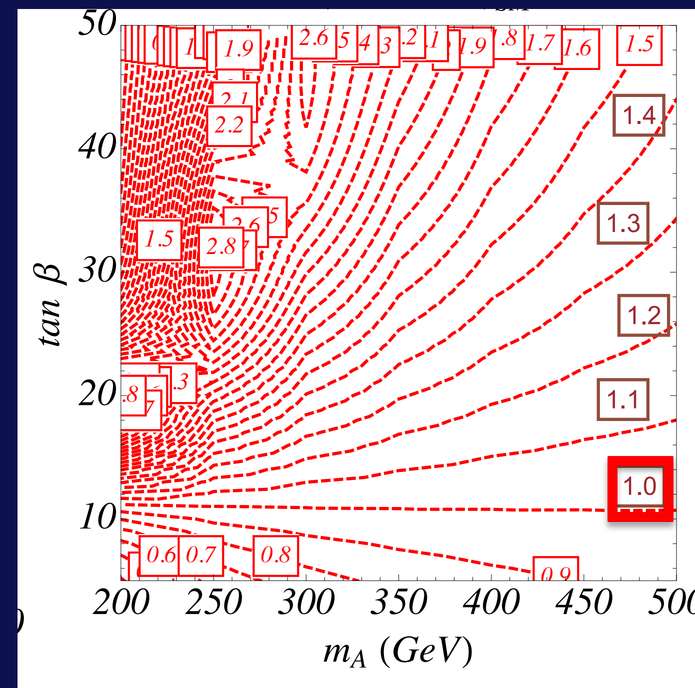
Higgs decays into gauge bosons mostly determined by bottom decay width

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

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

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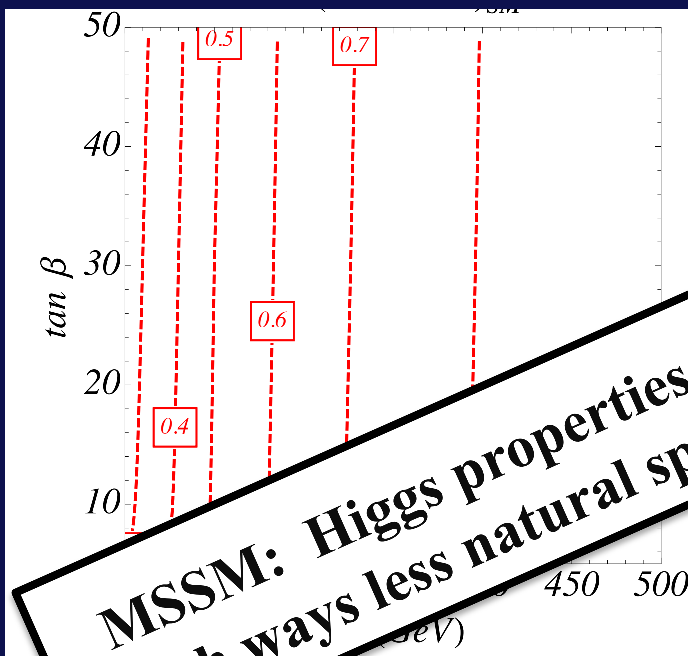
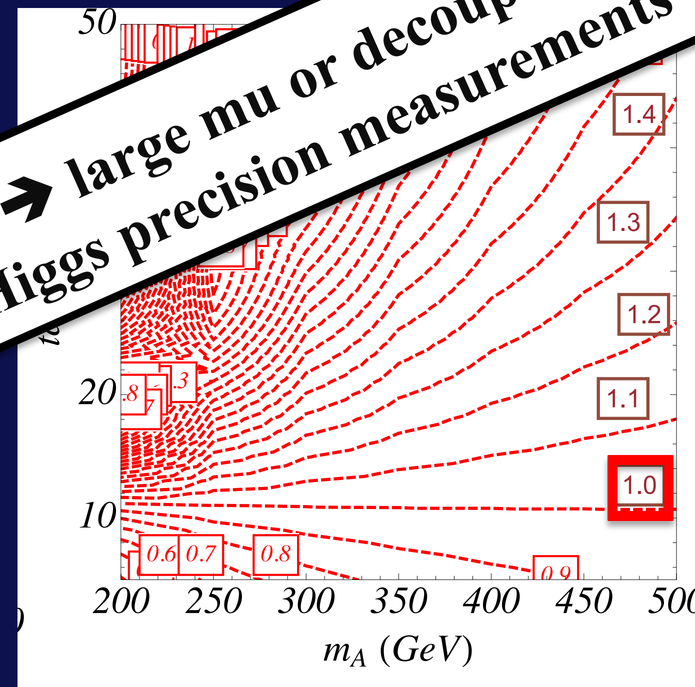


Sizeable μ ~ 2 M_{SUSY}



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

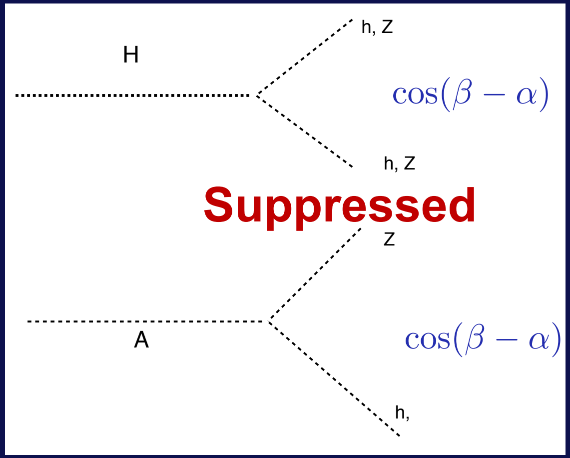
M.C., I. Low, N. Shah, Wagner'13

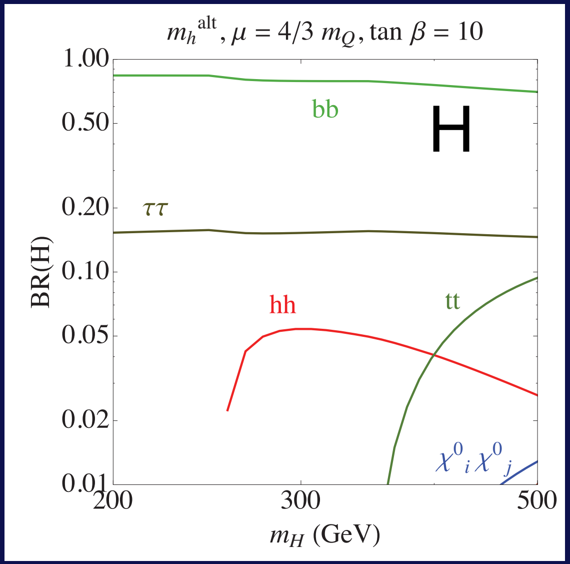
Searching for Heavy Higgs Bosons
- A variety of decay Branching Ratios -

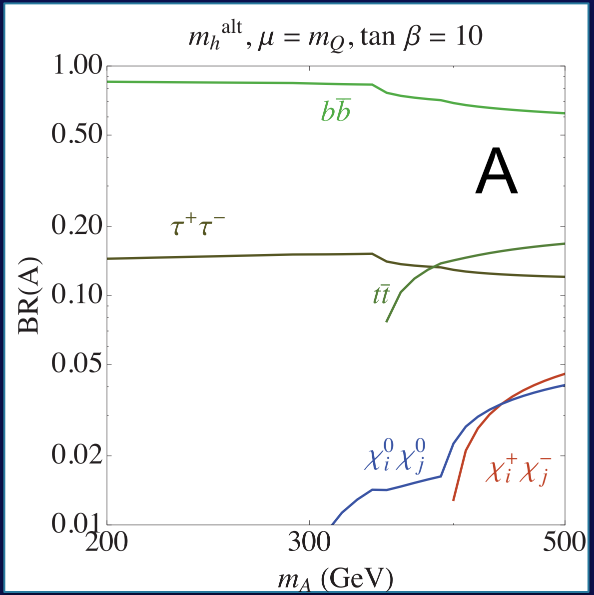
Craig, Galloway, Thomas'13; Su et al. '14, '15; M.C, Haber, Low, Shah, Wagner.'14

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

Alignment







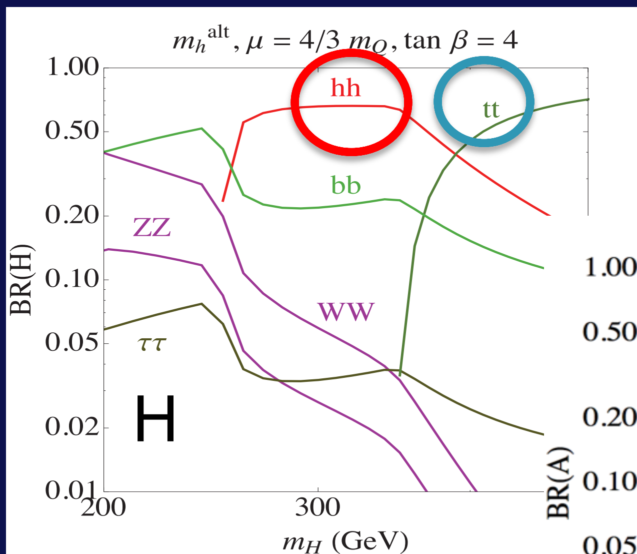
Sizeable tanβ ➔ very close to alignment, dominant bottom and tau decays;

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

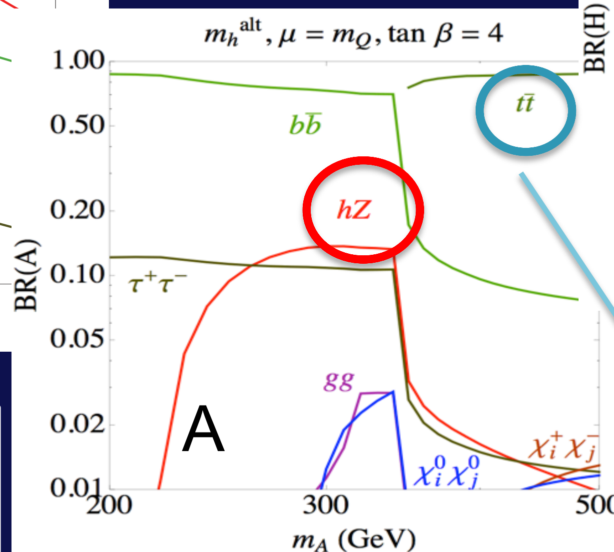
Production mainly via large bottom couplings: bbH

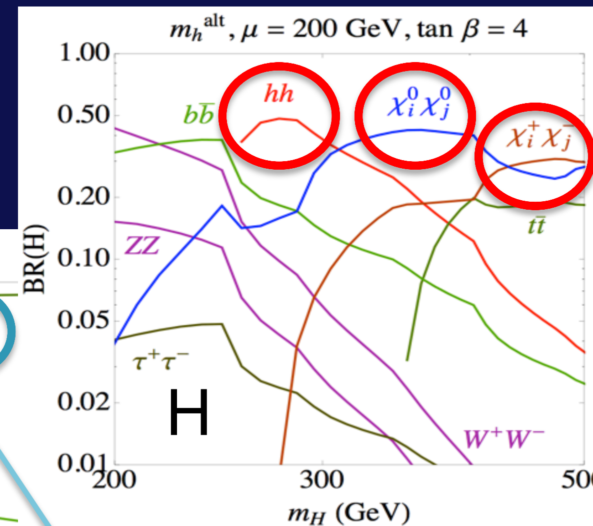
Searching for Heavy Higgs Bosons
- A variety of decay Branching Ratios -

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



Departure from Alignment





Precision Higgs constraints become important

Very challenging search

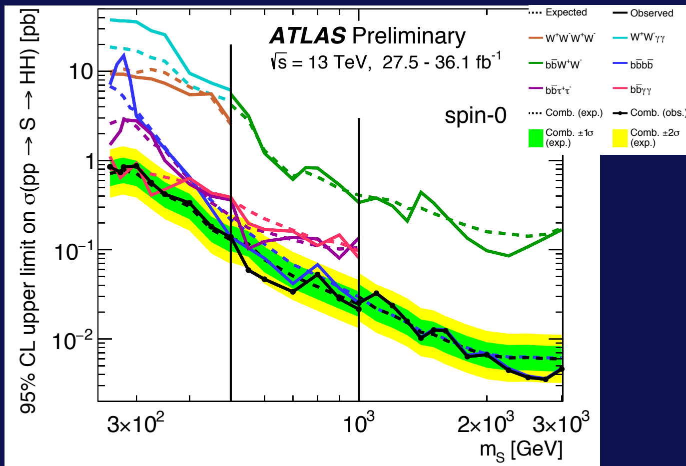
Smaller tanβ ➔ some departure from alignment,
H➔ hh, WW, ZZ and tt (also (A ➔ hZ, tt) become relevant.

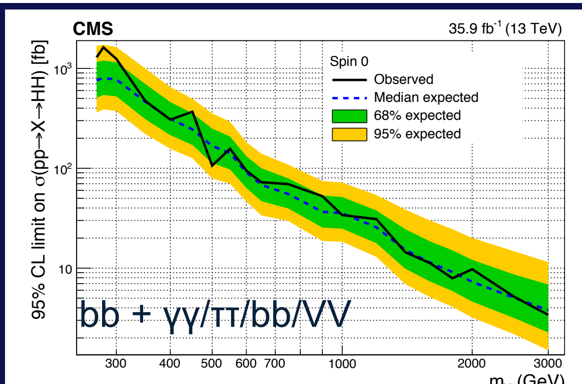
Production mainly via top loops in gluon fusion

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

Many ongoing A/H boson searches at LHC

CMS summary on H→hh searches

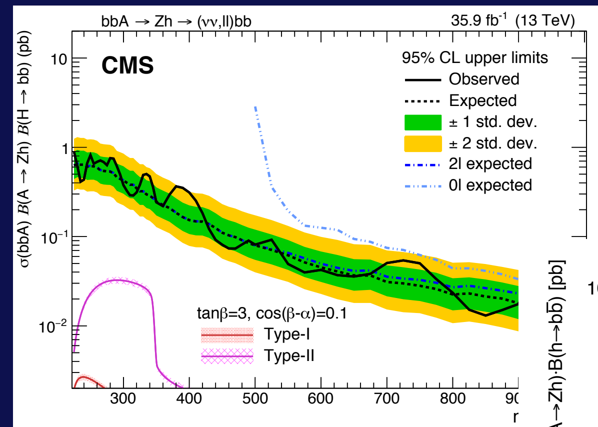




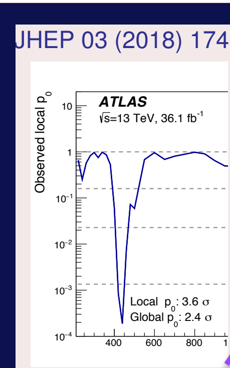
- Resonant Production

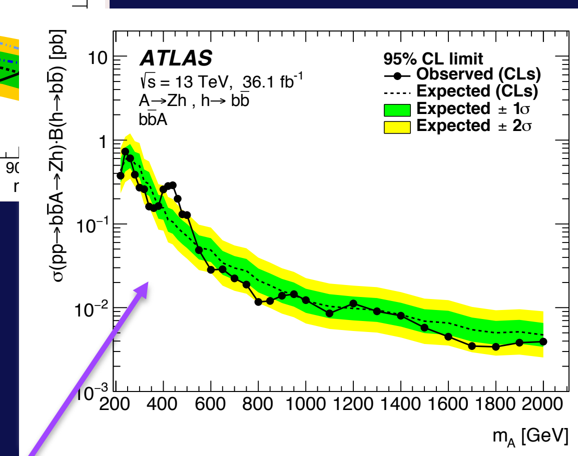
Upper limit between 4 fb and 1 to 2 pb

ATLAS/CMS, with A → Zh and h → bb



From b-quark Associated production



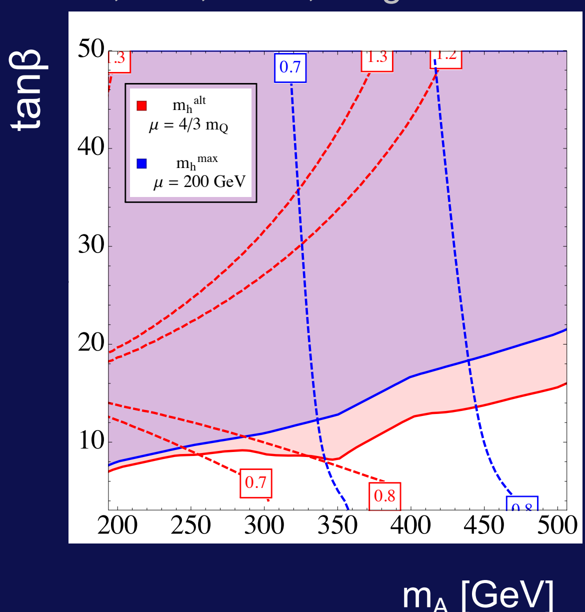


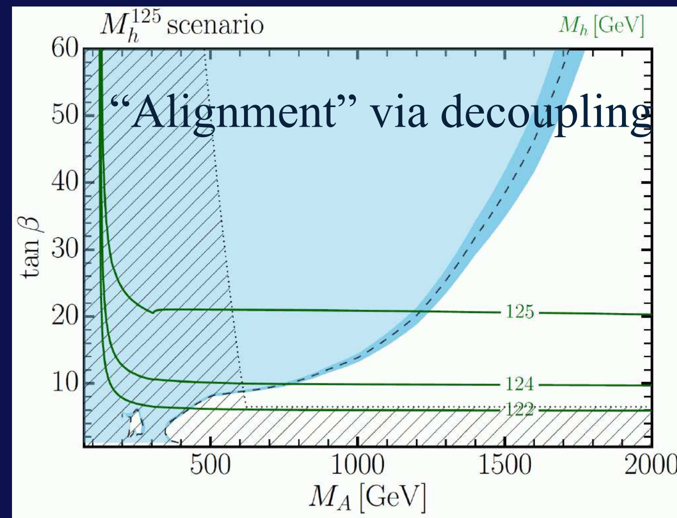
- Mild excess of events is observed around 440 GeV, mainly di-muon channel in the resolved category with 3+ *b*-tags.
- Local significance of this excess with respect to the background-only hypothesis is 3.6 σ.
- Global significance, accounting for the look-elsewhere effect is estimated to be 2.4 σ.

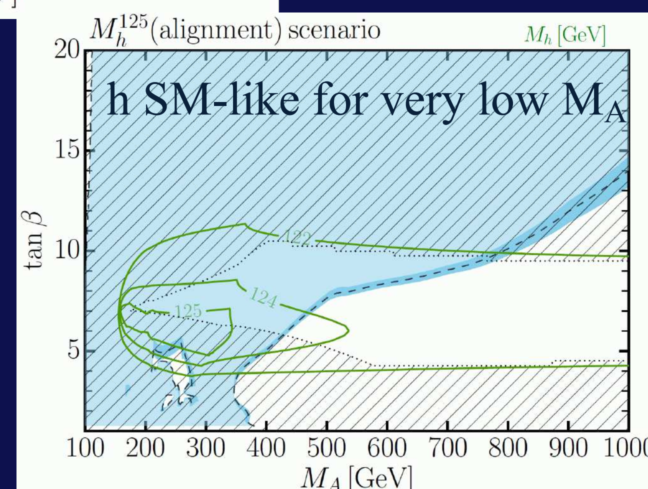
Complementarity between Higgs precision and A/H Searches

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

M.C, Low, Shah, Wagner + Haber







e. g. New benchmarks

Bahl et al. '18

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

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

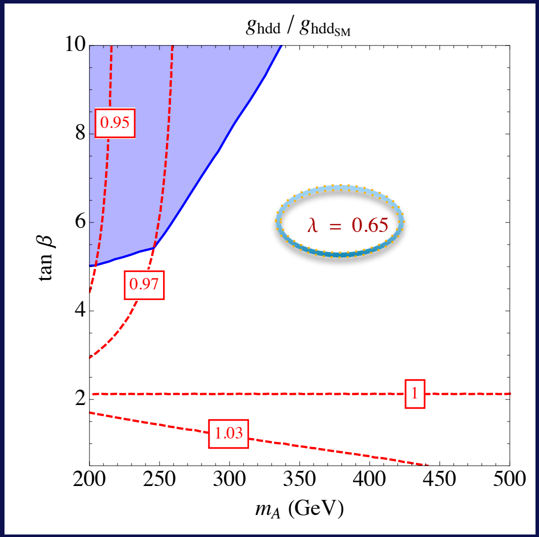
$$M_S^2(1,2) \simeq \frac{1}{\tan\beta} \left(m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2\beta + \delta_{\tilde{t}}\right)$$

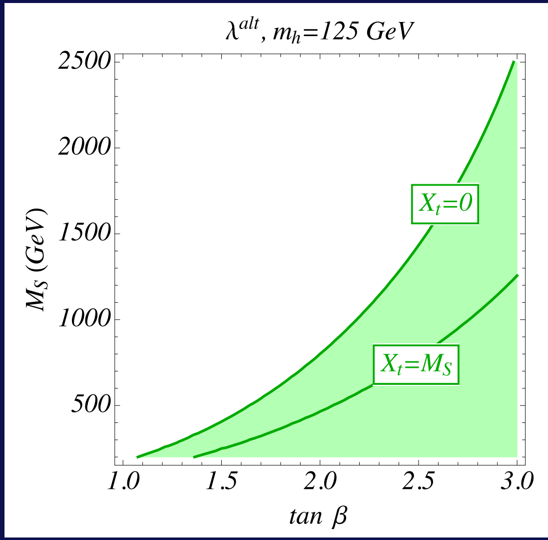
Last term from MSSM; small for moderate/small μA_t and small $\tan\beta$

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

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

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

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

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

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

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

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

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

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: $2\, m_{hS} < M_H$
- 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%)

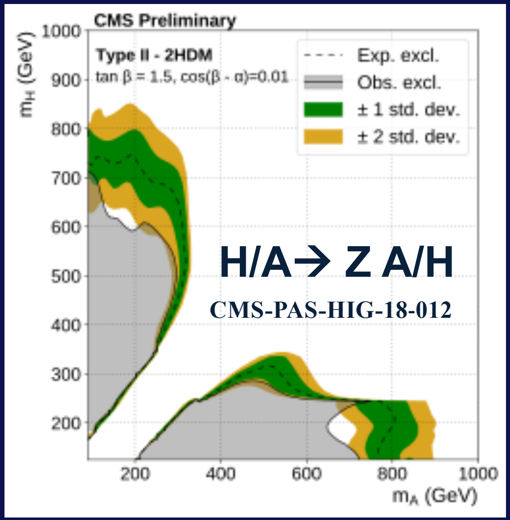
-- Other relevant decays: H → hh_S and A → Zh_S (20% to 50%, dep on mass)

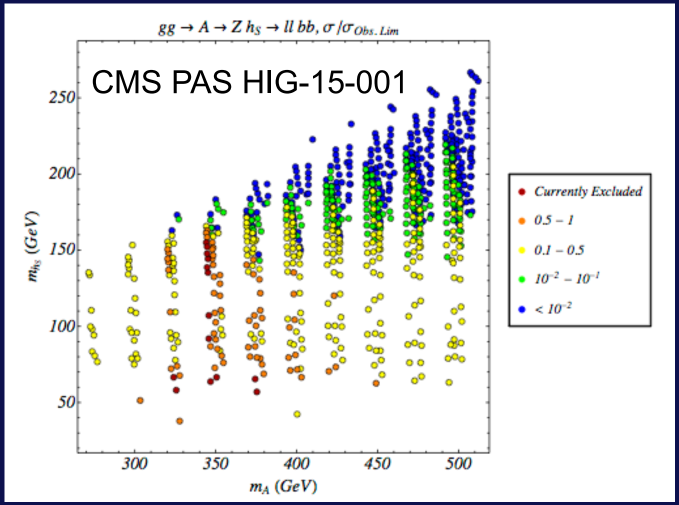
H → hh and A → hZ decays strongly suppressed due to alignment

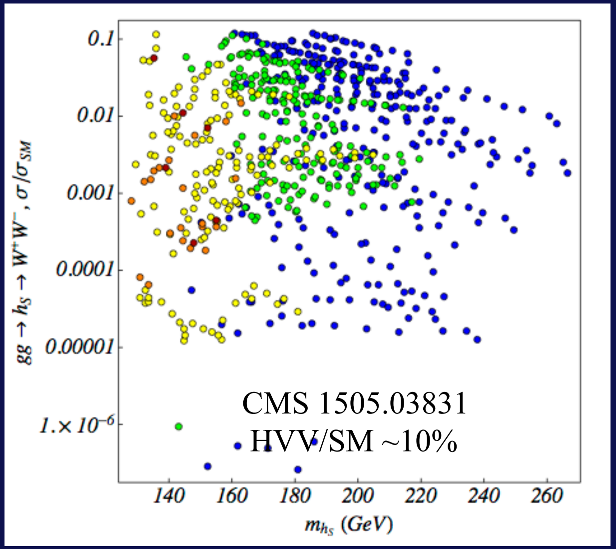
Others: H →hs hs; H→As Z; A→As hs; A→As h of order 10% or below

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







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

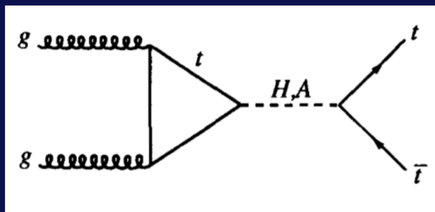
- **Promising H→ h h_S channels with h_S→ bb or WW (4b's or bb WW)**

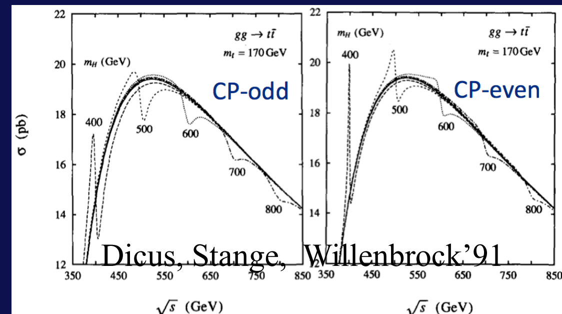
  Searches for H → ZA or A→ ZH should replace Z by h_{125} (Di-Scalar Search)

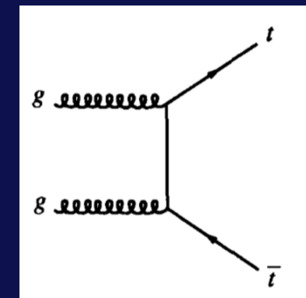
- Channels with missing energy: A → h a_s; H → Z a_s with a_s → Dark Matter

The challenging A/H ➔ tt channel: Interference effects

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





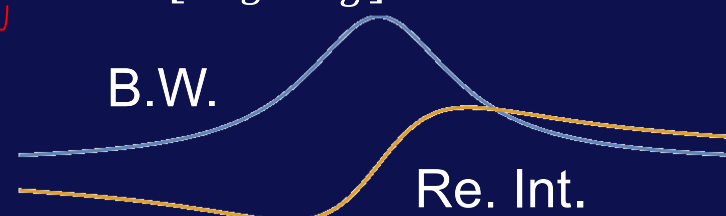


$$A_{sig} = c_{sig}\frac{\hat{s}}{\hat{s}-m^2+i\,\Gamma m} = c_{sig}\,\mathrm{P}(\hat{s})$$

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

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

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



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

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

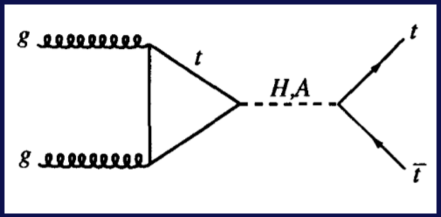
- Background real
- Re. Int.– from the real part of the propagator:

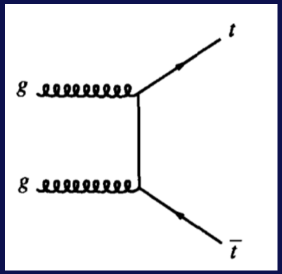
at parton level no contribution to the rate
➔ shift the mass peak. [When convoluting with PDF, may generate residual contribution to signal rate]

See also recent work by Craig, D'Eramo, Draper, Thomas, Zhang; Jung, Sung, Yoon; Gori, I.-W. Kim, Shah, Zurek

The challenging A/H → tt channel: Interference effects

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





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

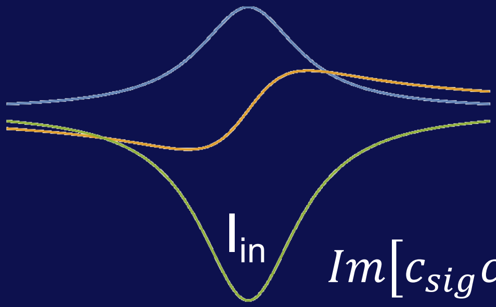
$$A_{bkg} = c_{bkg}\ \text{(slowing varying function of } \hat{s}\text{)}$$

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

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

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

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

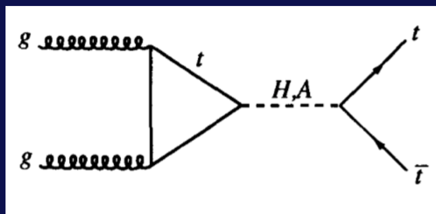


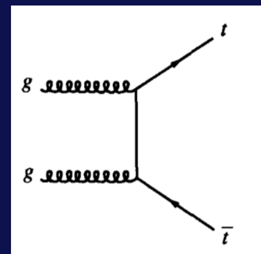
Im. Int.–from the imaginary part of propagator

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

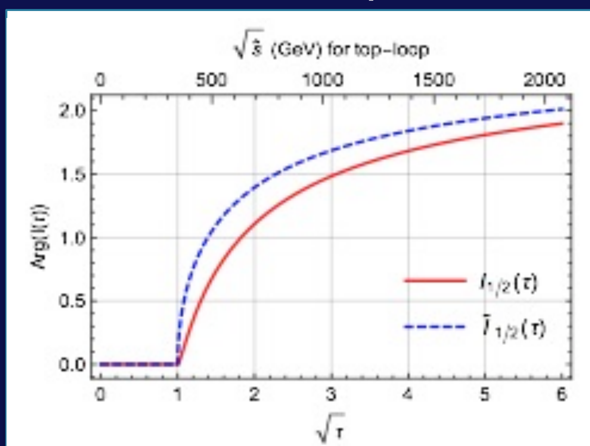
When phase $\delta_{sig}-\delta_{bkg}$ (strong phase) is none-zero, there is a new interference effect that cannot be neglected,

The challenging A/H ➔ tt channel: Interference effects

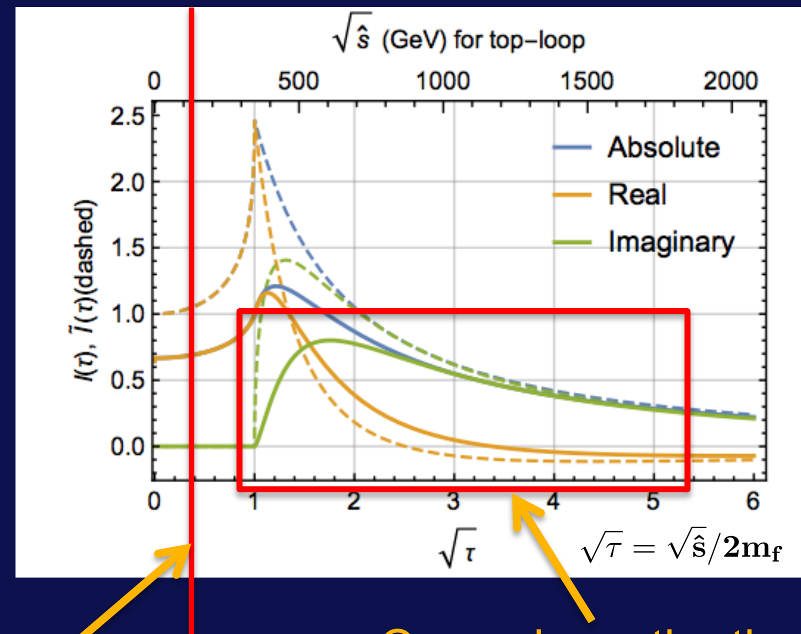




Phase of the loop function



Triangle loop function



SM Higgs
real & slowly varying

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

Background real

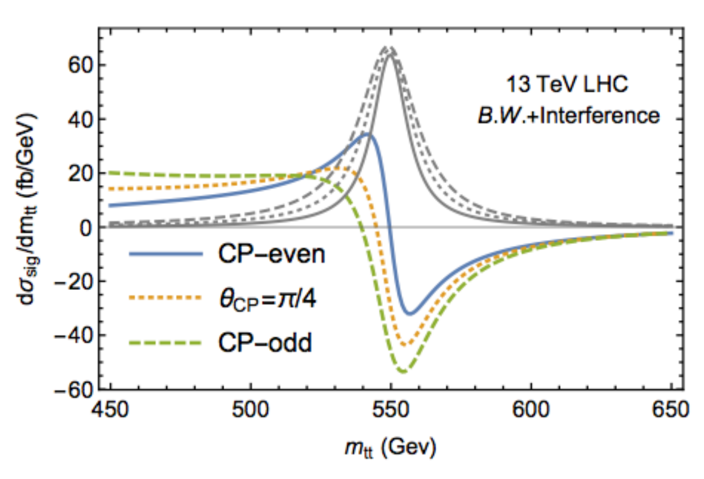
Real Interference from the real part of the propagator and real part of loop function (shifts the mass peak; no contribution to the signal rate besides residual effect of PDF's)

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

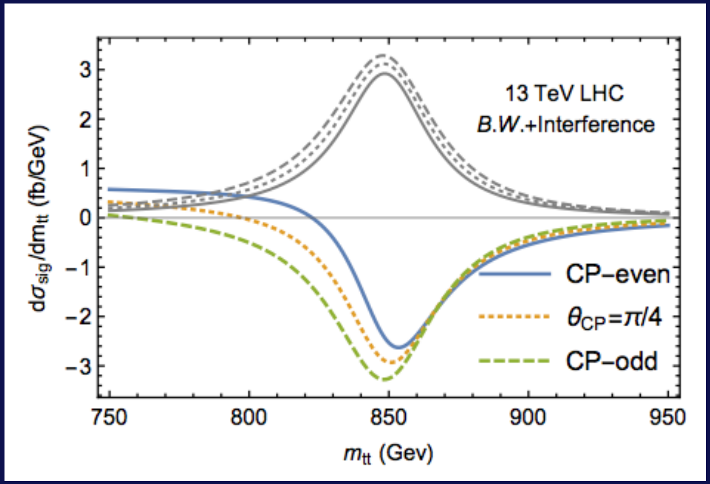
Special Line-shapes examples with one (pseudo) scalar

M.C., Liu '16

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



Interferences proportional to the real & imaginary part of the propagator are comparable in size



Interferences dominantly from the piece proportional to the imaginary part of the propagator, hence the pure dip structure

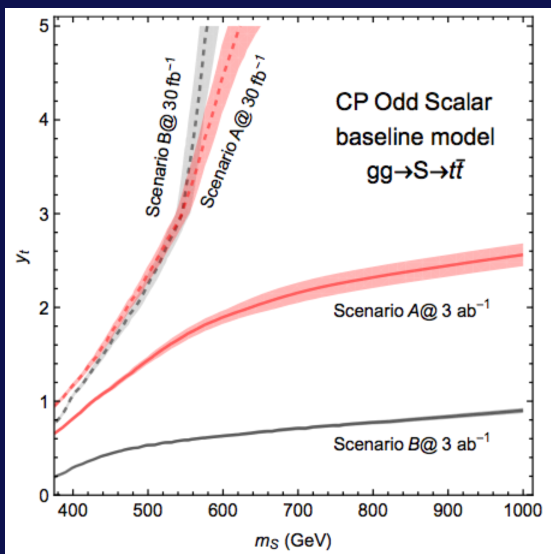
Searches not designed/optimized for bump-dip/ dip structure.
Smearing effects flatten the dips and bumps, making it harder.

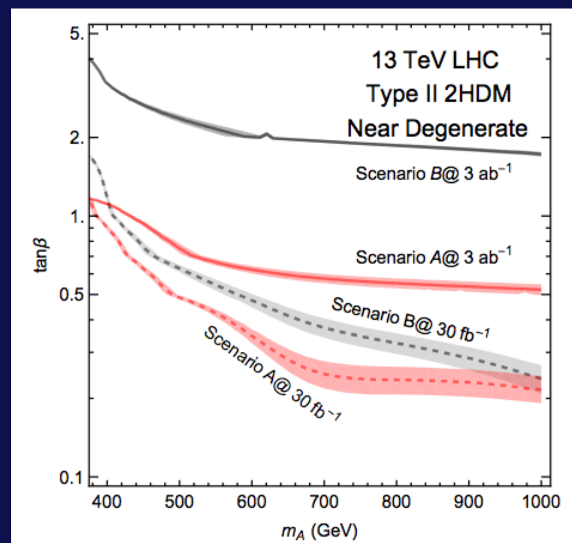
Impact of interference effect in A/H → tt at the LHC

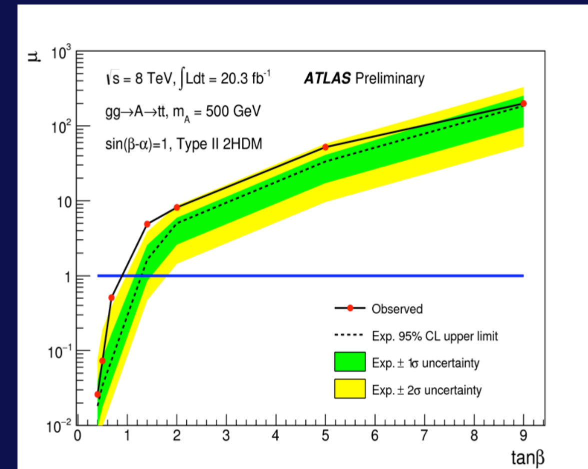
Projections for A/H → tt in Type II 2HDM

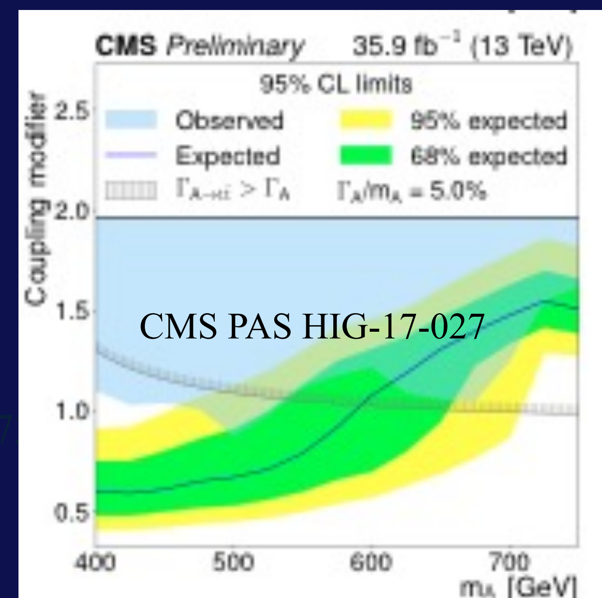
	$\Delta m_{t\bar{t}}$	Efficiency	Systematic Uncertainty
Scenario A	15%	8%	4% at 30 fb^{-1}, halved at 3 ab^{-1}
Scenario B	8%	5%	4% at 30 fb^{-1}, scaled with $\sqrt{L}$

M.C.,Zhen Liu









CMS PAS HIG-17-027

First interference studies at ATLAS and CMS

The largest deviation for m_A = 400 GeV and Γ_A/m_A = 4% local significance of 3.5 ± 0.3 σ, when accounting for the look-elsewhere the significance is 1.9 σstandard deviations. This excess is largely driven by the dilepton channel.

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 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^2_S in terms of the original quartic couplings & the vevs

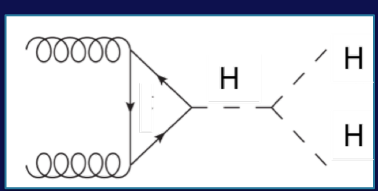
Parameters in the potential can be traded by

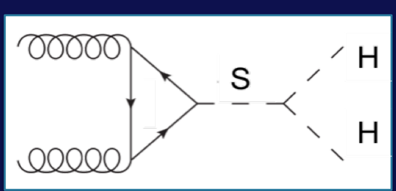
m_H =125 GeV, v=246 GeV

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:

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





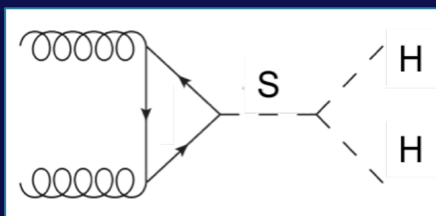
$$\lambda_{HHH} = -\frac{m_H^2}{2\tan\beta\, v}\left(\tan\beta\cos^3\theta - \sin^3\theta\right),$$

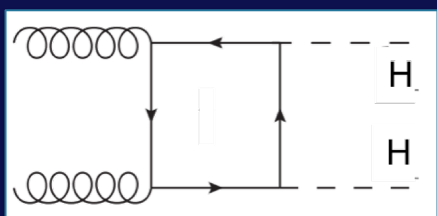
$$\lambda_{SHH} = -\frac{m_H^2}{2\tan\beta\, v}\sin 2\theta(\tan\beta\ \cos\theta + \sin\theta)(1 + \frac{m_S^2}{2m_H^2}).$$

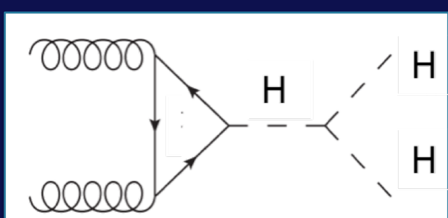
Interference Effects in Di-Higgs Production: gg → S → hh

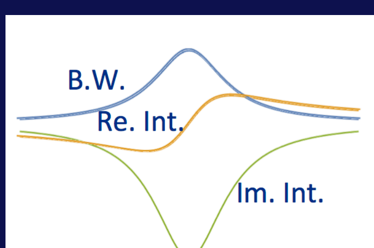
Models with additional singlets open a door for a strong first order phase transition

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









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

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

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

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

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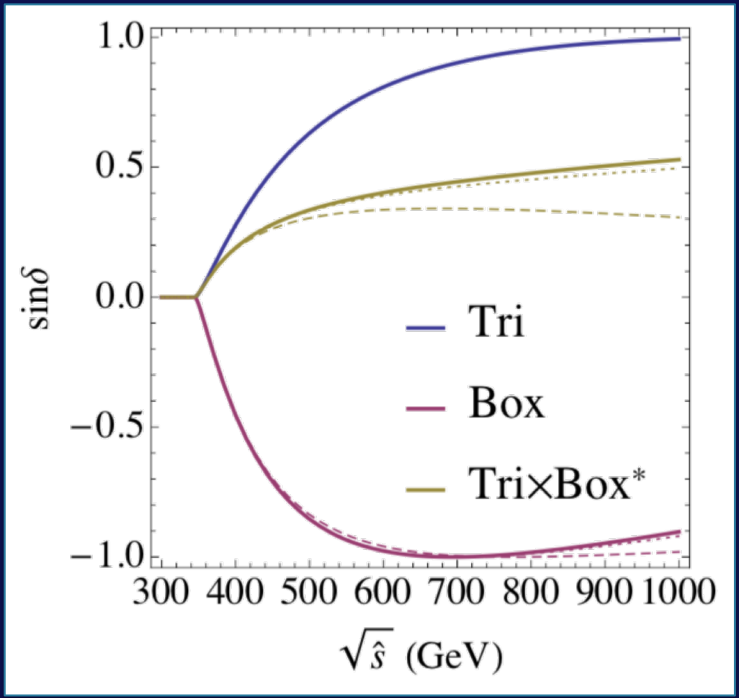
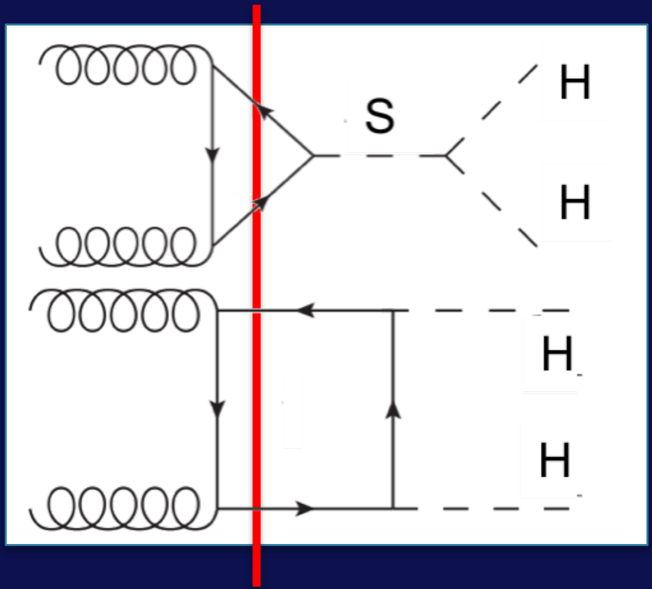
Strong phase in the loop functions

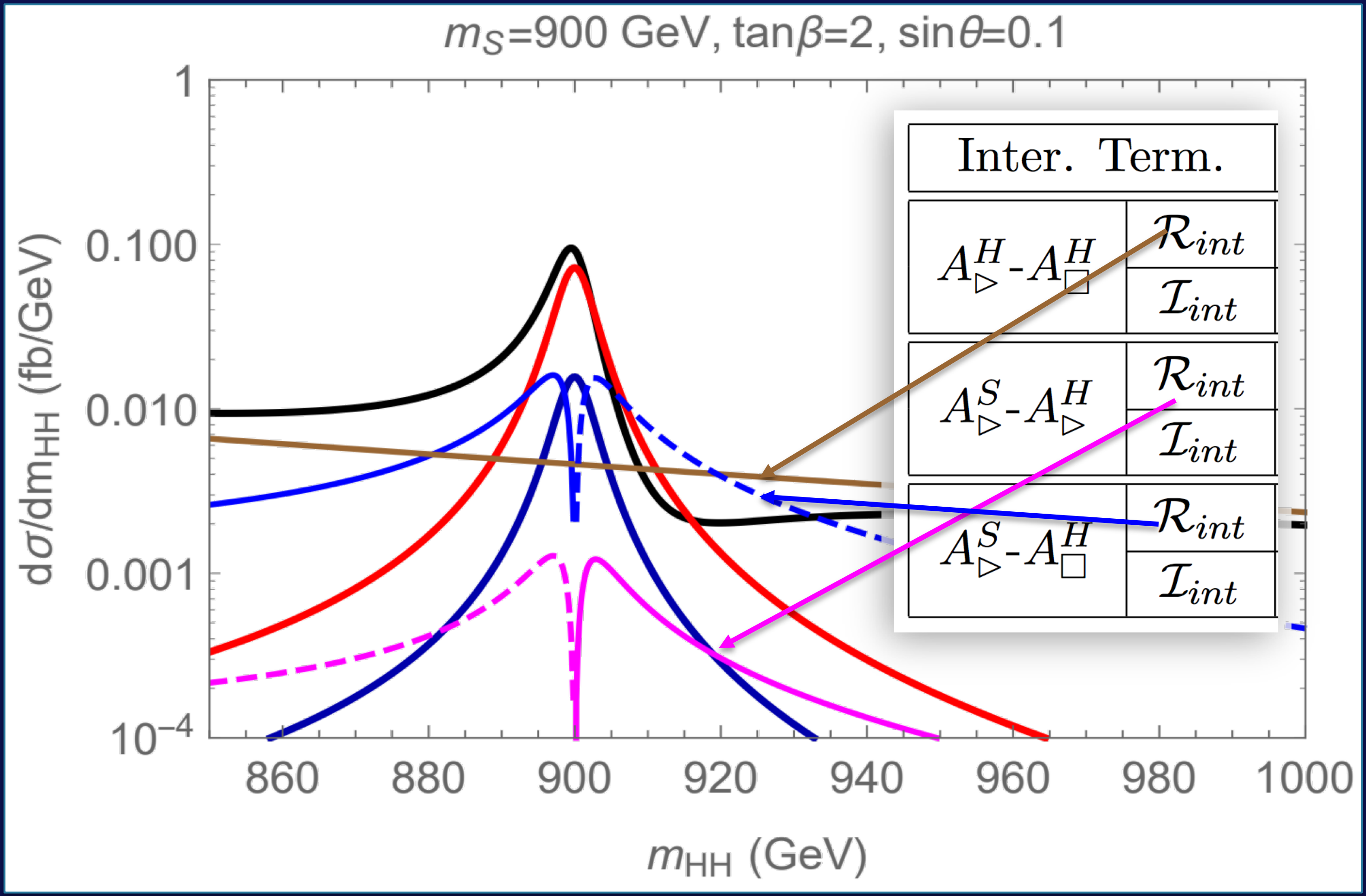




The solid, dotted, and dashed curves correspond to scattering angles of 0, 0.5 and 1, respectively

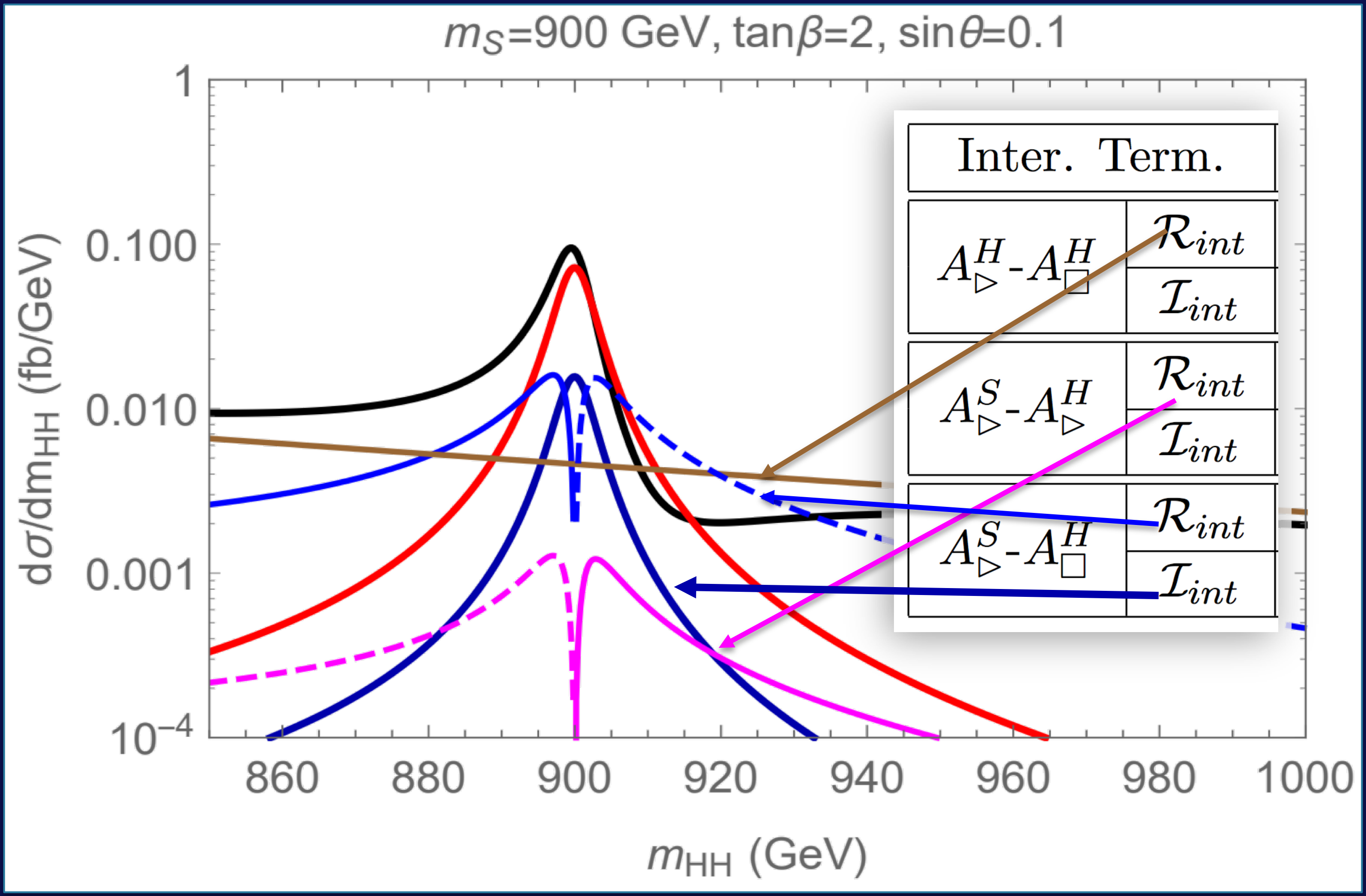
Relative strong phase (yellow curve) allows for a non-vanishing interference effect between the singlet resonance diagram and the SM box diagram.

Interference Line shape



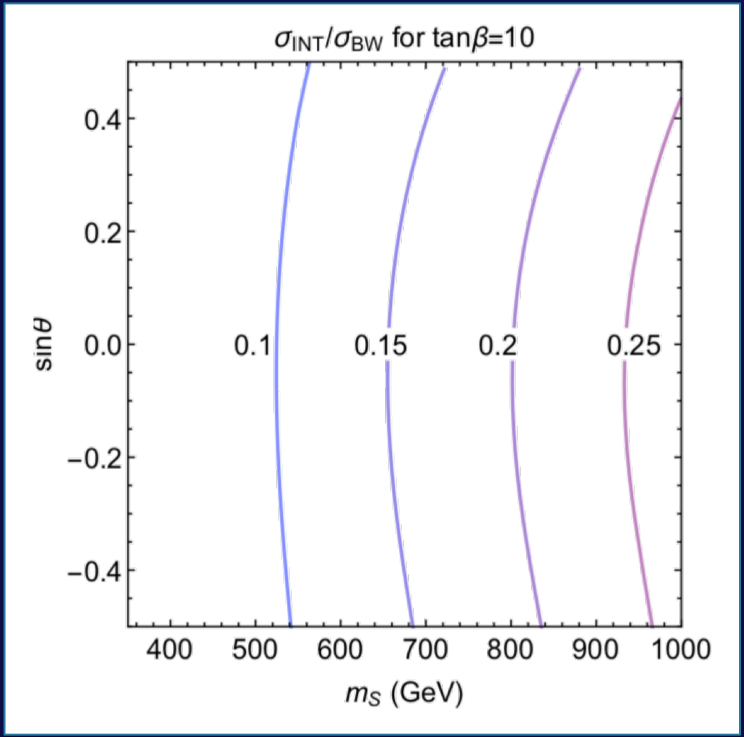
Logarithmic to see other components;
Dashed represent destructive interference;
Dark blue, unique on-shell constructive interference

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

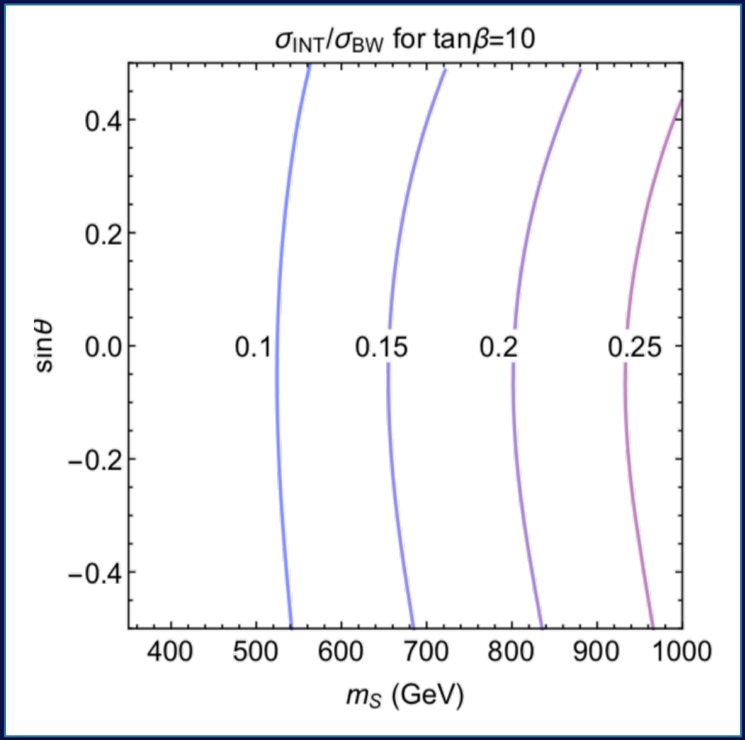


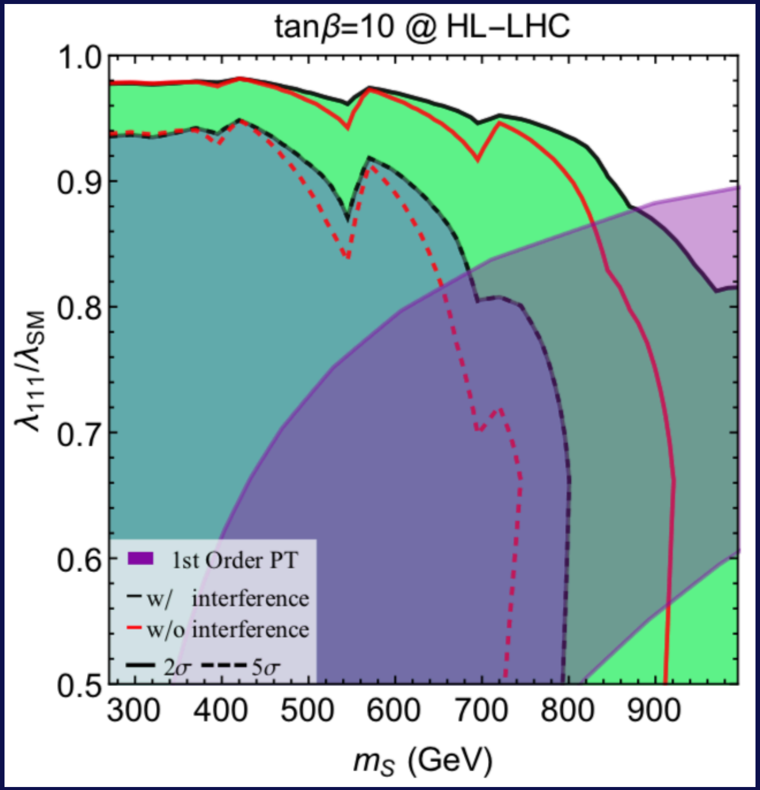
Relative size of the on-shell interference effect w.r.t. the resonant BW signal, averaged over scattering angle [-0.5,0.5]

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

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)

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

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

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

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

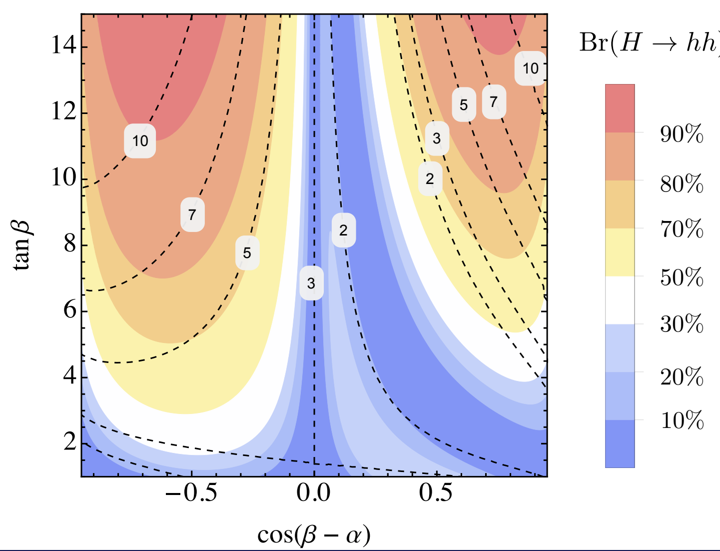


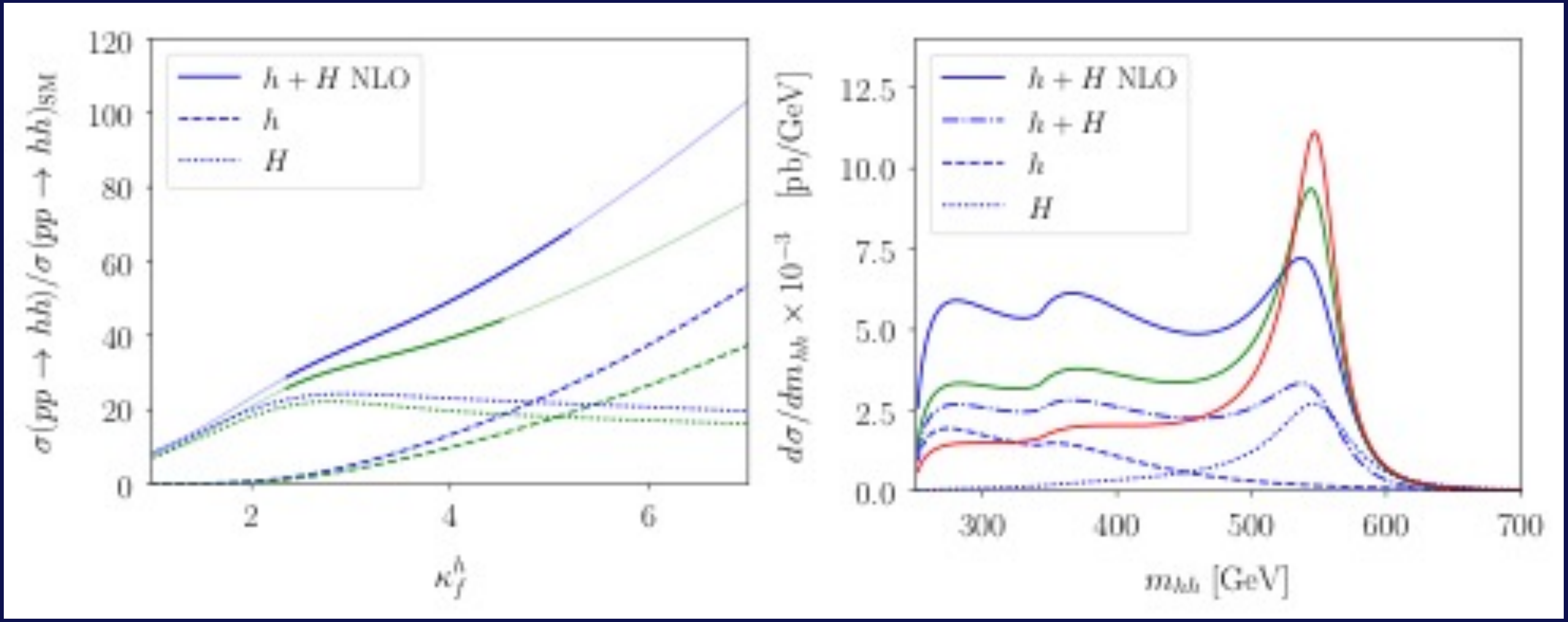
FIG. 1: The color coding shows the dependence of $\mathrm{Br}(H \to hh)$ on $c_{\beta-\alpha}$ and t_β for $M_H = M_{H^\pm} = 550$ GeV, $M_A = 450$ GeV. The dashed contours correspond to constant $|\kappa_f^h|$ for $n_f = 1$.

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

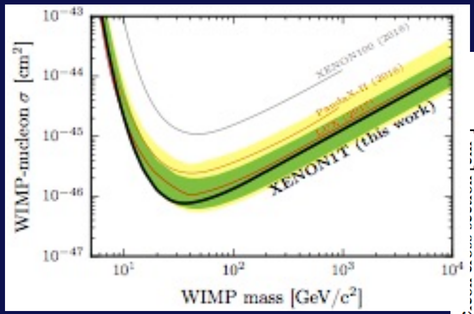


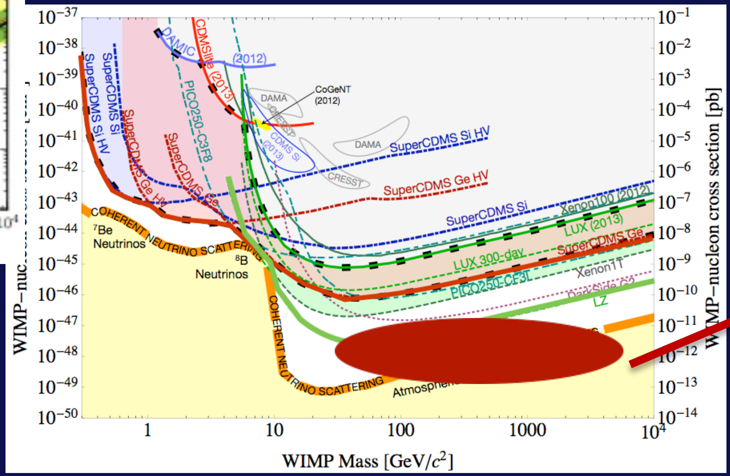
Cross section for Higgs pair production in units of the SM prediction as a function of κ_{hf} for $c(\beta-\alpha) = -0.45$ (-0.4) and MH = $M_{H\pm}$ = 550 GeV, M_A = 450 GeV in blue (green) at $\sqrt{s}$ = 13 TeV

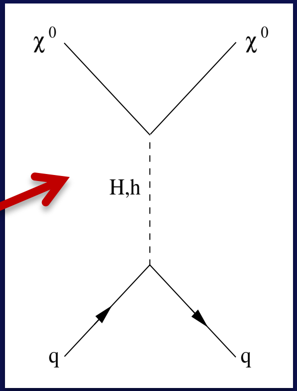
Invariant mass distribution for the different contributions to the signal with $c(\beta-\alpha) = -0.45$ and κ_{hf} = 5 (blue), κ_{hf} = 4 (green) and κ_{hf} = 3 (red) at $\sqrt{s}$ = 13 TeV, respectively.

Dark Matter Direct Detection

Starting to probe the Higgs portal







Close to Alignment (MSSM)

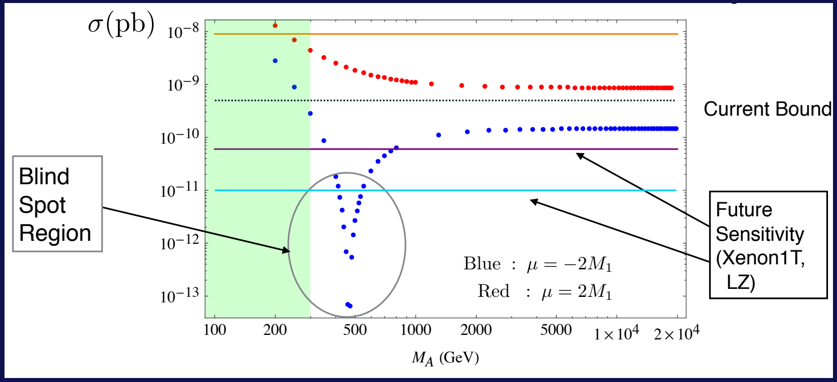
$$\sigma_p^{SI} \sim \left[(F_d^{(p)} + F_u^{(p)})(m_\chi + \mu \sin 2\beta)\frac{1}{m_h^2} + \mu \tan\beta \cos 2\beta(-F_d^{(p)} + F_u^{(p)}/\tan^2\beta)\frac{1}{m_H^2} \right]^2$$

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

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

Still room for a SUSY WIMP miracle

Huang, Wagner, '15



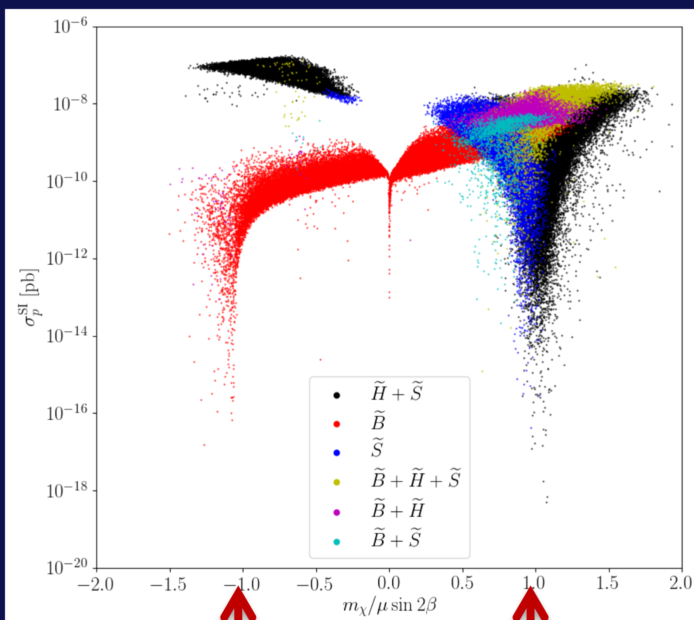
Blind Spots in Direct DM detection in the NMSSM

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

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

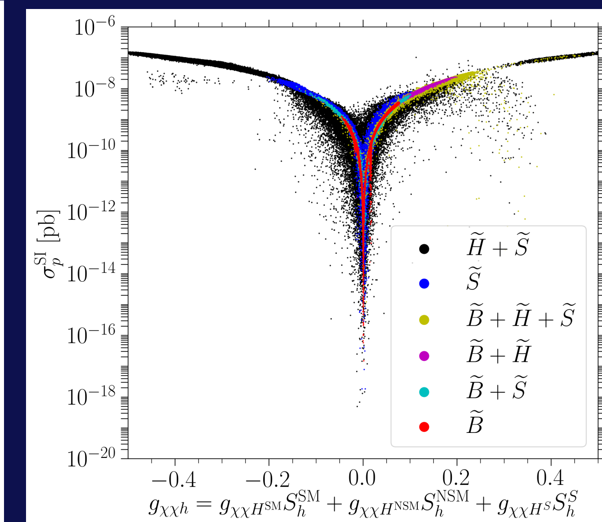
$$S_{h,s} \approx \frac{-2\lambda v \mu \epsilon}{(m_h^2 - m_{h_S}^2)}$$

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 Singlino-Higgsino or Bino-Higgsino admixtures.

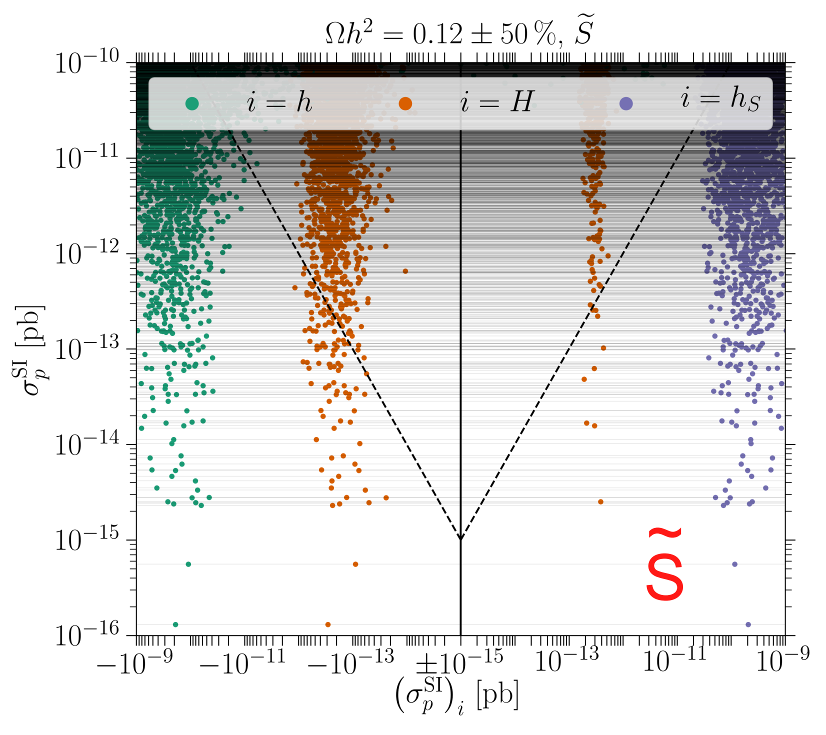
assumed 50% composition

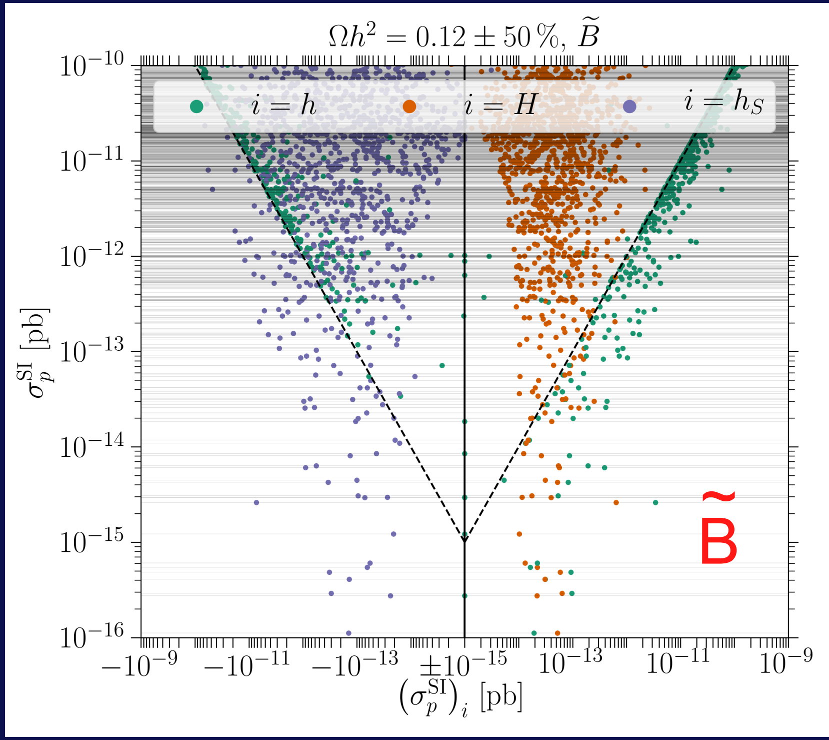
Baum, M.C. Shah, Wagner '18

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 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 perturbavity 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

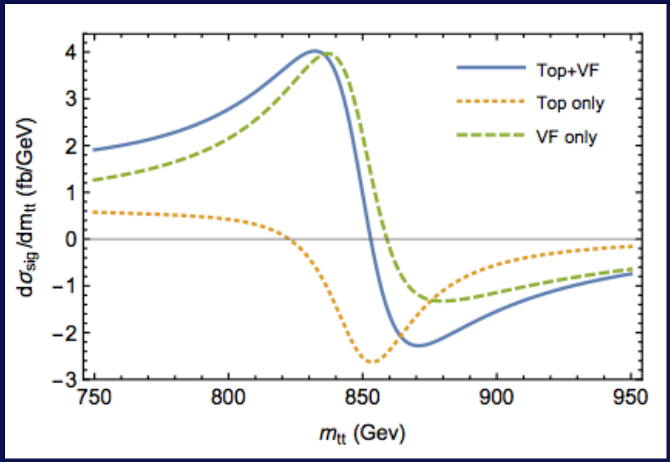
- Novel on-shell info on Higgs total width & light quark Higgs couplings
- Enhance LHC sensitivity to simple models with a strong FOPT
- Needed in scalar resonant searches above the top threshold

Extras

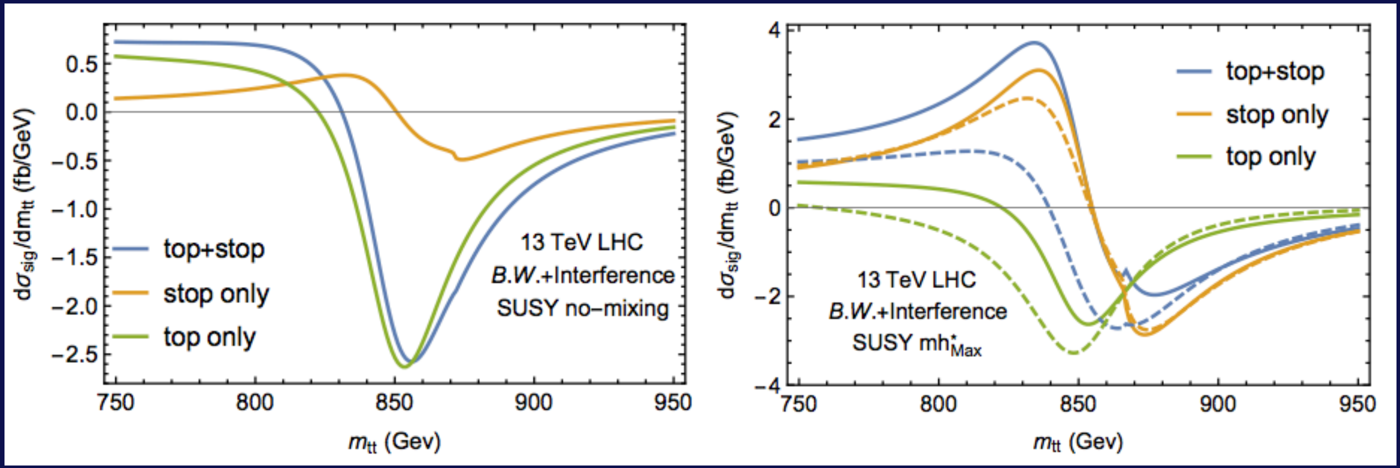
Special Line-shapes examples with additional BSM particles

M.C., Liu '16

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

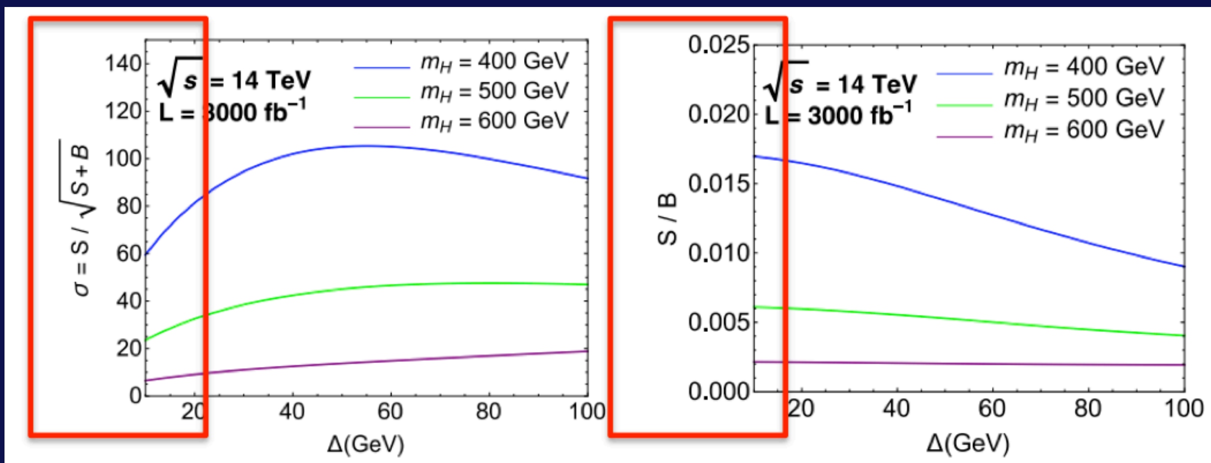


Stops in the loop function:
Zero L-R stop mixing➔ small interference (dip-bump structure), top quark dip structure prevails
Large L-R mixing ➔ dominant contribution, dip-bump structure prevails



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



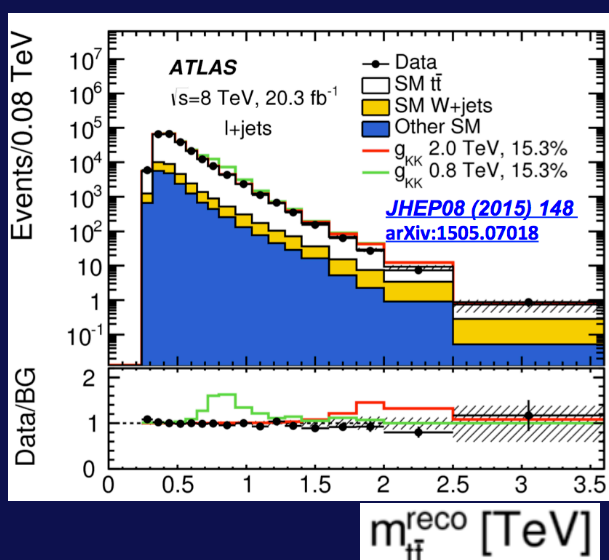
After detector smearing and reconstruction:

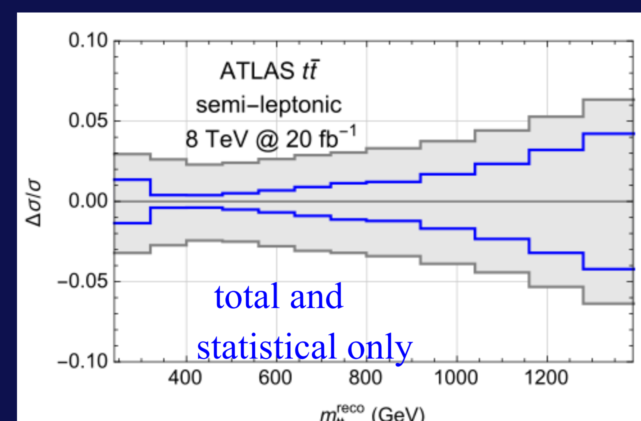
Statistically promising

Systematically challenging

Craig et al ‘15

Using Atlas 8 TeV Analysis

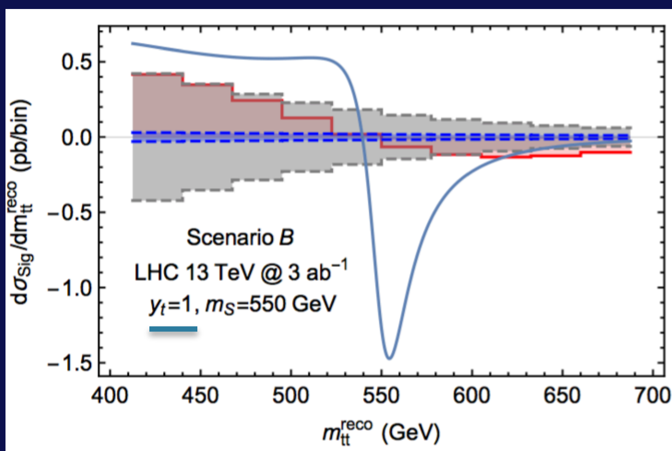


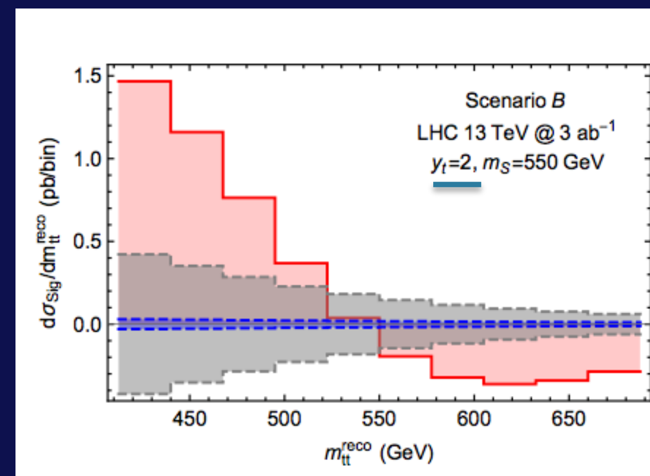


Prospects for searches in A/H→ tt : Benchmark Studies

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

Two Higgs Doublet models and a Theory of Flavor

- The Froggatt Nielsen mechanism: Effective Yukawa coupling

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

- New scalar singlet S obtains a vev: <S> =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

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

$$y_{\rm eff} = \epsilon^n y \qquad \epsilon = f/\Lambda$$

Issue: Scales undetermined

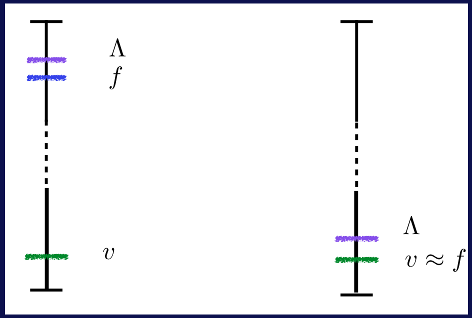
- How to define the scales? Can the Higgs play the role of the Flavon?

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

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

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

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

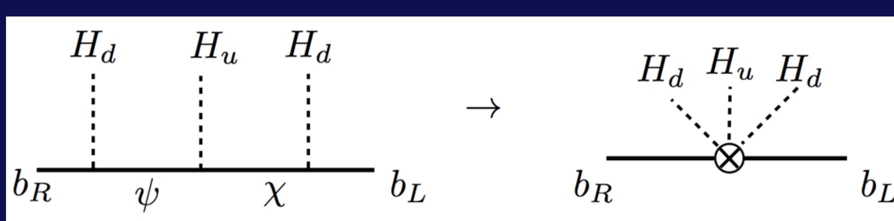
With effective Yukawa coupling: $y_i^{\rm eff} = \left(\frac{v_u v_d}{2\Lambda^2}\right)^{n_i} y_i$

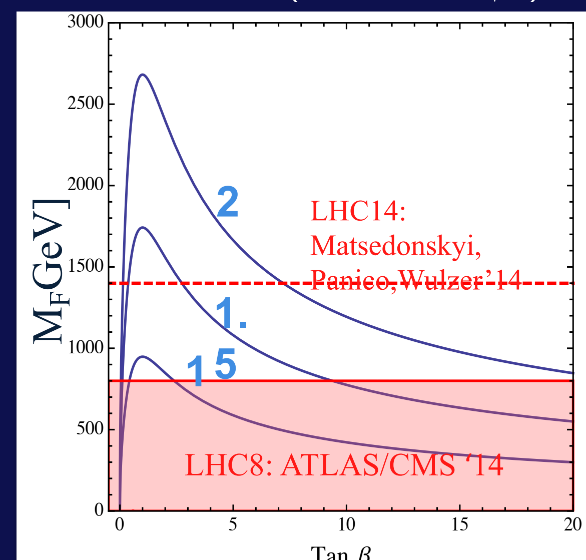
$$v^2 = v_u^2 + v_d^2$$
$$\tan\beta = v_u / v_d$$

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

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

$\overline{M} \equiv \sqrt{M_\eta M_\psi}$ $\bar{y} = (y_1 y_2 y_3)^{1/3}$ →





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

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

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

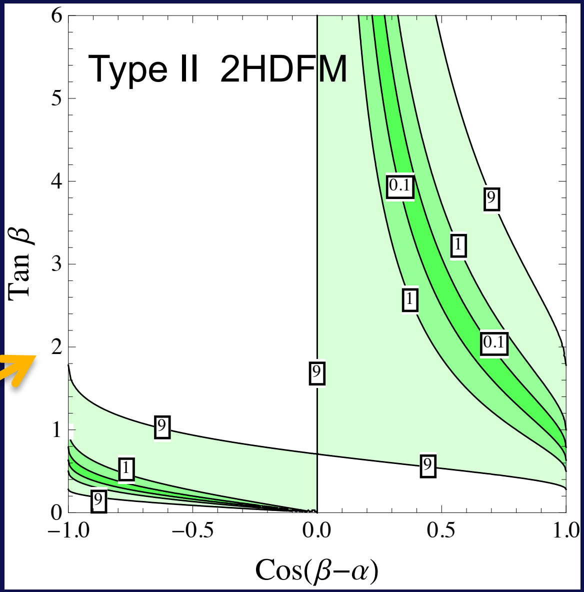
Higgs Production (at leading order) equivalent to a 2HDM type II

- Higgs coupling to the bottom (& charm) quarks

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

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

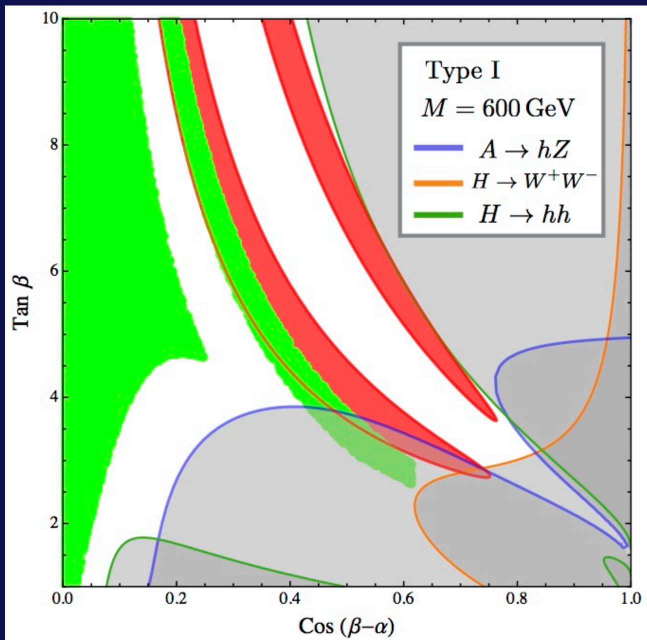
FCNCs at tree-level ⟷ Numerous Flavor constraints

Direct collider probes of heavy scalars ⟷ ATLAS and CMS searches

Benchmark scenarios to probe the model

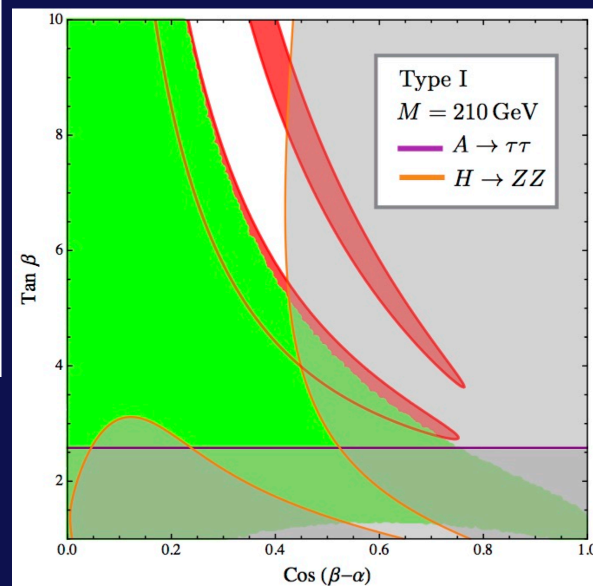
A predictive model with new Physics at LHC reach

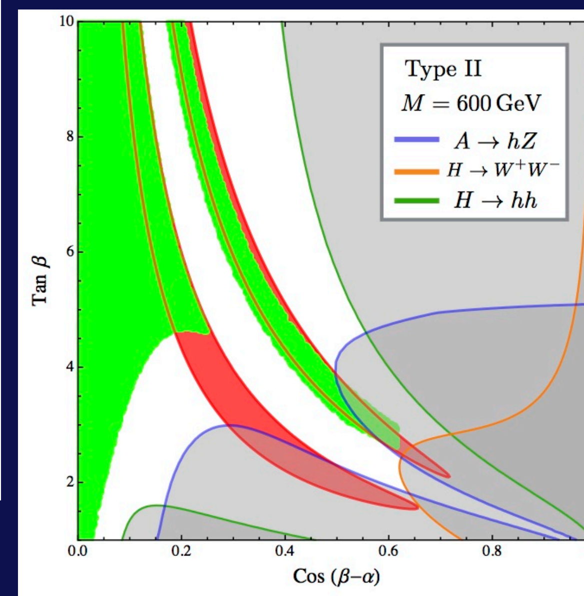
allowed regions beyond those in a 2HDM type I or II



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 phyiscs:
ε_K, Mixing in B_d and B_S system, b → s γ
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