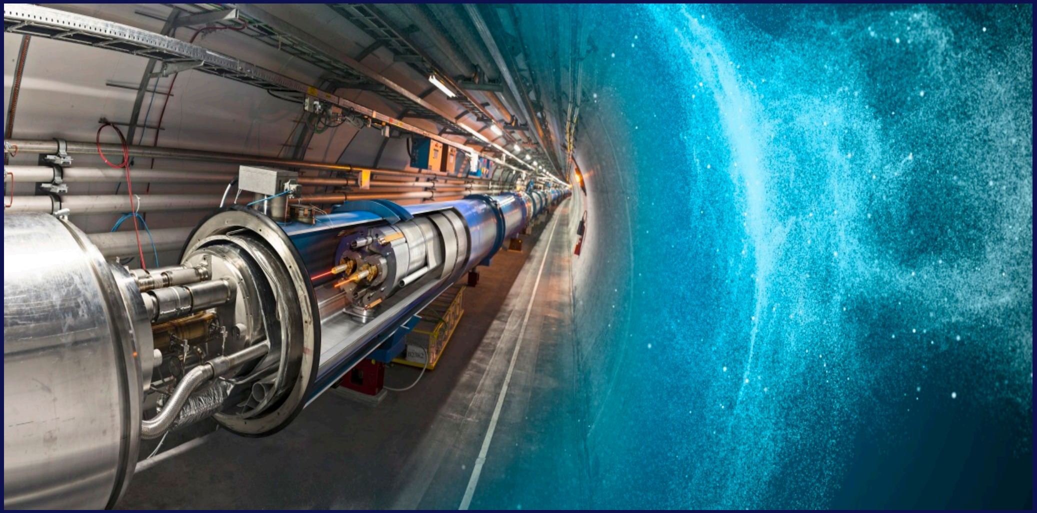
Particle Physics Unknows and the LHC



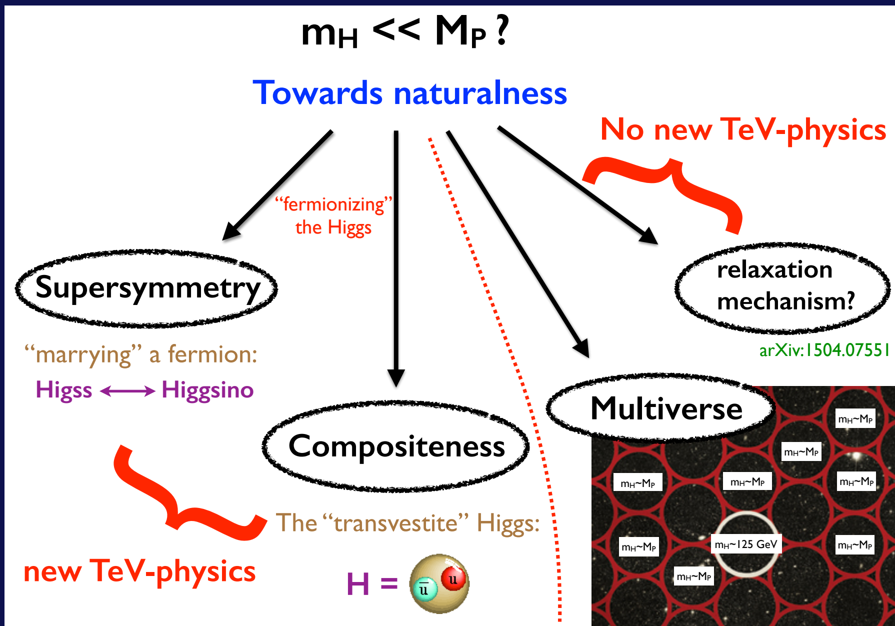
Marcela Carena

Fermilab and UChicago

Chicagoland Mini-Workshop on LHC Run II Analysis with Machine Learning

UChicago, January 15, 2018

New Physics Landscape after the Higgs Discovery



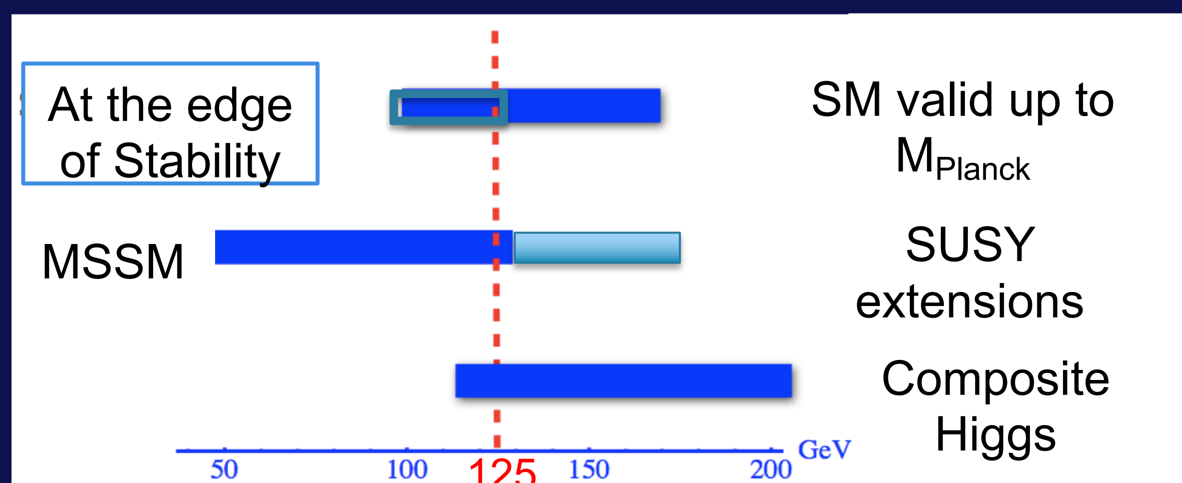
How far are we willing to go?

Under the Higgs lamp-post:

Composite

or SUSY

extensions



Big Particle Physics (and Cosmology) Questions
Require Big Ideas and Powerful Tools

- **The Higgs Mechanism**
- **Hierarchy of fermion Masses and Mixings**
- **Models of Neutrino Masses**

- **Dark Matter**
- **Baryogenesis/Leptogenesis**
- **Grand Unification**

What can be learned analyzing all the RUN II data?

What new tools/strategies (ML) may be required to get the most out of RUN II data?

The Higgs as a tool for Discovery: Exploiting the Higgs Connections

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

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

Flavor from the electroweak scale

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

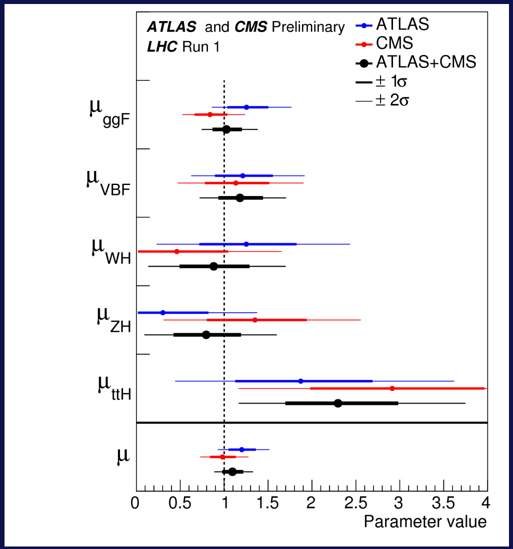
Higgs portals to Dark Matter

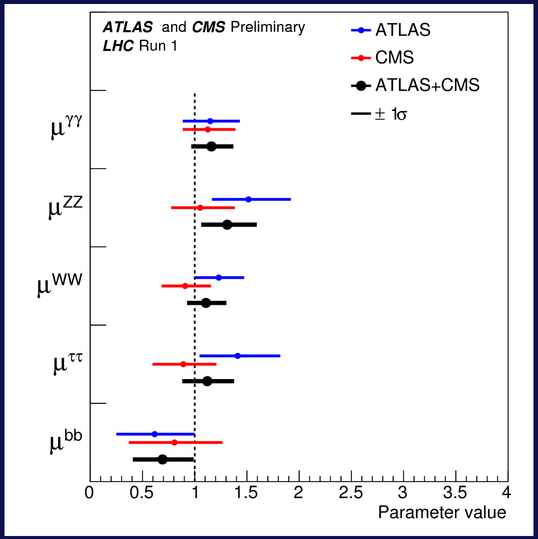
DM may predominantly couple to the SM particles through the SM Higgs. Extended Higgs sectors and/or Dark Higgs sectors (plus extended gauge symmetries) may play a role for DM and electroweak Baryogenesis

BSM alternatives can affect Higgs production & decay signal strengths

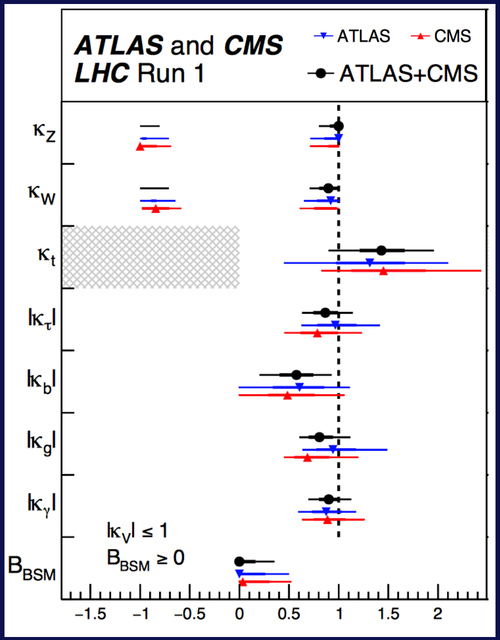
LHC RUN I Results

Higgs Properties in good agreement with SM predictions





Assuming no strict correlation between gluon and top couplings



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

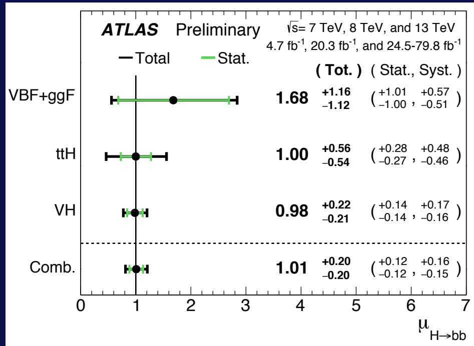
Coupling to fermions not fully established; Top & bottom couplings not directly observed

Higgs boson couplings measured to ~10-25% precision

Deviations from SM predictions quite possible

RUN 2 Results

New@ICHEP'18 : **Observation of H→bb**



Significance:
5.4σ observed
(5.5σ expected)

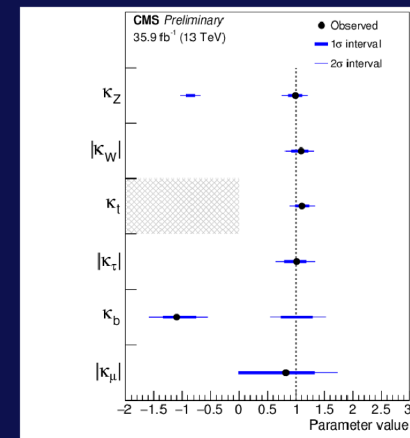
Observation of H → bb!!

Observation of H→ ττ

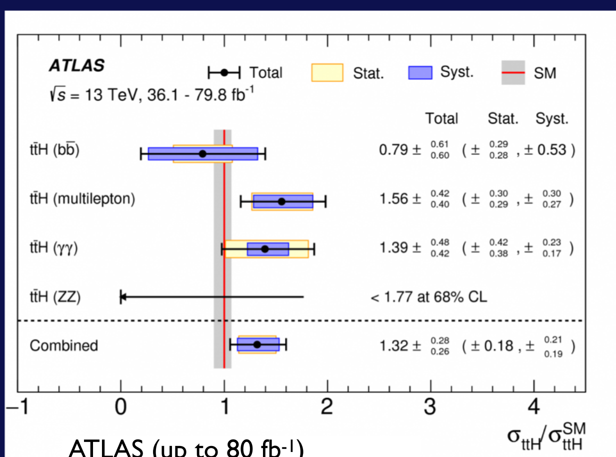
	CMS	ATLAS
$\mu_{\tau\tau}$	$1.09^{+0.15}_{-0.15}(\mathrm{stat})^{+0.16}_{-0.15}(\mathrm{syst})^{+0.10}_{-0.08}(\mathrm{th})^{+0.13}_{-0.12}(\mathrm{MCstat})^{*}$	$1.09^{+0.18}_{-0.17}(\mathrm{stat})^{+0.27}_{-0.22}(\mathrm{syst})^{+0.16}_{-0.11}(\mathrm{th})$
	Significance: **5.9σ** (5.9σ) observed (exp.)*	Significance: **6.4σ** (5.4σ) observed (exp.)*

Assuming no strict correlation between gluon & top couplings

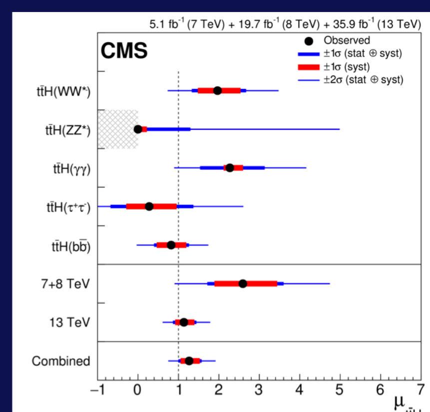
Consistency with SM



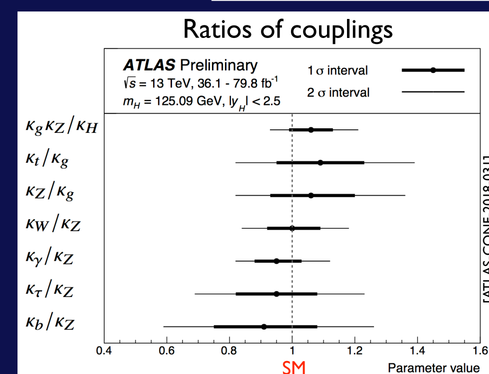
Observation of ttH production:
The Higgs boson reveals its affinity for the top quark



ATLAS (up to 80 fb⁻¹)
Run-2: **5.8σ** (4.9σ exp.)
Run-1+Run-2: **6.3σ** (5.1σ exp.)



CMS
Run-1+Run-2: **5.2σ** (4.2σ exp.)



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

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

Phenomenology of Extended Higgs Sectors at the LHC

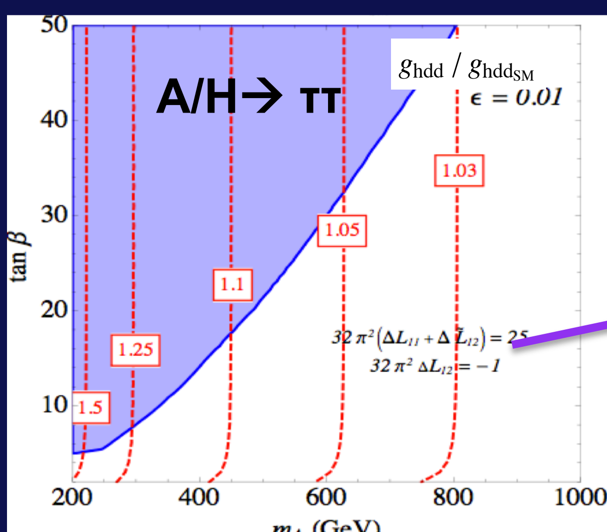
The Importance of Higgs Precision Measurements: The proximity to ALINGMENT

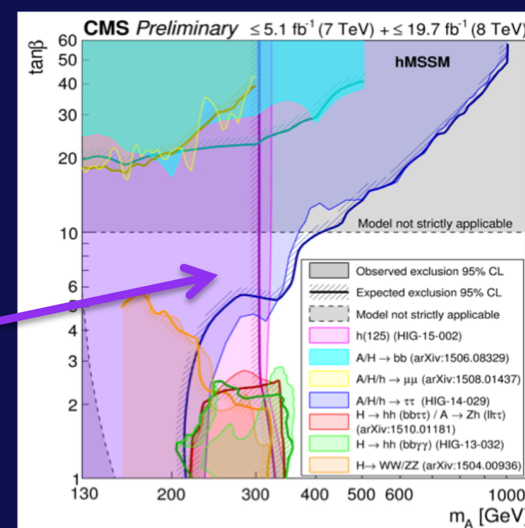
➔ The lightest Higgs coupling to fermions and gauge bosons is SM-like

- Alignment can be achieved by special parameter space or decoupling
- The couplings to down-type fermions not only dominate the Higgs width but also tend to be the ones that differ the most from the SM ones

Strong departure from Alignment has important consequences on A/H searches

Bottom coupling in the MSSM



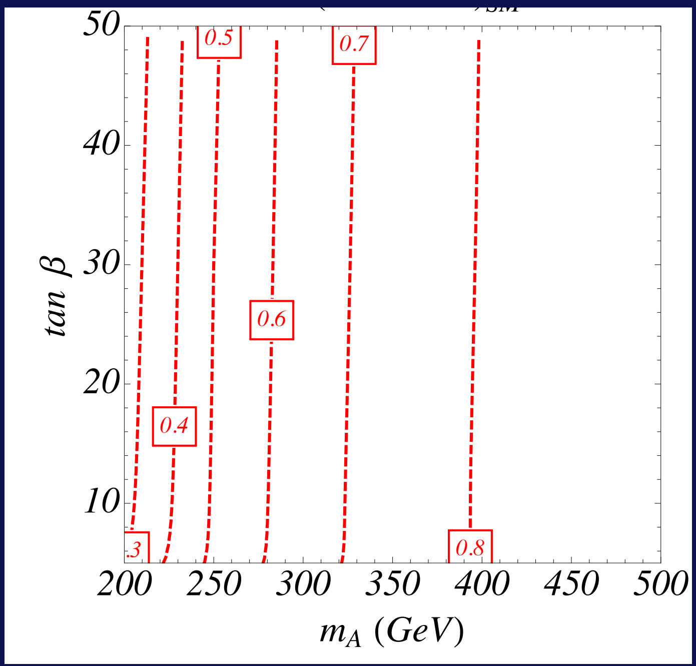


Small μ as analyzed by ATLAS/CMS
($\lambda_{6,7} \propto \mu A_t \simeq 0$ => No Alignment)

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

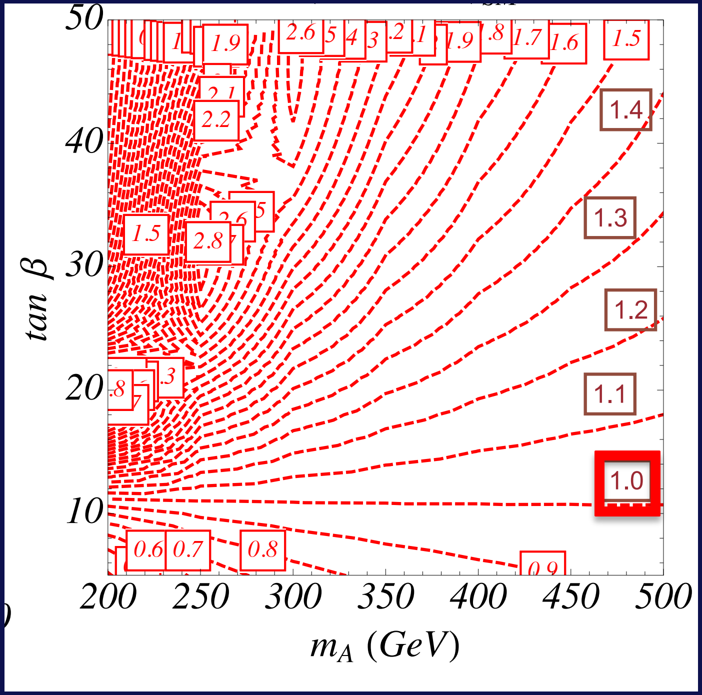
Small μ (no Alignment)



MSSM example

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

Sizeable μ ~ 2 M_{SUSY} (Alignment)



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

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

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

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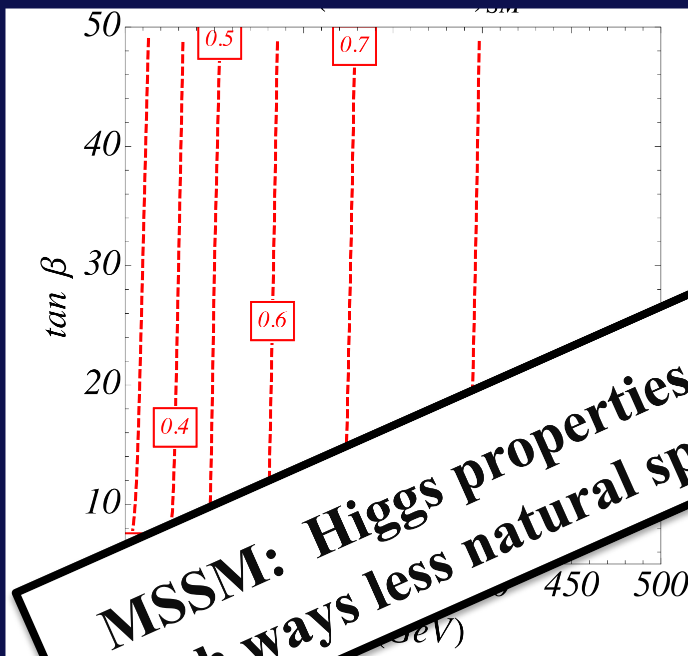

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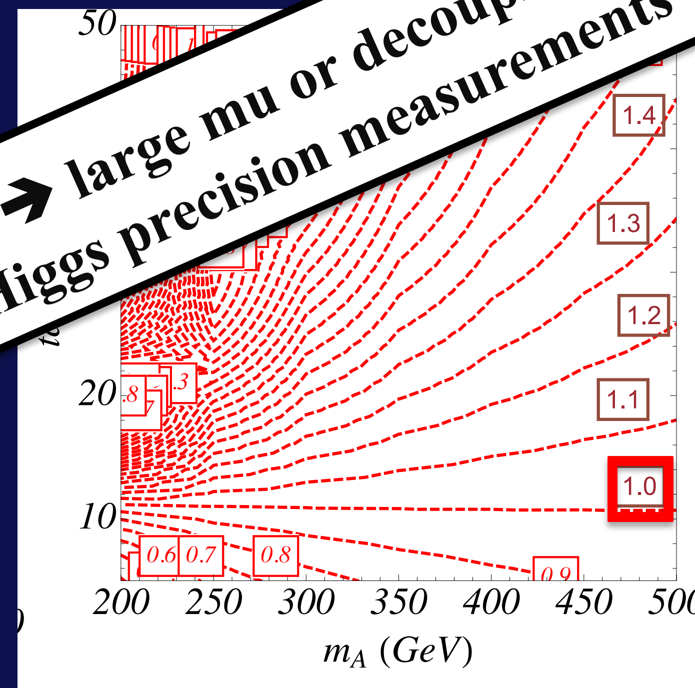

MSSM: Higgs properties close to SM-like ➔ large mu or decoupling
Both ways less natural spectra just from Higgs precision measurements

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

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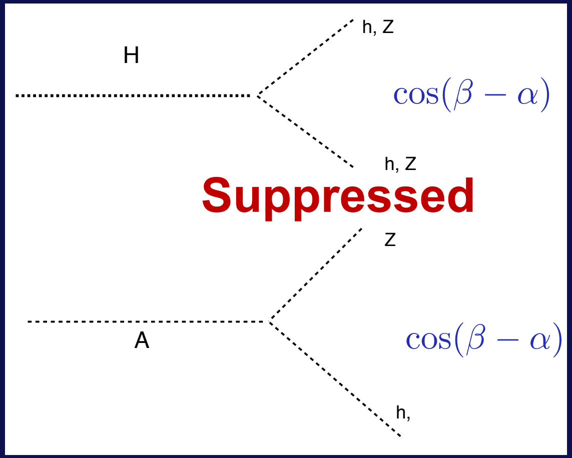
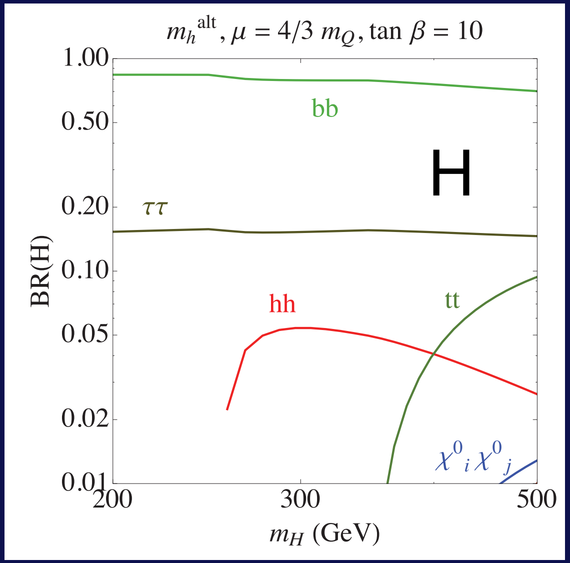
Heavy Higgs Bosons: A variety of decay Branching Ratios

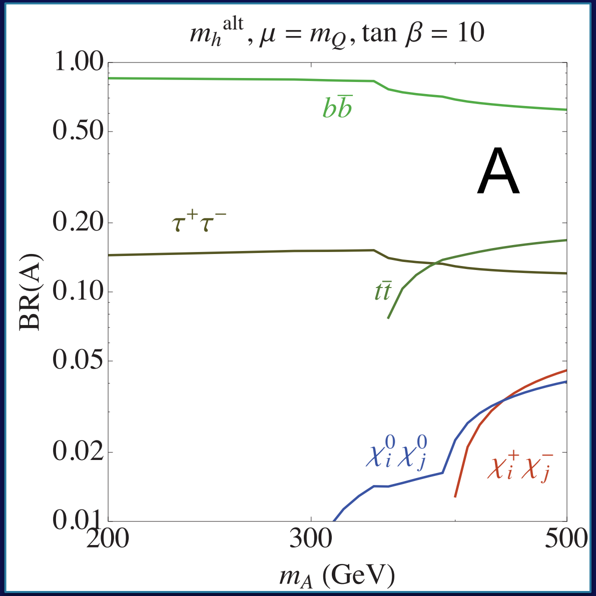
Craig, Galloway, Thomas'13; Su et al. '14, '15; M.C, Haber, Low, Shah, Wagner.'14

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

Alignment







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

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

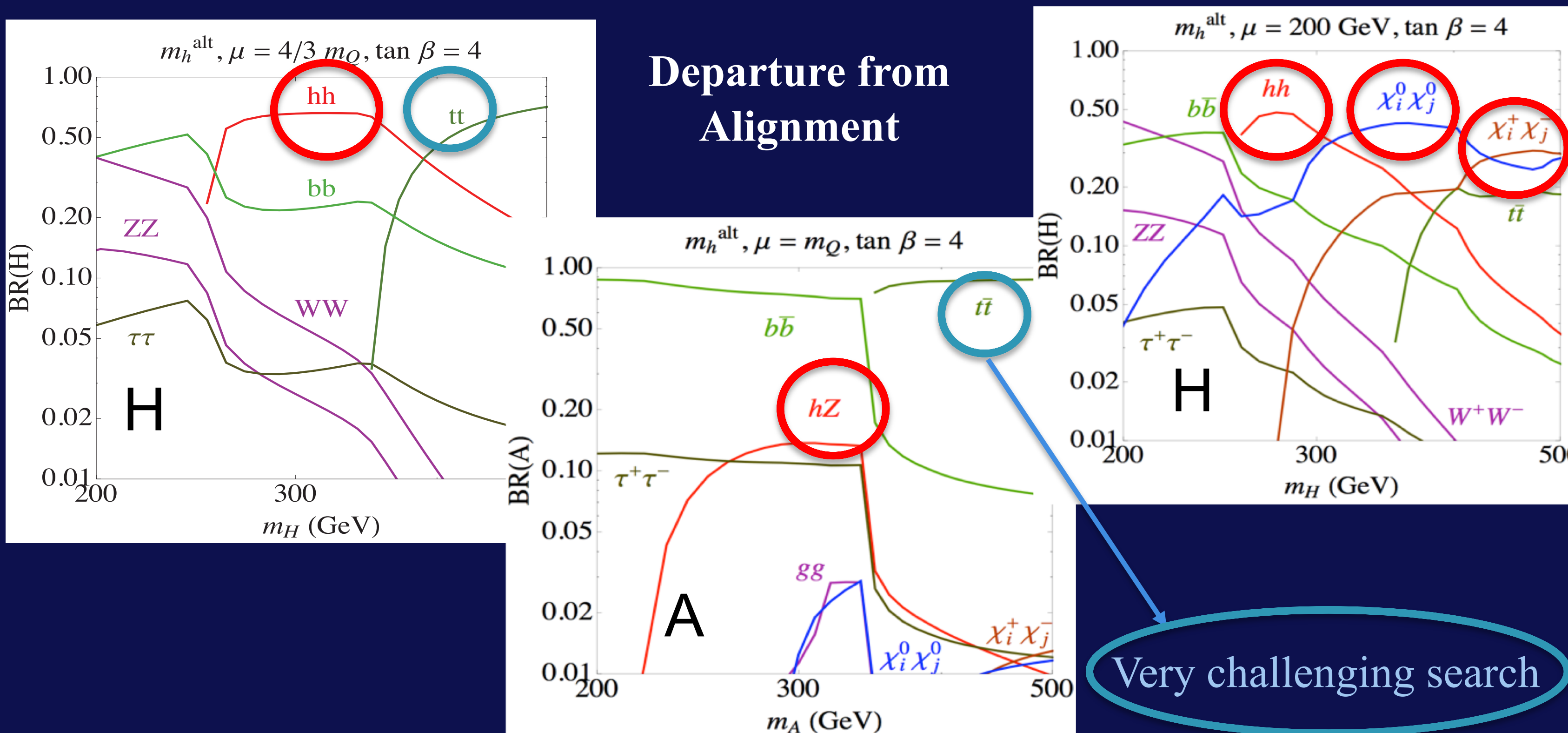
Production mainly via large bottom couplings: bbH

Heavy Higgs Bosons: A variety of decay Branching Ratios

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

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

Departure from Alignment



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**)

2HDM plus Additional Singlet @ LHC reach
- NMSSM properties close to Alignment -

Singlet spectra and decays

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

Doublet-like A and H decays:

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

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

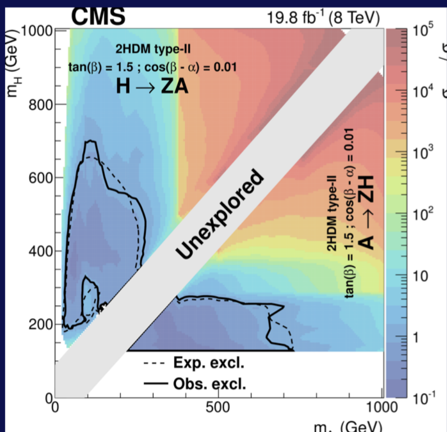
-- Other relevant decays: H → hh_S and A → Zh_S (20% to 50%, dep on mass)

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

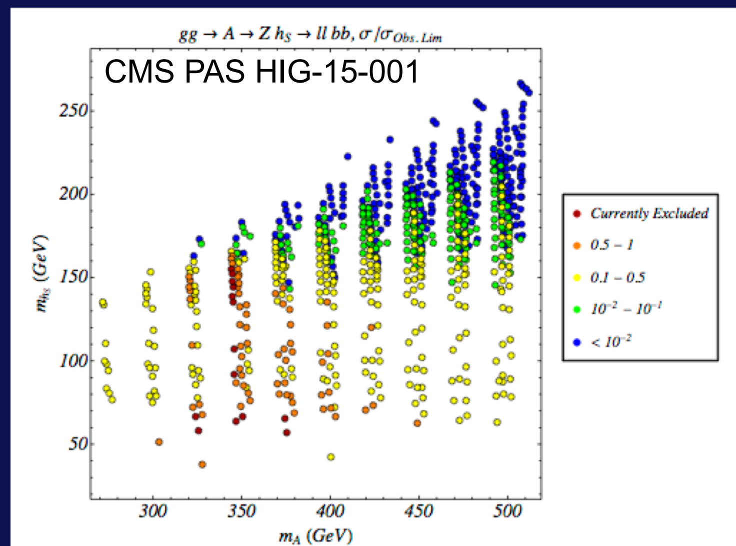
Others: H →hs hs; H→As Z; A→As hs; A→As h of order 10% or below

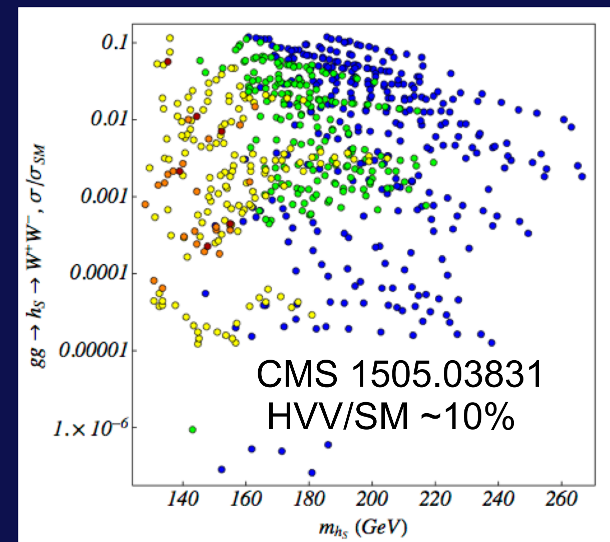
Ongoing searches at the LHC are probing exotic Higgs decays

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



CMS-PAS-HIG-15-001

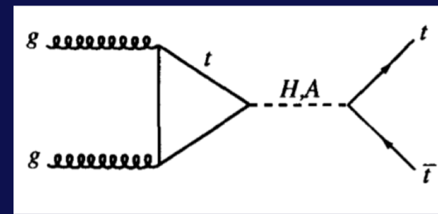


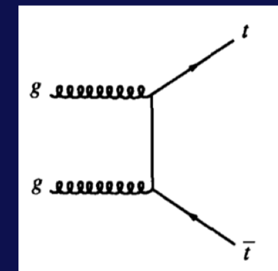


- **Promising H→ h h_S channels with h_S→ bb or WW (4b's or bb WW)**
- **Searches for H /A→ Z(A/H) should replace Z by h_{125} (Di-scalar Searches)**
- Channels with missing energy: A → h a_s; H → Z a_s with a_s → Dark Matter

The challenging A/H ➔ tt channel: Interference effects

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





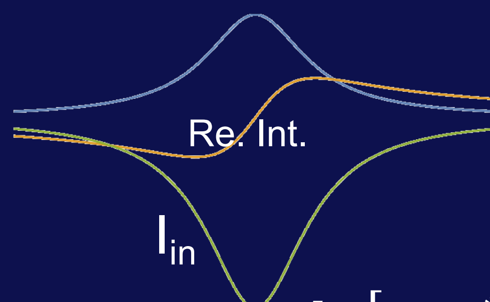
$$A_{sig} = c_{sig}\frac{\hat{s}}{\hat{s}-m^2+i\,\Gamma m} = c_{sig}\,\mathrm{P}(\hat{s})$$

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

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

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

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



Im. Int.–from the imaginary part of propagator

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

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

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

M.C., Liu '16

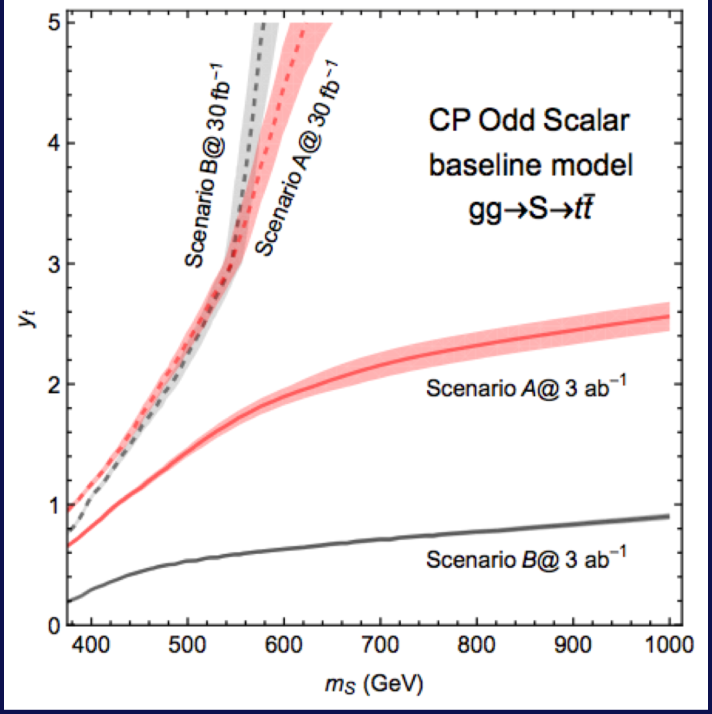
See also recent work by Craig, D'Eramo, Drapper, Thomas, Zhang; Jung, Sung, Yoon; Gori, I.-W. Kim, Shah, Zurek

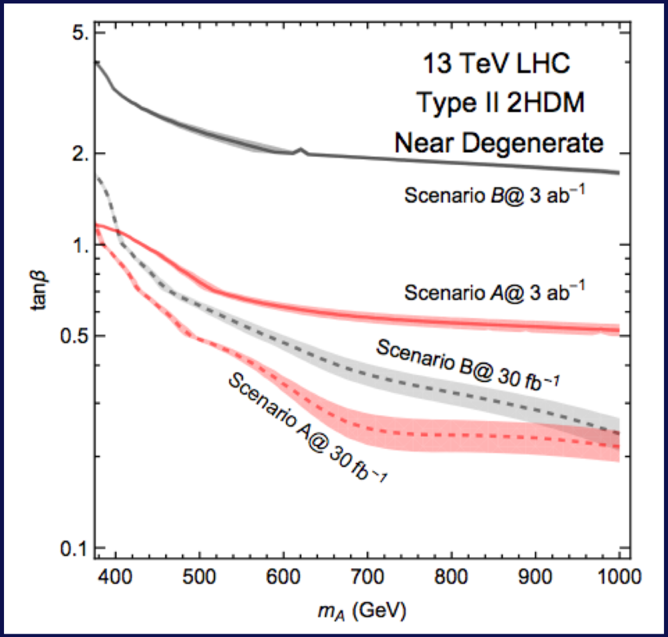
Impact of interference effect in A/H → tt at the LHC

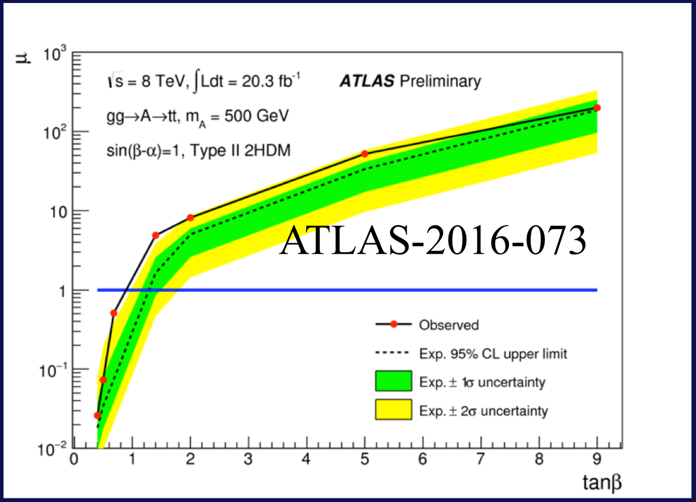
Projections for A/H → tt in Type II 2HDM

M.C., Liu '16

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







First interference studies at ATLAS

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

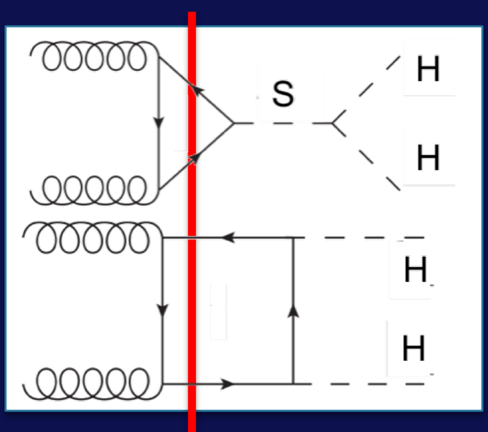
- Interference effect can enhance di-Higgs production up to 40%, improving reach

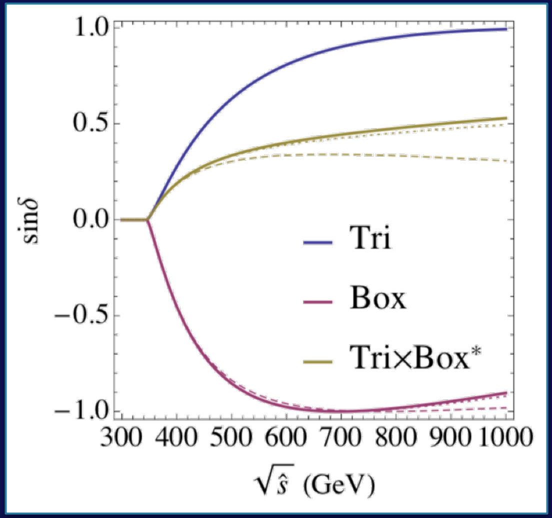
$$V(s,\phi) = -\mu^2\phi^\dagger\phi - \frac{1}{2}\mu_s^2 s^2 + \lambda(\phi^\dagger\phi)^2 + \frac{\lambda_s}{4}s^4 + \frac{\lambda_{s\phi}}{2}s^2\phi^\dagger\phi,$$

Parameters in the potential traded by $\tan_\beta (\equiv v_s/v)$, m_H =125 GeV, v=246 GeV, m_S and $\sin\theta$

Singlet-doublet mixing governed by $\sin\theta$ and di-Higgs final states are characterized by two trilinear coupling: $L \supset \lambda_{HHH}H^3 + \lambda_{SHH}SH^2$.

Strong phase in the loop functions

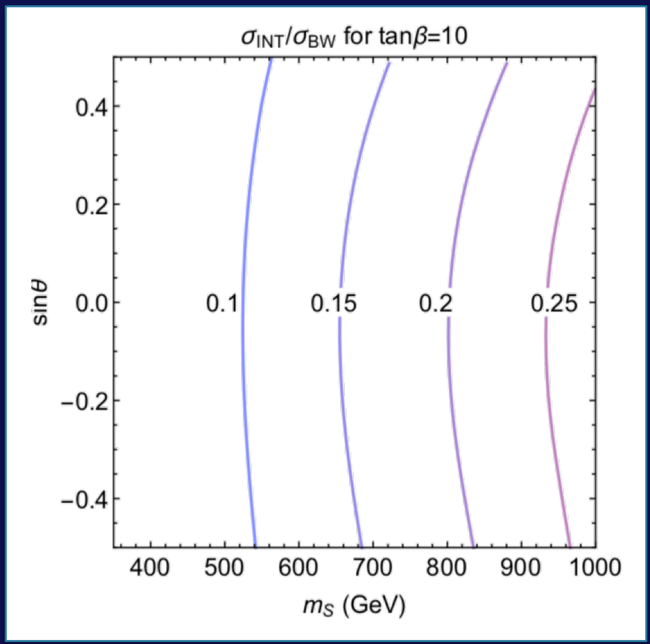


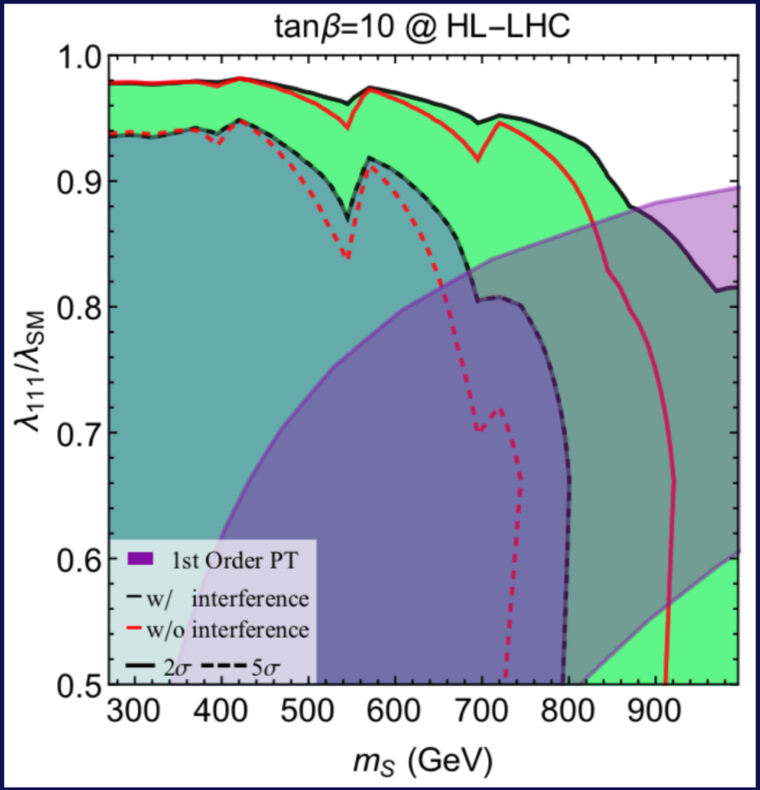


Relative strong phase (yellow curve) allows for a non-vanishing interference effect between the singlet resonance diagram and the SM box diagram.

Relevance of the on-shell interference

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





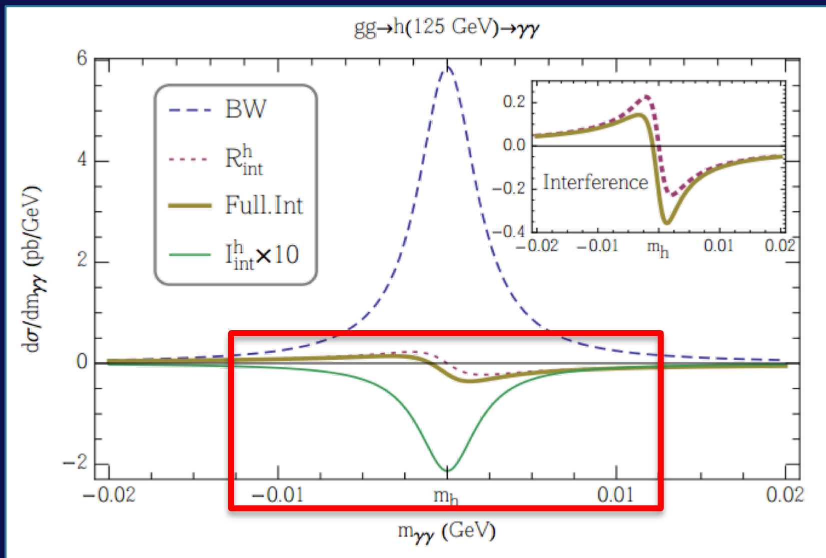
Based on the pp → HH → bbγγ, analysis [arXiv:1502.00539] we perform a differential analysis of the lineshapes:

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

Interference effects can affect Higgs LHC interpretations

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



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

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

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

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

ATLAS and CMS combination

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

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

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

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

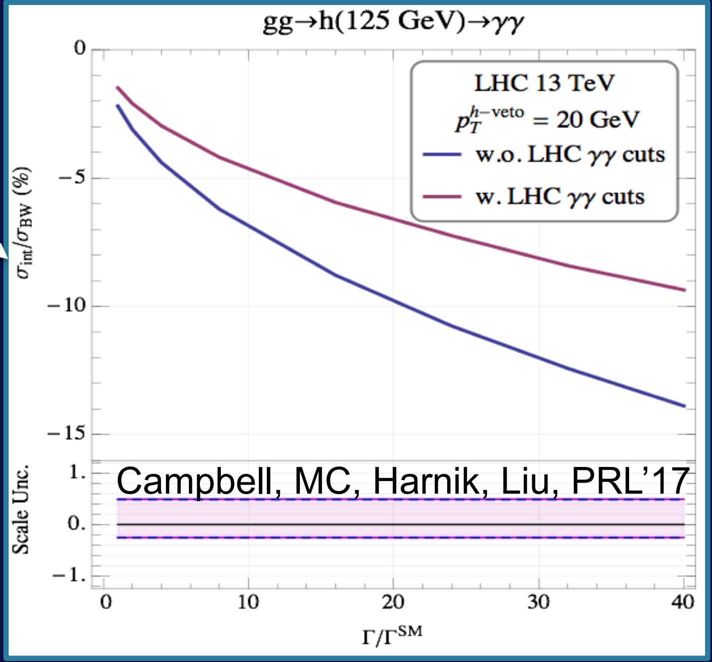
In the extreme case where observed Higgs couplings increase by factor f, and Higgs total width by factor f^4 ➔ All on-shell cross sections remain the same as SM predictions

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

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

Unique piece that does not depend on total width

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



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

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

Differential distributions can help improve on the width information!

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)

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

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

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

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

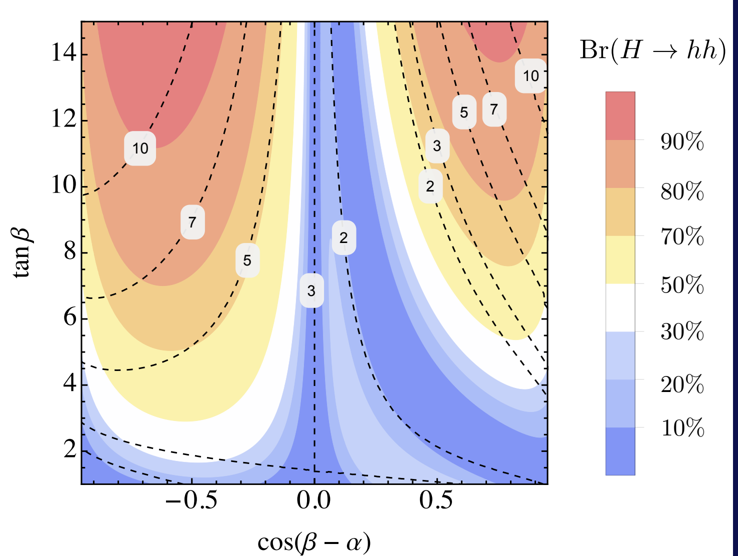


FIG. 1: The color coding shows the dependence of $\mathrm{Br}(H \to hh)$ on $c_{\beta-\alpha}$ and t_β for $M_H = M_{H^\pm} = 550$ GeV, $M_A = 450$ GeV. The dashed contours correspond to constant $|\kappa_f^h|$ for $n_f = 1$.

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

Visible in resonant & non-resonant, dedicated LHC searches

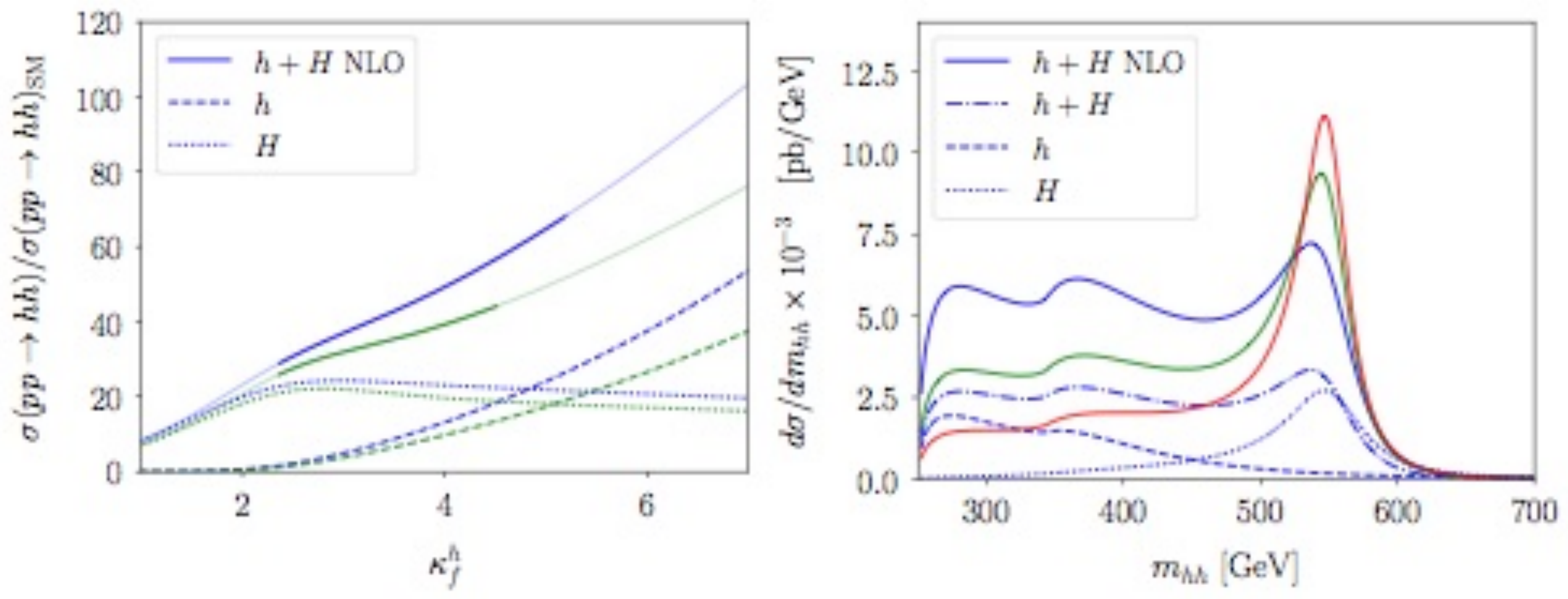


FIG. 2: Left: Cross section for Higgs pair production in units of the SM prediction as a function of κ_f^h for $c_{\beta-\alpha} = -0.45$ (-0.4) and $M_H = M_{H^\pm} = 550$ GeV, $M_A = 450$ GeV in blue (green) at $\sqrt{s} = 13$ TeV. Right: Invariant mass distribution for the different contributions to the signal with $c_{\beta-\alpha} = -0.45$ and $\kappa_f^h = 5$ (blue), $\kappa_f^h = 4$ (green) and $\kappa_f^h = 3$ (red) at $\sqrt{s} = 13$ TeV, respectively. Solid (dot-dashed) lines correspond to the NLO (LO) calculation for the sum of the resonant and non-resonant production, while dotted (dashed) lines correspond to the pure resonant (non-resonant) contributions.

Dark Matter searches at the LHC: Simplified Models

- **Models designed to involve only a few new particles and interactions**
- Can be understood as a limit of a more general new-physics scenario, where all but the lightest dark-sector states are integrated out.
- **A broad variety of DM candidates and Mediators**

Scalar s-channel mediators, Various types of Higgs portals to DM,
Vector s-channel mediators DM, t-channel flavored mediators, ….

Mono-object searches for DM
The most model-independent searches for dark matter at the LHC.

The targeted interaction is pp→ $\chi\chi$+X,
where the X represents the “mono” system of observable particles
recoiling against the DM pair $\chi\chi$, that is identifyed as missing transverse momentum

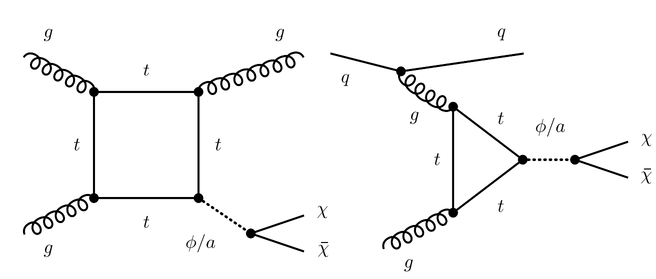
X can be a system composed of jets, photons, weak bosons (γ, W, Z),
Higgs bosons, or heavy flavor quarks (b and t)

Mono-object searches for DM

Scalar and Pseudoscalar mediator, s-channel

Monojet search

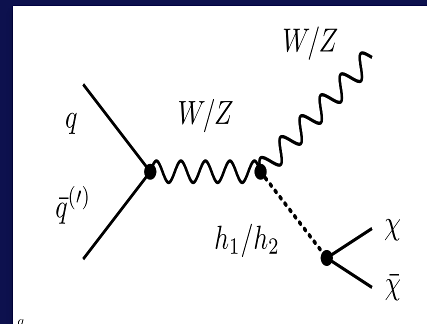
mχ,mφ/a, gχ, gu,



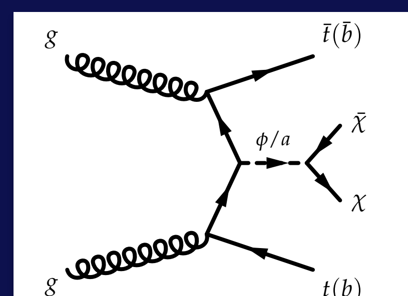
$$\mathcal{L}_\phi = g_\chi \phi \bar{\chi}\chi + \frac{\phi}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i \right) .$$

$$\mathcal{L}_a = i g_\chi a \bar{\chi} \gamma_5 \chi + \frac{ia}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i \right) .$$

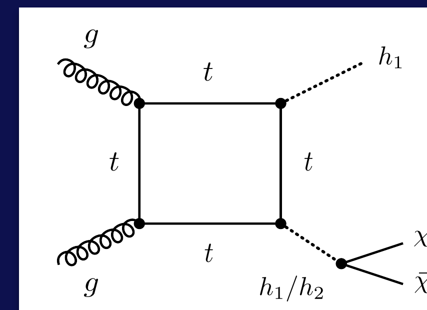
Mono-V search

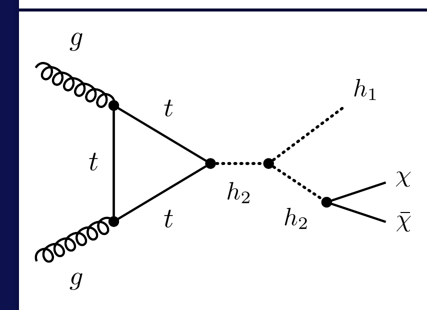


Top (bottom) pair search



Mono-Higgs search





Sensitivity of mono-boson searches (W,Z,H) to this model is low, UNLESS we consider the effects of the Higgs portal (upper middle diagram or right diagrams).

With the MFV assumption, however, the top and bottom quarks can play an important role in the phenomenology.

Is it possible to use ML techniques to improve exploration of the Higgs realm? [both SM Higgs and Higgs extended sectors]

• ML improves object tagging:
e.g., top tagging (W. Hopkins@ML4Jets'18) ;
hadronic Higgs tagging (arXiv:1807.10768v3: boosting H→ bb with ML),
➔ these can propagate into improvements in the H->tt and H->hh searches
Important to generate signal events w/ interference, not just a bump hunting
Perform scalar resonant searches above the top threshold;
Enhance LHC sensitivity to simple models with a strong first order phase transition

• ML improves results for complex final states (e.g., high multiplicity (and hence combinatoric) is problematic for traditional taggers)
➔ Use as alternative method in searching for ttH with heavy Higgs decaying to top or bottom pairs
e.g., Convolutional Neural Networks used for the discovery of top Yukawa in tth

• ML for higher order QCD correction calculations (?)
h → γγ is statistically limited but ML might help in reducing the +50%-30% scale uncertainty in the theory calculation of the interference effect and help with obtaining novel on-shell info on the Higgs total width

• Other ideas for ML for Higgs and DM searches …..