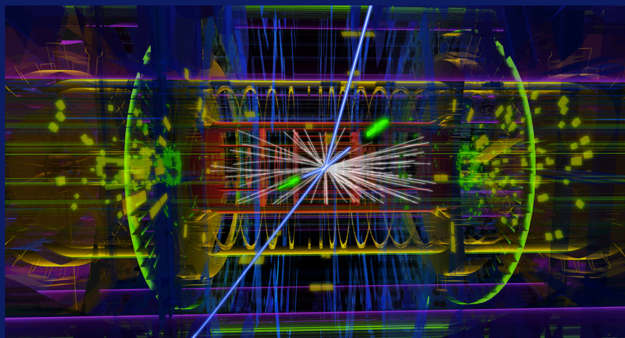
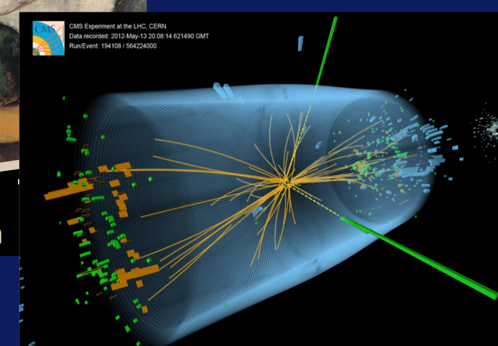
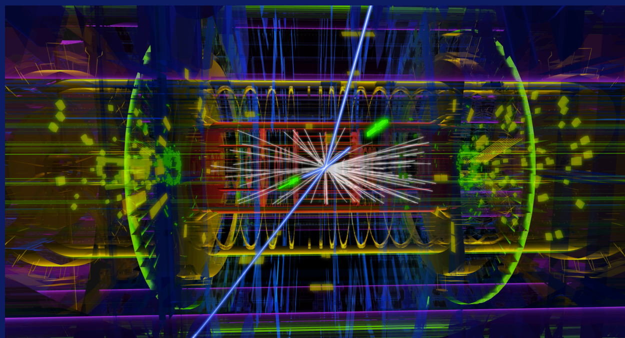


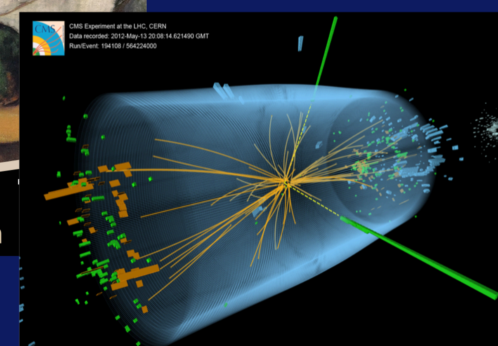


Marcela Carena
Fermilab and UChicago

LPNHE-Paris, September 2nd 2016

The many Higgs of Cézanne





Marcela Carena

Fermilab and UChicago

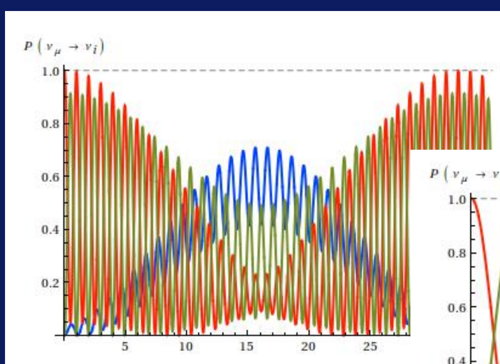
LPNHE-Paris, September 2nd 2016

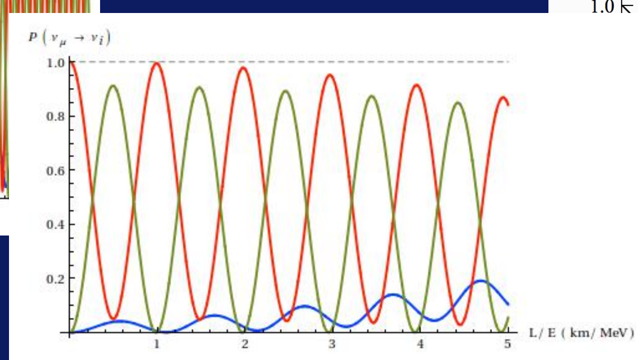
Lots going on in particle physics in the last quarter of a century

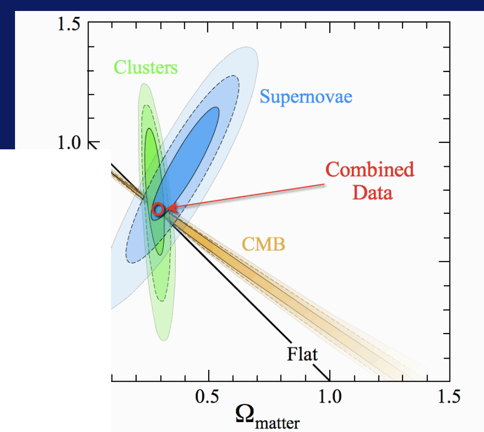
- **Top quark & tau neutrino discovery @Fermilab**
- **Higgs discovery @CERN**

Within the SM

- Neutrino Oscillations led to convincing evidence of neutrino masses
- CMB studies led to conclusive evidence of Dark Matter
- Supernova & CMB studies led to evidence of Dark Energy







Beyond the SM

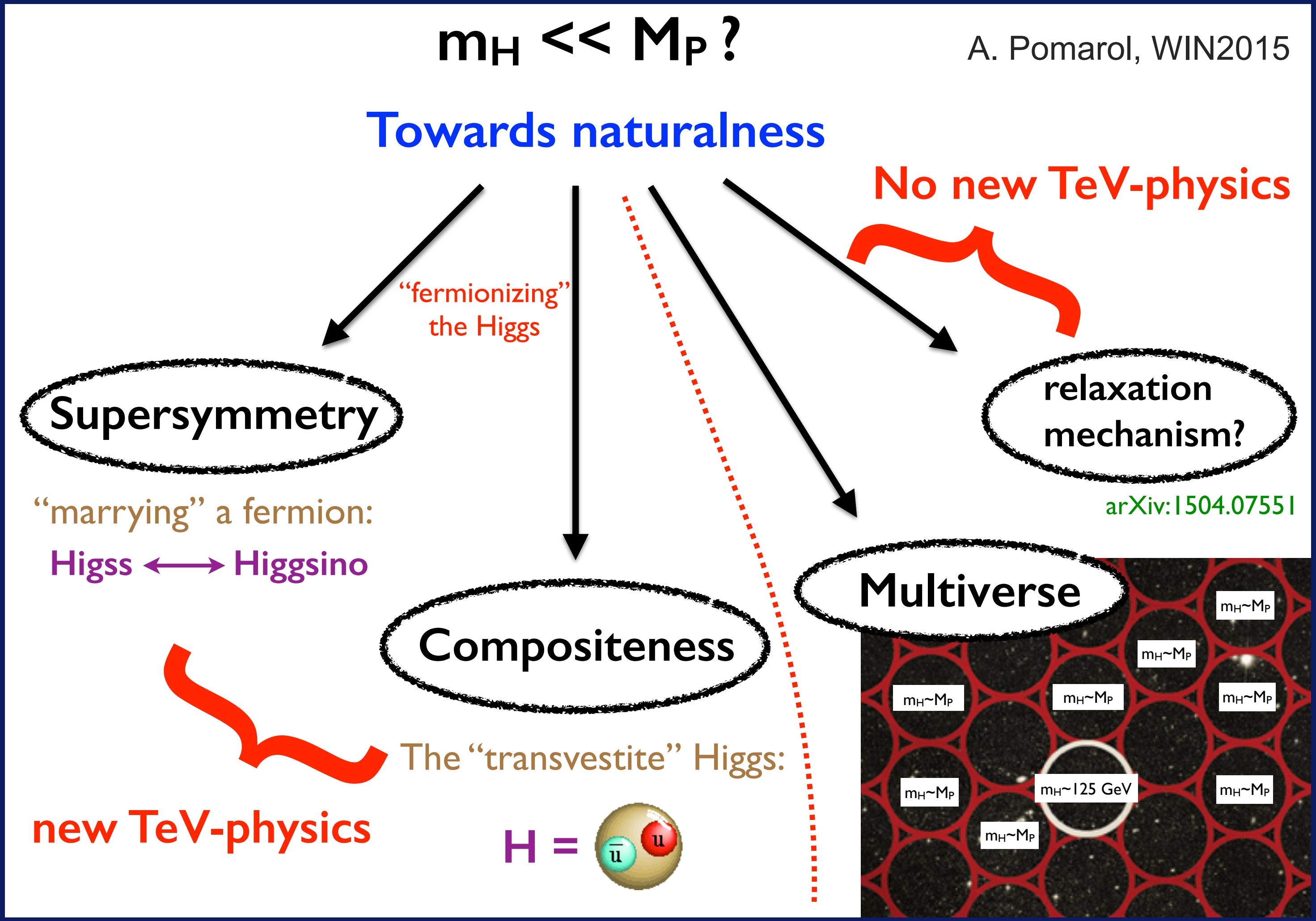
Precision Measurements yield relevant implications for model building

i.e. ruled out SM electroweak baryogenesis

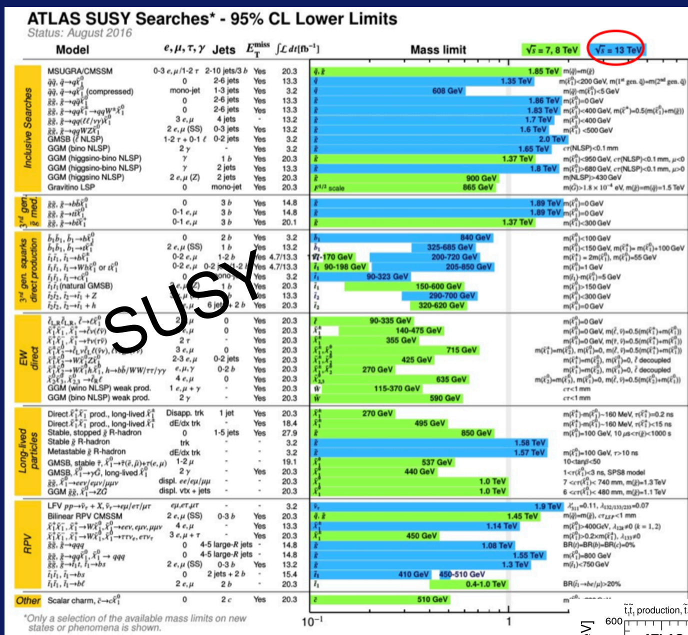
The Naturalness Argument

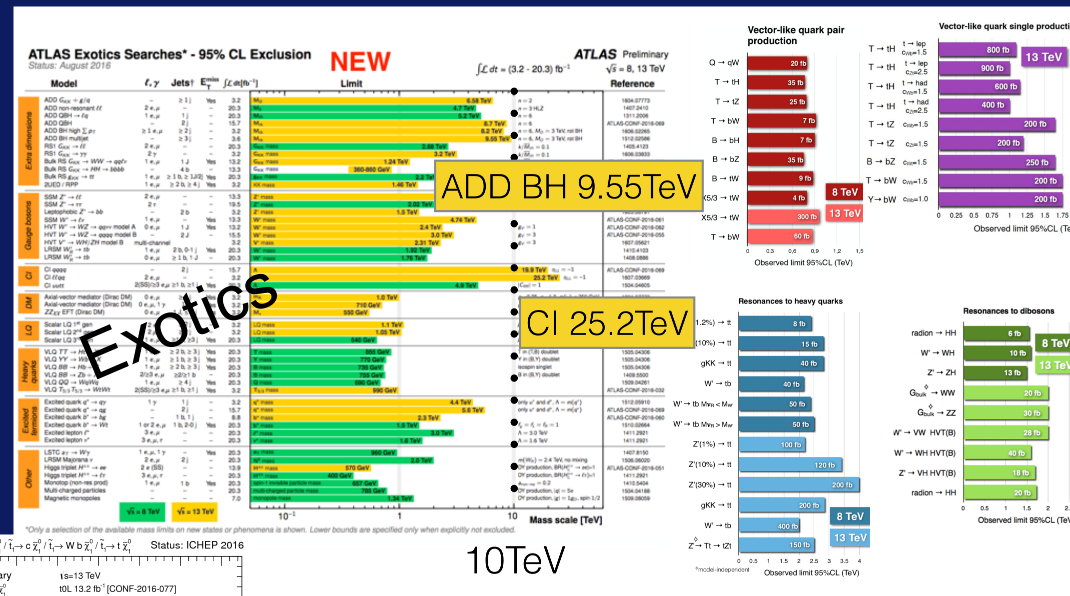
The Higgs boson should be accompanied by BSM physics at a similar scale, ~TeV

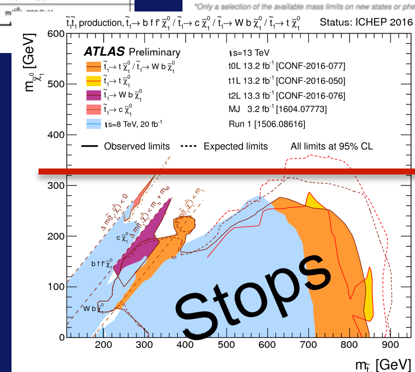
how far are we willing to go?



The situation at the LHC (ICHEP 2016)





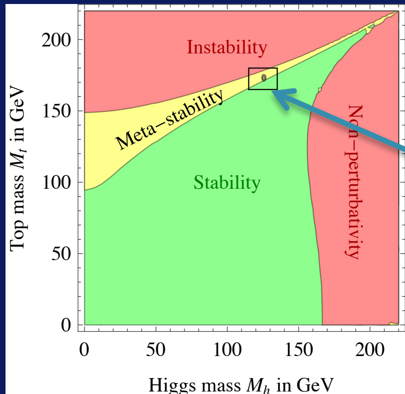


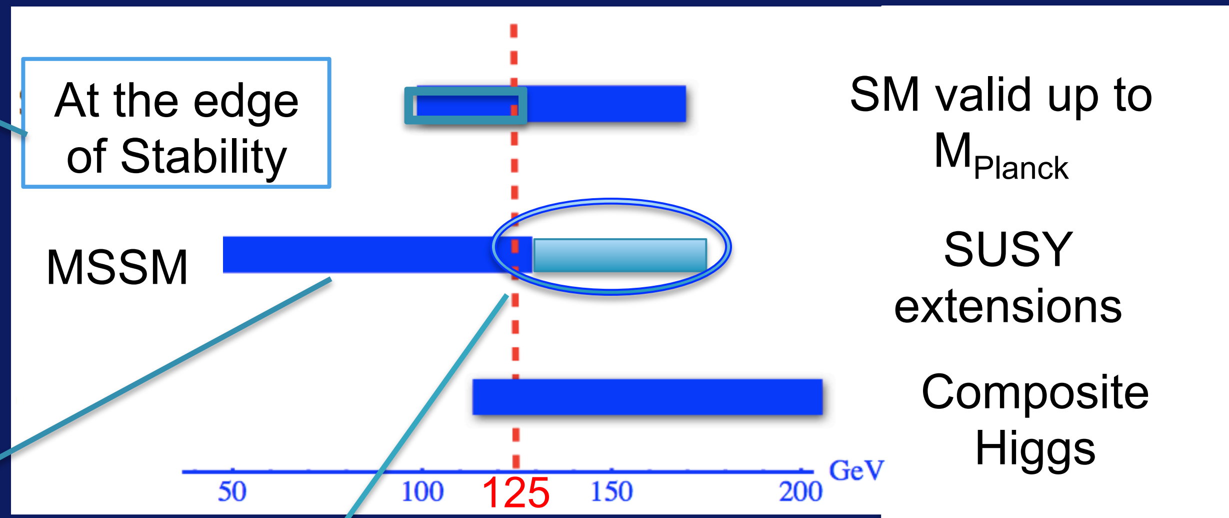
Still, the canonical BSM paradigm well motivated;

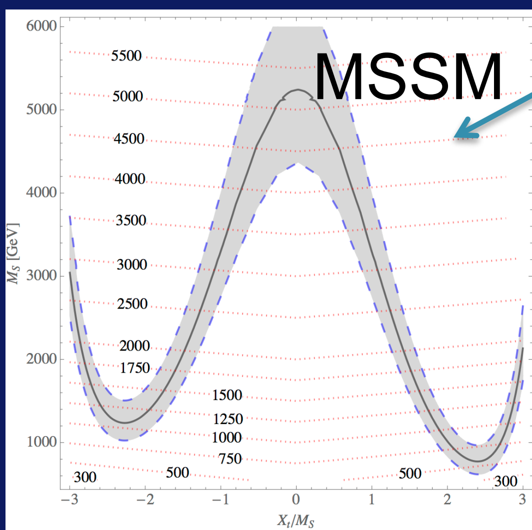
could imply that discoveries at LHC + dark matter detection are coming soon

Should intensify/broaden experimental probes as much as possible

Look under the Higgs lamp-post:

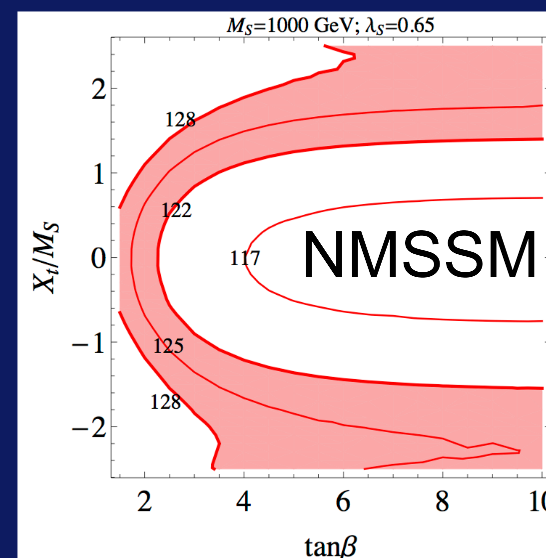






MSSM Singlet extensions
or extended gauge sectors

see Wagner's talk

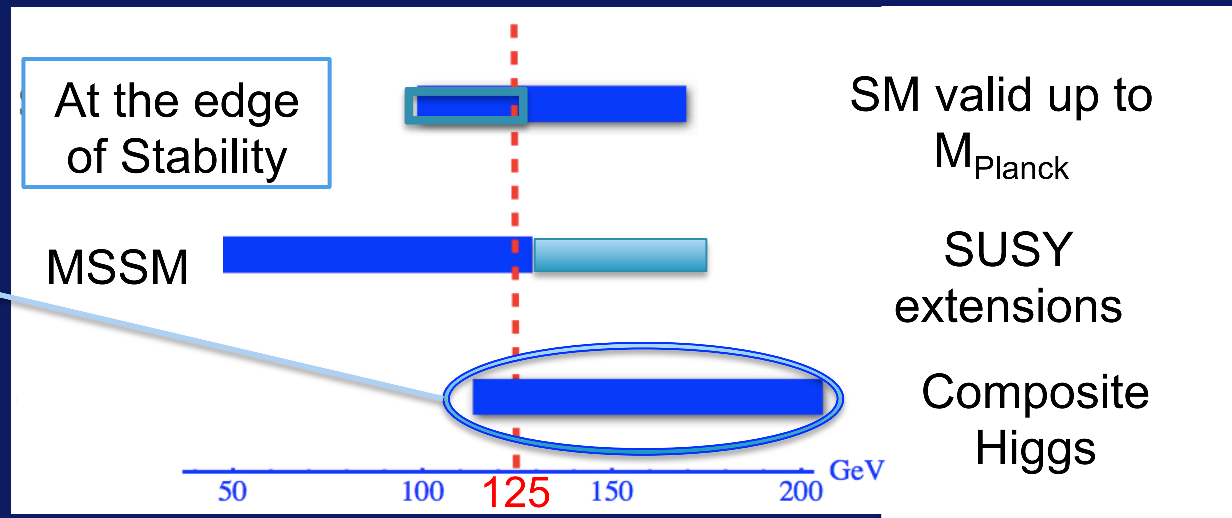


NMSSM + mh ~ 125 GeV: naturally compatible with stops at the electroweak scale, thereby reducing the degree of fine tuning to get EWSB

Look under the Higgs lamp-post:

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

➔ dynamical origin of EWSB



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

Additional option: 2HDMs to explain flavor @EW scale
Higgs boson as Frogatt-Nielsen Flavon

Higgs production & decay signal strengths in good agreement with SM

Still direct measurement of bottom & top couplings subject to large uncertainties

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

Data on SM-like Higgs signal strengths → Alignment

The MSSM: a type II 2HDM

See Wagner's talk

If the mixing in the CP-even sector is such that cos (β-α) = 0

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

H and A couplings to down (up)-quarks are enhanced (suppressed) by tanβ

This situation is called ALIGNMENT and occurs for

- large values of m_A → Decoupling
- specific conditions **independent of M_A → Alignment without Decoupling**

Departures from alignment quantized by an exp. in cos (β-α),
BUT Higgs –bottom coupling is controlled by $\boldsymbol{\eta = \cos_{\beta-\alpha}\, t_\beta}$

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

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

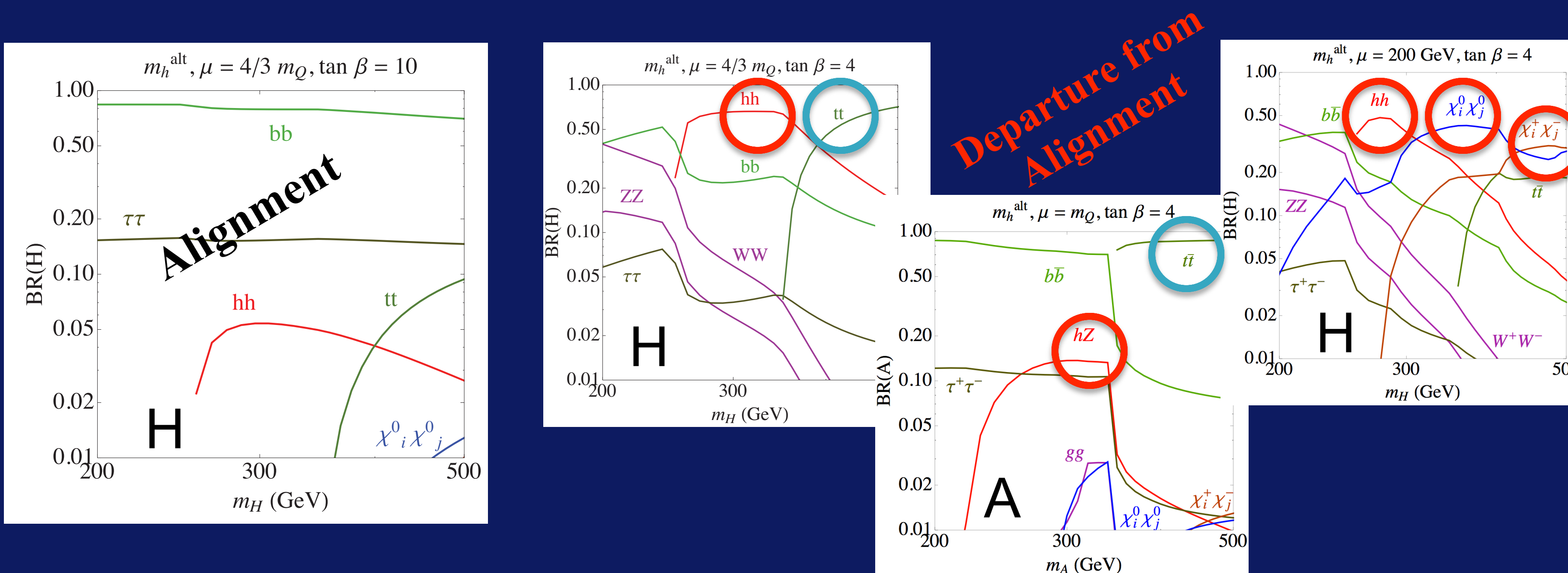
$$g_{huu} \approx (1 + t_\beta^{-2} \eta)\, g_f \,,$$

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

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



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

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

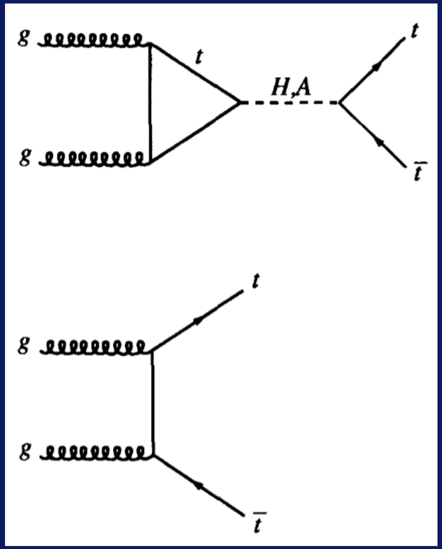
Production mainly via large bottom couplings: bbH

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

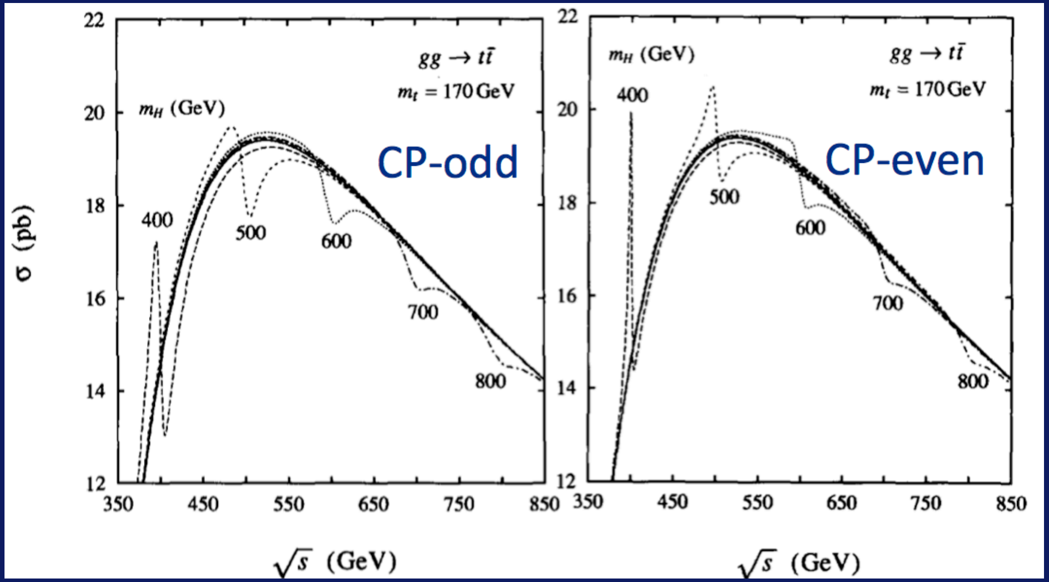
If low μ, then chargino and neutralino channels open up (impact on H/A ➔ **ττ**)

The challenging A/H ➔ tt channel: Interference effects



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

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

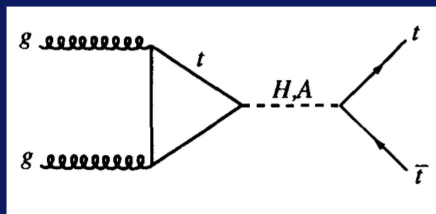


Heavy scalars common in many BSM scenarios: SUSY, 2HDMs, Gauge symmetry extensions, Composite models ,…

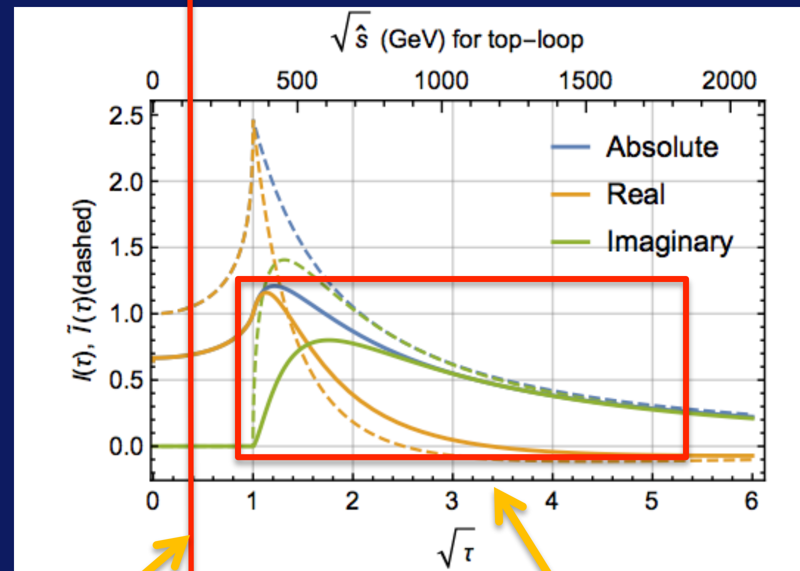
Hierarchical coupling to fermions ➔ Dominant decay into top pairs

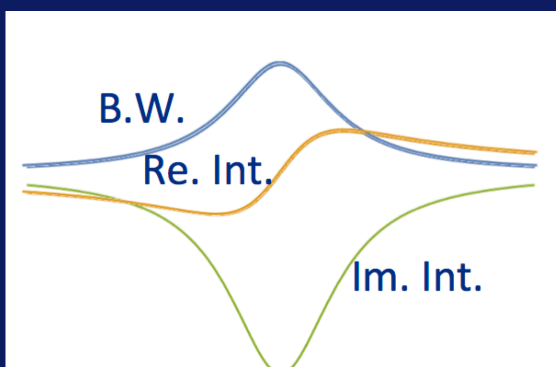
Craig, Draper, Erasmo, Thomas, Zhang '15, Jung, Sung, Yoon .'15; Gori, Kim,Shah, Zurek'15 Hajer, Li, Liu Shiu'15; Djouadi, Ellis and Quevillon' 16; Craig, Hajer, Li, Liu, Wang16; Fuchs, Thewes, Weiglein,'14; M.C., Liu'16

The challenging A/H ➔ tt channel: Interference effects



Triangle loop function





SM Higgs:
real and slowly varying

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

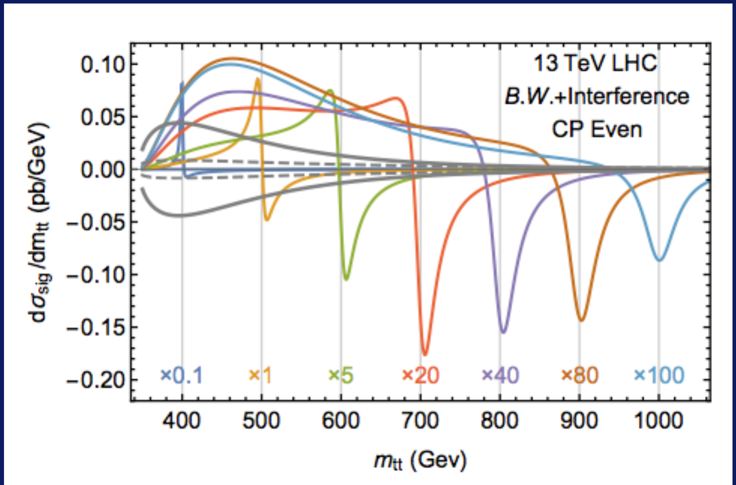
Background real

Real Interference from the real part of the propagator and real part of loop function (shifts the mass peak)

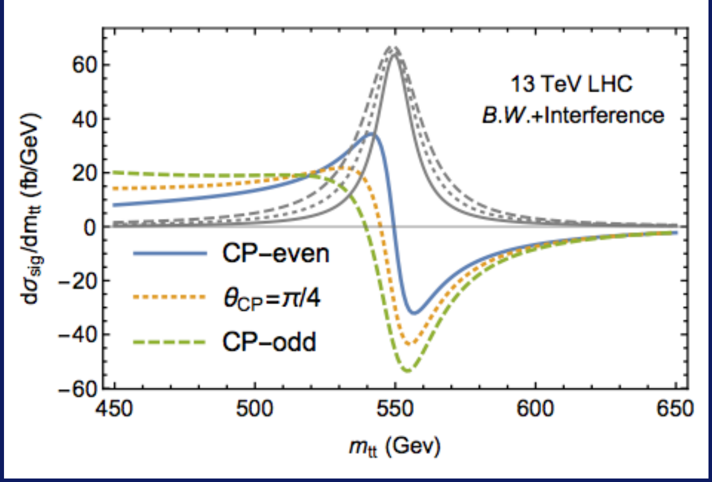
Im. Interference from the imaginary part of propagator with imaginary part of loop function (rare case, changes signal rate)

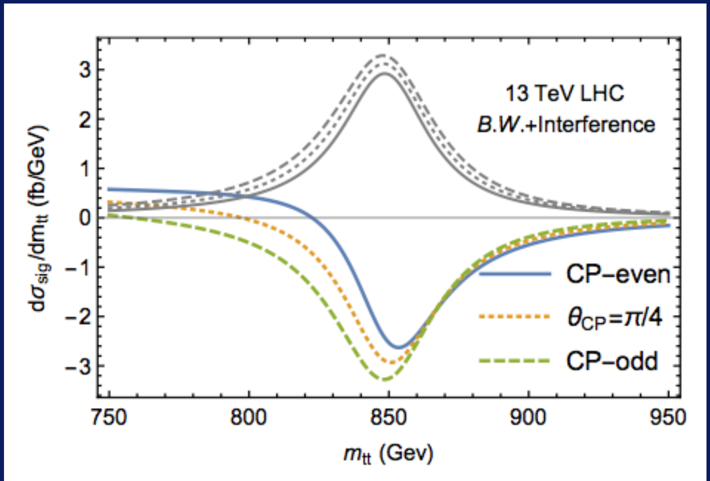
Special Line-shapes examples with one (pseudo) scalar

Differential cross sections of various heavy CP-even scalar signals



BSM lineshapes for various CP phase eigenstates for heavy scalar masses at 550 GeV and 850 GeV



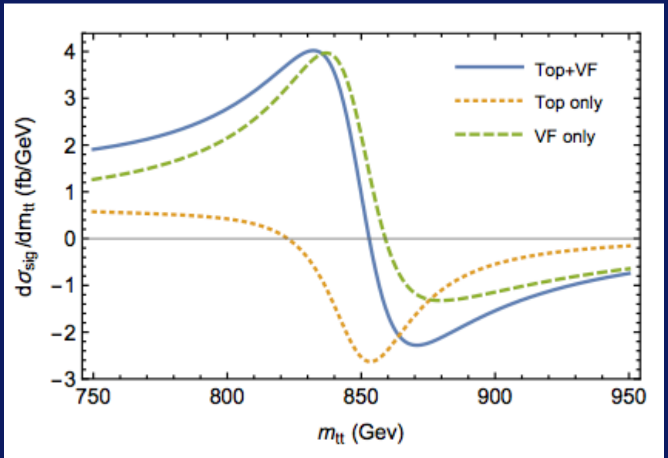


Searches not designed/optimized for bump-dip/ dip structure.

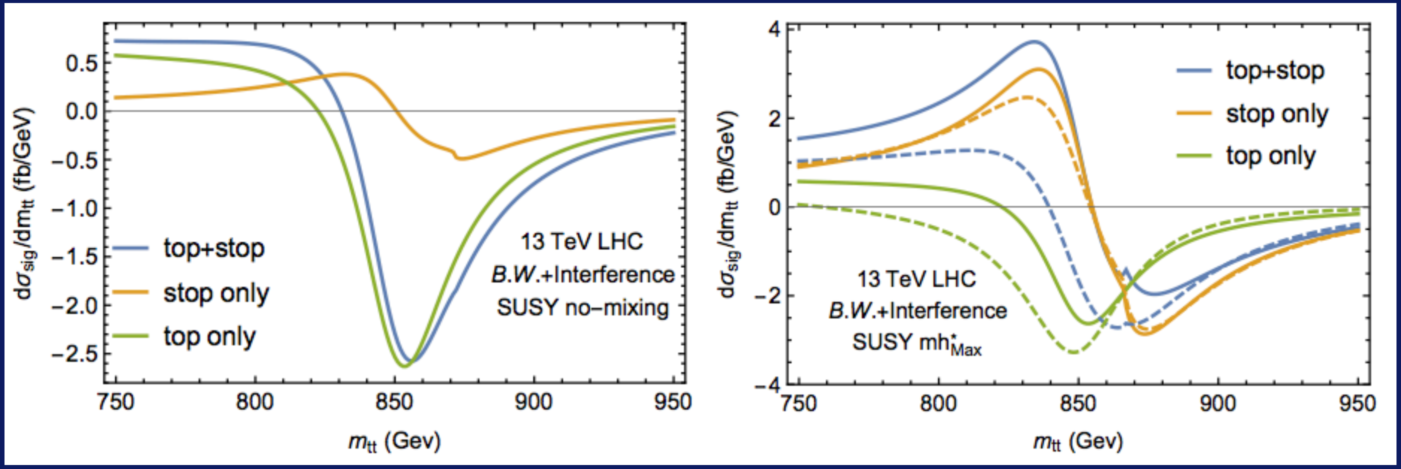
Smearing effects flatten the dips and bumps, making it harder.

Special Line-shapes examples with additional BSM particles

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

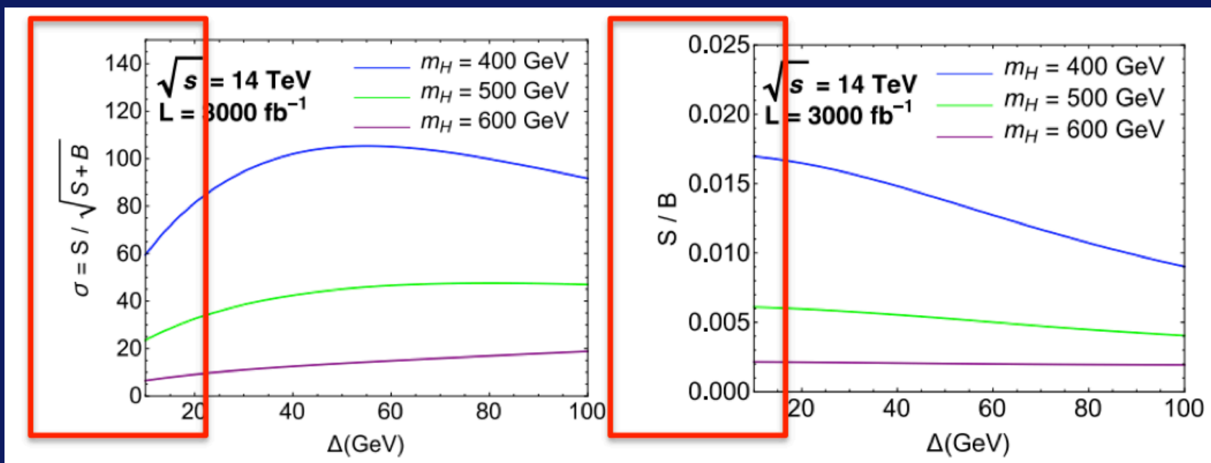


Stops in the loop function:
Zero L-R stop mixing ➔ small interference (dip-bump structure), top quark dip structure prevails
Large L-R mixing ➔ dominant contribution, dip-bump structure prevails



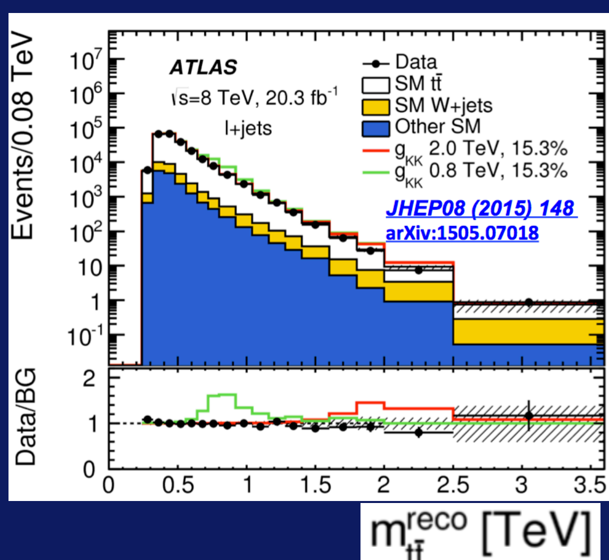
The challenging A/H ➔ tt channel: Systematic Uncertainties

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

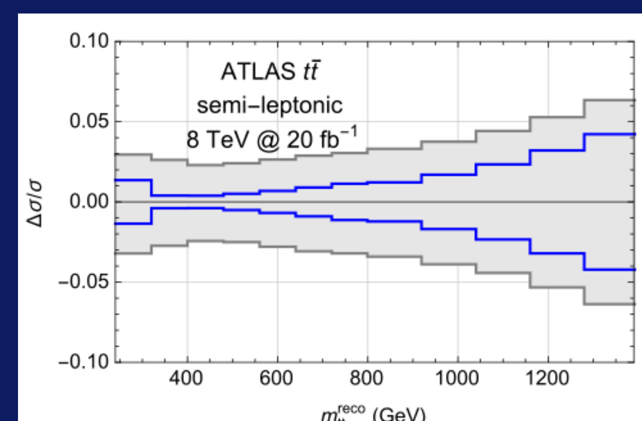


After detector smearing
and reconstruction:
Statistically promising
Systematically challenging
Craig et al '15

Using Atlas
8 TeV Analysis



➔

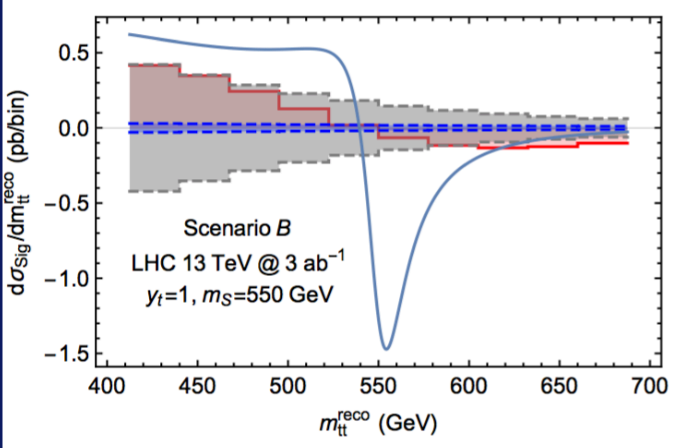


Prospects for searches in A/H→ tt : Benchmark Studies

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 $\sqrt{L}$

M.C., Liu'16



Blue line: the signal lineshape before smearing

Red bins: signal after smearing and binning
Blue and gray histograms: background statistical and uncertainties after smrearing & binning

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

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

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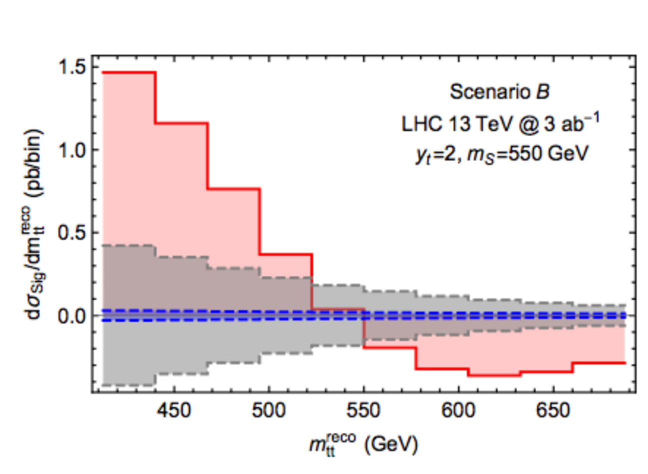

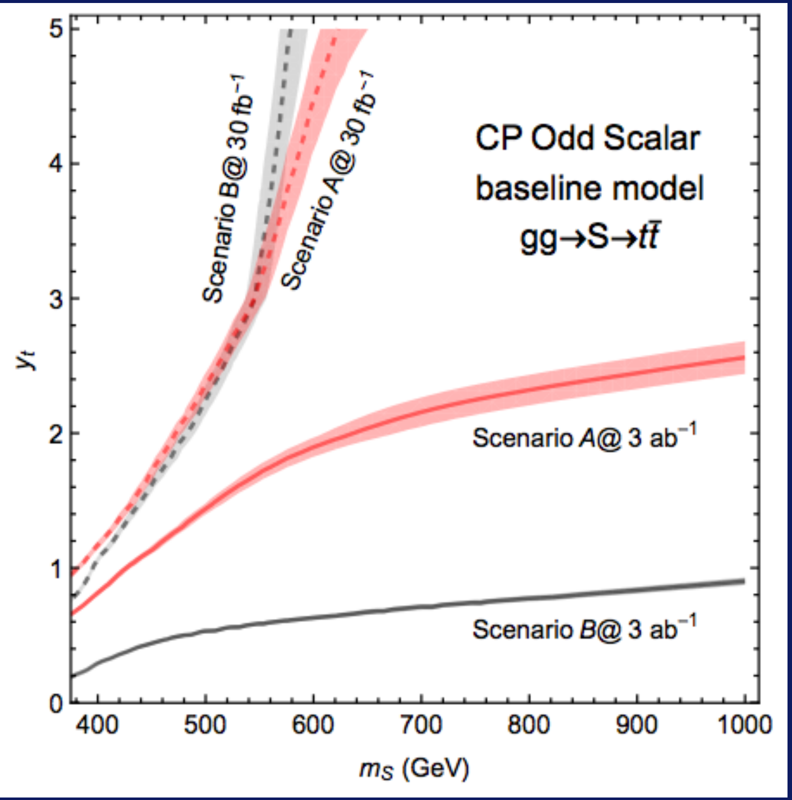

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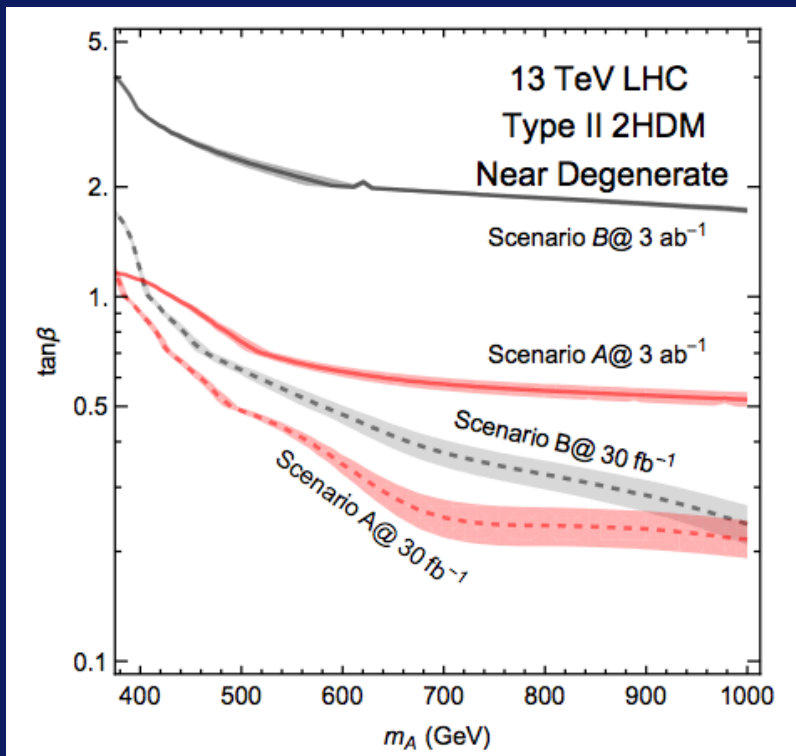
These studies are important for any new heavy scalar that couples to top pairs

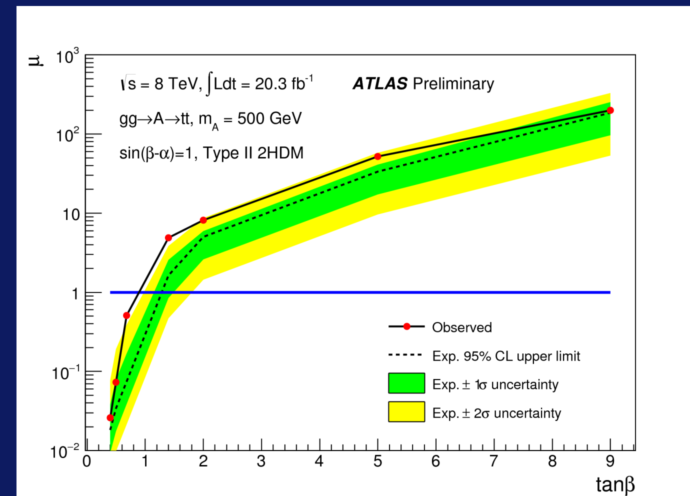
Impact of interference effect in A/H → tt at the LHC

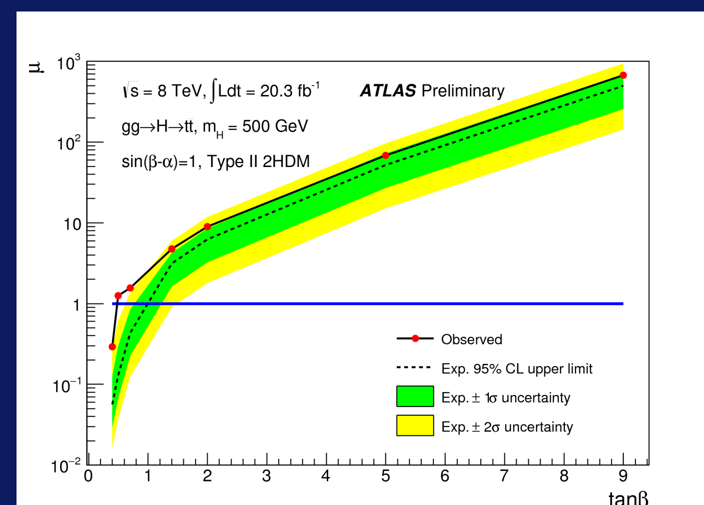
Projections for A/H →tt in Type II 2HDM



M.C., Liu ‘16

First interference studies at ATLAS

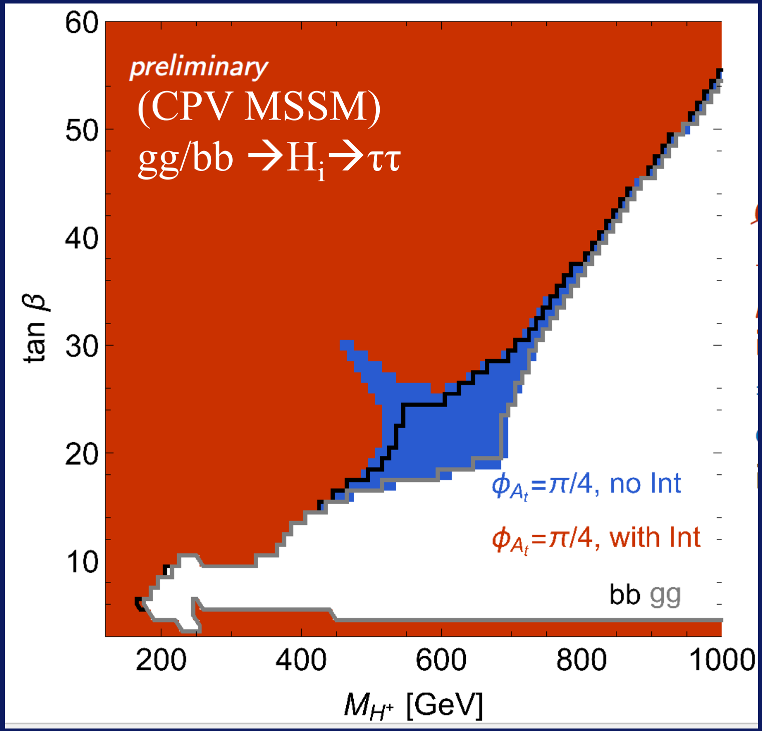




ATLAS-2016-073

Impact of interference effects in $H_i \rightarrow \tau\tau$ at LHC (CPV case)

Destructive Interference effects between two heavy scalars



$\not{C}\not{P}$ benchmark:
$M_h^{\mathrm{mod}+}$ with $\phi_{A_t} = \pi/4$
$\mu = 1000\,\mathrm{GeV}$
interference included

⇒ significant shift of exclusion bounds
impact of **bb** and **gg**

Fuchs, Weiglein, et al, to appear

Naturalness and the Alignment in the NMSSM

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

- Well known additional contributions to m_h

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

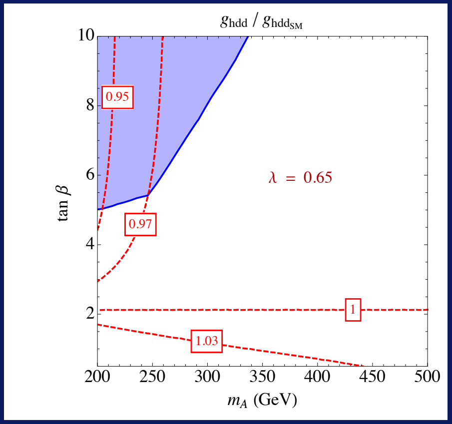
- Less well known:
  sizeable contributions to the mixing between MSSM CP-even eigenstates

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

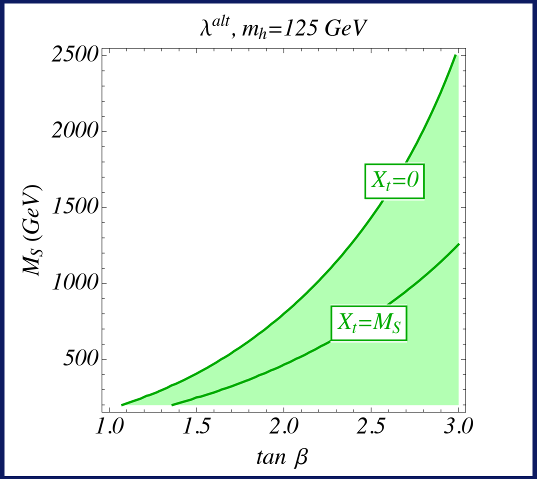
Last term from MSSM; small for moderate/small μA_t and small $\tan\beta$

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

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



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

Previously was assumed implicitly that the singlets are either decoupled, or not significantly mixed with the MSSM CP-even states

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

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

Needs to vanish in alignment

For tanβ < 3 and λ ~ 0.65, plus κ in the perturbative regime, it follows that in order to get small mixing in the Higgs sector, m_A and μ are correlated

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

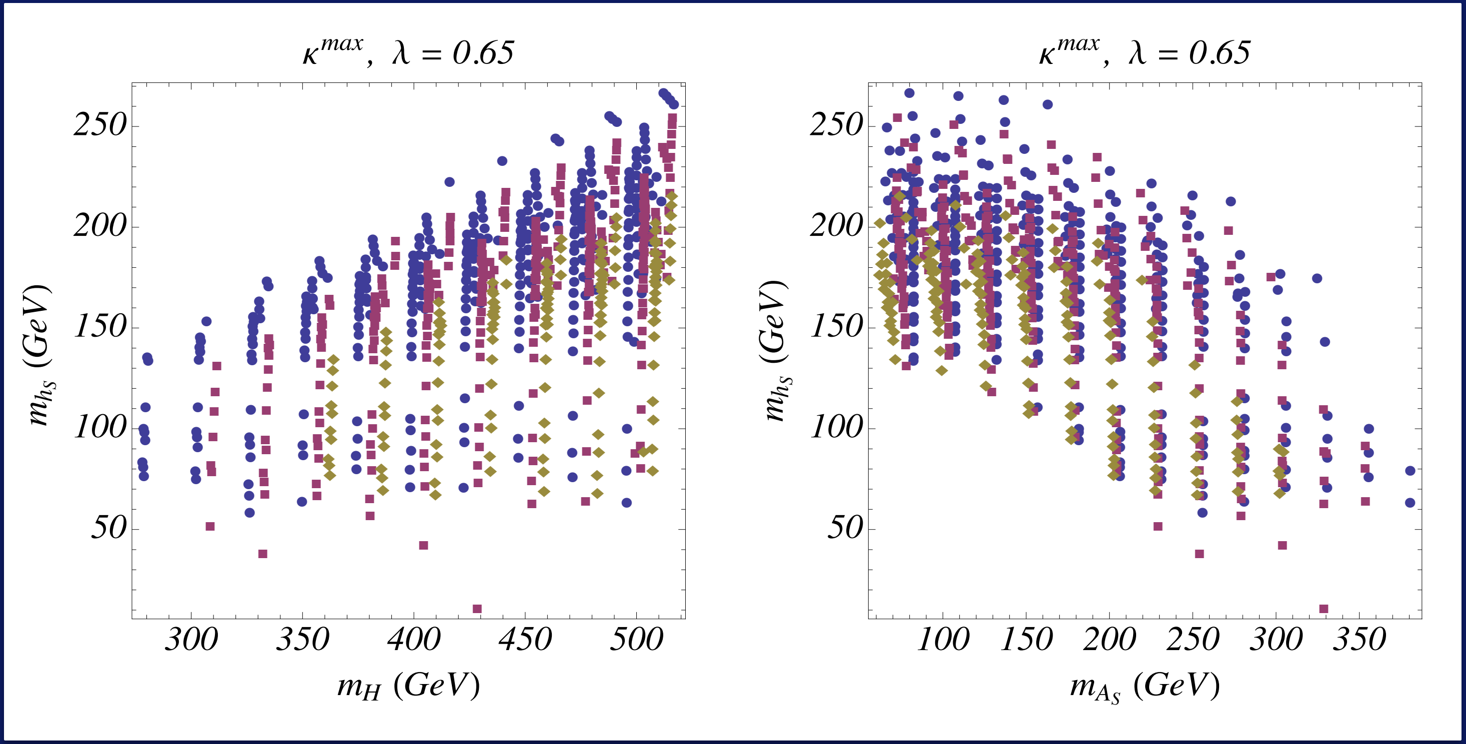
$$\mathbf{m_A \approx \frac{2|\mu|}{\sin 2\beta}}$$

Since both m_A and μ should be small, we see again that alignment and naturalness come together in a beautiful way 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

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

Singlet Spectra



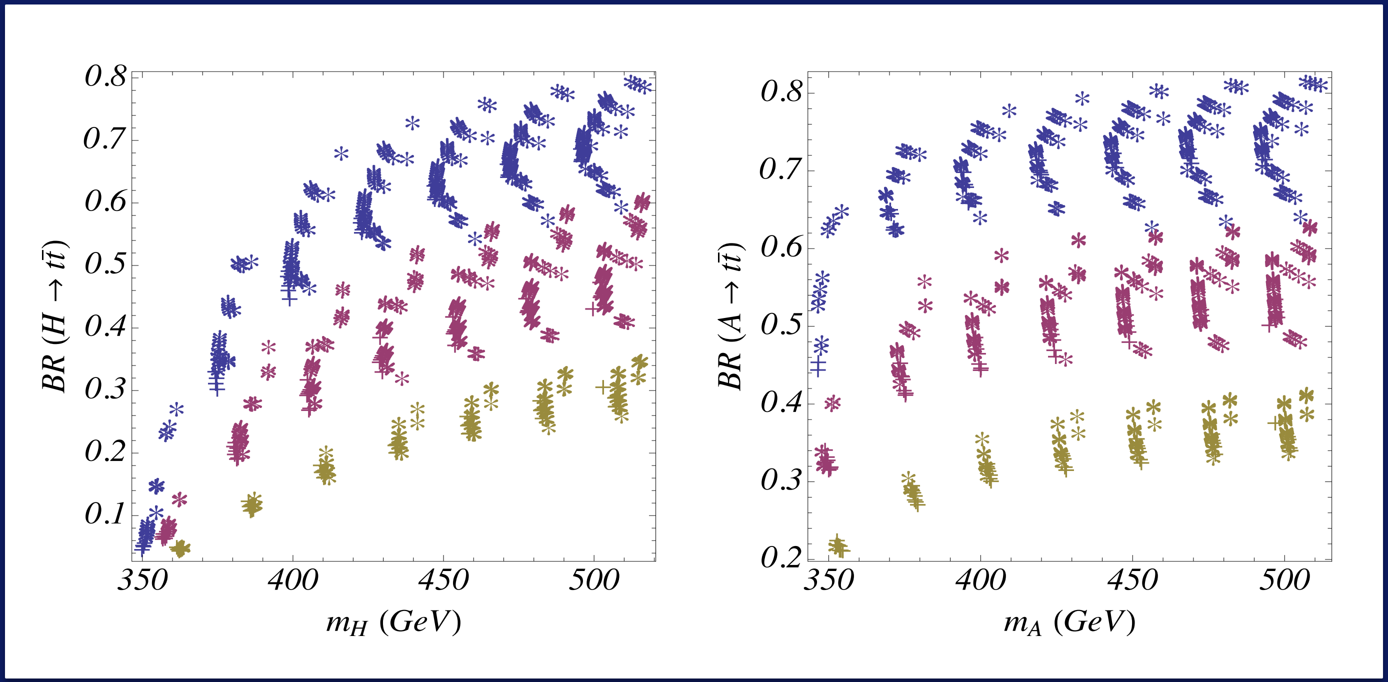
Heavier CP-even Higgs can decay to lighter ones

Anticorealation between singlet –like CP-even and CP-odd masses

. tan β =2 . tan β =2.5 . tan β =3

Scan of over parameter space with allowed misalignment from precision Higgs measurements and searches (e.g. Φ → WW)
NMSSMTools + HiggsBounds/Signals

MSSM-like A and H decays into top pairs



. tan β =2 . tan β =2.5 . tan β =3

Significant decays into top pairs,

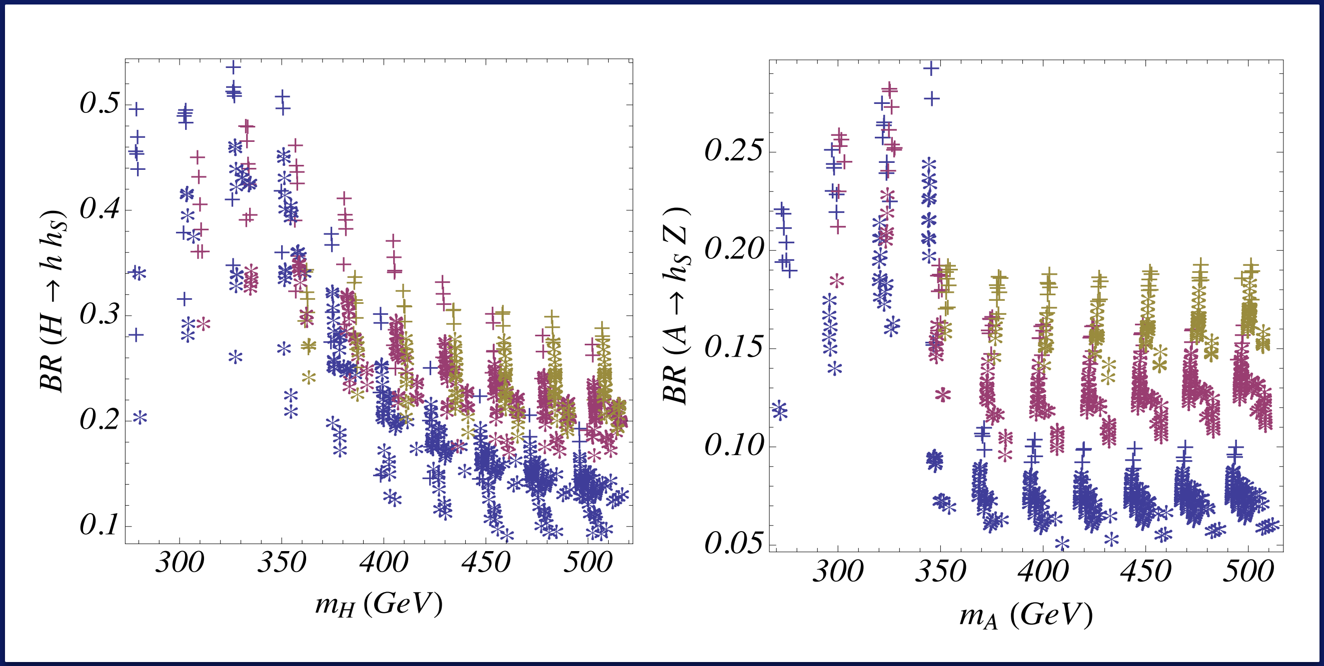
BR's depend on tanβ

May be somewhat suppressed by decays involving to non-SM particles

Decays into Neutralinos and Charginos above top threshold between 10 and 50%

MSSM-like A and H decay into lighter Higgs bosons and Z's

$H \rightarrow hh_S$



$A \rightarrow h_S Z$

. tan β =2 . tan β =2.5 . tan β =3

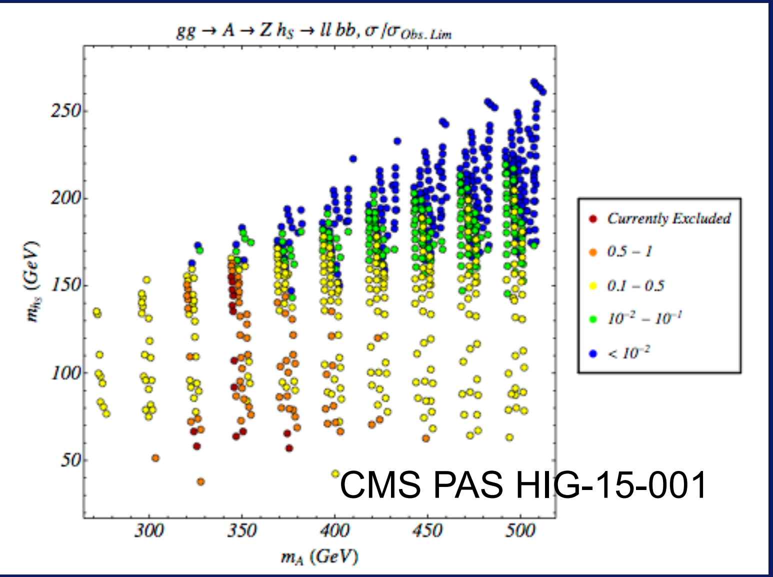
H → hh and A → hZ decays strongly suppressed due to alignment

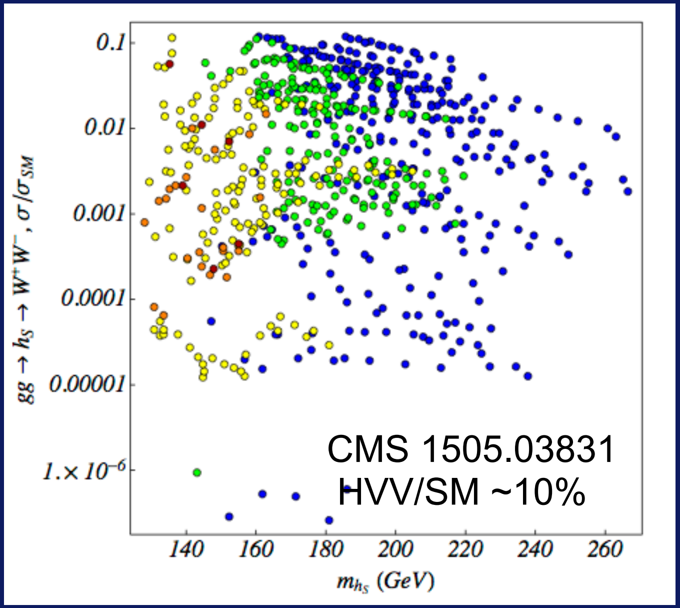
Others: H → hs hs; H → As Z; A → As hs; A → As h of order 10% or below

Singlet-like scalars: h_S mainly decays to bb and WW ; a_S mainly decays to bb

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



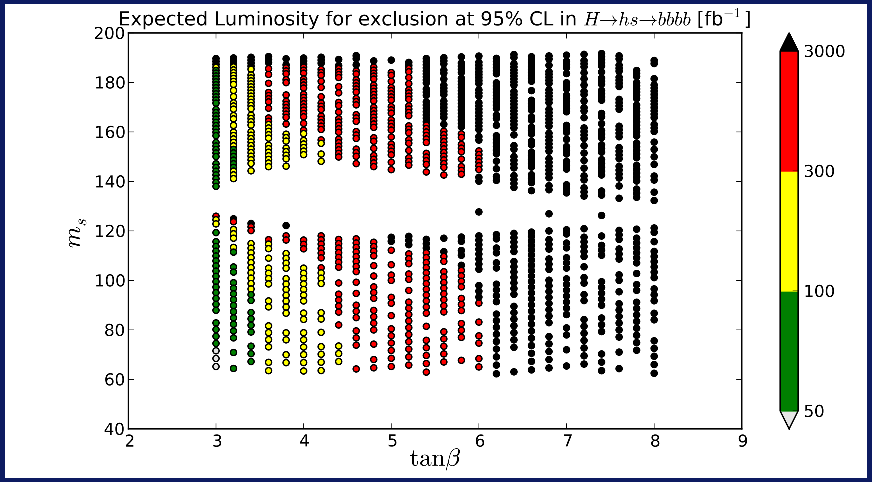


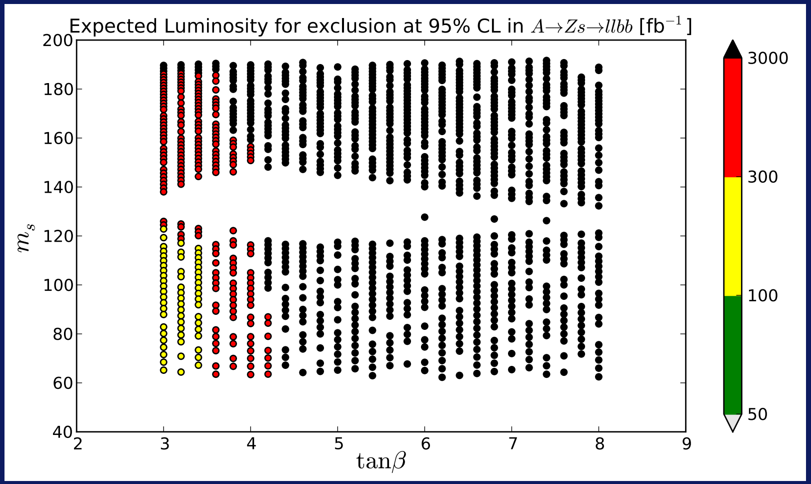
- Promising H → h h_S channels with hs → bb or WW (4b's or bbWW)

- Channels with missing energy: A → h a_s; H → Z a_s with a_s → neutralinos possible for tanβ ~ 4 to 6 (lighter singlet spectrum)

Ongoing searches at the LHC are probing exotic Higgs decays

- Exploring the “wedge” in the NMSSM

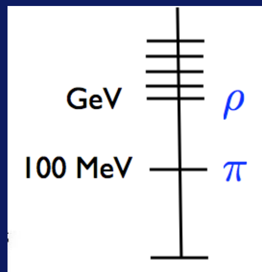




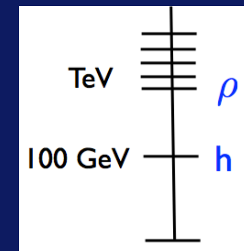
Very crude extrapolation
ATLAS 4b’s **arXiv:1606.04782**

Extrapolation based on
CMS PAS HIG-16-010

Composite Higgs Models
The Higgs as a pseudo Nambu-Goldstone Boson (pNGB)



Inspired by pions in QCD



QCD with 2 flavors: global symmetry $SU(2)_L \times SU(2)_R / SU(2)_V$.

π^{+-} π^0 are Goldstones associated to spontaneous breaking

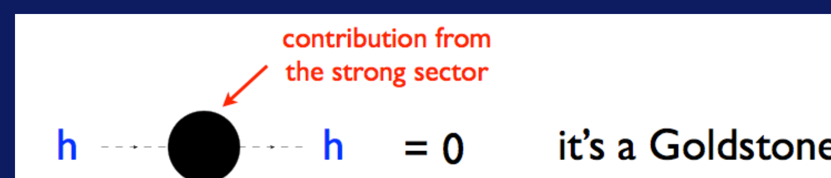
$$g, g' \to 0 \quad \& \quad m_q \to 0 \quad \Rightarrow m_\pi = 0$$

$$m_q \neq 0 \Rightarrow m_\pi^2 \simeq m_q B_0$$

$$e \neq 0 \Rightarrow \delta m_{\pi^\pm}^2 \simeq \frac{e^2}{16\pi^2} \Lambda_{QCD}^2$$

Higgs is light because is the pNGB -- a kind of pion – of a new strong sector

Mass protected by the global symmetries



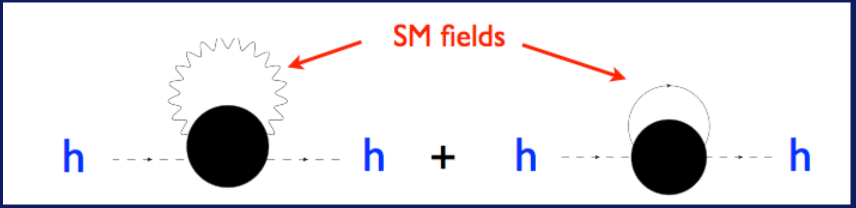
A tantalizing alternative to the strong dynamics realization of EWSB

Georgi,Kaplan'84

Higgs as a PNGB

Light Higgs since its mass arises from one loop

Mass generated at one loop: explicit breaking of global symmetry due to SM couplings



Dynamical EWSB: large set of vacua, some of them break $SU(2)_L \times U(1)_Y$

The Higgs potential depends on the chosen global symmetry
AND
on the fermion embedding in the representations of the symmetry group

Higgs mass challenging to compute due to strong dynamics behavior

$$m_H^2 \propto m_t^2 M_T^2 / f^2$$

Composite-sector characterized by a coupling $g_{cp} \gg g_{SM}$ and scale $f \sim$ TeV

New heavy resonances ➔ $m_\rho \sim g_\rho f$ and $M_{cp} \sim m_\rho \cos_\psi$

New Heavy Resonances being sought for at the LHC

Minimal Composite Higgs models phenomenology

-- All About Symmetries --

Choosing the global symmetry [SO(5)] broken to a smaller symmetry group [SO(4)]
-- at an intermediate scale f larger the electroweak scale -- such that:
the Higgs can be a pNBG, the SM gauge group remains unbroken until the EW scale
and there is a custodial symmetry that protects the model from radiative corrections

Higgs couplings to W/Z determined by the gauge groups involved

SO(5) ➔ SO(4)

SO(5) ×U(1) smallest group: $\supset G^{EW}_{SM}$ & cust. sym. & H = pNGB

Other symmetry patterns with additional Higgs Bosons

Model	Symmetry Pattern	Goldstone's
SM	SO(4)/SO(3)	W_L, Z_L
–	SU(3)/SU(2)×U(1)	W_L, Z_L, H
MCHM	SO(5)/SO(4)×U(1)	W_L, Z_L, H
NMCHM	SO(6)/SO(5)×U(1)	W_L, Z_L, H, a
MC2HM	SO(6)/SO(4)×SO(2) ×U(1)	$W_L, Z_L, h, H, H^{\pm}, a$

Higgs couplings to SM fermions depend on fermion embedding

With Notation $\mathrm{MCHM}_{\text{Q-U-D}}$

5, 10,
5-5-10, 5-10-10, 10-5-10
14-14-10, 14-1-10

SO(5) Representations

Generic features:

Suppression of all partial decay widths and all production modes

Enhancement/Suppression of BR's dep. on the effect of the total width suppression

Simplest Minimal Composite Higgs: ATLAS 8 TeV data

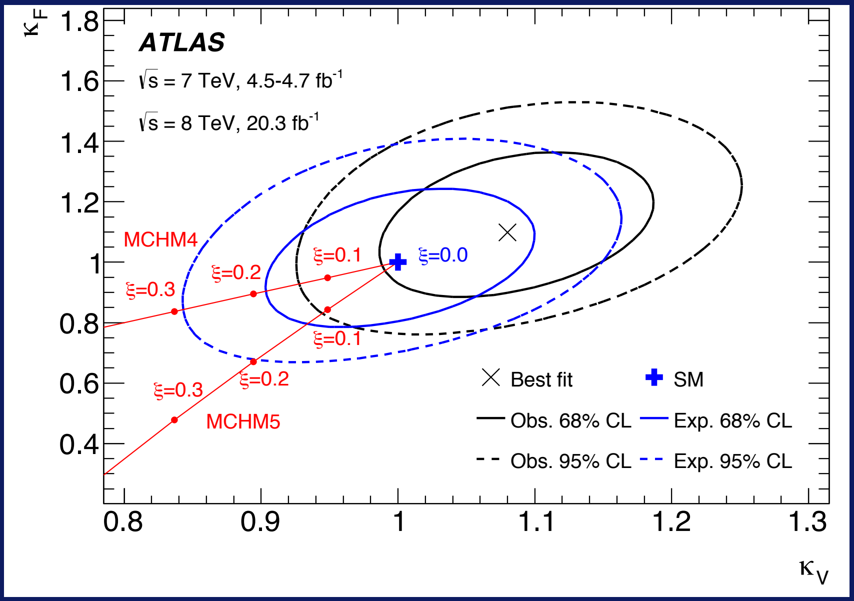
MCHM4➔ fermions in spinor representation of SO(5)

$$\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$$

MCHM5➔ fermions in fundamental representation of SO(5)

$$\kappa_V = \sqrt{1-\xi} \qquad \kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

$\xi = v^2/f^2$

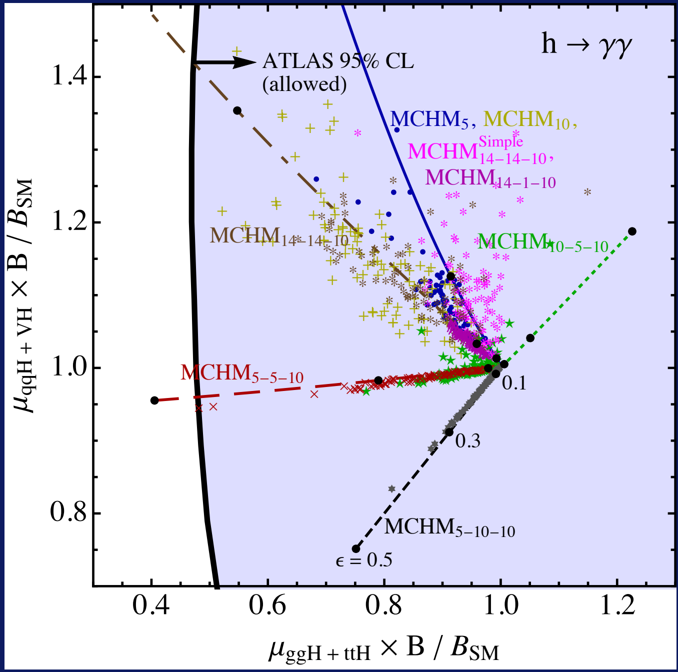


Model	Lower limit on f	
	Obs.	Exp.
MCHM4	710 GeV	510 GeV
MCHM5	780 GeV	600 GeV

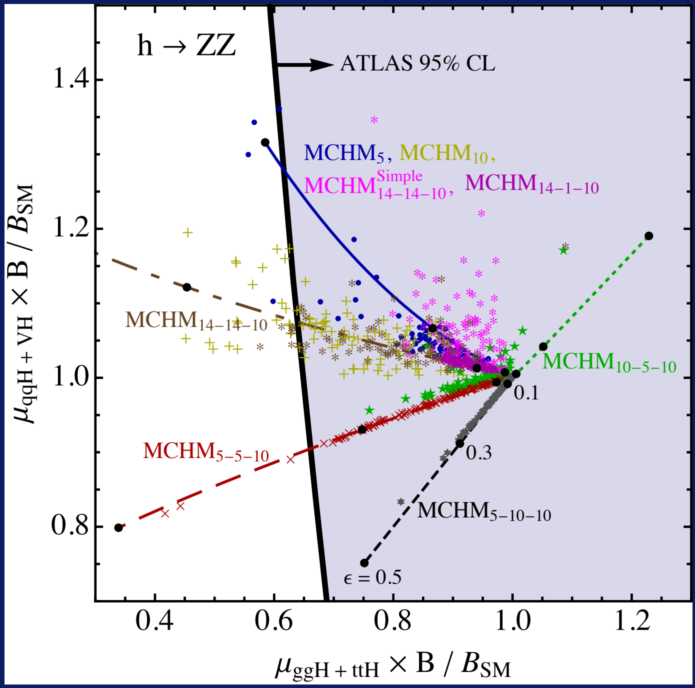
CERN-PH-EP-2015-191

More diverse Minimal Composite Higgs models confronting data

h to di-photons



h to ZZ



After EWSB: $\varepsilon = v_{SM}/f$ and precision data demands f > 500 GeV

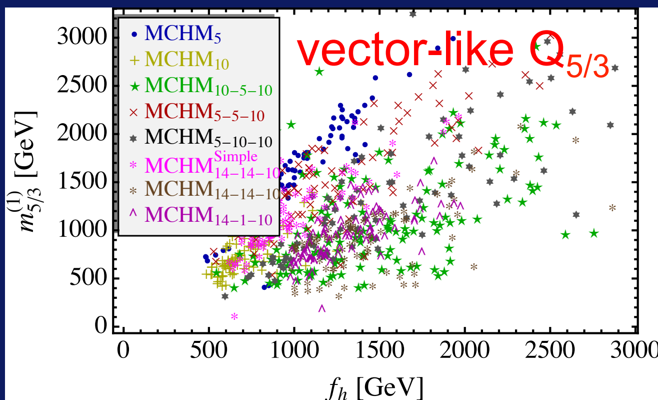
M.C., Da Rold, Ponton'14

- More data on Higgs observables will distinguish between different realization in the fermionic sector, providing information on the nature of the UV dynamics
- Extended global gauge symmetries imply a heavy Higgs sector that may be strongly constrained by Higgs data: e.g. the inert 2HDM implies a light Higgs spectra + MET
- Lots of model building underway to confront with LHC13 data

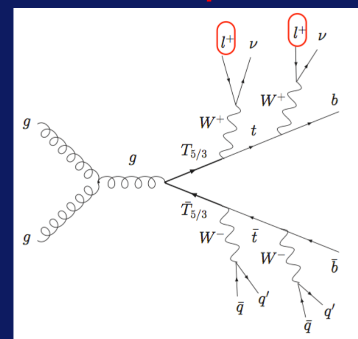
Composite pNGB Higgs Models predict light Fermions

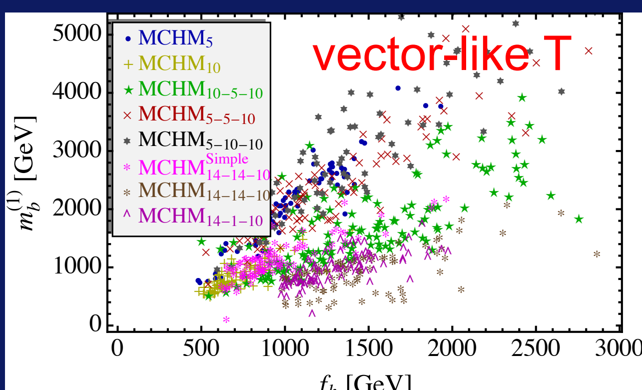
Pair production, single production, or exotic Higgs production of vector-like fermions

[masses in the TeV range and possibly with exotic charges: Q = 2/3,−1/3, 5/3,8/3,−4/3]



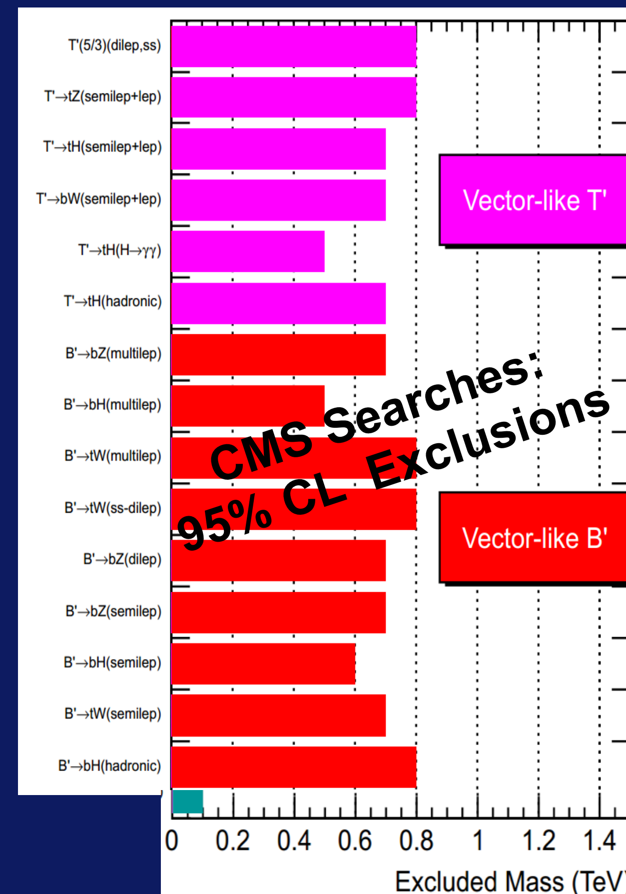
SS di-leptons





Large variety of signatures, many with energetic leptons

M.C., Da Rold, Ponton’14



LHC exclusion for M_f < 800 GeV]

Composite Twin Higgs may elude color top partners at the TeV scale (Greco’s talk)

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

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

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

Issue: Scales undetermined

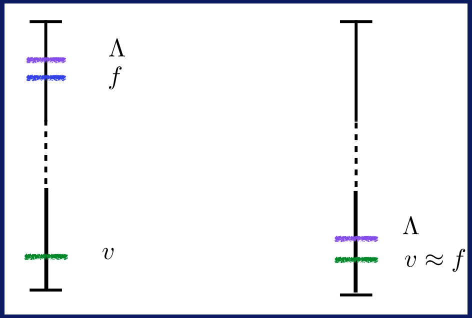
- How to define the scales? Can the Higgs play the role of the Flavon?

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

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

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 $n_b \to 0$)

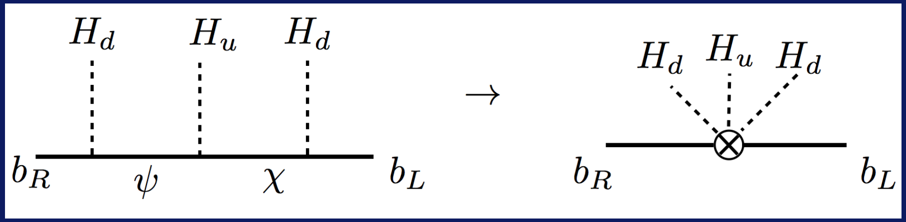
With effective Yukawa coupling: $y_i^{eff} = \left(\frac{v_u v_d}{2\Lambda^2}\right)^{n_i} y_i$

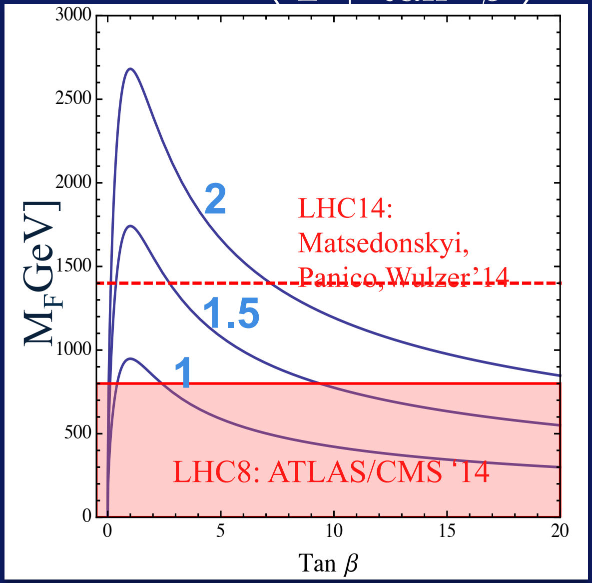
$$v^2 = v_u^2 + v_d^2$$
$$\tan\beta = v_u / v_d$$

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 β = 1)
can be slightly larger depending on UV completion

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





Many interesting, measurable effects can probe this idea

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

FCNCs at tree-level ⟷ Numerous Flavour constraints

Direct collider probes of heavy scalars ⟷ ATLAS and CMS searches

Propose Benchmark scenarios to probe the model

Lightest (SM-like) Higgs bosons couplings

- Flavor Structure by fixing flavor charges

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

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

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

- 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) :

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

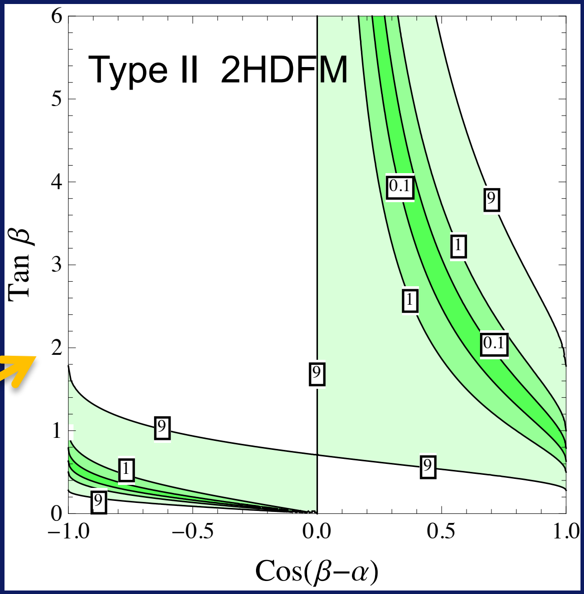
Higgs Production (at leading order) equivalent to a 2HDM type II

- Higgs coupling to the bottom (& charm) quarks

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

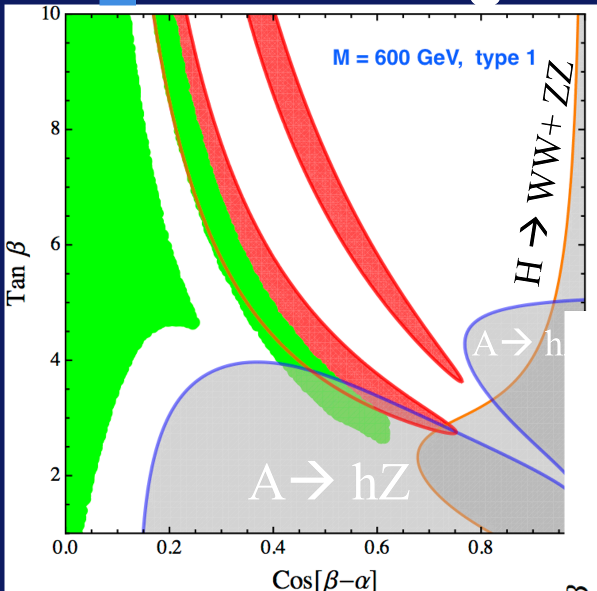
VERY DIFFERENT BEHAVIOUR

- 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



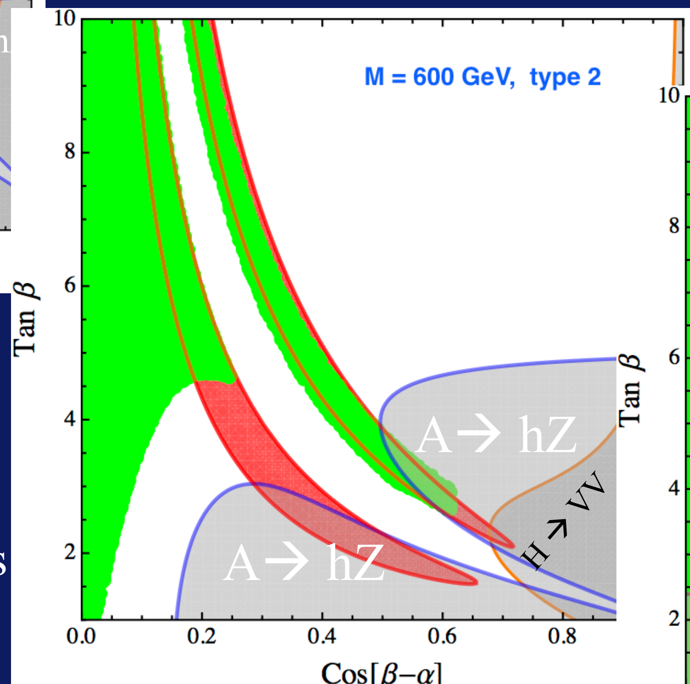
A predictive model with new Physics at LHC reach

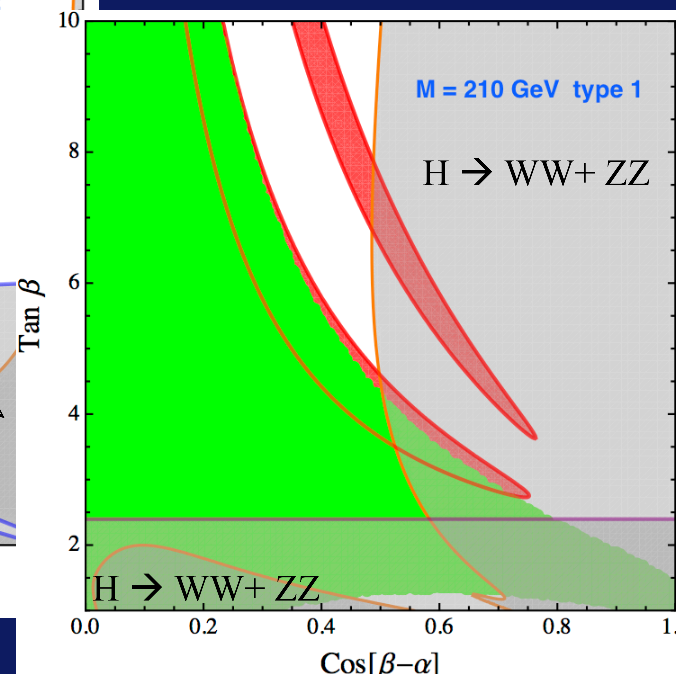
allowed regions beyond those in a 2HDM type I or II



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

Other channels: H →hh, and searches for TeV range fermions

Great possibilities for direct collider searches !!

Outlook

The 125 GeV Higgs can be accommodated in in many BSM scenarios with light partners

Precision measurements of the Higgs signals call for a significant degree of alignment that in turn has important implications for the searches for additional Higgs bosons.

In the MSSM:

Bounds on A/H from direct searches and precision Higgs measurements are model dependent and should be interpreted with care.

Departures from alignment yield decays of A/H into gauge bosons, h and top pairs (EWikinos)

In the NMSSM:

Necessary degree of alignment without decoupling is tied to a light Higgsino, Singlino and singlet –like Higgs sector and allows for light stops with modertae mixing.
Good for achieving the 125 Higgs mass and compatible with perturbavity up to M_{GUT}

New search channels for A/H decaying to Higgs like singlets and gauge bosons

Composite Higgs Models and 2HDFM

Constrained by Higgs precision data & can have additional Higgs boson signals probed at LHC

Complementarity between precision measurements and direct additional Higgs searches very important to efficiently probe extended SUSY Higgs sector or various 2HDMs

(Low energy) SUSY in the Fight