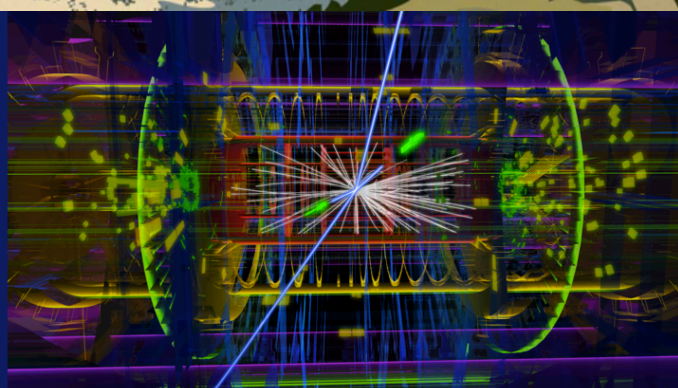
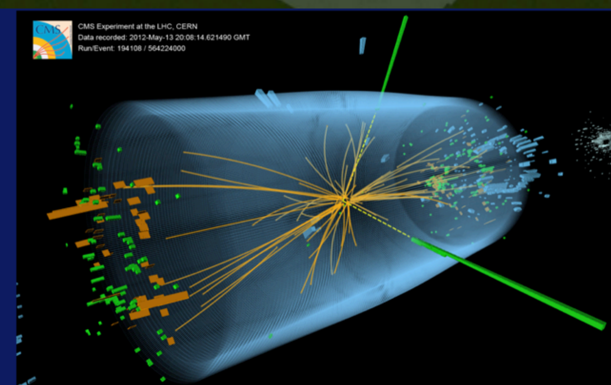
Higgs Physics and Dark Matter

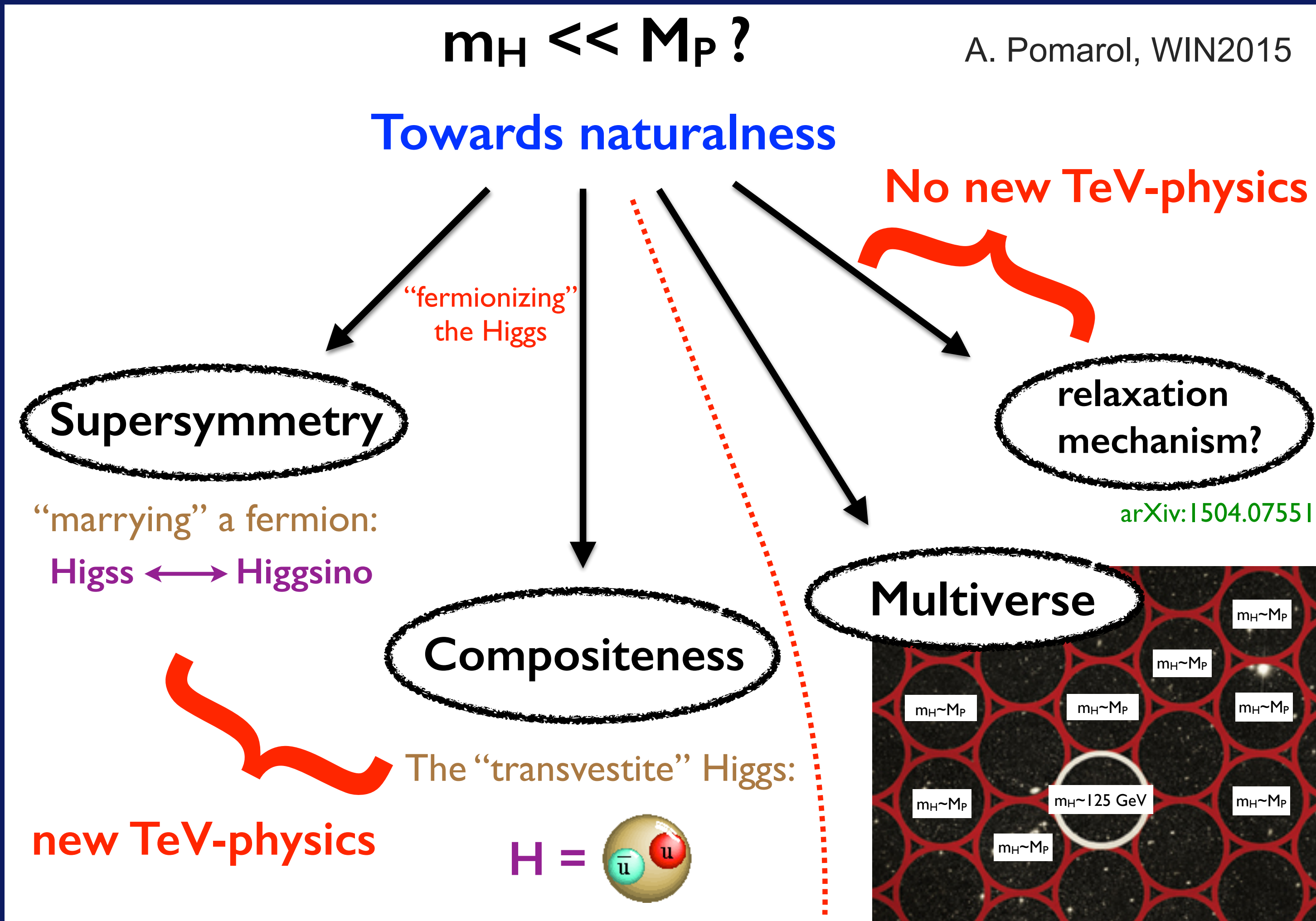




Marcela Carena
Fermilab and Uchicago

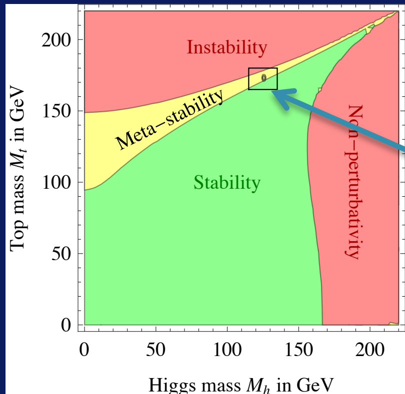
Invisibles17 Workshop, UZH, Zurich, June 12, 2017

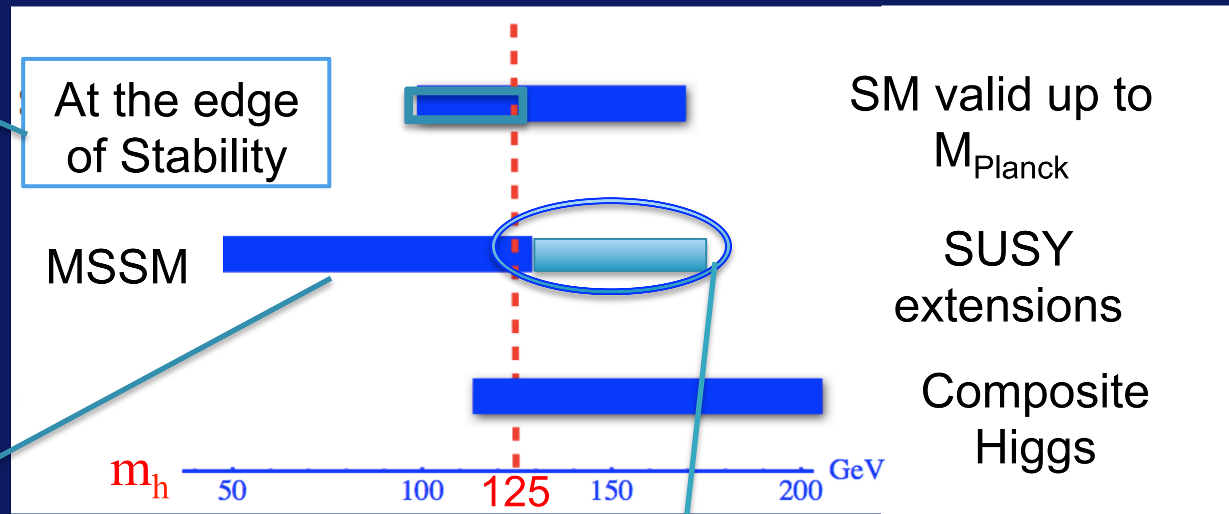
New Physics Landscape after the Higgs Discovery

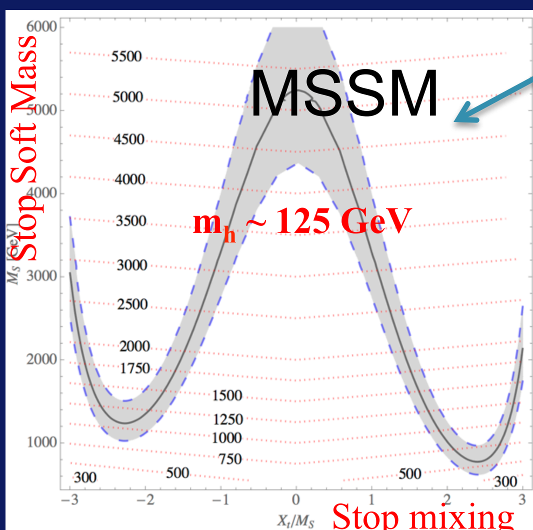


How far are we willing to go?

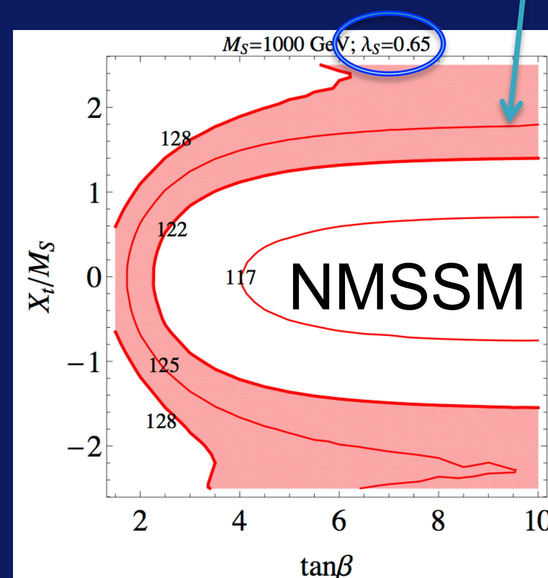
Looking under the Higgs lamp-post:







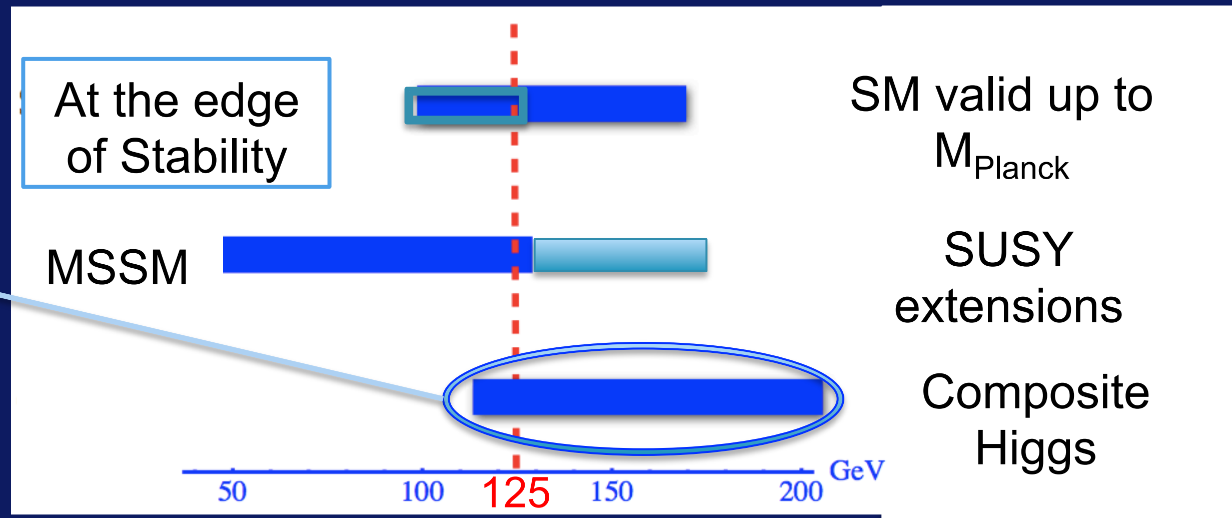
Splitting in stop SUSY breaking mass parameters can accommodate one light stop with minimal impact to gluon fusion



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

Looking under the Higgs lamp-post:

No Higgs above a certain scale, at which the new strong dynamics turns on
➔ dynamical origin of EWSB

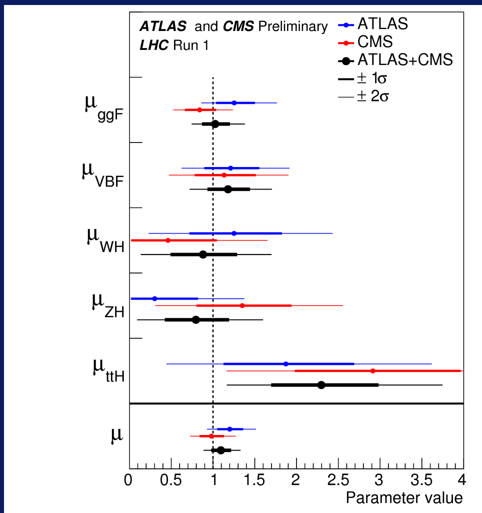


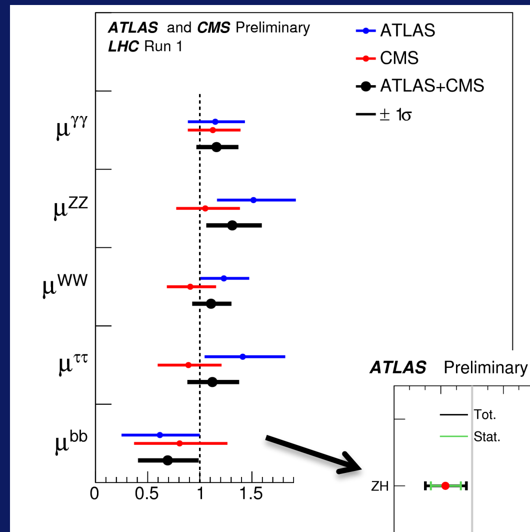
New strong resonance masses constrained by EW data and direct searches
Higgs ➔ scalar resonance much lighter that other ones

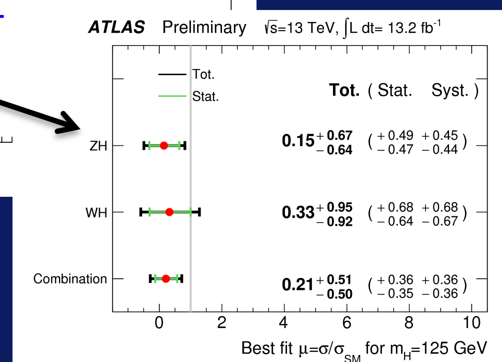
Additional option: 2HDMs to explain flavor @EW scale
Higgs bosons as the Frogatt-Nielsen Flavon

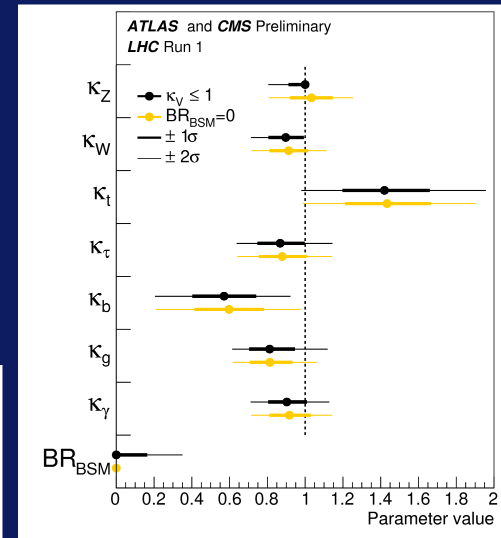
All these BSM alternatives can affect Higgs production & decay signal strengths

Higgs Properties in good agreement with SM predictions







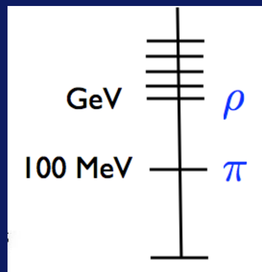


Still direct measurement of bottom & top couplings subject to large uncertainties
Moderate deviations from SM predictions possible

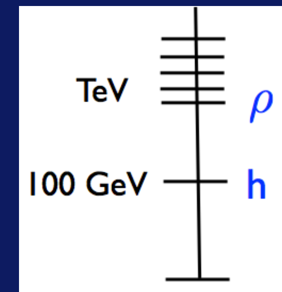
In Run 2 data, suppression of bottom coupling still present

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

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



Inspired by pions in QCD



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

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

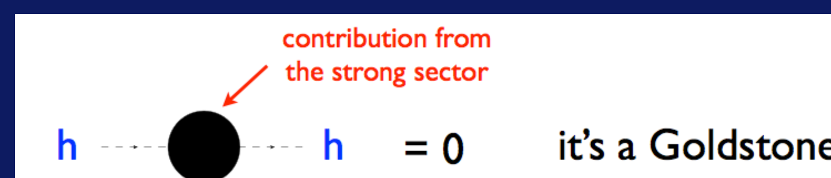
$$g, g' \to 0 \quad \& \quad m_q \to 0 \quad \Rightarrow m_\pi = 0$$

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

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

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

Mass protected by the global symmetries



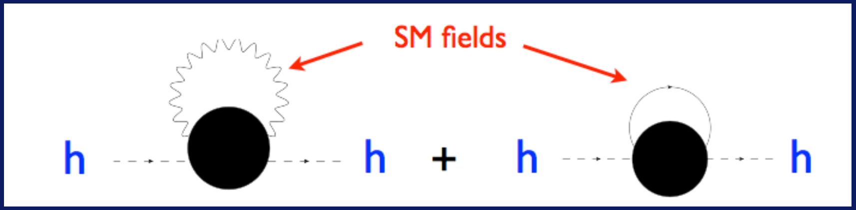
A tantalizing alternative to the strong dynamics realization of EWSB

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 $f \sim \text{TeV}$

New heavy resonances ➔ $m_\rho \sim g_{cp} f$ 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: ⊃ G^{EW}_{SM} & cust. sym. & H = pNGB

Other symmetry patterns, some 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 effects of the total width suppression

Simplest Minimal Composite Higgs

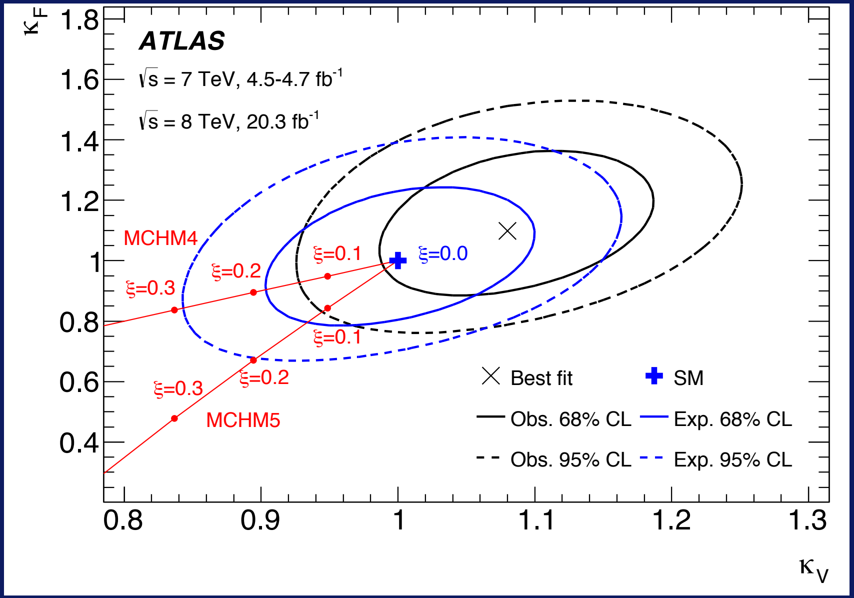
MCHM4 ➔ fermions in spinorial **4** representation of SO(5)

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

MCHM5 ➔ fermions in fundamental **5** representation of SO(5)

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

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

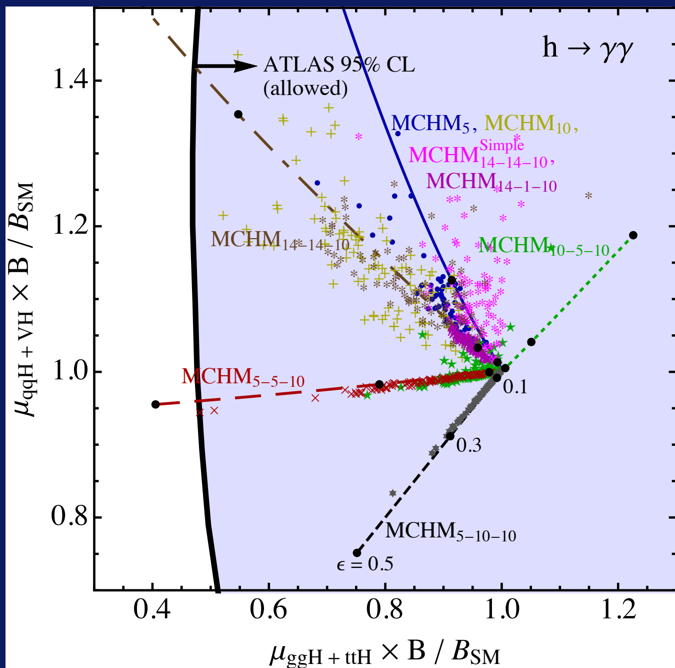


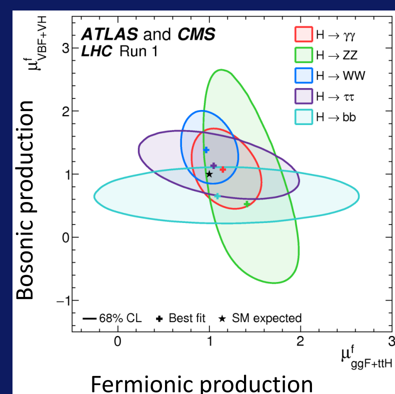
Model	Lower limit on f	
	Obs.	Exp.
MCHM4	710 GeV	510 GeV
MCHM5	780 GeV	600 GeV

CERN-PH-EP-2015-191

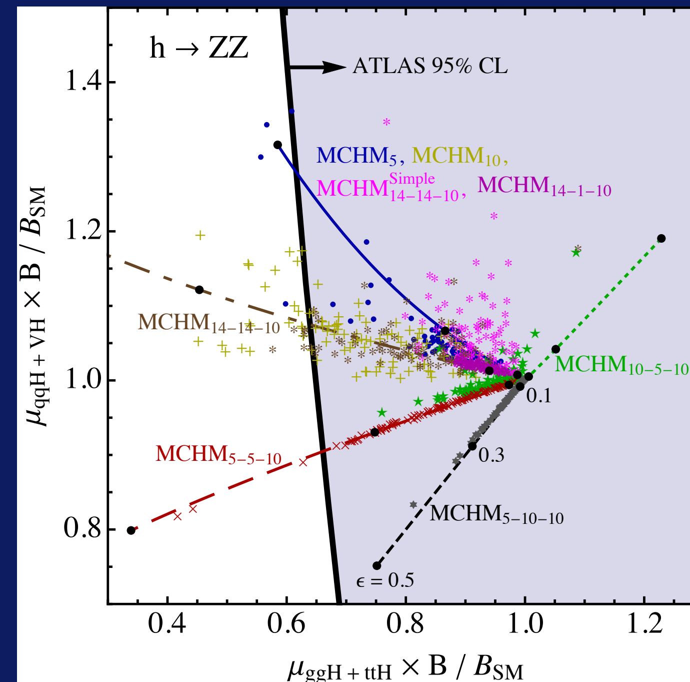
More diverse Minimal Composite Higgs models confronting data

h to di-photons





h to ZZ



M.C., Da Rold, Ponton'14

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

- More data on Higgs observables may distinguish between different realizations in the fermionic sector, providing information on the nature of the UV dynamics

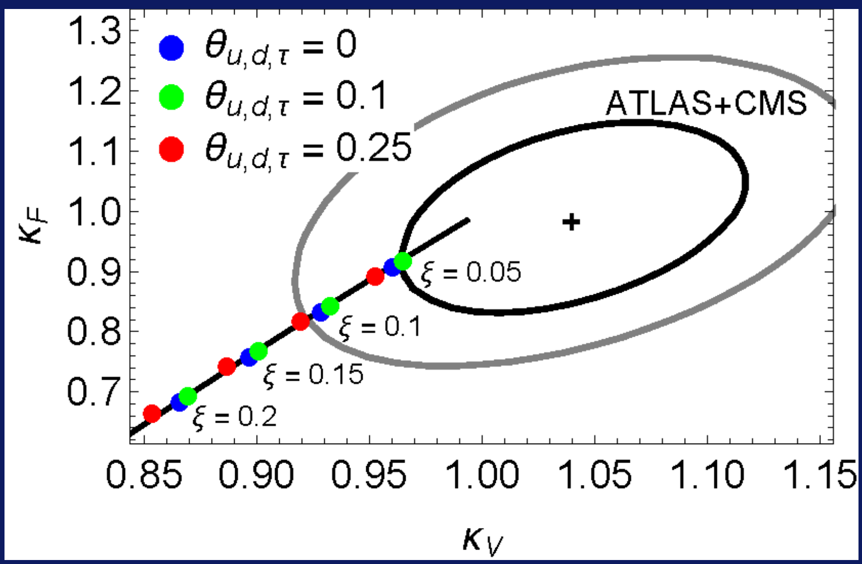
Two Higgs Doublet Composite Models

Data on Higgs signal strengths ➔ almost Alignment: h_{125} almost SM

[SO(6)/SO(4) x SO(2)] x U(1) with fermions in 6plet rep. J. Mrazek et al.1105.5403

De Curtis et al. 1602.06437

Precision Higgs measurements



M.C., Davidovich, Machado, Panico, to appear.

K_V: main dependence on $\xi = v^2/f^2$

$$\kappa_V \simeq \cos\alpha \cos\tilde{\alpha}\sqrt{1-\xi}$$

K_F: dependence on the Higgs mixing

$$\kappa_t \simeq \frac{c_\alpha c_{\tilde{\alpha}}}{c_{\theta_u} c_\gamma c_{\tilde{\gamma}} + s_{\theta_u}(s_\gamma + s_{\tilde{\gamma}})} \frac{1-2\xi}{\sqrt{1-\xi}}$$

Small violation of custodial symmetry

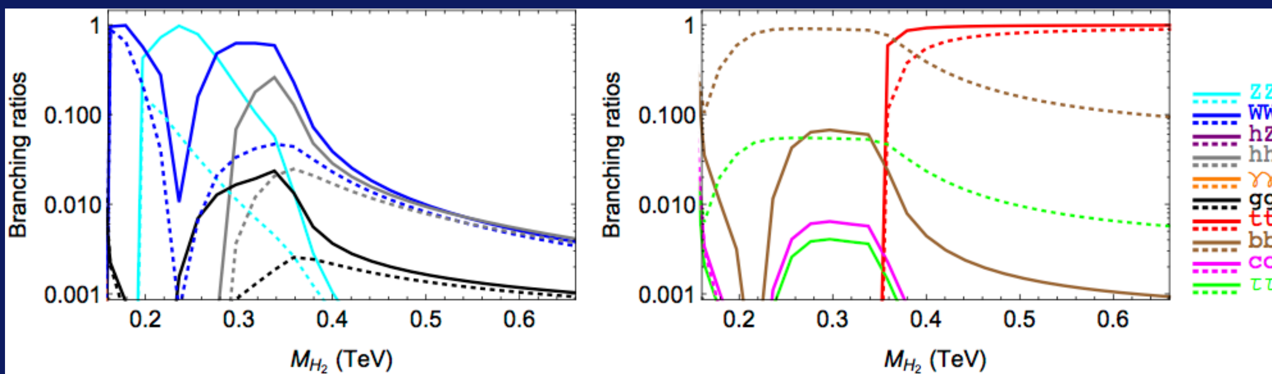
Small violation of CP, only after inclusion of the bottom sector

C_1P and C_2 invariance broken by $\Theta \neq 0$, but $CP_{C2HDM}=C_1P\,C_2$ preserved.

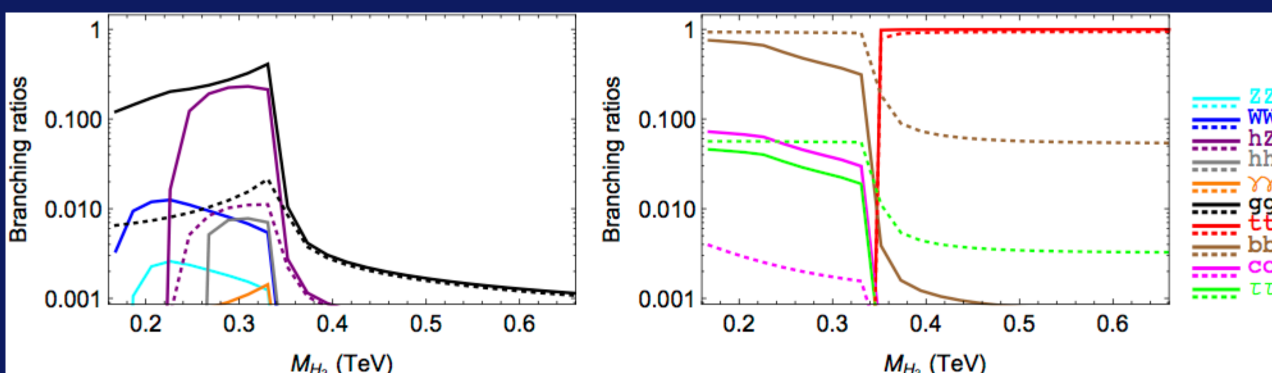
Additional Higgs Sector

SO(6)/SO(4) x SO(2)] x U(1) with fermions in 6plet rep.

- masses almost degenerate
- Fermiophilic (HDIM at alignment)
- Second Higgs doublet gets vev's that are misaligned: custodial invariance broken



H_2 is mainly H, but is defined as the custodial triplet component



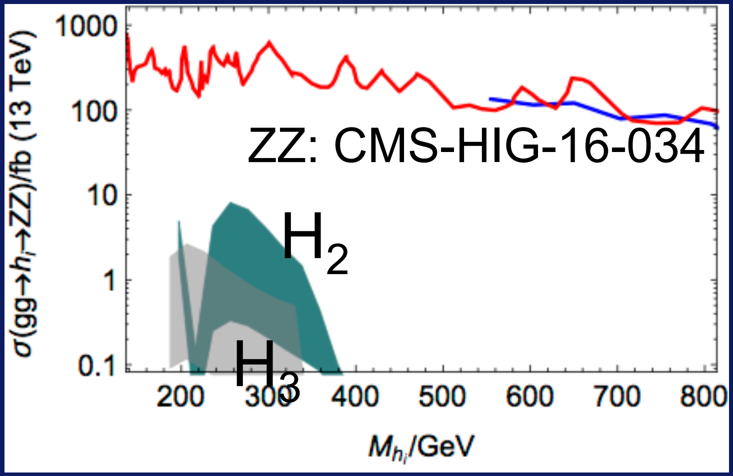
H_3 is mainly A, but is defined as the custodial singlet component

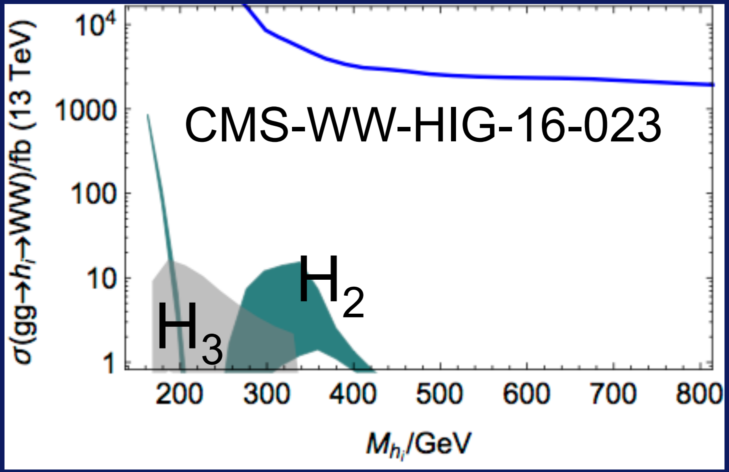
M.C., Davidovich, Machado, Panico, to appear

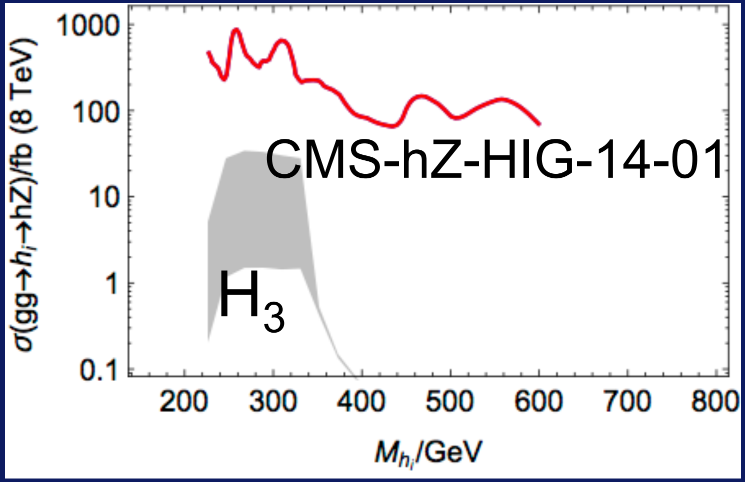
Solid: $\tan\theta_u = \tan\theta_d = \tan\theta_\tau = 0.1$
Dashed: $\tan\theta_u = 0.1$; $\tan\theta_d = \tan\theta_\tau = 1$

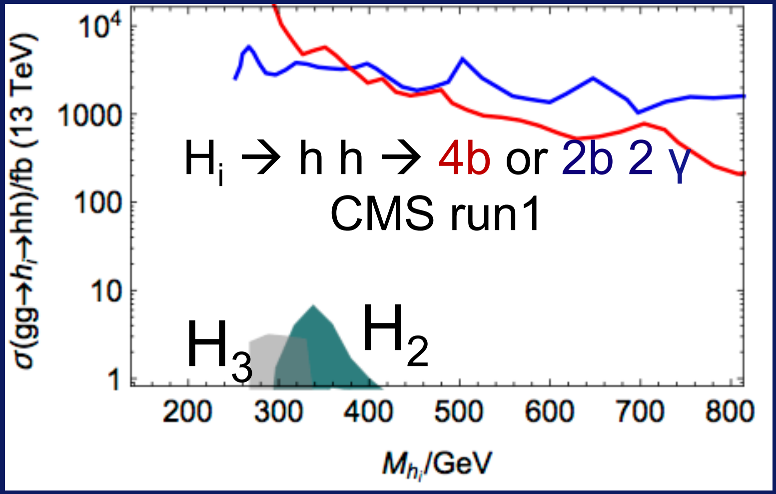
Searches for additional Higgs Bosons

SO(6)/SO(4) x SO(2)] x U(1) with fermions in 6plet rep



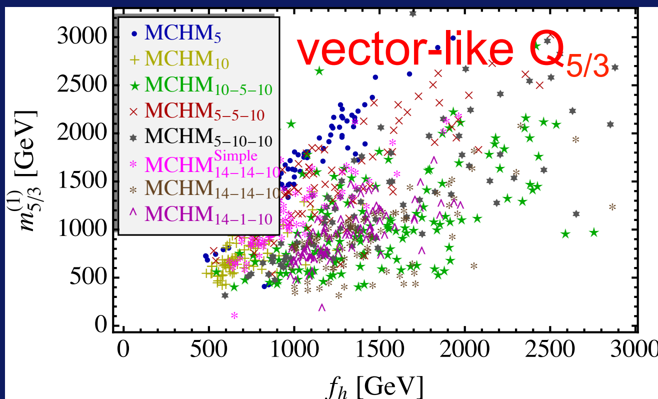




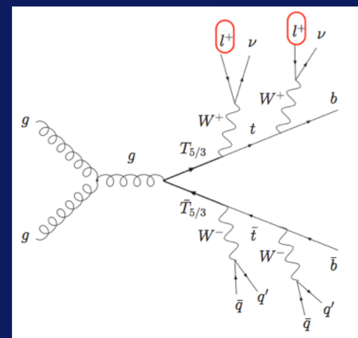


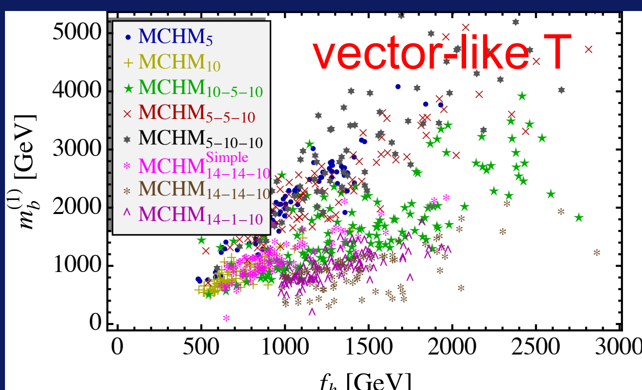
Composite pNGB Higgs Models predict light Fermions

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]

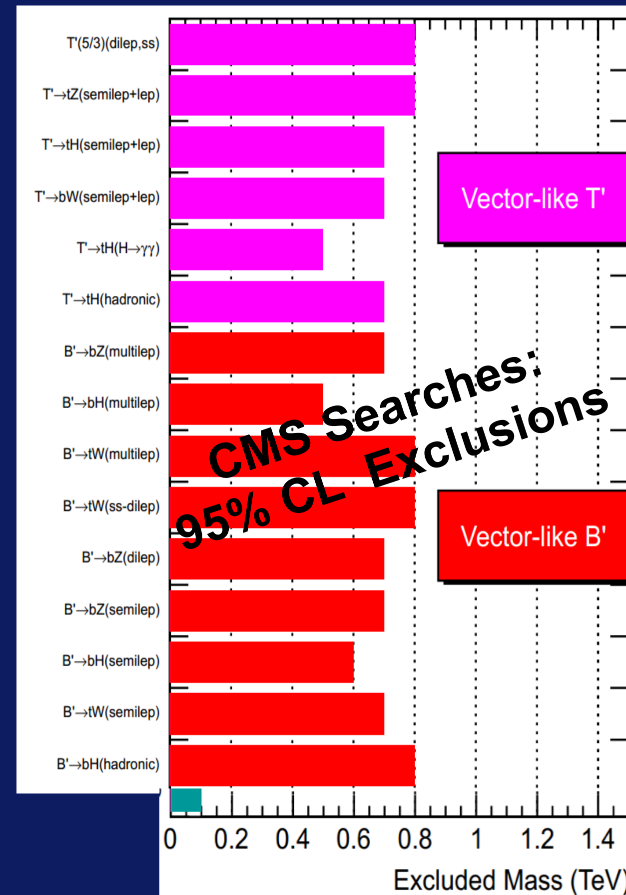


SS di-leptons





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

An Elementary Higgs Boson

e.g. Minimal SUSY: a 2HDM, type II

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

The couplings of the lightest Higgs to fermions and gauge bosons are SM.

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**

Valid for any 2HDM

Gunion and Haber ’03

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

If no CP violation in the Higgs sector:

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

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

An Elementary Higgs Boson

e.g. Minimal SUSY: a 2HDM, type II

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.

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This situation is called ALIGNMENT and occurs for

- large values of m_A → Decoupling — See N. Shah's talk
- 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 $\boldsymbol{\eta = \cos_{\beta-\alpha}\, t_\beta}$

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

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

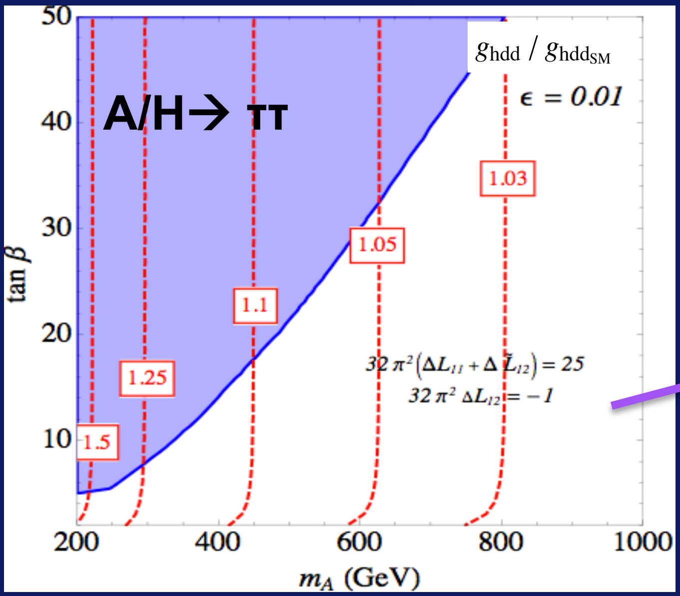
$$g_{huu} \approx (1 + t_\beta^{-2}\eta)\, g_f \,,$$

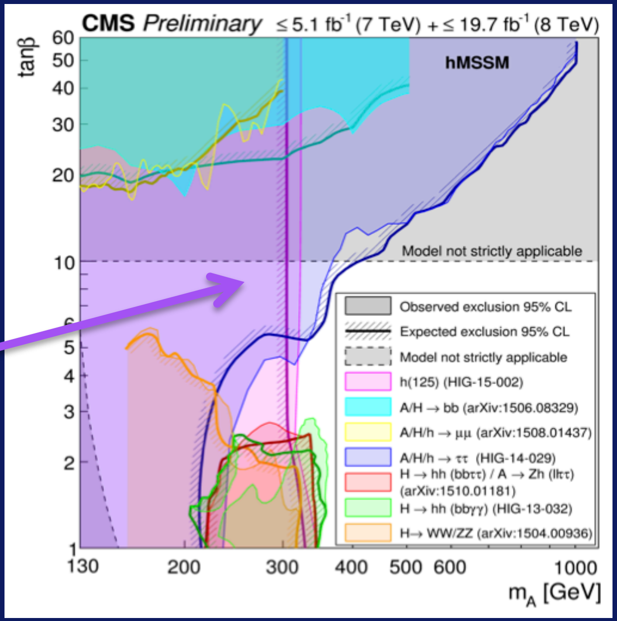
Impact of Precision Higgs measurements on A/H searches strongly correlated to the proximity to Alignment without decoupling

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

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

Bottom coupling in the MSSM





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

For moderate to large tanβ and small μ

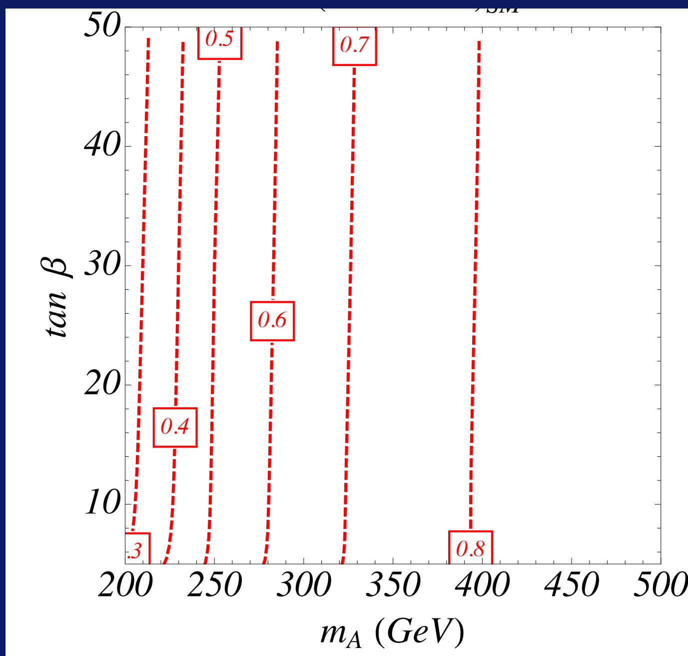
➔ no dependence on tanβ or on the stop mixing

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

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

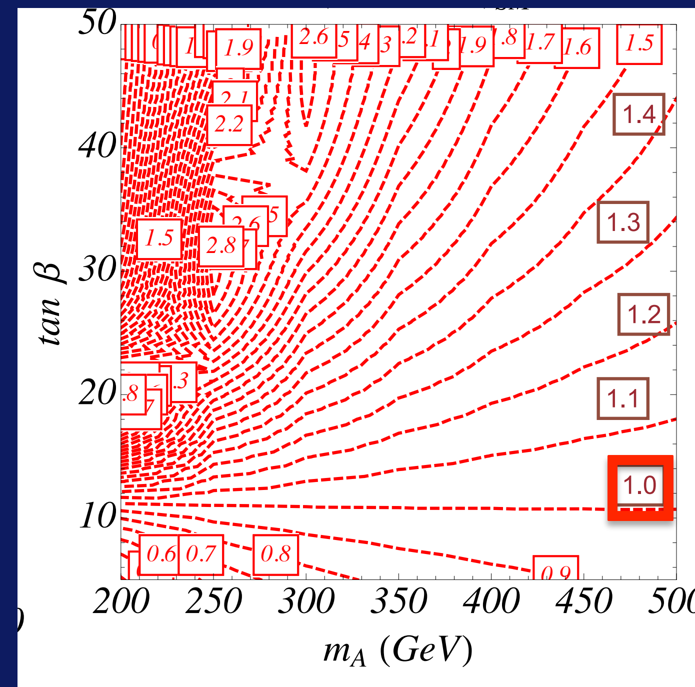
Higgs decays into gauge bosons mostly determined by bottom decay width

Small μ (no Alignment)



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

Sizeable μ ~ 2 M_{SUSY} (Alignment)



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

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

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

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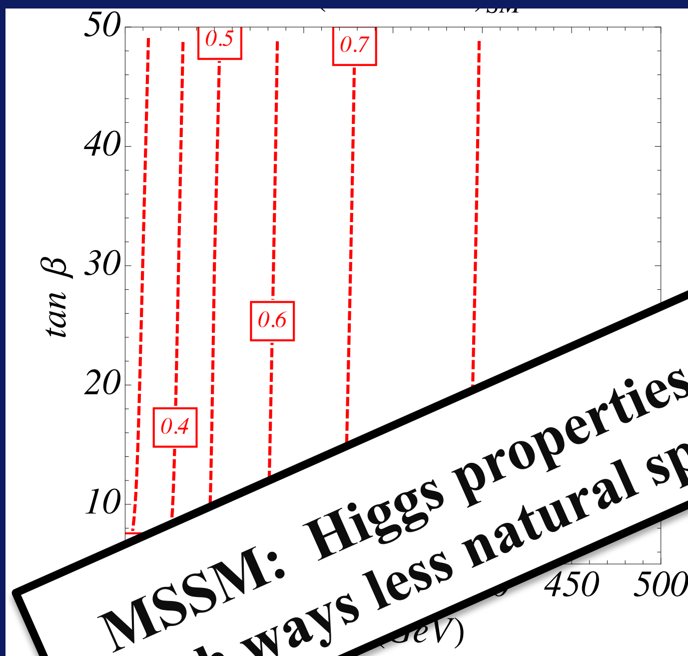
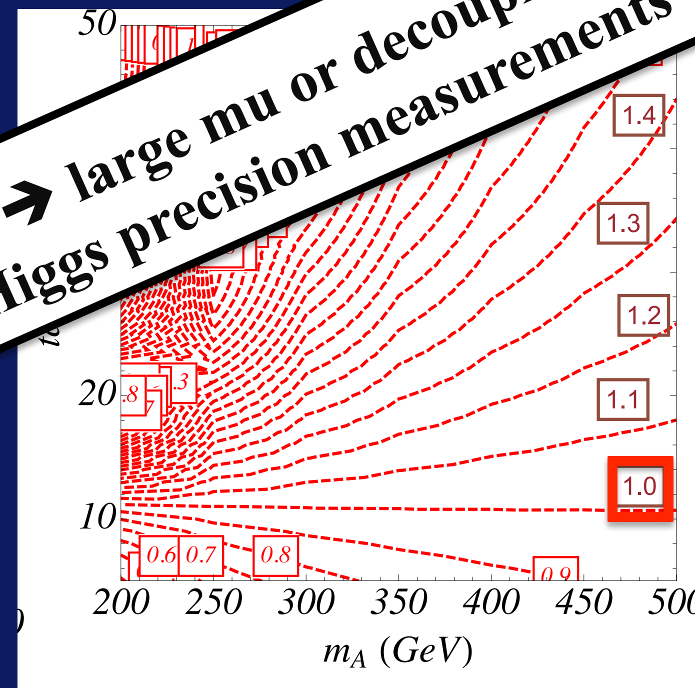


Sizeable μ ~ 2 M_{SUSY}



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

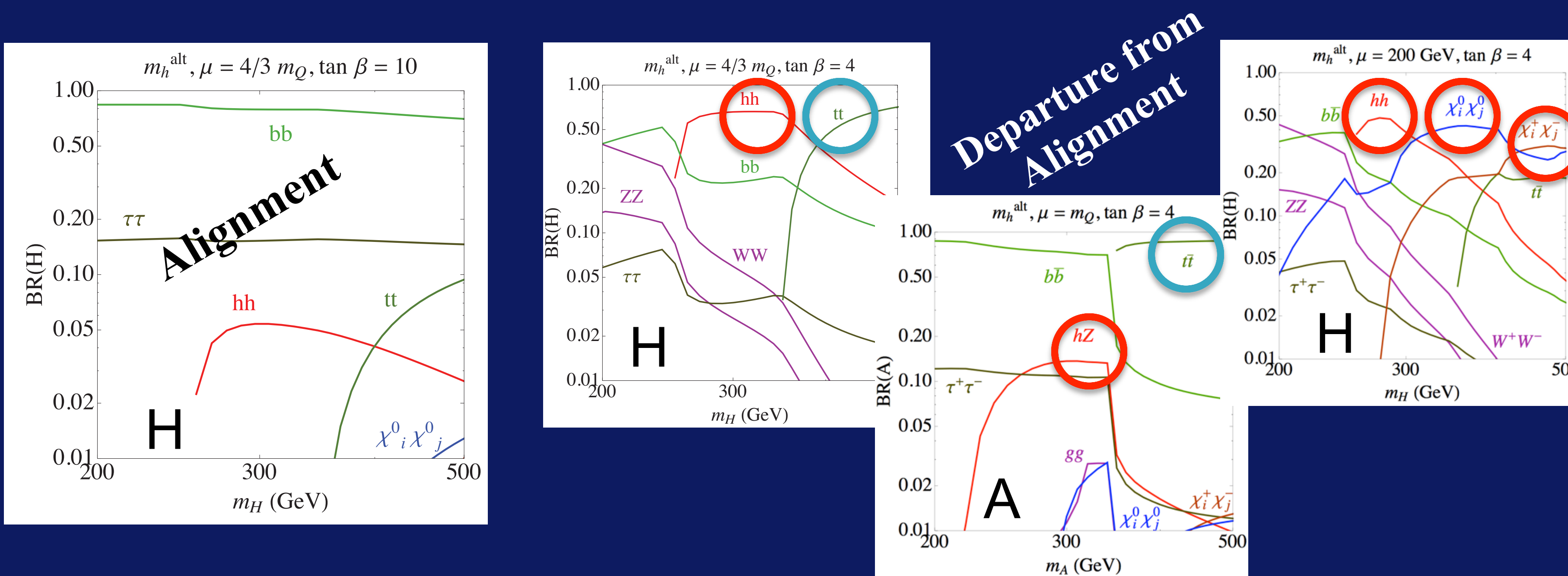
e.g. Tauphobic Benchmark

M.C., I. Low, N. Shah, Wagner'13
MC, Heinemeyer, Stal, Wagner, Weiglein'14

Heavy Higgs Bosons: A variety of decay Branching Ratios

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

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



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

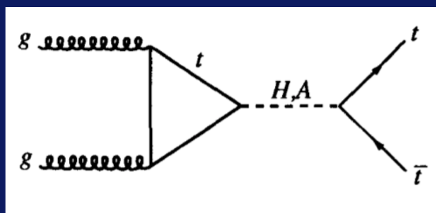
while $g_{Hhh} \simeq g_{HWW} \simeq g_{HZZ} \simeq g_{AhZ} \simeq 0$

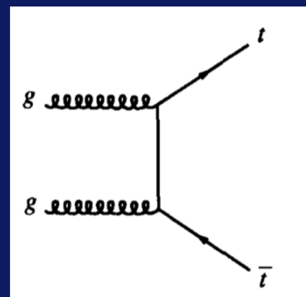
Production mainly via large bottom couplings: bbH

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

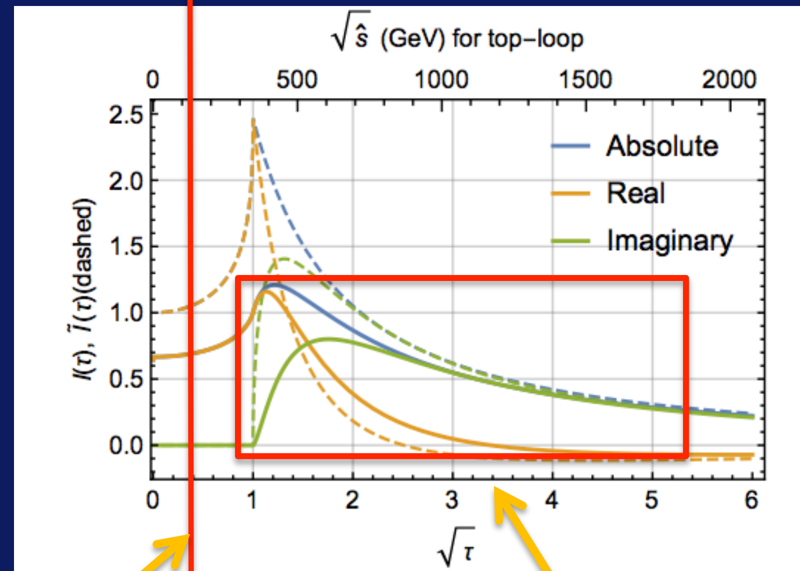
If low μ, then chargino and neutralino channels open up (impact on H/A ➔ **ττ**)

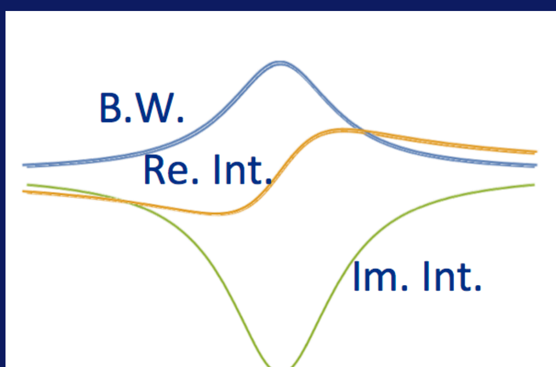
The challenging A/H ➔ tt channel: Interference effects





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)

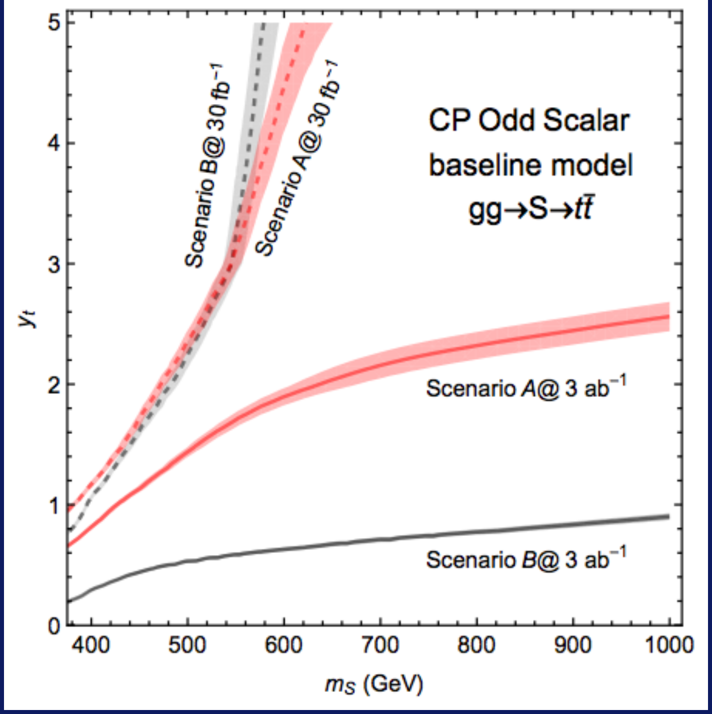
Im. Interference from the imaginary part of propagator with imaginary part of loop function (rare case, changes signal rate)

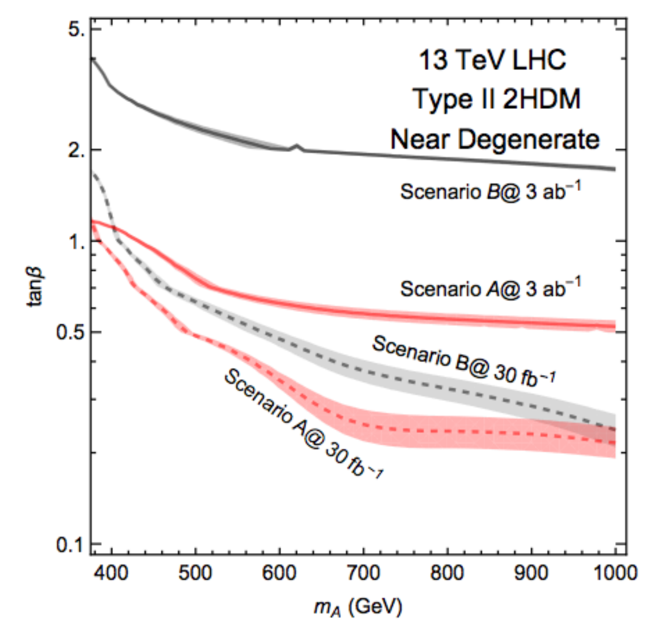
Impact of interference effect in A/H → tt at the LHC

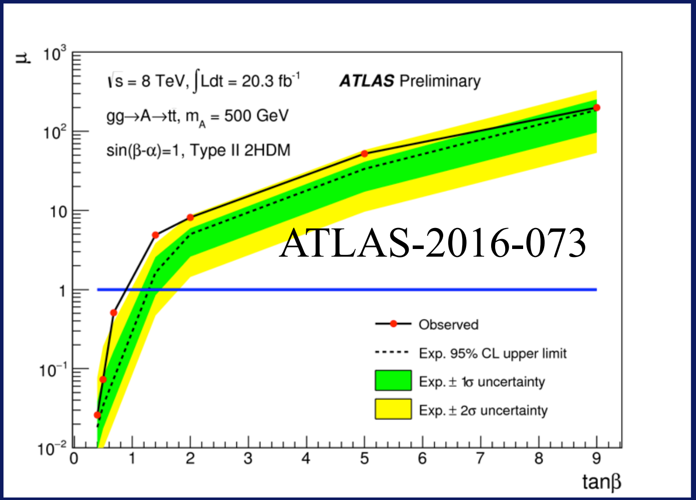
Projections for A/H → tt in Type II 2HDM

M.C., Liu '16

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







First interference studies at ATLAS

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

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

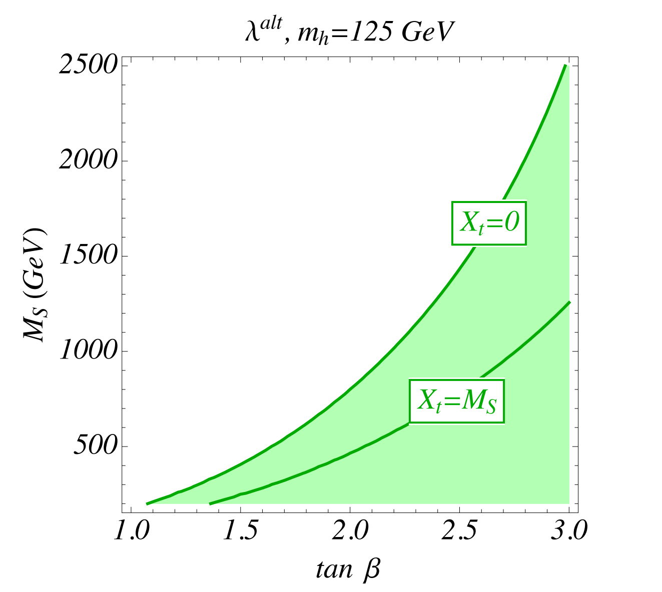
- Less well known:
  sizeable contributions to the mixing between MSSM CP-even eigenstates

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

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

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



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

Aligning the Singlet

If singlet also at LHC reach, precision Higgs data demands high degree of alignment.

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

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

Needs to vanish in alignment

For tanβ < 3 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

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

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

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

of interest for Dark Matter

NMSSM properties close to Alignment

Singlet Spectra and decays

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

MSSM-like A and H decays:

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

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

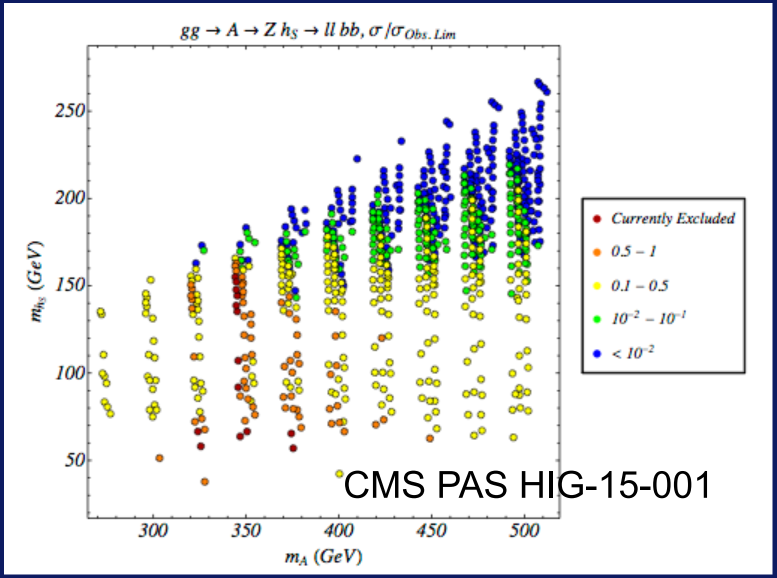
-- Other relevant decays: H → hh_S and A → Zh_S (20% to 50%, dep on mass)

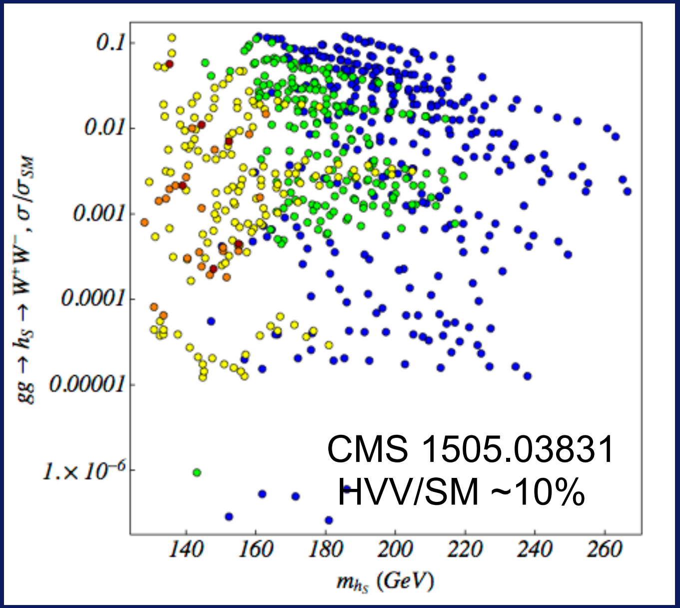
H → hh and A → hZ decays strongly suppressed due to alignment

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

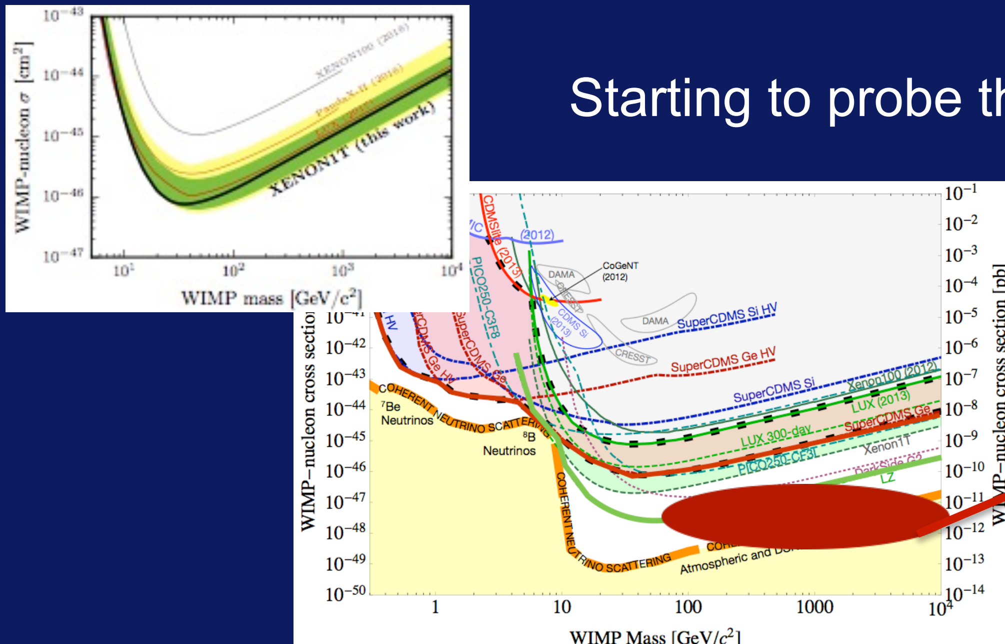
- Complementarity between $gg \to A \to Z\, h_S \to ll\, bb$ and $gg \to h_S \to WW$ searches



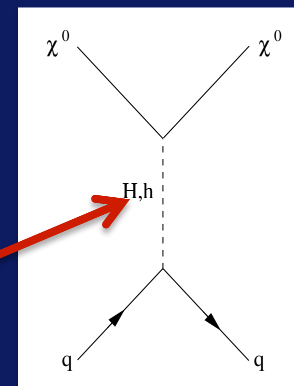


- **Promising $H \to h\, h_S$ channels with hs → bb or WW (4b's or bbWW)**
- **Searches for $H \to ZA$ or $A \to ZH$ should consider should consider to replace Z by h_{125} (with $A/H \to a_S/h_S$)**
- Channels with missing energy: $A \to h\, a_s$; $H \to Z\, a_s$ with $a_s \to$ neutralinos possible for tanβ ~ 4 to 6 (lighter singlet spectrum)

Dark Matter Direct Detection



Starting to probe the Higgs portal



Close to Alignment

Similar calculation for neutrons

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

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

Still room for a SUSY WIMP miracle

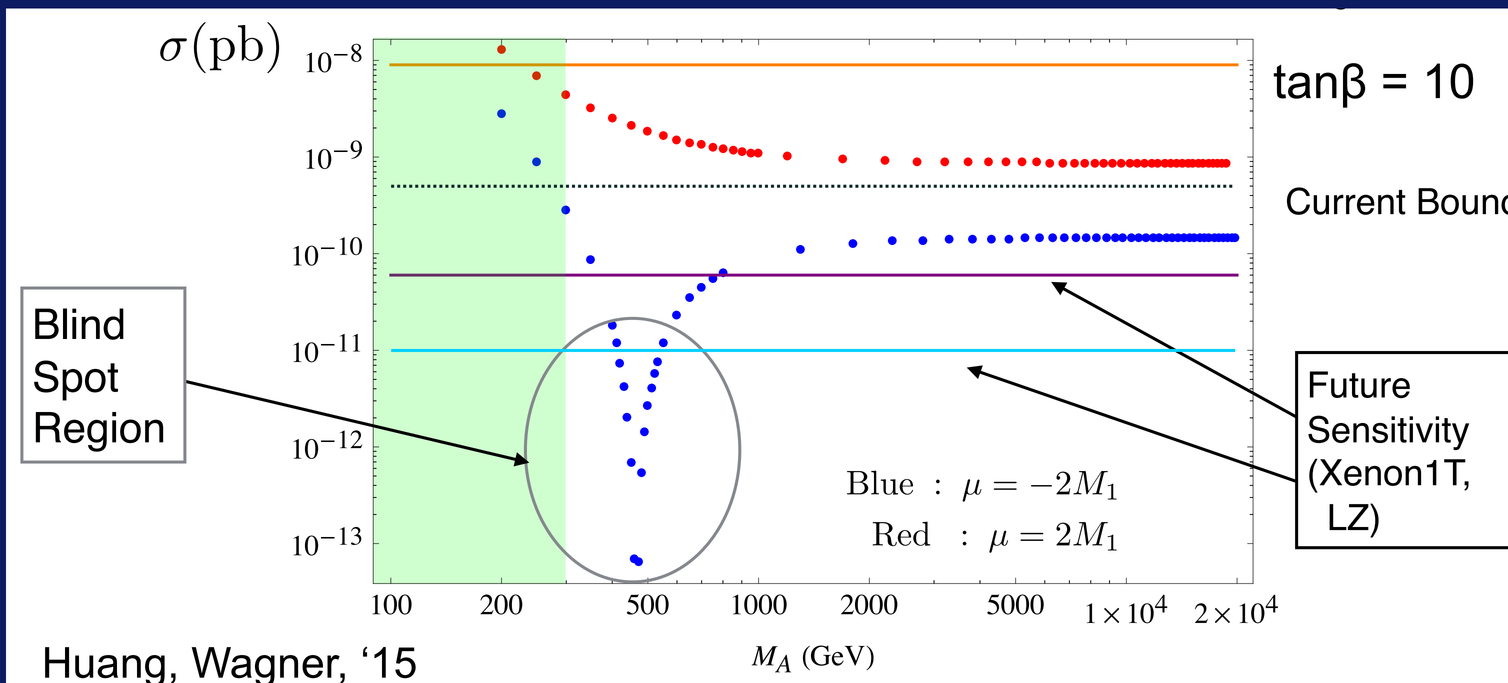
Blind Spots in Direct Dark Matter Detection

The cross section is greatly reduced when the parameters fulfilled the approximate relation

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

For moderate to large tanβ implies:

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

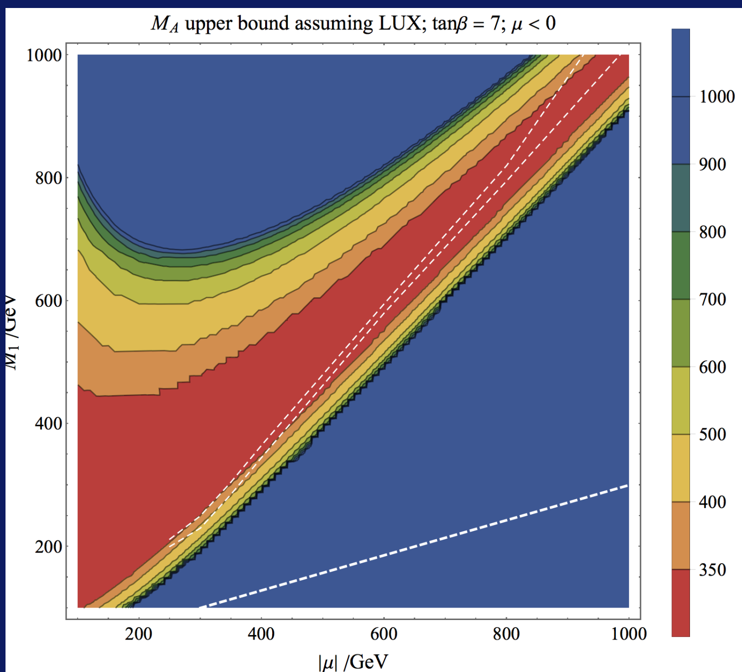


Huang, Wagner, '15

Restrictions on M_A from Dark Matter

Assuming the neutralinos provide the whole relic density (non-thermal)

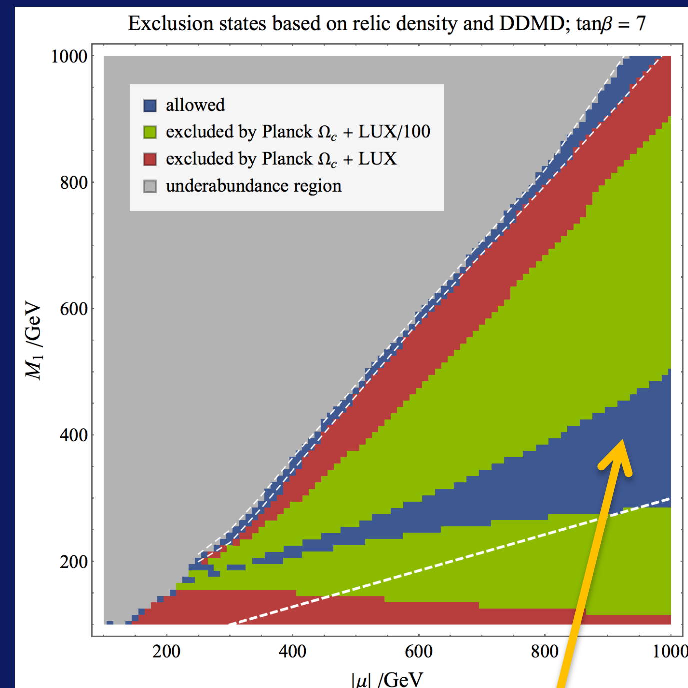
Upper bound on M_A for $\mu < 0$



Strong Restrictions on the Well Tempered Region (region between dashed white lines)

Roglans, Spiegel,Sun,Huang, Wagner ’17
Also Badziak, Olechowski,Szczerbiak ‘17

Assuming Thermal Relic Density



Resonant Annihilation to tune the correct relic density (M_A~2 M_1)
Plus blind spot effect for direct detection bounds

Blind Spots in Direct DM detection in the NMSSM

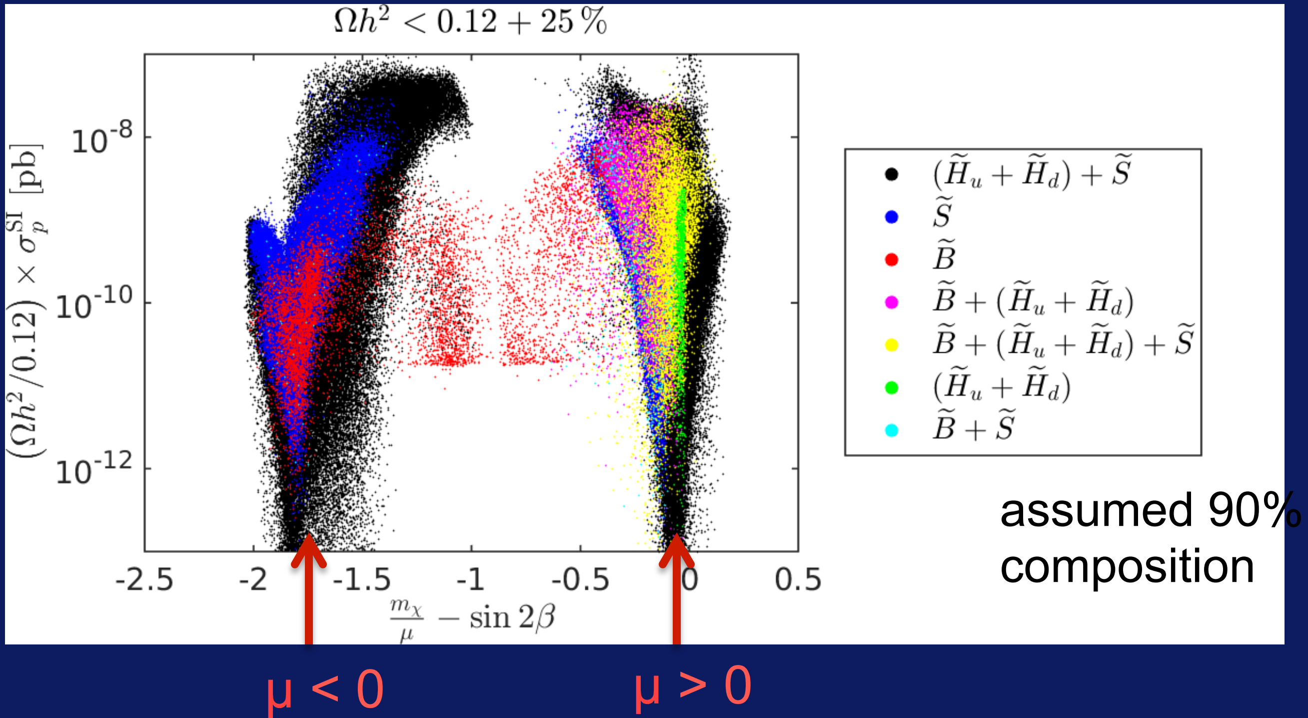
Possible to have a three way cancellation between the hs, h and H contributions

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

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

Cheung, Papucci, Sanford, Shah, Zurek '14

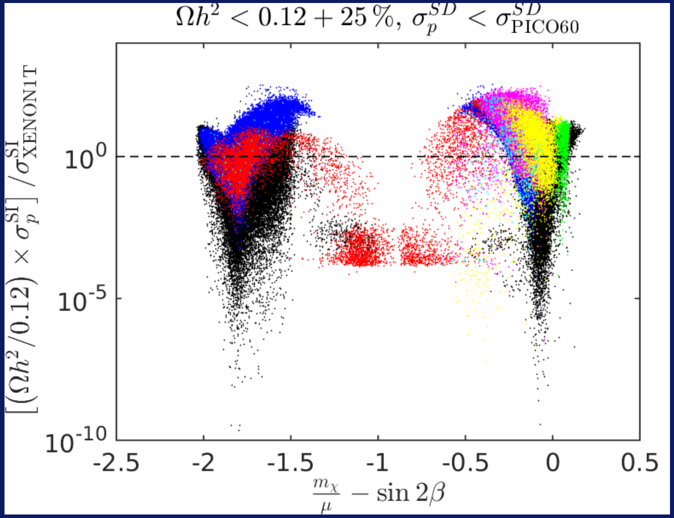
Singlino-Higgsino opens a region of destructive interference for μ positive



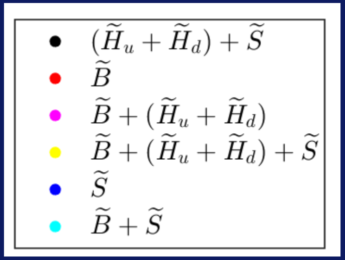
Baum, M.C, Shah, Wagner to appear

Blind Spots in Direct DM detection in the NMSSM

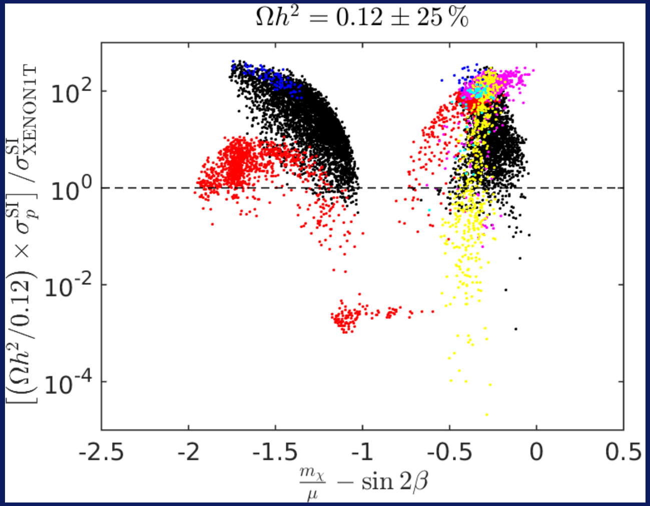
Normalized to Xenon1T arXiv:1705.06655 and including PICO-60 arXiv:1702.07666

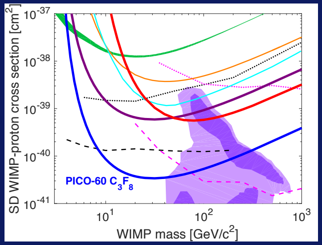


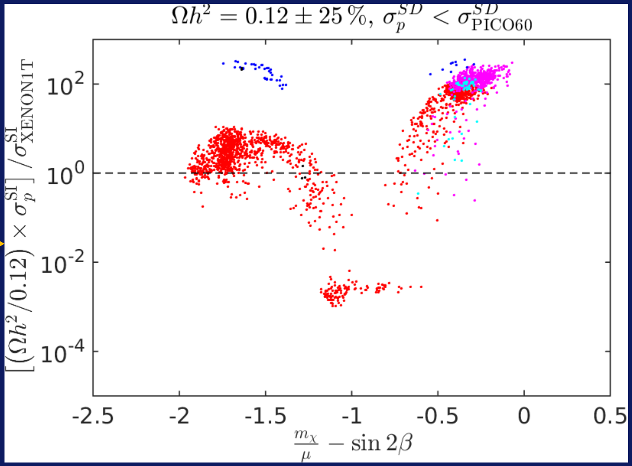
Baum, M.C, Shah, Wagner, to appear



Assuming thermal relic density







Need to relax/enlarge scan to most efficiently populate the blind spots

Outlook

The 125 GeV Higgs can be accommodated 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 and Dark Matter

In the MSSM:

Alignment calls for sizeable mu or heavy M_A

Dark Matter at the Well tempered, Bino-Higgsino region, may avoid constraints provided extra Higgs bosons are light. This calls for alignment

Departure from Alignment yield A/H decays 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 moderate 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

Blind spots for Direct DM searches may profit from Light Singlino-Higgsino region (TBC)

Composite Higgs Models (PNGB)

Model Building constrained by Higgs precision data

Can have Heavy Higgs bosons with non universal couplings to WW/ZZ

+ CP violation emerging in the bottom quark and tau lepton sectors