Implications of the Higgs Discovery for SUSY and Beyond

Marcela Carena
Fermilab & U. of Chicago

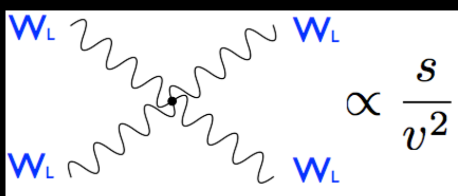
SUSY 2014: the 22nd International Conference on Supersymmetry and Unification of Fundamental Interactions
University of Manchester, July 2014

New Physics beyond the SM is needed to explain many observed phenomena

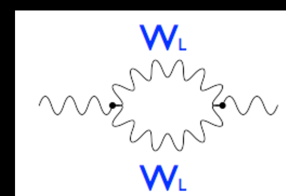
- Dark matter, matter-antimatter asymmetry, dynamical origin of fermion masses, mixings, additional CP violation … -

- None of the above demands NP at the EW scale

Before the Higgs discovery, we knew that some new phenomena had to exist at the EW scale, otherwise:

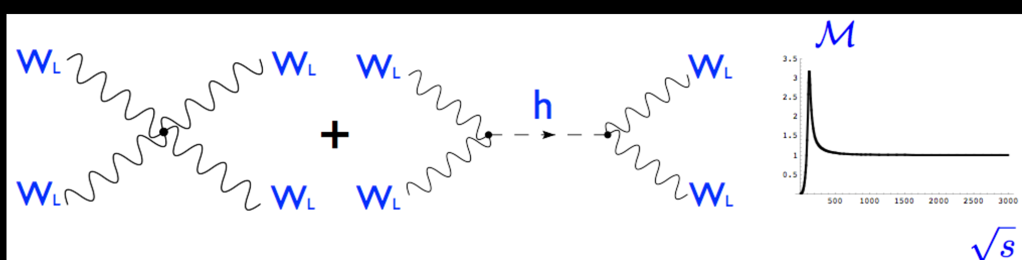


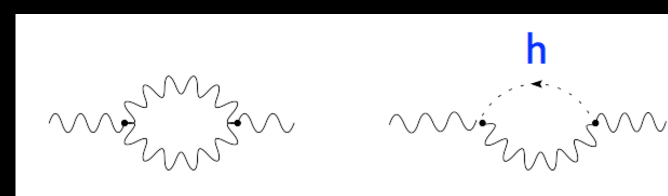
Unitarity lost at high energies



Loops are not finite

The Higgs came to the rescue





Loops are finite

We expect New Physics beyond the Higgs boson
But , at which scale?

M_{weak}? M_{LHC}? ……… M_N?.....M_{GUT}? M_{Planck} ?

• The Higgs is special : it is a scalar

Scalar masses are not protected by gauge symmetries: $\mathcal{L} \propto m^2|\phi|^2$

At quantum level scalar masses have quadratic sensitivity to UV physics

$$\delta m^2 = \sum_{B,F} g_{B,F}(-1)^{2S} \frac{\lambda^2_{B,F} m^2_{B,F}}{32\pi^2} \log(\frac{Q^2}{\mu^2})$$

**Although the SM with the Higgs is a consistent theory,
light scalars like the Higgs cannot survive
in the presence of heavy states at GUT/String/Planck scales**

Fine tuning $\longleftrightarrow$ **Naturalness problem**

Two possible Solutions:

Supersymmetry: a fermion-boson symmetry

The Higgs remains elementary but its mass is protected by the new fermion-boson symmetry

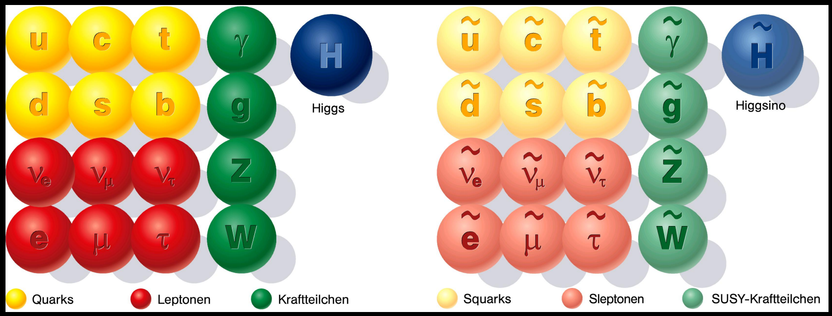
Composite Higgs Models:

The Higgs does not exist above a certain scale, at which the new strong dynamics takes place

Both options imply changes in the Higgs phenomenology,
and new particles and/or additional Higgs bosons
that *may* be seen at the LHC or indirectly in rare decay processes

SUSY has many good properties

- **Allows a hierarchy between the electroweak scale and the Planck/unification scales**
- **Generates EWSB automatically from radiative corrections to the Higgs potential**
- Allows gauge coupling unification at ~10^{16} GeV
- Provides a good dark matter candidate, the LSP
- Allows the possibility of electroweak baryogenesis
- String friendly



SUSY UNITED Vs COMPOSITE CITY

SUSY and Naturalness

• Higgs mass parameter protected by the fermion-boson symmetry:

$$\delta \mathrm{m}^2 = 0$$

In practice, no SUSY particles seen at LHC yet

➔ SUSY broken in nature

$$\boxed{\delta \mathrm{m}^2 \propto \mathrm{M}^2_{\mathrm{SUSY}}}$$

If $M_{SUSY} \sim M_{weak}$ $\longrightarrow$ Natural SUSY

If $M_{SUSY} \ll M_{GUT}$ $\longrightarrow$ big hierarchy problem solved

SUSY Weltschmerz*?

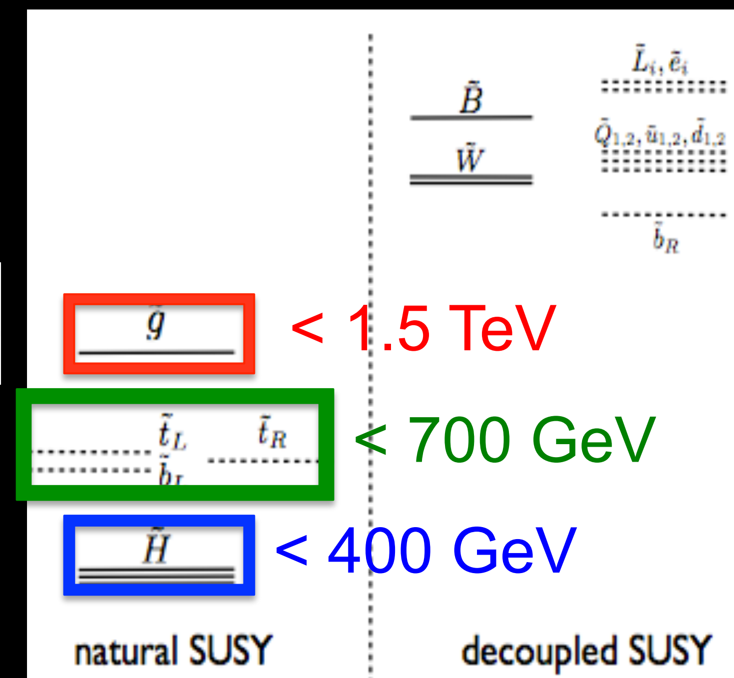
- **Not all SUSY particles play a role in the Higgs Naturalness issue**
- **Higgsinos, stops (left handed sbottoms) and gluinos are special**

$$\left(m_{H_u}^2 + |\mu|^2\right) - b/t_\beta - m_Z^2 c_{2\beta}/2 = 0$$

$$\delta m_{H_u}^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2\right) \log \frac{\Lambda}{\mathrm{TeV}}$$

$$\delta m_{H_u}^2|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

Extensions of the MSSM may improve tuning

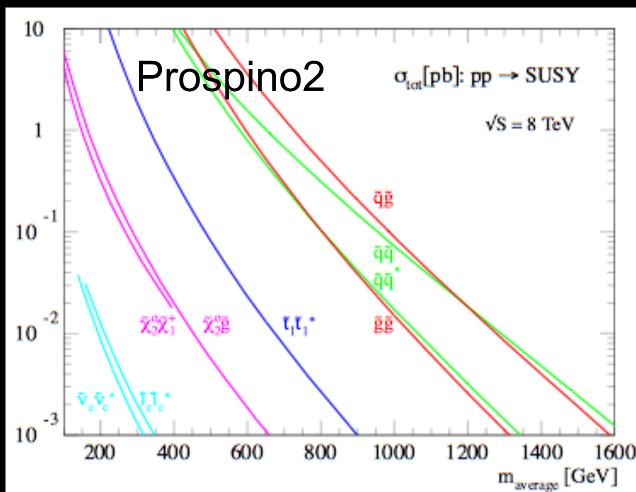


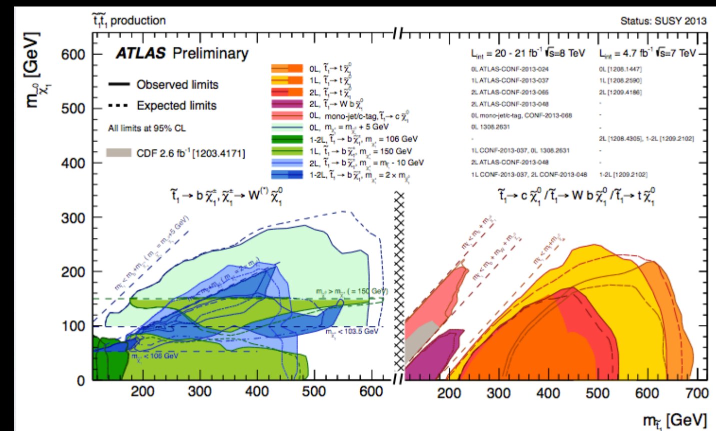
Papucci, Rudermann, Weiler ‘11

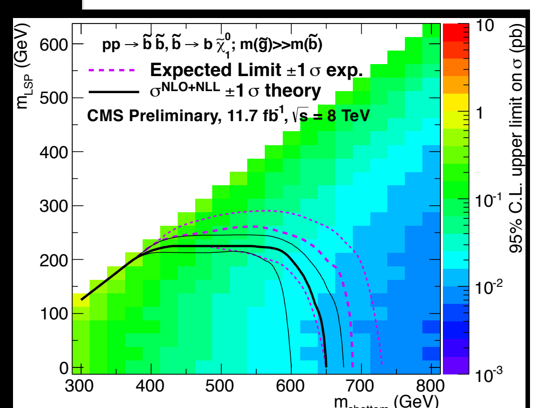
- So why didn’t we discover SUSY already at LEP, Tevatron, or LHC8?

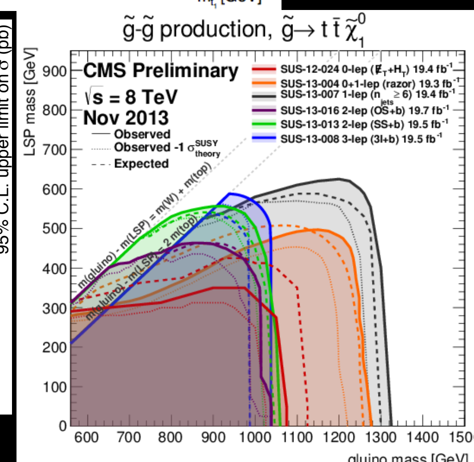
** The feeling experienced by someone who understands that physical reality can never satisfy the demands of the mind*

There is no rigorous definition of Natural SUSY models, but ATLAS and CMS are aggressively pursuing the direct signatures of "naturalness".

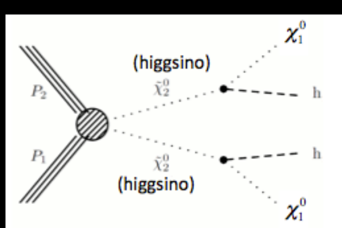




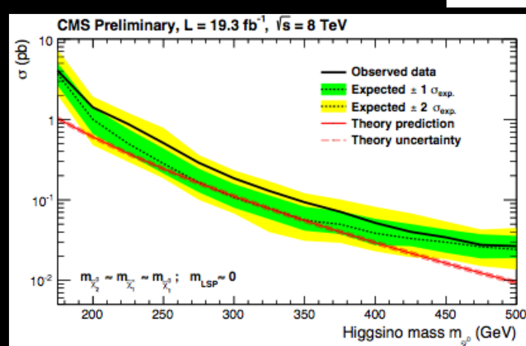


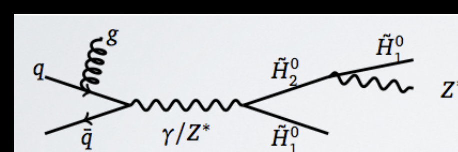


What about Higgsinos?



2 H→bb + MET





Monojet or VBF to tag the event,
plus soft leptons from off-shell *Z or W?*

SUSY implies multiple Higgs bosons, differing in their masses and other properties

Minimal Higgs Sector: Two SU(2) doublets H_d and H_u (2HDM effective theory)

- One SM doublet: $H_{SM} = \mathrm{Re}\, H^o_d \cos\beta + \mathrm{Re}\, H^o_u \sin\beta$ with $\tan\beta = v_u / v_d$
- And an orthogonal combination of non-SM Higgs $H = \begin{pmatrix} H + iA \\ H^{\pm} \end{pmatrix}$

Strictly speaking, the CP-even modes mix and none behaves like the SM one

$$h = -\sin\alpha\, \mathrm{Re}\, H^o_d + \cos\alpha\, \mathrm{Re}\, H^o_u \qquad H = \cos\alpha\, \mathrm{Re}\, H^o_d + \sin\alpha\, \mathrm{Re}\, H^o_u$$

The lightest Higgs h behaves like the SM one when **$\sin\alpha = -\cos\beta$** and

one recovers the SM as an effective theory

a) **In the decoupling limit** → all non-SM like Higgs bosons are heavy

b) **In the alignment limit** → for certain values of the quartic couplings and $\tan\beta$,

independent of the non-SM-like Higgs mass values

Naturalness demands A/H light for $\tan\beta \sim 1$ (e.g NMSSM)

$$\tan^2\beta \approx \frac{m^2_{H_d} + \mu^2 + M^2_Z/2}{m^2_{H_u} + \mu^2 + M^2_Z/2}$$

Alignment without Decoupling

$\sin\alpha = -\cos\beta$ ➔ h has SM like properties

Decoupling: Large CP odd Mass (M_A > 500 GeV)

Alignment : independent of the CP odd mass value
for intermediate (MSSM) and small (NMSSM) $\tan\beta$

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

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

Haber, Gunion ‘03
MC, Low, Shah, Wagner ‘13

$$\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$$

Valid for any 2HDM

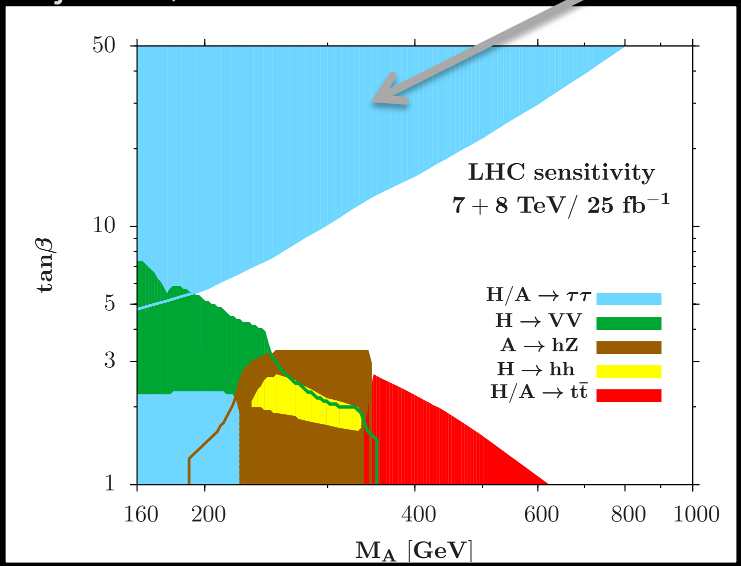
$$\begin{aligned} V =\ & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \mathrm{h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)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

Is it more important to measure Higgs couplings with the highest precision possible
Or
Find new ways of searching for additional Higgs states?

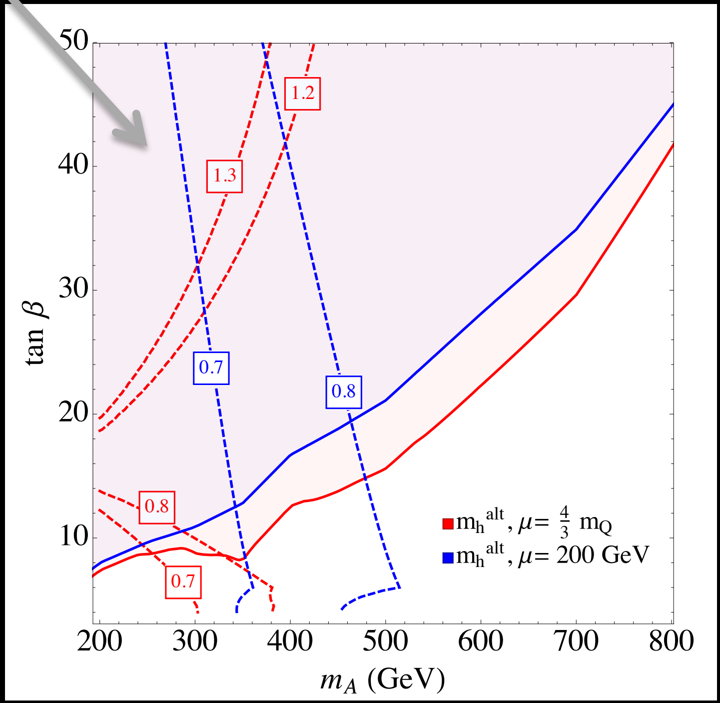
Wagner’s talk

ATLAS/CMS strong limits in A/H → τ τ via gluon fusion and bbA/H production and compatible with h being the 125 GeV SM-like Higgs

Djouadi, Quevillon'13



σ (ggh) x BR(h→WW*/ZZ*) SM norm. in the MSSM with (dashed-red) and without (dashed blue) alignment



At low tanβ, it is important to look for H → WW+ ZZ, hh, tt ; A → Zh, tt

(stop masses > 10 TeV)

Weaker lower bound on m_A, strong tanβ dependence for alignment

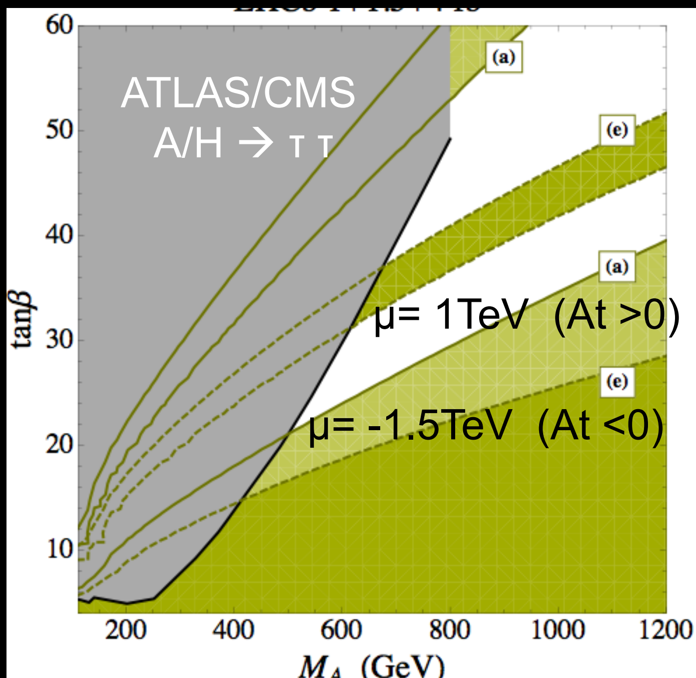
M.C, Low, Shah, Wagner'13 + Haber'14

Similar features in other SUSY extensions or more general 2 Higgs Doublet Models

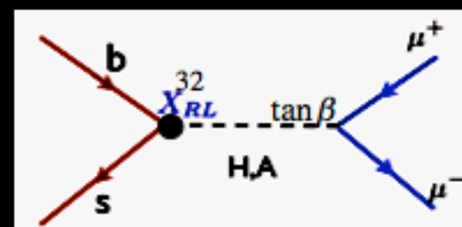
Indirect limits on the SUSY spectrum from rare processes

The Higgs-flavor connection in the MSSM with Minimal Flavor Violation

Altmannshofer, MC, Shah, Yu ’13



$B_s \to \mu^+\mu^-$



$$\frac{y_t^2}{16\pi^2}\,\frac{\mu A_t}{m_{\tilde t}^2}\,\frac{\tan\beta^3}{M_A^2}$$

LHCb Projections: 1 (7 TeV) +1.5 (8 TeV)+4 (13 TeV) fb^{-1}

SM central value with 30% effects of NP allowed

SUSY effects intimately connected to the structure of the squark mass matrices

Is SUSY hiding?

It is possible to make SUSY models where the superpartners are well within the kinematic reach of LHC8, but the missing energy signatures or the jet activity are degraded

- Compressed spectra: e.g. stop mass ~ charm mass + LSP mass

M.C., Freitas,Wagner '08

- Stealth SUSY: long decay chains soften the spectrum of observed particles from SUSY decays

- R parity violation: the LSP is not the dark matter, but decays

Some models can be motivated by naturalness, the right DM density; others not especially motivated by anything but the need to hide

ATLAS and CMS are closing the gaps even for these

Natural SUSY Model Building

- connect the lightness of the third generation sfermions to the heaviness of third generation fermions

  ➔ address flavor as part of the SUSY breaking mechanism

- alleviate the tension of a Higgs mass that needs sizeable radiative corrections from stop contributions

$$m_h^2 = \underbrace{M_Z^2 \cos^2 2\beta}_{< (91\ \mathrm{GeV})^2} + \Delta m_h^2$$

$$\frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

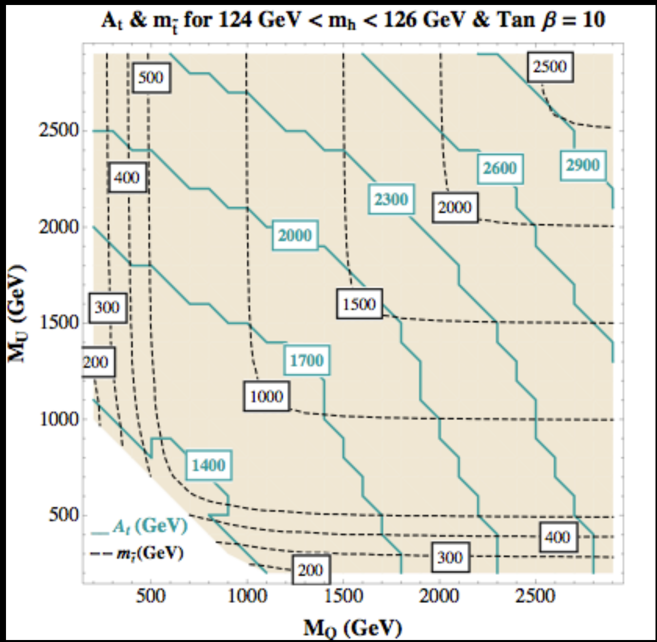
MSSM

large stop mixing or large stop masses

One stop can be light and the other heavy

or

in the case of similar stop soft masses both stops should be > 500 GeV



M. C., Gori, Shah, Wagner '11

Similar results from
Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon; Draper Meade, Reece, Shih
Heinemeyer, Stal, Weiglein'11; Ellwanger'11; Shirman et al.

Extensions of the MSSM

• MSSM with explicit CP violation (radiatively induced): no effect on m_h

Pilaftsis, Wagner '99

• Add new degrees of freedom that contribute at tree level to mh (new quartics)

new F term contributions ➔ e.g. additional SM singlets or triplets

Garcia –Pepin's talk

Possible additional CP violation at tree level ➔ relevant for EW baryogenesis

and/or additional D terms ➔ models with enhanced weak gauge symmetries

New gauge bosons (~ a few TeV) at LHC reach?

McGarrie and & Harries talk

• A more model-independent approach: (SUSY breaking as a perturbation)

SUSY 2HDM effective field theory with higher dimensional operators

Dine, Seiberg, Thomas; Antoniadis, Dudas, Ghilencea, Tziveloglou; M.C, Kong, Ponton, Zurita

look at specific examples singlet, triplets with Y =0 ; 1, and extra gauge bosons

Effects most relevant for small tanβ; for $M_A >$ 400 GeV pheno very close to MSSM

Otherwise, new decay channels: H to AA/AZ, and H^+ to W^+A may be open (alignment?)

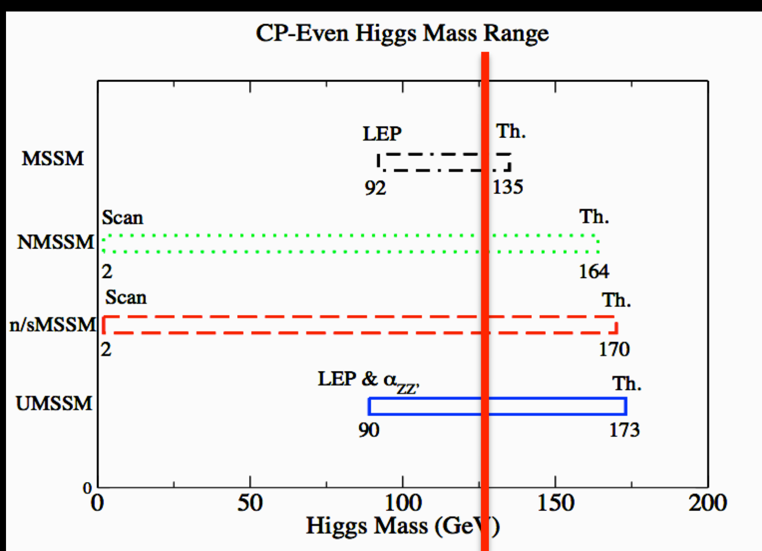
Singlet extensions of the MSSM

A solution to the μ problem: Superpotential ∋ $\lambda_s S H_u H_d$ → $\mu_{eff} = \lambda_s \langle S \rangle$

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda_S^2 v^2 \sin^2 2\beta + \text{rad. corrections}$$

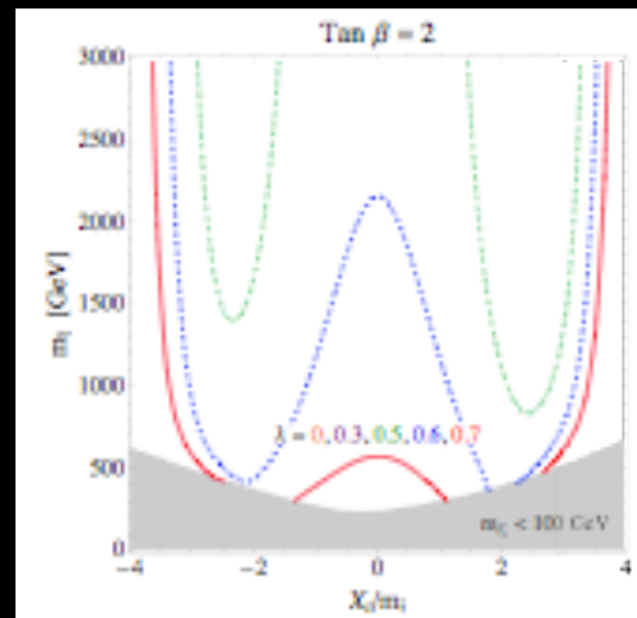
Main one-loop level contributions common with the MSSM

Model	MSSM	NMSSM	nMSSM	UMSSM
Symmetry	-	Z_3	Z_5^R, Z_7^R	$U(1)'$
Superpotential	$\mu\Phi_2 \cdot \Phi_1$	$\lambda_S S \Phi_2 \cdot \Phi_1 + \frac{\kappa}{3} S^3$	$\lambda_S S \Phi_2 \cdot \Phi_1 + t_F S$	$\lambda_S S \Phi_2 \cdot \Phi_1$
H_i^0	2	3	3	3
A_i^0	1	2	2	1



m_{H1} =125 GeV

Barger, Langacker, Shaughnessy '07



Hall, Pinner, Ruderman'11

At low tan beta,
trade requirement on large stop mixing by
sizeable trilinear Higgs-Higgs singlet coupling λ_S

SUSY with extended Gauge Sectors

TeV scale new gauge interactions, and MSSM Higgs bosons charged under them :

D term lifting of m_h^{tree}

requires extended gauge and Higgs sectors are integrated out in a non-SUSY way

Simplest example: extended $SU(2)_1 \times SU(2)_2$ sector spontaneously broken to $SU(2)_L$

bi-doublet Σ under the two SU(2) gauge groups acquires $\langle\Sigma\rangle = u$

Heavy gauge boson: $M_{W'}^2 = (g_1^2 + g_2^2)\, u^2/2$ $SU(2)_L$: $g^2 = g_1^2 g_2^2/(g_1^2 + g_2^2)$

Flavor option: 3rd gen. fermions and Higgs doublets charged under $SU(2)_1$,
2nd and 1st gen. charged under $SU(2)_2$.

$$\boxed{m_h^2|_{tree} = \frac{g^2\Delta + g'^2}{4} v^2 \cos^2 2\beta}$$

with $\Delta = \left(1 + \frac{4m_\Sigma^2}{g_2^2 u^2}\right)\left(1 + \frac{4m_\Sigma^2}{(g_1^2 + g_2^2)u^2}\right)^{-1}$

m_Σ

~~SUSY~~ mass

Batra, Delgado, Kaplan, Tait' 03

For $m_\Sigma \rightarrow 0$ one recovers the MSSM; for $m_\Sigma \gg M_{W'}$ the D term is that of $SU(2)_1$

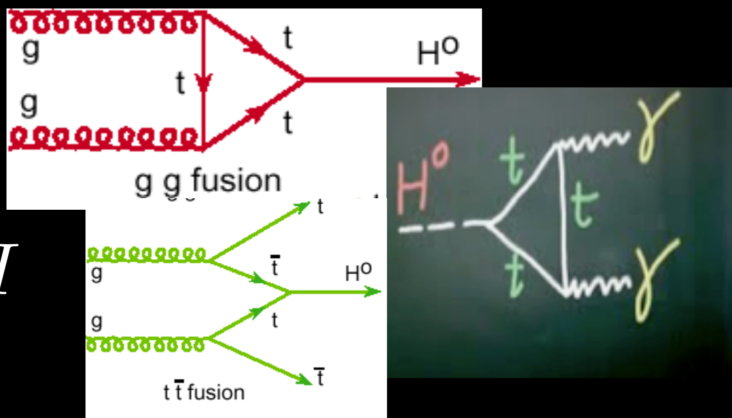
For $m_\Sigma \sim M_{W'}$ and $g_1 \sim g_2 \sim O(1)$ ➔ $m_h \sim 125$ GeV

without heavy stops or large stop mixing

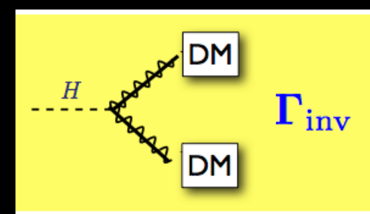
What do the Higgs Production and Decay rates tell us?

Many different pieces of information: $B\sigma(p\bar{p} \to h \to X_{\rm SM}) \equiv \sigma(p\bar{p} \to h) \dfrac{\Gamma(h \to X_{\rm SM})}{\Gamma_{\rm total}}$

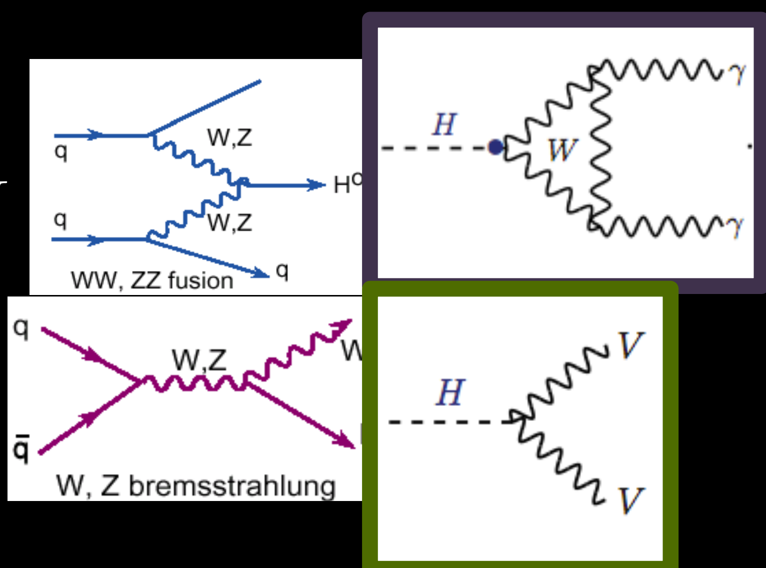
$t\bar{t}H$



also $\quad H \to b\bar{b}, \tau^+\tau^-$



VVH



Different patterns of deviations from SM couplings if:

- New light charged or colored particles in loop-induced processes
- Modification of tree level couplings due to mixing effects
- Decays to new or invisible particles

crucial info on NP from Higgs precision measurements

Loop induced Couplings of the Higgs to Gauge Boson Pairs

Low energy effective theorems

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^\dagger_{F,i}\mathcal{M}_{F,i}\right) + \sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^2_{B,i}\right)\right] F_{\mu\nu}F^{\mu\nu}$$

Ellis, Gaillard, Nanopoulos'76, Shifman,Vainshtein,Voloshin, Zakharov'79, Kniehl and Spira '95
M. C, Low, Wagner '12

Similarly for the Higgs-gluon gluon coupling

Hence, W (gauge bosons) contribute negatively to Hγγ,
while top quarks (matter particles) contribute positively to Hgg and Hγγ

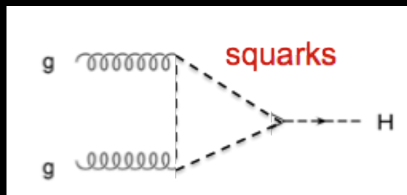
- New chiral fermions will enhance Hgg and suppress hγγ
- To reverse this behavior matter particles need to have negative values for

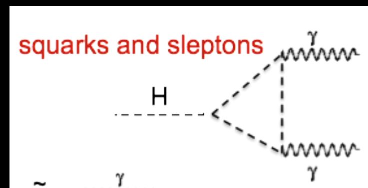
$$\frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^\dagger_{F,i}\mathcal{M}_{F,i}\right) \qquad \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}^2_{B,i}\right)$$

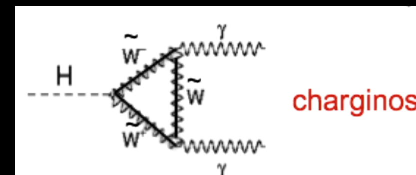
For a study considering CP violating effects and connection with EDM's and MDM's see
Voloshin'12; Altmannshofer, Bauer, MC'13, Brod et al.; Primulando et al.

Possible departures in the production and decay rates at the LHC

- **Through SUSY particle effects in loop induced processes**







$$\delta A^{\tilde f}_{\gamma\gamma,gg} \propto \frac{m_f^2}{m_{\tilde f_1}^2 \; m_{\tilde f_2}^2}\left[m_{\tilde f_1}^2 + m_{\tilde f_2}^2 - X_f^2\right]$$

$$\delta A^{\tilde\chi^\pm}_{\gamma\gamma} \propto -\frac{g^2 v^2 \sin 2\beta}{M_2 \mu - \frac{1}{2} g^2 v^2 \sin 2\beta}$$

If a particle's mass is proportional to the Higgs vev, contributes with the same sign of the top loop. But mixing can alter the sign

- Light stops and gluon fusion production

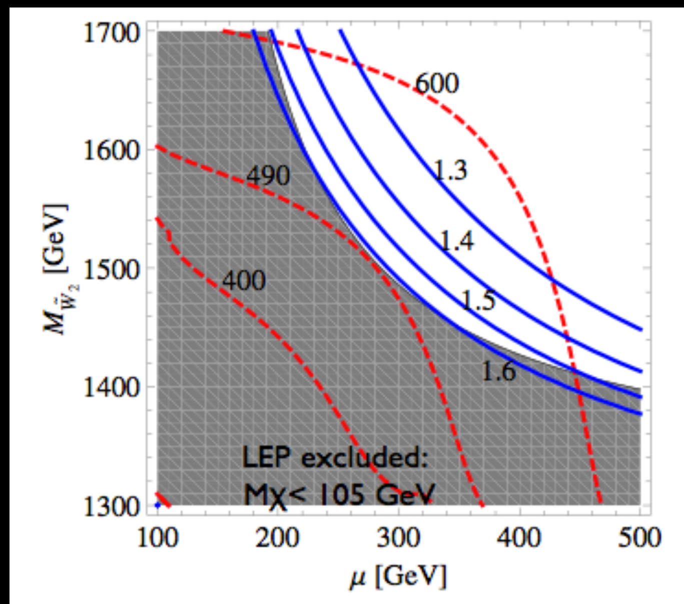
MSSM ➔ increase the gluon fusion rate but, for large stop mixing X_t required by m_h~125 GeV, mostly leads to moderate suppression

Singlet extensions at low tanβ ➔ no need for large X_t, hence more freedom in gluon fusion

- MSSM Light staus with large mixing (sizeable μ and tanβ) can enhance Higgs to di-photons without changing any other rates.

- Singlet extensions with light charginos, depending on sign of $M_2\mu$, can enhance Higgs to di-photon rate for small tanβ

•Gauge extensions with light charginos enhance Higgs to di-photons for strong coupling



Lou, Lee, Talapillil, Wagner'12

In the presence of light strongly coupled gauginos
m_h can be increased due to RG evolution of the Higgs quartic couplings at low energies

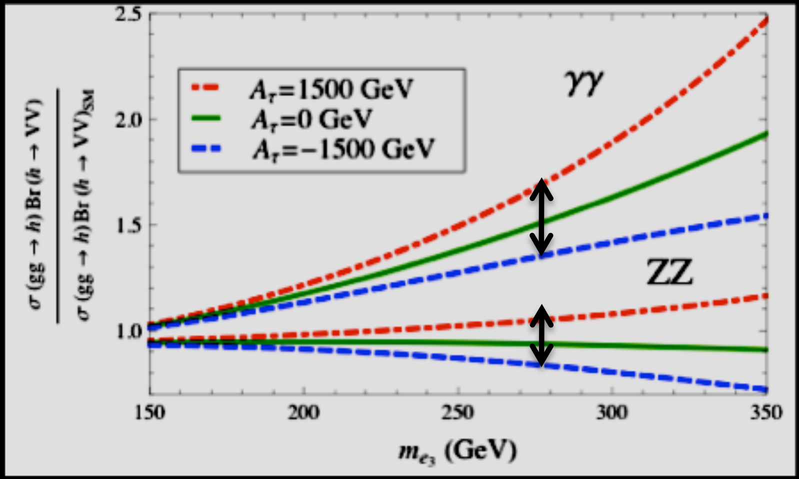
Possible departures in the production and decay rates at the LHC cont'd

• Through enhancement/suppression of the Hbb and Hττ coupling strength via mixing in the scalar sector

This affects in similar manner BR's into all other particles

MSSM: Additional modifications of the Higgs rates into gauge bosons via stau induced mixing effects in the Higgs sector

NMSSM : Wide range of WW/ZZ and γγ rates due to Higgs-singlet mixing (λ_S)



MC, Gori, Shah, Wagner,'11 + Wang'12

pMSSM/MSSM fits: Arbey, Battagllia, Djouadi, Mahmoudi '12
Benbrik, Gomez Bock, Heinemeyer, Stal, Weiglein, Zeune'12

• Through vertex corrections to Yukawa couplings: different for bottoms and taus

This destroys the SM relation BR(h→bb)/BR(h→ττ) ~ m_b^2/m_τ^2

• Through decays to new particles (including invisible decays)

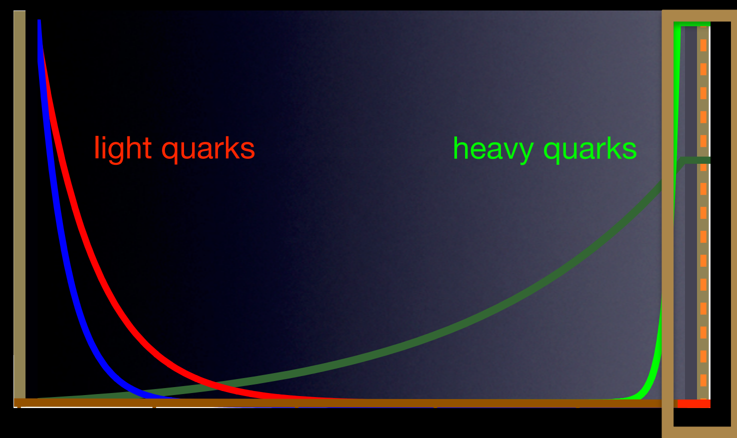
This affects in similar manner BR's to all SM particles

Models of composite Higgs

- Embedding the SM (with the Higgs) in a warped extra dimension

Randall Sundrum

UV brane



KK modes:
IR localized

IR brane

Warped extra dimension models address, at the same time,
the **gauge hierarchy problem and the flavor problem**

Fermion localization depends exponentially on O(1) parameters related to 5D **masses.**
Overlap integrals with the IR-localized Higgs give fermion mass hierarchies

Grossman, Neubert; Ghergetta, Pomarol

RS-GIM protection of FCNCs **Still new symmetries needed to fit KK SM excitations in the few to several TeV mass range**

Agashe, Delgado, May, Sundrum; Agashe, Contino, Da Rold, Pomarol; M.C. Delgado, Ponton, Tait, Wagner

Composite Higgs Models: Higgs as a PNGB

Inspired in pions of QCD

Georgi,Kaplan'84; Agashe et al '03
Arkani-Hamed et al '01; Schmaltz '04

- **The pNGB Higgs arise from the spontaneous breaking of a global symmetry by some underlying strong dynamics**
- **Higgs mass protected by the global symmetry, and generated at one loop by explicit breaking of global symmetry due to SM couplings**

Model Building: choose the global symmetry and the fermion embedding

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

Pattern of Symmetry breaking

gauge: $SU(2)_L \times U(1)_Y \longrightarrow U(1)_Q$

$\uparrow \qquad \uparrow$

global: $SO(5) \underset{E \sim f}{\rightarrow} SU(2)_L \times SU(2)_R \underset{E \sim v}{\rightarrow} SU(2)_V$ custodial

Contino et al. ; Redi et al.; de Curtis et al.

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

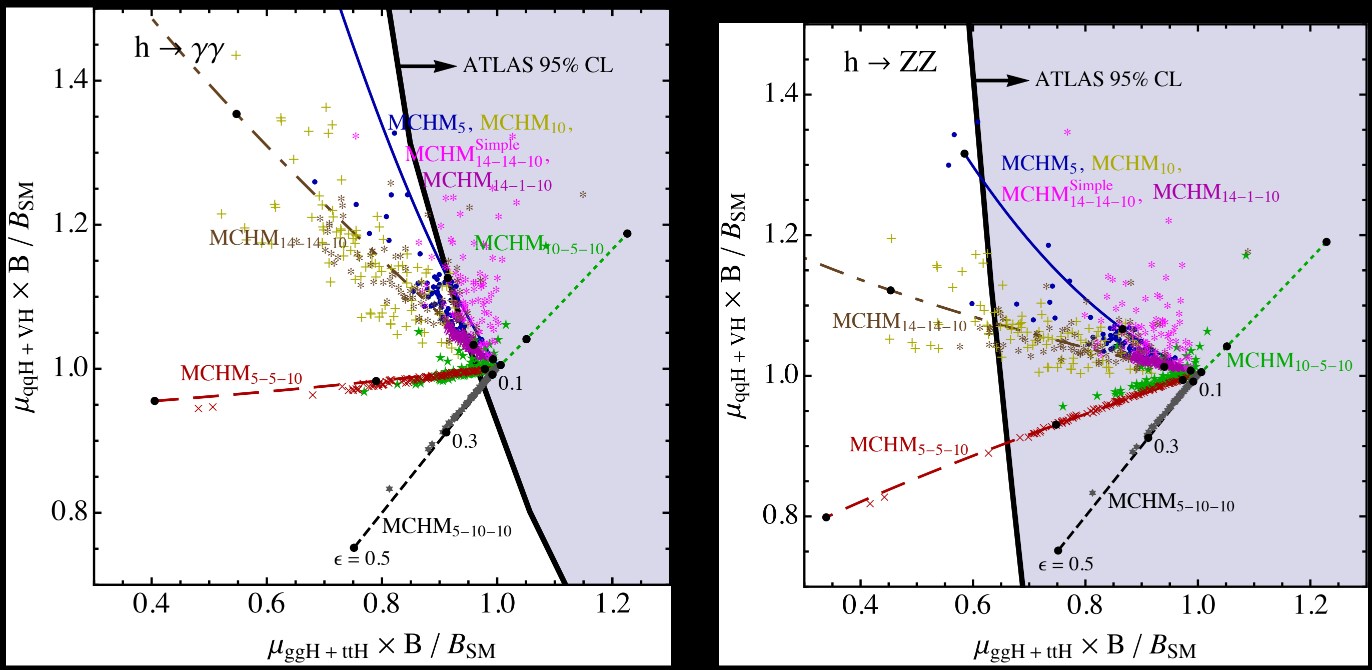
Each chiral SM-fermion → vector-like composite-fermion

pNGB Higgs models confronting data

- **Higgs couplings to W/Z determine by the gauge groups involved**
  - i.e. $MCHM_X$ ➔ SO(5)/SO(4)
- **Higgs couplin**gs to SM fermions depend on fermion embedding X

considering many different SO(5) fermion embeddings

M.C., Da Rold, Ponton'14

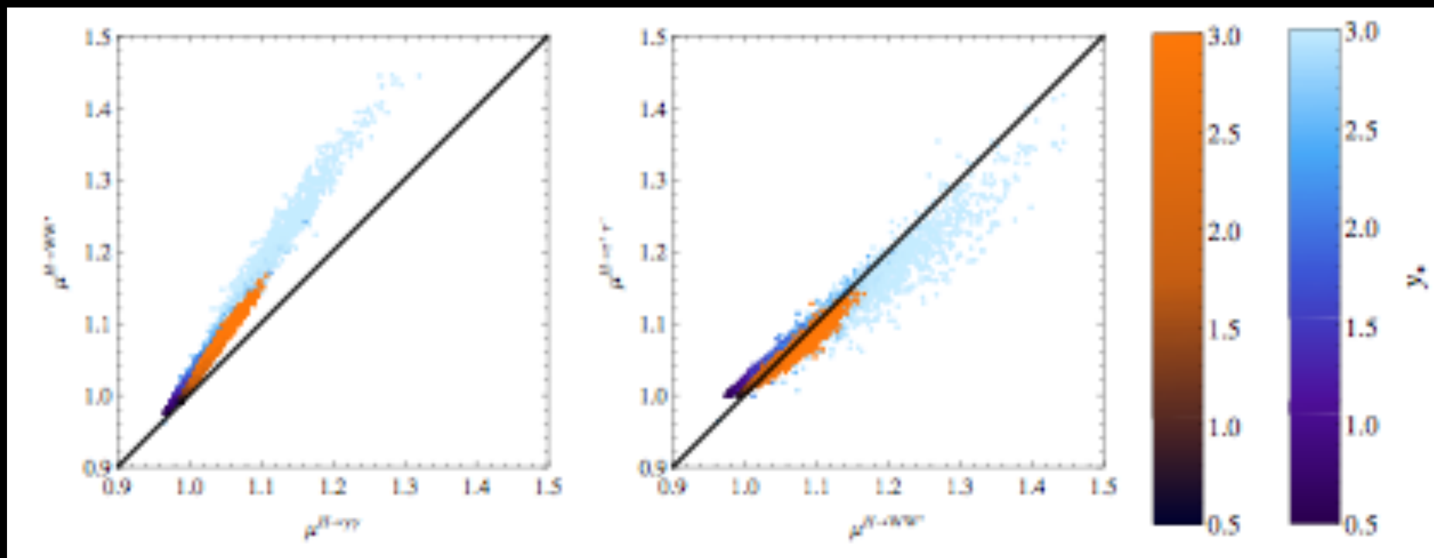


Main effects due to SM fermions and gauge bosons mixing with composite fermion and gauge boson sectors, respectively

Minimal effects from heavy/strong resonance effects in the loops

Composite RS-type Higgs models confronting data

Archer, M.C., Carmona, Neubert in prep.



The correlation between signal strengths including all production processes
for different final states for MKK = 4 TeV varying the Yukawa strength
for bulk Higgs (orange) and IR brane Higgs (blue)

Main effects due to high multiplicity of heavy/strong resonance effects in the loops

We are exploring the Higgs connections

- In there a Higgs portal to dark matter and/or other dark sectors?
- Is Baryogenesis generated at the EWSB scale?
- How does the Higgs talk to neutrinos ?
- What are the implications of the Higgs sector for flavor?
- Is the Higgs a portal to new particles and new energy scales?
- Is the Higgs related to inflation or dark energy?
- What is the dynamical origin of the electroweak scale?

The power of the dark side

Holds the Universe together and makes ***85% of all the matter in it!***

Interacts very weakly
(not charged)

→ **Gravity** ✓.

→ **Higgs-like Interactions ?**

SUSY and the WIMP Miracle ?

- If the LSP is the lightest neutralino it will behave as WIMP dark matter
- In the MSSM the lightest neutralino is generically a mixture of the Bino, Wino, and the two Higgsinos
- If you are more ambitious, can try to require that the LSP is a thermal relic with the correct abundance to explain all ALL dark matter

SUSY and the WIMP "Miracle"

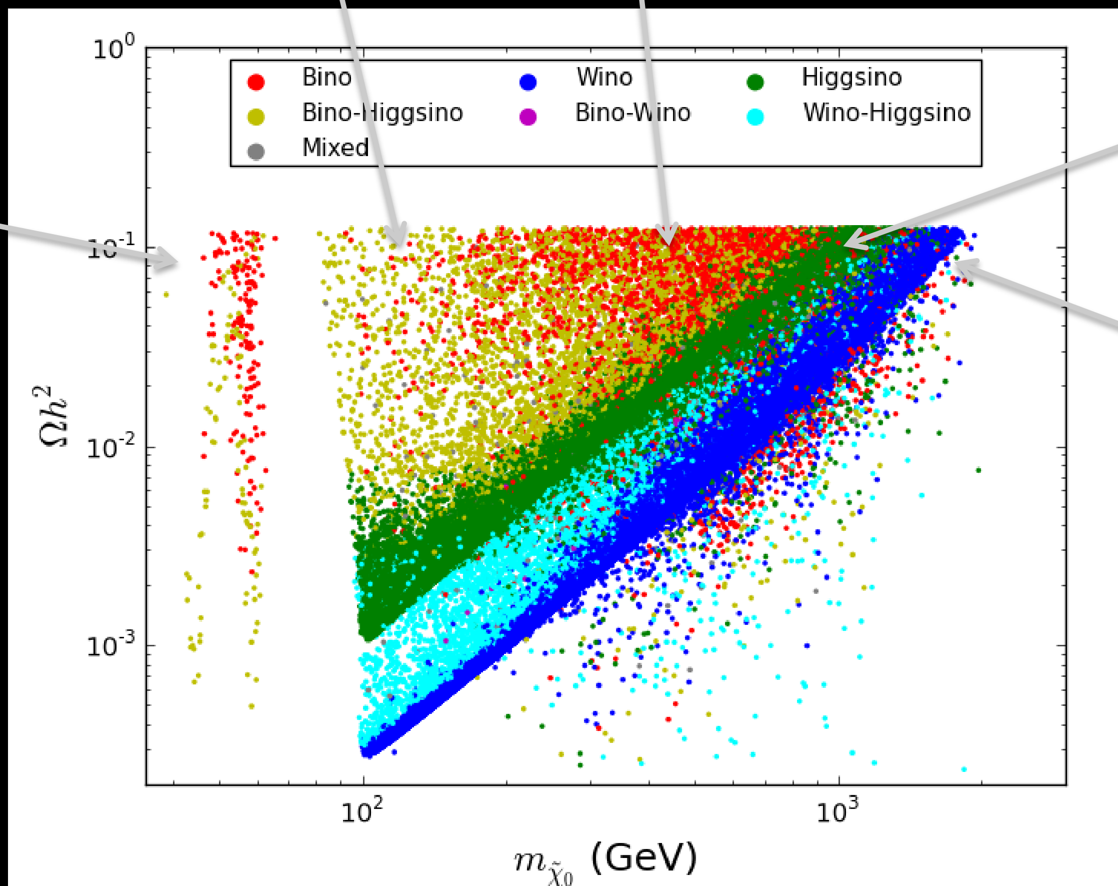
Bino-Higgsino mixture, closest case to the WIMP Miracle

Pure Bino needs co-annihilation with other quasi-degenerate superpartners

Bino-like that can annihilate through the h or Z "funnels"

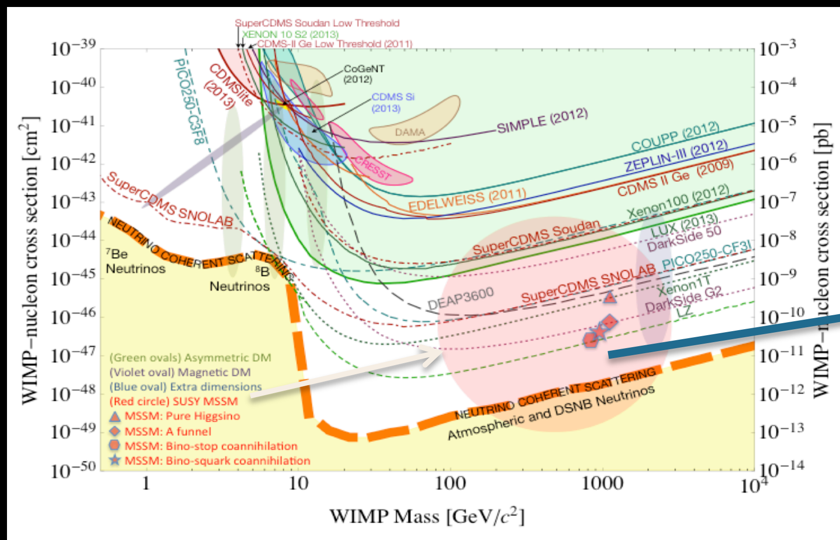
Higgsino, ~ 1.5 TeV

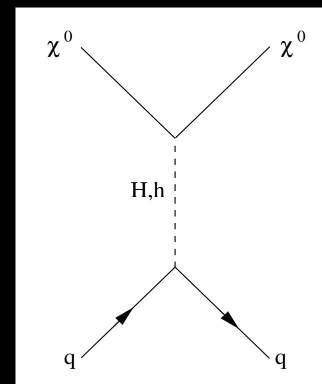
Wino, ~ 3 TeV



Hewett, Rizzo et al. '13

Are the SUSY neutralinos hiding from DM direct detection?





- Mixed Wino-Higssino or Bino-Higgsino ➔ can have suppressed couplings (with the Higgs bosons by tuning M_2 (M_1), tan β and μ
- Pure Winos, Binos, or Higgsinos have no tree level coupling to the Higgs bosons so SI cross section is suppressed
- Relevant destructive interference between h and H possible

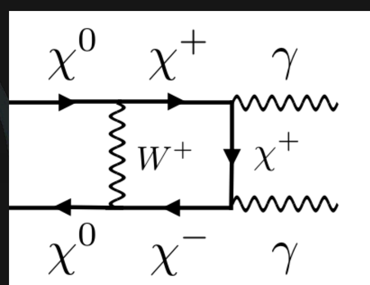
Cheung, Hall, Pinner, Ruderman-12;Huang, Wagner'14

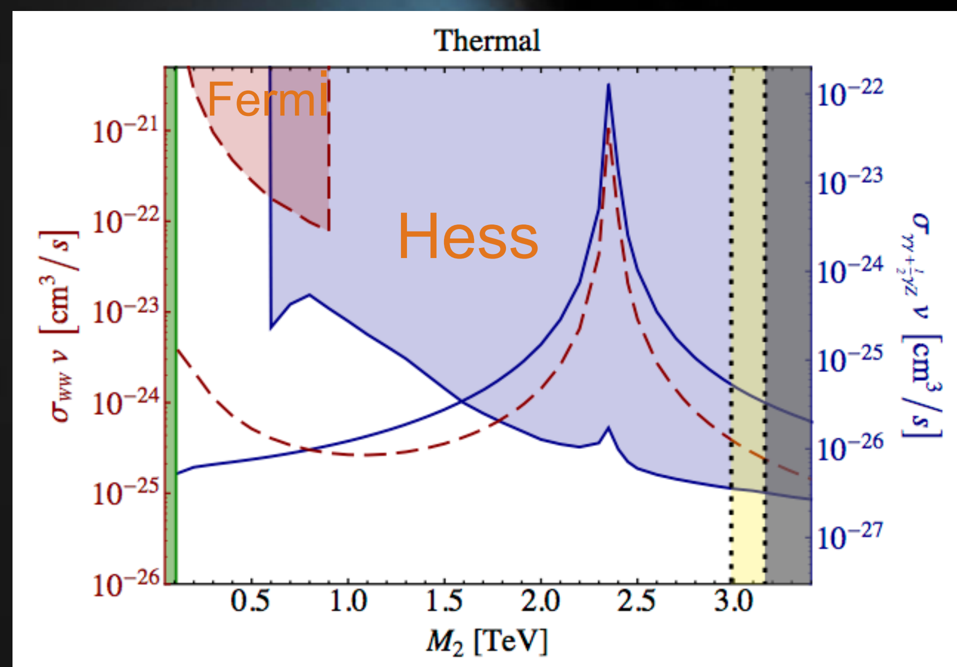
Pure states

- Pure Winos, Binos, or Higgsinos have no tree level coupling to the Higgs bosons so SI cross section is suppressed

- Pure Winos, if we also require correct thermal relic abundance, ruled out by Hess gamma ray line bounds

Cohen, Lisanti, Pierce, Slatyer '13

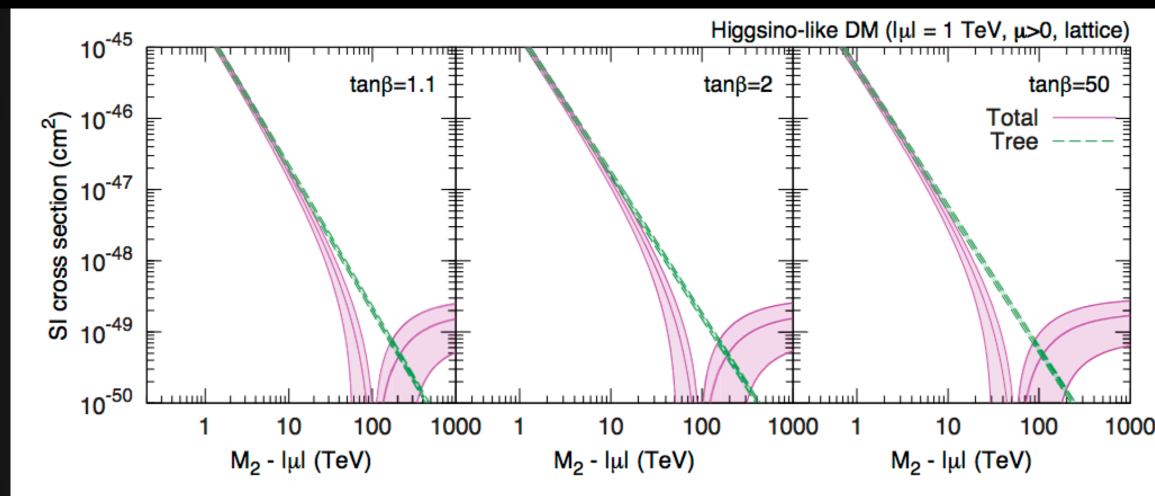




Pure states

- Almost pure Higgsinos with mass ~ 1 TeV have very suppressed SI cross sections and are not ruled out (yet) by indirect detection constraints

Hisano et al ’13; Hill,Solon ‘14



- ➔ Dirac Split SUSY offers a UV completion for Higgsino DM

Fox, Kribs, Martin ‘14

- Pure Binos with lighter masses can also have very suppressed SI cross sections, but correct thermal relic abundance requires staus, stops, or charginos at LHC

Revolutionary advances
in our understanding of the Universe
are driven by
powerful ideas and powerful instruments

EWSB Mechanism $\longleftrightarrow$ LHC

What's Next?

The existence of Dark Matter and the Matter-Antimatter Imbalance implies new physics which may be accessible to experiments in this decade

We are only at the beginning of understanding the Dynamical generation of particle masses