Higgs and flavour physics near the Fermi scale

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"Rewarding science", LNF Frascati, 24 June 2015

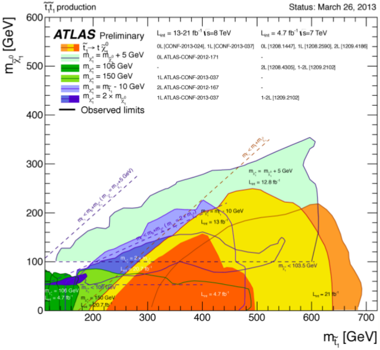
The Standard Model

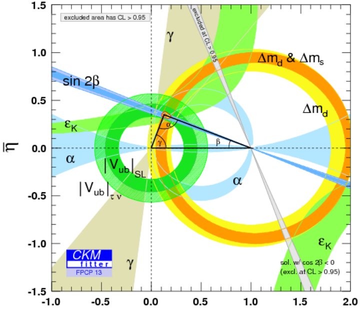
?The Standard Model?

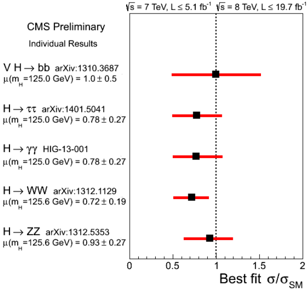
? Supersymmetry ? ??? ? Composite models ?

Neat indications of NP:

Gravity, Dark Matter, ν, ... but:







The Hierarchy Problem of the Fermi scale [Wilson 1971,...]

$m_h \approx \Lambda$ [$\Lambda =$ highest scale h couples to, e.g. $M_{\rm Planck}$]

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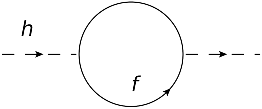
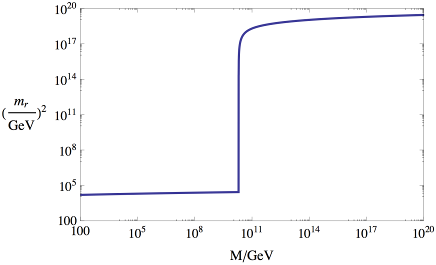
$\Lambda =$ "cutoff"? Misleading: SM is renormalizable and divergences do not appear.



$$\mathcal{L} \supset y\, h \bar{f} f \quad \Rightarrow \quad \frac{dm_h^2}{d\log\mu} = -\frac{3y^2}{4\pi^2} M_f^2$$

$$m_h^2(m_h^2) \simeq m_h^2(M_{NP}) - a M_{NP}^2 \log \frac{M_{NP}^2}{m_h^2}$$



Fine tuning $\Delta \simeq a M_{NP}^2 / m_h^2$

[e.g. $a \propto y^2$]

Hierarchy Problem: initial condition $m_h^2(M_{NP})$ to be chosen with precision $\sim 1/\Delta$

Physics at the Fermi scale depends on details of way shorter distances!

Where is New Physics? Theory

Answer $\simeq$ attitude towards the hierarchy problem

1 **Protect the mass of the scalars** from any NP ['t Hooft 1979, ...]

The Fermi scale is "natural" small Δ $\Rightarrow$ $M_{NP} \lesssim$ TeV

Examples: Supersymmetry composite Higgs models

No evidence for NP puts pressure on this "standard" attitude

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2 **Short distance assumptions** M_{NP} can be $\gg$ TeV

[W. Bardeen, Foot, Shaposhnikov, Dubovsky, Strumia,...]

$\Delta \simeq aM_{NP}^2/m_h^2$ with $a \ll 1$ (delicate, e.g. gravity?)

3 **Accept a large tuning** M_{NP} can be $\gg$ TeV

e.g. anthropic selection of parameters [Weinberg 1987, Agrawal et al 1997, ...]

This PhD thesis [defended 27 Nov 2013]

General motivation

Look for "natural" New Physics at current and future experiments

Where?

→ Higgs (SM and new ones) — Barbieri Buttazzo Kannike S Tesi 1304.3670
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→ Flavour — Barbieri Campli Isidori S Straub 1108.5125
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This seminar

Out: a lot, e.g. composite Higgs models, vacuum stability

In: more recent developments of above topics

Can new "Higgses" be the lightest new particles around?

Yes, in various natural models. For example in Supersymmetry

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MSSM

$m_h^2 \leq m_Z^2 \cos^2 2\beta + \Delta_t^2 \quad \Rightarrow \quad \Delta_t \gtrsim 85$ GeV $\quad \Rightarrow$ stops heavier than ~ 1.5 TeV

Fine tuning worse than 1%! $\quad \dfrac{dv^2}{dm_{H_u}^2} \simeq \dfrac{4}{g^2} \qquad \delta m_{H_u}^2 \sim -\dfrac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log \dfrac{\Lambda}{m_{\tilde{t}}}$

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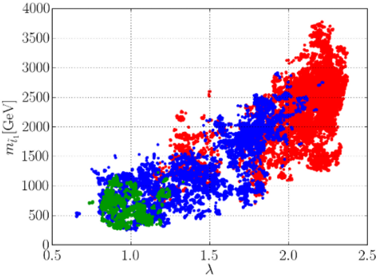
NMSSM

Extra singlet S $\Delta W = \lambda S H_u H_d + f(S)$

$m_h^2 \leq m_Z^2 c_{2\beta}^2 + \Delta_t^2 + \lambda^2 v^2 s_{2\beta}^2$

Fine tuning better than 5%! $\dfrac{dv^2}{dm_{H_u}^2} \simeq \dfrac{\kappa}{\lambda^3}\dfrac{1}{t_{2\beta}}$

[green points, $\tan\beta \lesssim 5$]



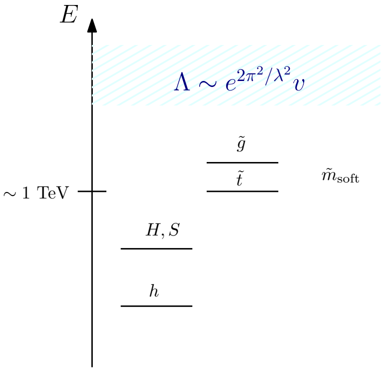
Gherghetta et al. 1212.5243 [$\Lambda = 20$ TeV]

Model, and plan of the next 6 slides

NMSSM with $\lambda \sim 1$ and heavy stops & gluinos

[$\lambda \gtrsim$ 0.7 needs a completion before the GUT scale]

Goal = strategy to look for the extra Higgses



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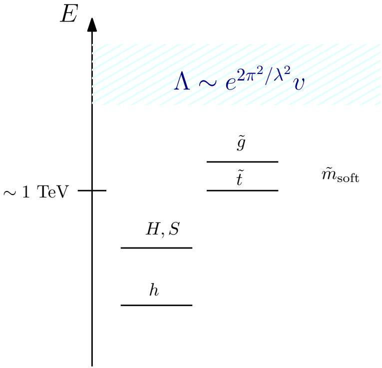
They are:

CP-even h_1, h_2, h_3 (from h, S, H)

CP-odd A, A_s

$H^\pm$



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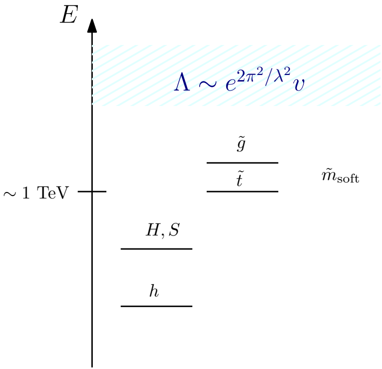


Assumptions

Only loop contribution = top-stop Δ_t

No invisible decays $h_1, h_2 \to \chi\chi, \ldots$

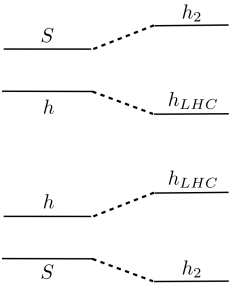
A useful parametrization

(generic NMSSM, no scatter plots..)

$$\mathcal{H}_{\rm ph} \equiv \begin{pmatrix} h_3 \\ h_1 \\ h_2 \end{pmatrix} = R^T \begin{pmatrix} H \\ h \\ S \end{pmatrix}, \quad R = \boxed{R^{12}_{\delta} R^{23}_{\gamma} R^{13}_{\sigma}}$$

$$m_{h_1} = 125 \text{ GeV}$$

$$\mathcal{M}^2 = \begin{pmatrix} \widetilde{\mathcal{M}}^2(m^2_{H^\pm}, \lambda, t_\beta, \Delta_t) & & \\ vM_1 & vM_2 & M_3^2 \end{pmatrix} = R^T \mathrm{diag}(m^2_{h_3}, m^2_{h_1}, m^2_{h_2}) R$$



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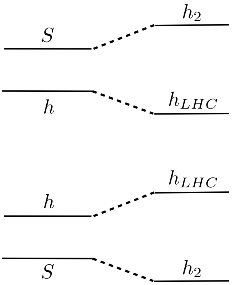

Analytic relations!

$$\delta,\ \gamma,\ \sigma\left(m_{h_2},\ m_{h_3},\quad m_{H^\pm},\ \lambda,\ t_\beta,\ \Delta_t\right)$$

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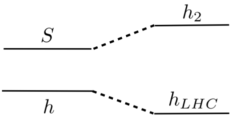

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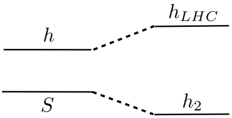


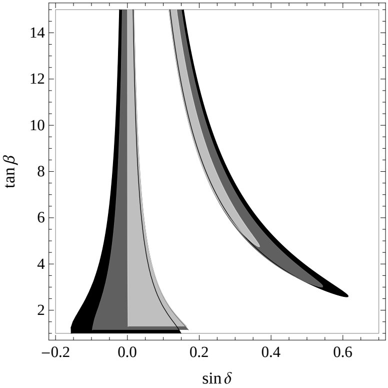
A motivated limiting case

$m_{h_3} \gg m_{h_{1,2}}$ and $\sigma, \delta \to 0$ [free pars: $m_{h_2}, t_\beta, \Delta_t, \lambda$]

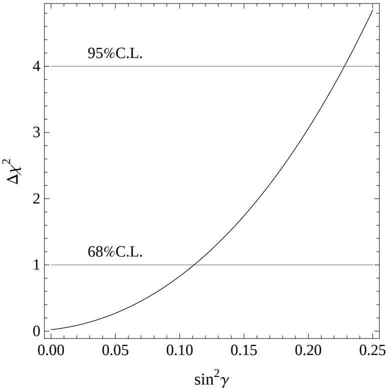
$$\left[h_{\text{LHC}} = h_1 = c_\gamma(c_\delta h - s_\delta H) + s_\gamma S\right]$$

$$\frac{g_{h_1 tt}}{g^{\text{SM}}_{htt}} = c_\gamma\left(c_\delta + \frac{s_\delta}{\tan\beta}\right), \qquad \frac{g_{h_1 bb}}{g^{\text{SM}}_{hbb}} = c_\gamma(c_\delta - s_\delta \tan\beta), \qquad \frac{g_{h_1 VV}}{g^{\text{SM}}_{hVV}} = c_\gamma c_\delta$$

LHC8 status



$s^2_\gamma = 0,\ 0.15,\ 0.3$



Higgs couplings and fit

$$\left[h_{\rm LHC} = h_1 = c_\gamma(c_\delta h - s_\delta H) + s_\gamma S\right]$$

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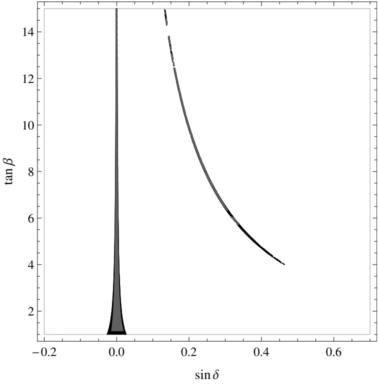
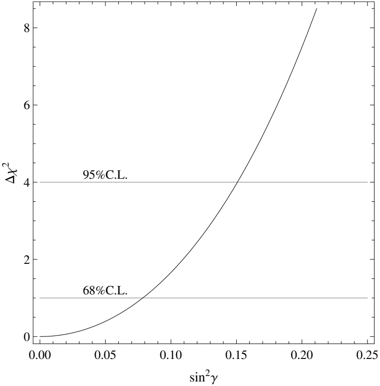
LHC14 (300 fb^{-1}) projections





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$[\delta, \sigma \to 0]$

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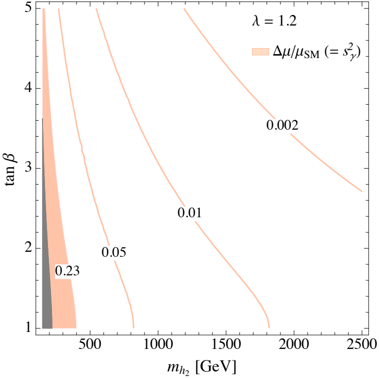
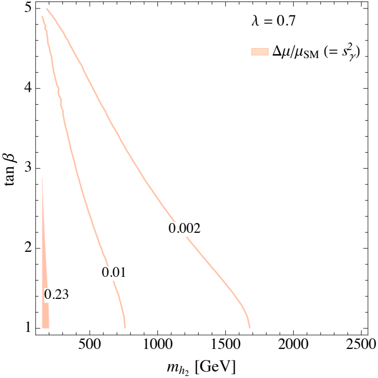
$[\Delta_t = 70 \div 80$ GeV, ininfluent$]$





Doublet H decoupled $[\delta, \sigma \to 0]$

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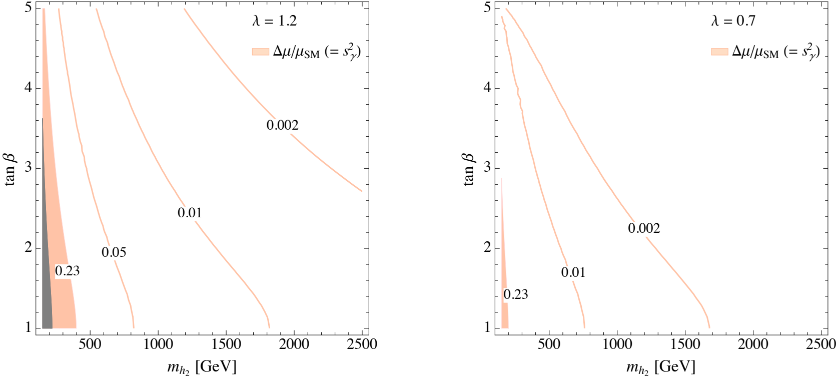


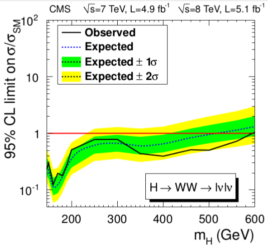
Direct searches of h_2: $m_{h_2} > 250$ GeV: VV dominates [second channel hh]

$m_{h_2} < 250$ GeV: signal $= s_\gamma^2 \times$ SM

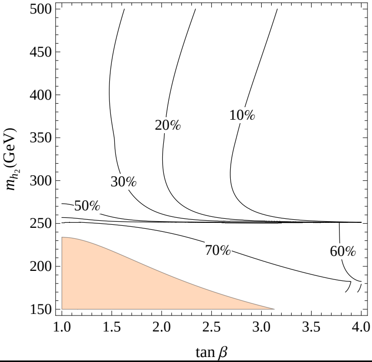
h_2 at the LHC and beyond

In 2013 everybody was looking for top partners!

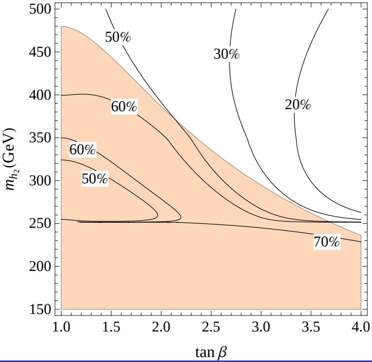
Only available searches in VV:



$\lambda = 0.8$



$\lambda = 1.4$



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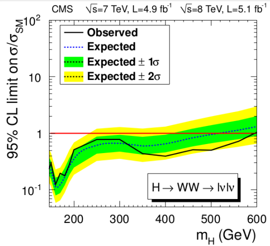
Only available searches in VV

Also $h_2 \to hh$ seemed promising:



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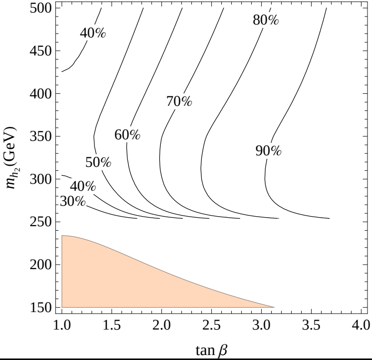

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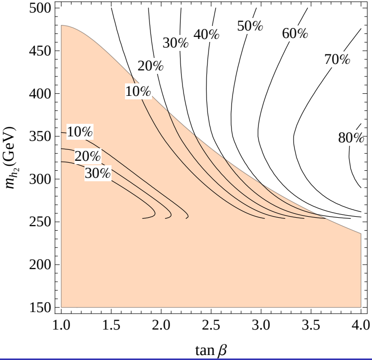
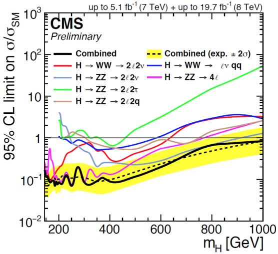


Now plenty of scalar searches!

General validity, NMSSM particular application:

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_{h_2}^2 - m_h^2}, \quad \text{only 2 free pars.!}$$

$$M_{hh}^2 = m_Z^2 c_{2\beta}^2 + \frac{\lambda^2 v^2}{2} s_{2\beta}^2 + \Delta_t^2, \quad \Delta_t \text{ little impact}$$



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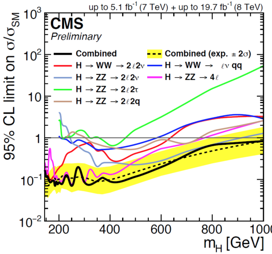

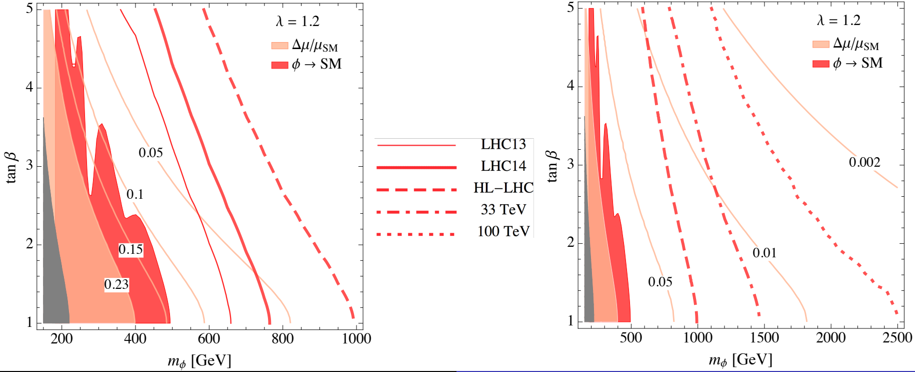

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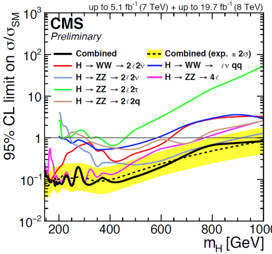

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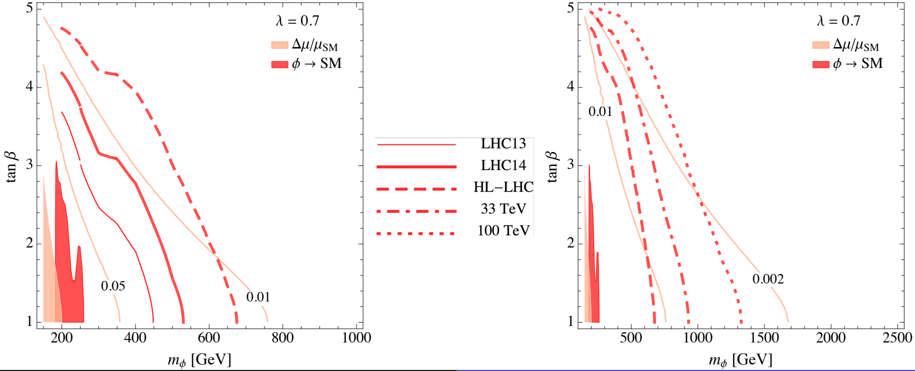

Higgses self couplings

Actually all V pars. matter for triple Higgs couplings...but dominant one is v_s!
[Buttazzo S Tesi 1505.05488]

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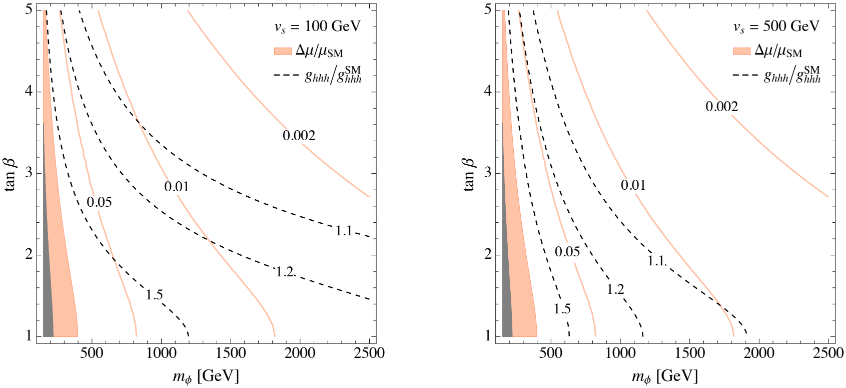
- ◇ $h_2 \to hh$ typically less important than $h_2 \to VV$, especially for $m_{h_2} \gg m_W$
- ◇ g_{hhh}: deviations expectable at the HL-LHC!



HL-LHC sensitivity: $\sim 50\%$ [from Snowmass report Dawson et al 1310.8361]

Flavour and $U(2)^3$

Flavour: motivation and $U(2)^3$

Flavour and the SM $$|V_{\rm CKM}| \sim \begin{pmatrix} 1 & 0.2 & 4\cdot 10^{-3} \\ 0.2 & 1 & 4\cdot 10^{-2} \\ 9\cdot 10^{-3} & 4\cdot 10^{-2} & 1 \end{pmatrix}$$

$$(y_u, y_c, y_t) \sim (10^{-6}, 10^{-2}, 1) \qquad (y_d, y_s, y_b) \sim (10^{-5}, 10^{-3}, 10^{-2})$$

Flavour and NP $\mathcal{L}_{\rm NF} = \sum_i \frac{1}{\Lambda_i^2}\mathcal{O}_i \quad \Rightarrow \quad \boxed{\Lambda_i \gtrsim 10^4 \div 10^5\ \text{TeV}}$

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Possible solution: $\qquad \mathcal{L}_{\rm NP} = \sum_i \xi_i \frac{c_i}{\Lambda_i^2}\mathcal{O}_i \qquad c_i \sim O(1)$

ξ_i small thanks to some "propriety" (e.g. a **flavour symmetry**)

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ξ_i small thanks to some "propriety" (e.g. a **flavour symmetry**)

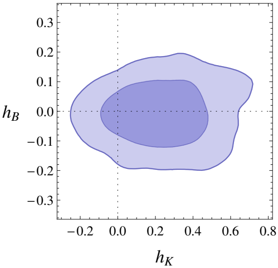
$U(2)^3 = U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}$ — Barbieri Isidori et al 1105.2296

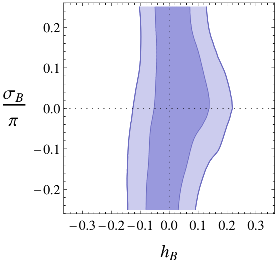
- ✓ $\xi \sim V_{CKM}^{2\div 4} \Rightarrow$ $\Lambda \sim$ a few TeV is OK with flavour constraints
- ✓ interesting phenomenology behind the corner
- ✓ separate 3rd generation from the first two → ideal for natural theories!

Bounds and new effects

$\Delta F = 2$

$h_{K,B} \simeq c_{K,B} \left(\frac{3\text{TeV}}{\Lambda}\right)^2$





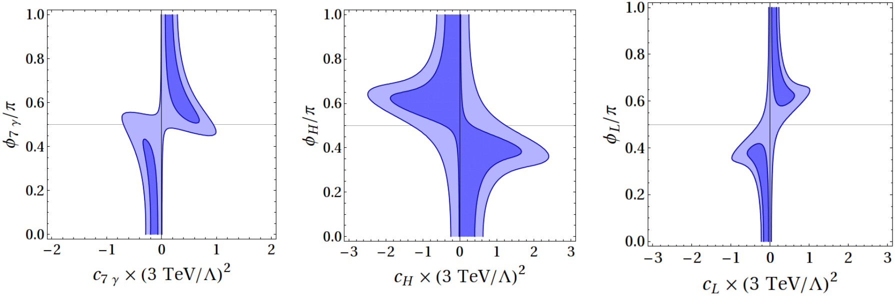
Take-home messages

- Data consistent with $\mathcal{L}_{\rm NP} = \sum_i \xi_i \frac{c_i}{\Lambda_i^2}\mathcal{O}_i$ and $|c_i| = 0.2 \div 1$
- Larger effects allowed than in other models (e.g. $U(3)^3$)

see also Buras, Girrbach 1206.3878

Bounds and new effects

$\Delta F = 1$ $\qquad$ $b \to s(d)\ell\bar{\ell},\ b \to s(d)\nu\bar{\nu}$



Take-home messages

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see also Buras, Girrbach 1206.3878

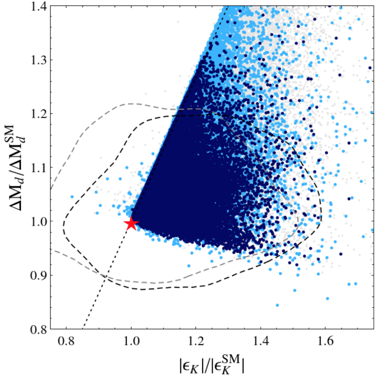
All points: allowed by LHC8 searches

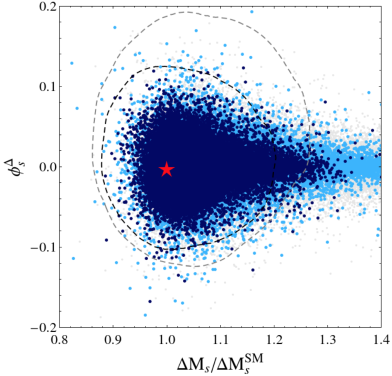
Darker: conservative exclusions

Lighter: compressed spectra, ...

[Dashed: $\Delta F = 2$ fit]

Barbieri Buttazzo S Straub 1402.6677



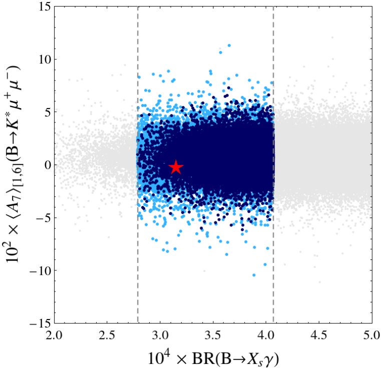


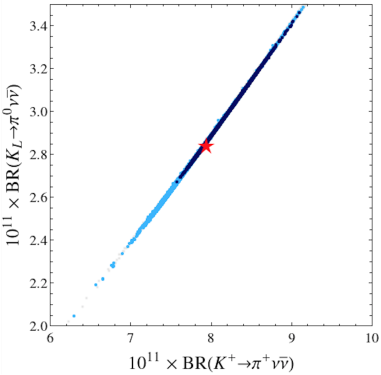
What if no sparticles observed at the LHC14?

Then only promising observables: ϕ_s $\Delta M_{d,s}$

$U(2)^3$ + SUSY: $\Delta F = 1$ vs the LHC

Barbieri Buttazzo S Straub 1402.6677





Target for LHCb: $A_7 \sim 2-3\%$

NA62 will measure $BR_{K^+ \to \pi^+ \nu \bar{\nu}}$ at $\sim 10\%$

Specific correlation could allow to distinguish $U(2)^3$ from other models

Conclusions

[stay tuned with EPJplus for a more complete overview]

Higgs and flavour measurements: what do they imply for natural New Physics?

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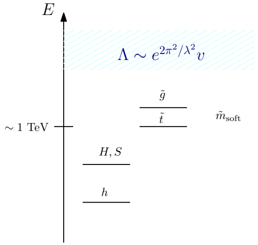
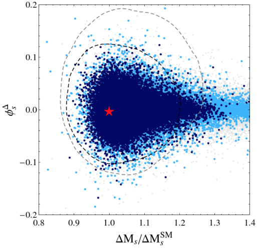


→ The NMSSM Higgs sector

[$h_2 \to VV, hh$, h couplings, g_{hhh}]

→ A $U(2)^3$ symmetry & the flavour of NP

[ϕ_s, $|V_{ub}|$, $b \to s(d)\ell\bar{\ell}, \nu\bar{\nu}, \ldots$]



Higgs and flavour measurements: what do they imply for natural New Physics?

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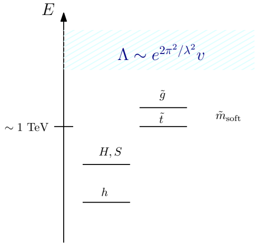

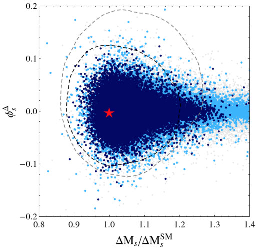

What next? A lot!

Flavour: improve on SM predictions (ϵ_K, ϵ'_K,...)

Higgses: phenomenology of CP-odd ones, H,...

NP unrelated to Hierarchy Problem: Dark Matter, ...

Many thanks to...

Riccardo Barbieri

Dario Buttazzo

Andrea Tesi

David M. Straub

Kristjan Kannike

Many thanks to...

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Istituto Nazionale di Fisica Nucleare

And to the INFN for the Fubini prize!

Back up Higgses

Extrapolation of direct searches

We started from (and improved)

i) Collider Reach (β) Salam Weiler 2014   ii) Thamm Torre Wulzer 1502.01701

m_0 excluded at LHC8, obtain m_1 at future collider via $B(s_1, L_1, m_1) = B(s_0, L_0, m_0)$

$$B(s, L, m) \propto L \times \int d\hat{s}\, \frac{1}{\hat{s}}\, \hat{s}\hat{\sigma}(\hat{s})\, \frac{d\mathcal{L}}{d\hat{s}}(s)$$

Assumptions/limitations

$\rightarrow$ Not valid if systematics dominate and change significantly from 0 to 1

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$$B(s, L, m) \propto L \times \frac{\Delta \hat{s}}{m^2}\, c\, \frac{d\mathcal{L}}{d\hat{s}}(s)\Big|_{\hat{s}=m^2} \qquad \hat{s}\hat{\sigma}(\hat{s}) = c \;\Rightarrow\; \frac{d\mathcal{L}}{d\hat{s}} \text{ drives the reach}$$

$$L_1\, c_{ij}\, \frac{d\mathcal{L}_{ij}}{d\hat{s}}(s_1)\Big|_{\hat{s}=m_1^2} = L_0\, c_{ij}\, \frac{d\mathcal{L}_{ij}}{d\hat{s}}(s_0)\Big|_{\hat{s}=m_0^2}$$

Assumptions/limitations

→ Not valid if systematics dominate and change significantly from 0 to 1

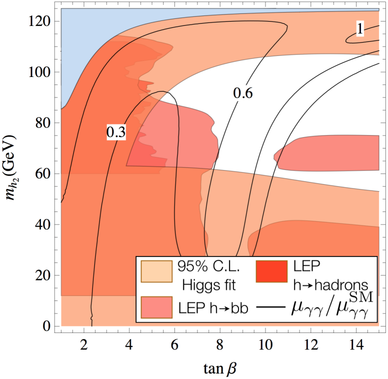
→ $\hat{s} \gg m_{\rm bkg}$ [i.e. not valid at $\hat{s} \sim 2m_t$ for $h_2 \to hh(4b)$]

→ $\frac{\Delta \hat{s}}{m^2} \ll 1$ i.e. not valid if analysis depends a lot on shape far from peak

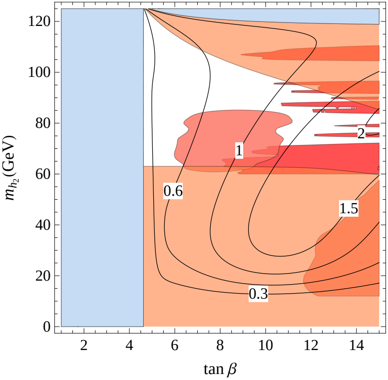
Singlet-like state lighter than 125 GeV

hard to see, but exploration already started

$\lambda = 0.1, \Delta_t = 85$ GeV



$\lambda = 0.8, \Delta_t = 75$GeV



$[m_{h_3} = 500$ GeV, $s_\sigma^2 = 10^{-3}$, $v_s = v]$

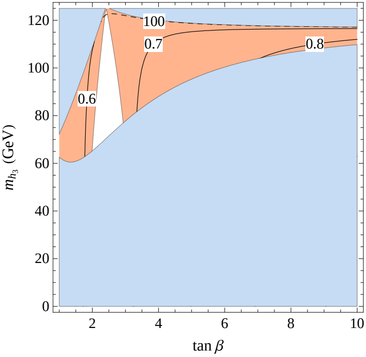
see e.g. Badziak et al. 1304.5437,...

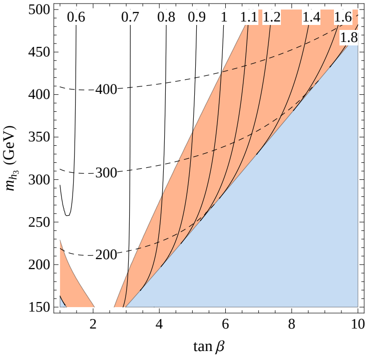
Singlet S decoupled $[\gamma, \sigma = 0, \quad m_{h_2} \gg m_{h_1}, m_{h_3}]$

$$\frac{g_{h_3 tt}}{g^{SM}_{htt}} = s_\delta - \frac{c_\delta}{t_\beta} \qquad \frac{g_{h_3 bb}}{g^{SM}_{hbb}} = s_\delta + t_\beta c_\delta \qquad \frac{g_{h_3 VV}}{g^{SM}_{hVV}} = s_\delta \qquad [\Delta_t = 75 \text{ GeV}]$$

Status fit LHC8:

dashed: $m_{H^\pm}$ cont: λ





$m_{H^\pm} > 480$ GeV from $B \to X_s \gamma$!

$[\widetilde{\mathcal{M}}^2_{12}(t_\beta, \dots) = 0 \to \delta = 0]$

h_3 phenomenology: more similar to MSSM

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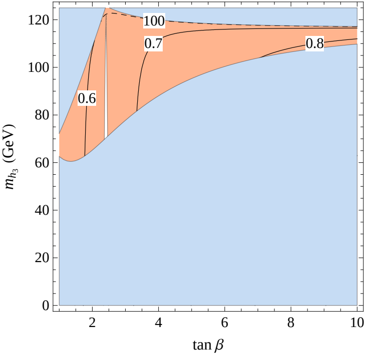
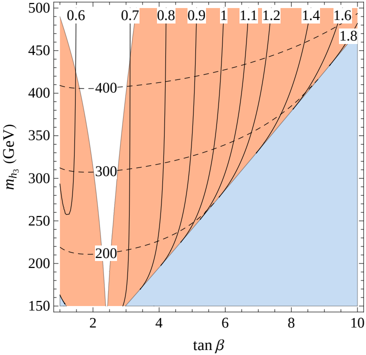
Projections fit LHC14 (300 fb^{-1}): dashed: $m_{H^\pm}$ cont: λ





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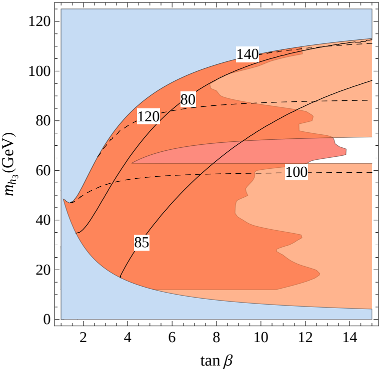

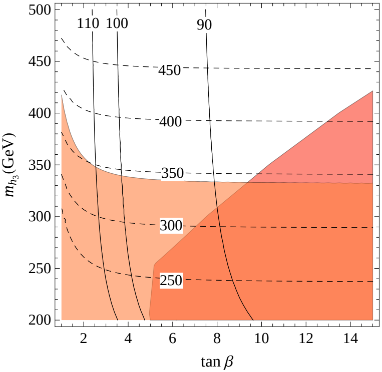

Red regions excluded by direct searches at LEP and CMS

Projections fit LHC14: above regions completely excluded

[if $\frac{\mu A_t}{m_{\tilde{t}}^2}$ very large, conclusions could change...]

Back up Flavour

Modelling $U(2)^3$ $= U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}$

$U(2)^3$ exact $\longrightarrow$ $m_u = m_d = m_s = m_c = 0,\ V_{CKM} = 1$

$$Y_u = y_t \left(\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right) \qquad Y_d = y_b \left(\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right)$$

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- Minimal $U(2)^3$: only 1 doublet $V \sim (2, 1, 1)$ to explain CKM

$V_{\rm CKM}(s_u, s_d, \delta, \epsilon_L) \rightarrow$ all **4** physical pars. from tree-level observables!

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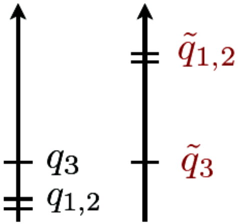
Assumption: all flavour violation controlled by $\Delta Y_{u,d}$, V

i.e. $\mathcal{L}_{\rm NP}$ built with bilinears like $\bar{\mathbf{q}}_{\mathbf{L}} V \gamma_\mu q_{3L}$, $\bar{\mathbf{q}}_{\mathbf{L}} \Delta Y_d \mathbf{d}_{\mathbf{R}}$

Example: $\mathcal{L}_{\rm NP} \supset \dfrac{c_L^B e^{i\phi_B}}{\Lambda^2} (\mathbf{V}_{\mathbf{tb}} \mathbf{V}^*_{\mathbf{ti}})^2 \, (\bar{d}_L^i \gamma_\mu b_L)^2, \quad i = d, s \qquad [B^0_{d,s} - \bar{B}^0_{d,s}]$

Supersymmetric realisation of $U(2)^3$



SUSY with heavy $1,2$ generations

✓ flavour-blind CP violation (EDMs)

✓ ok with collider bounds

Impossible in $U(3)^3$!

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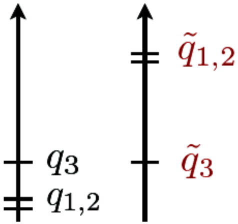

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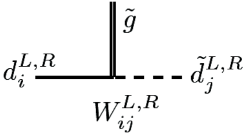
Impossible in $U(3)^3$!

$$\mathcal{L}_{F-breaking} \sim \tilde{q}^\dagger \, \tilde{m}^2(\Delta Y, V) \, \tilde{q}$$

$$W^L \simeq \begin{pmatrix} c_d & \kappa^* & -\kappa^* s_L e^{i\gamma} \\ -\kappa & c_d & -c_d s_L e^{i\gamma} \\ 0 & s_L e^{-i\gamma} & 1 \end{pmatrix}$$

$$W^R \simeq 1 + O(y_s/y_b) \qquad \kappa = s_d e^{i\beta}$$



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} \left(1 + F_{\tilde{g}} + F_{H^\pm} + F_{\tilde{H}^\pm} + F_{\tilde{W}} + F_{\tilde{B}} \right)$$

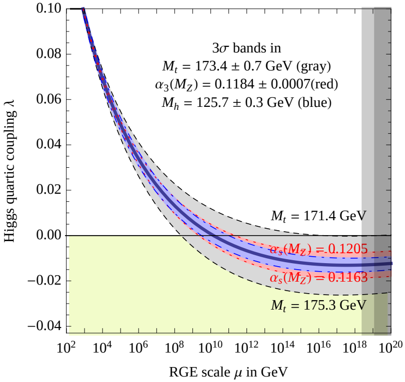
Back up Vacuum stability

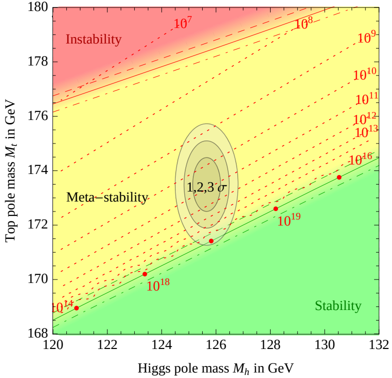
$$\Big($$

Other *neat* indications of a NP scale?

SM vacuum is metastable $\Rightarrow$ does not require NP!

[DM and neutrinos can be included without further destabilising]





Buttazzo Degrassi Giardino Giudice S Salvio Strumia 1307.3536

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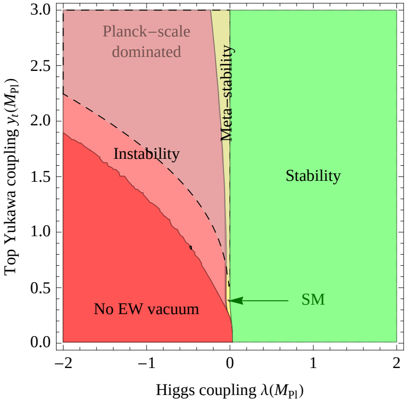

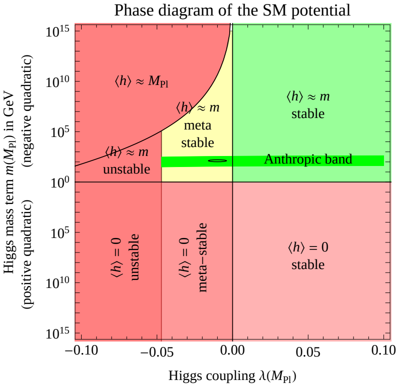

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But: λ and y_t are "crytical", accident or deep meaning?

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