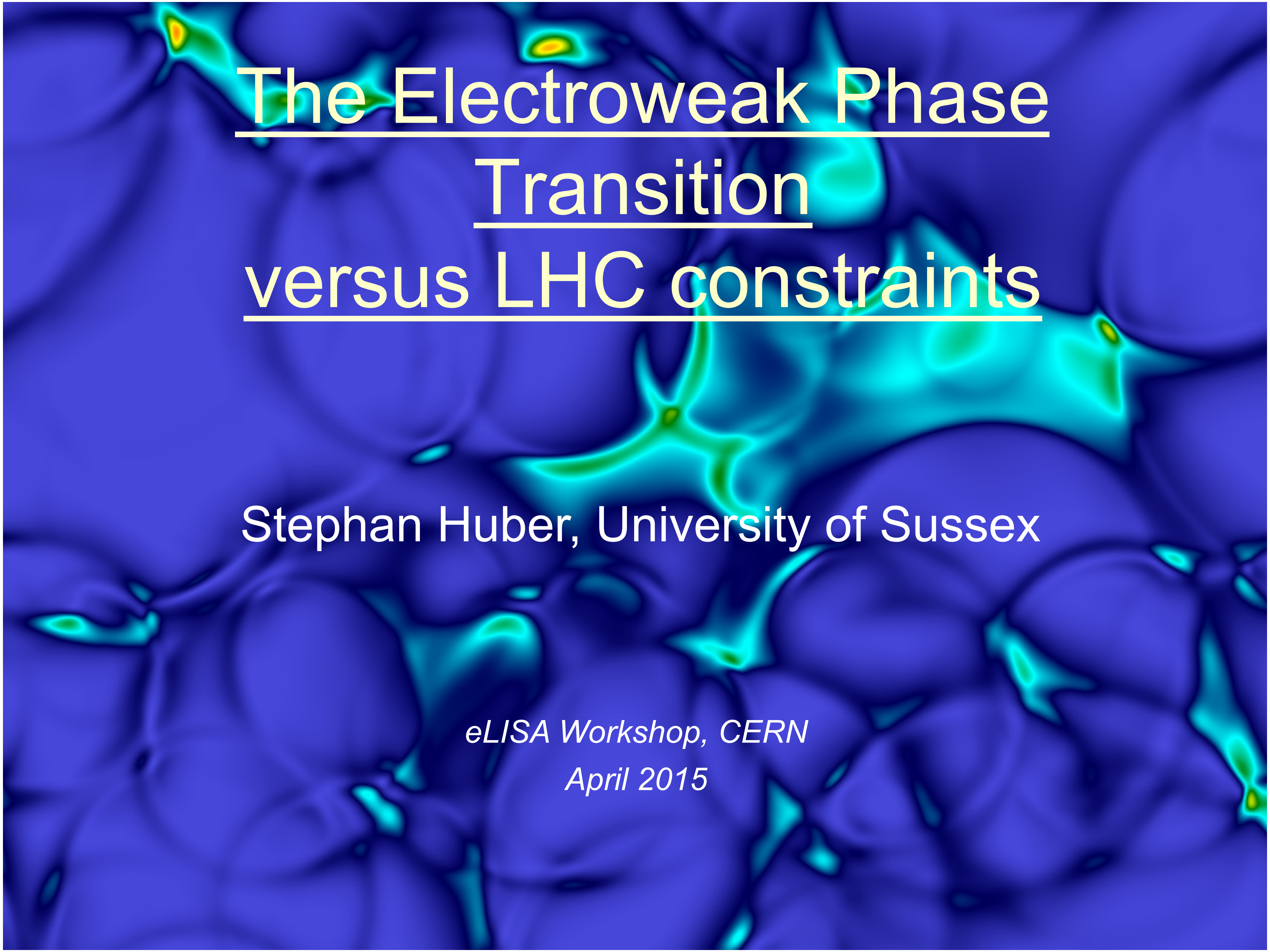


The Electroweak Phase Transition versus LHC constraints

Stephan Huber, University of Sussex

eLISA Workshop, CERN

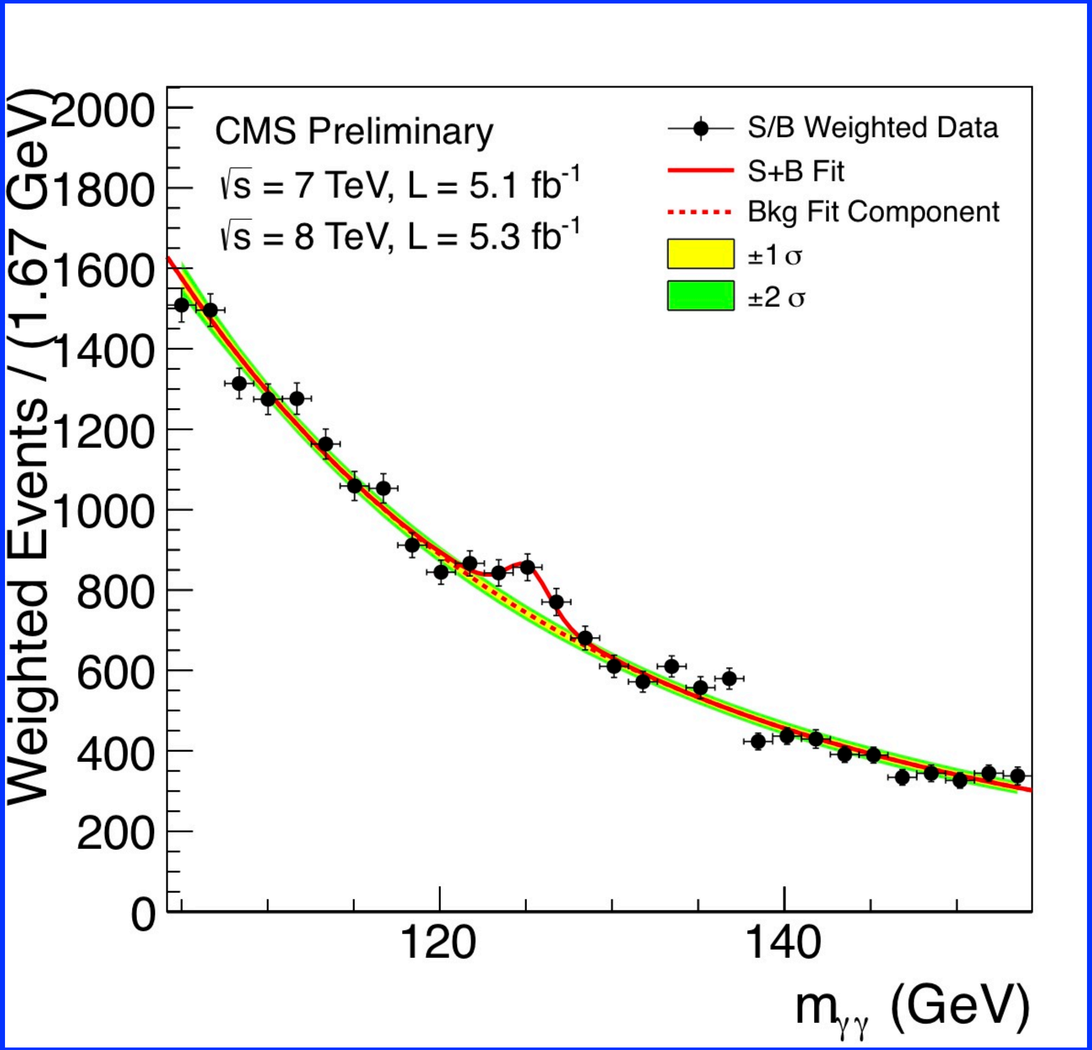
April 2015

Higgs discovery:

- Di-photon channel:

  (summer 2012)

- No other particles found

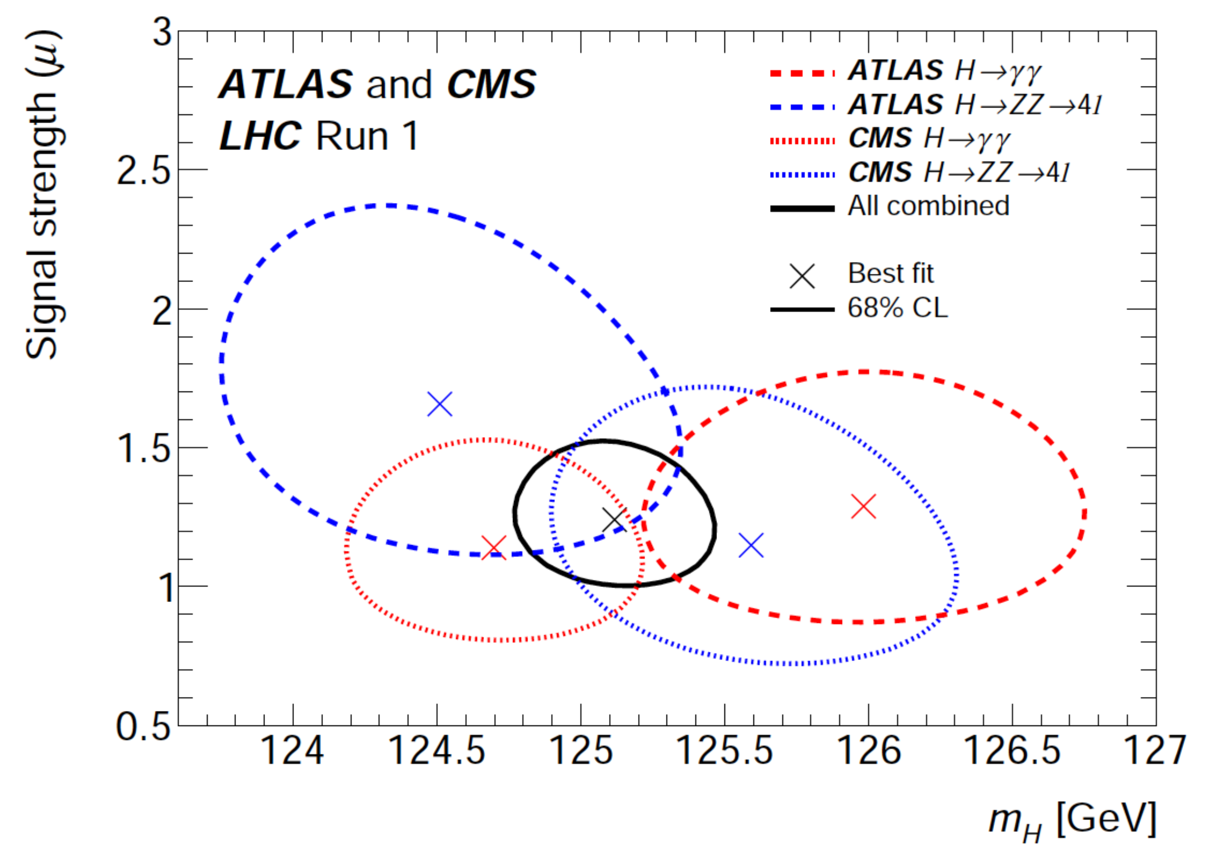


Light Higgs, but no electroweak phase transition in the minimal standard model

m_H=125.1 ± 0.2 GeV

Measured branching fractions:

[ALTAS,CMS 1503.07589]

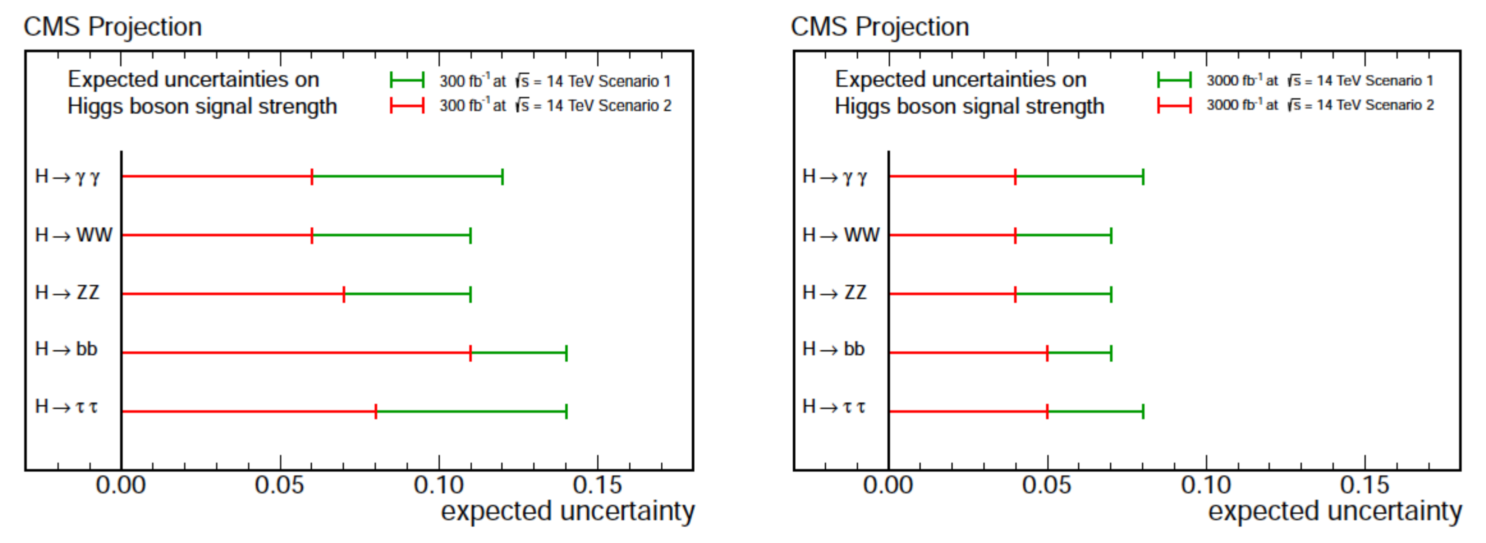


➔ Higgs is very SM-like

The future:

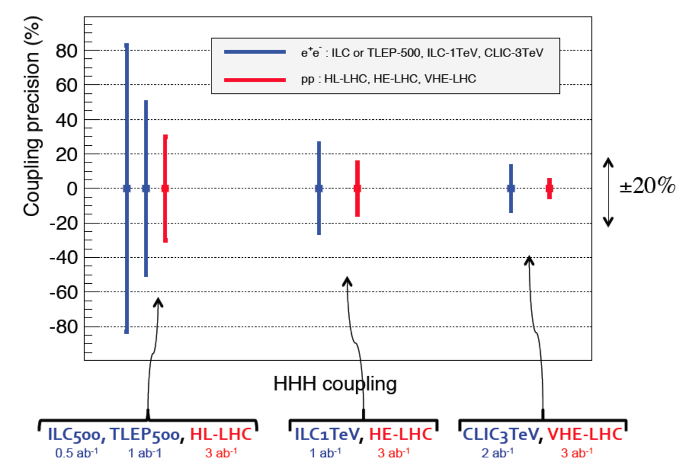
[CMS 1307.7135]

- Higgs branching fractions



- Enhanced sensitivity to new particles, in particular new scalars

- Higgs self coupling



[TLEP 1308.6176]

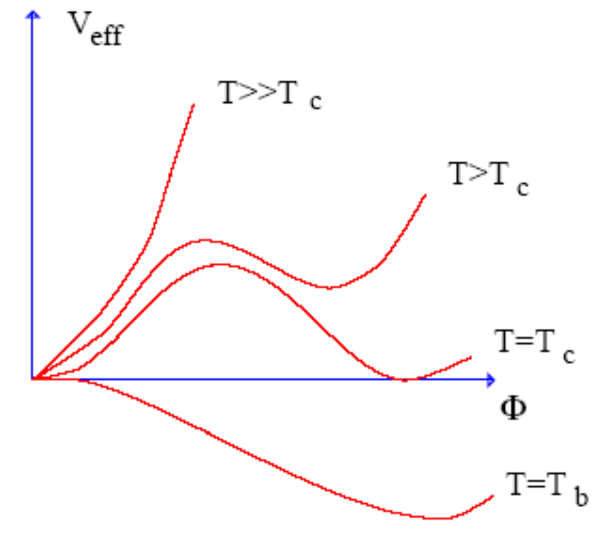
The strength of the PT

Thermal potential:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$

- Bosons in the plasma:

  SM: gauge bosons



Lattice: crossover for m_h>80 GeV → requires NEW PHYSICS!

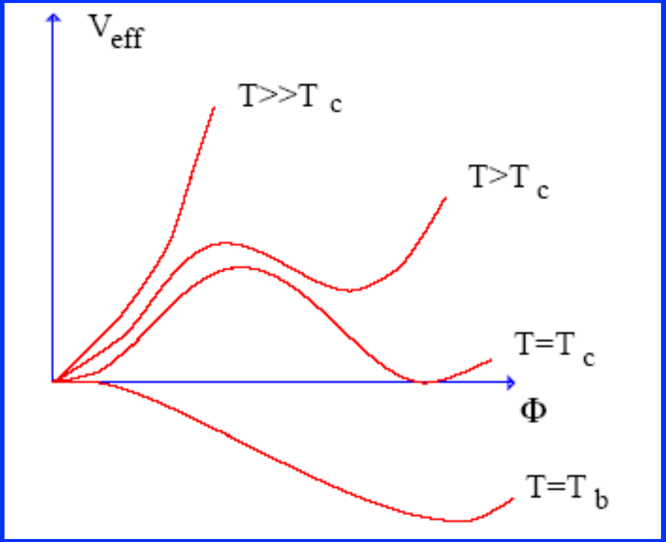
Kajantie, Laine, Rummukainen, Shaposhnikov 1996

Csikor, Fodor, Heitger 1998

The strength of the PT

Thermal potential:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$



- Bosons in the plasma:

  SM: gauge bosons

  SUSY: light stops [Laine, Nardini, Rummumainen '12]

  2HDM: heavy Higgses [Dorsch, SJH, No '13]

- tree-level: extra singlets: $\lambda S H^2$, NMSSM, etc. [Kozaczuk et al.'14]

- replace H^4 by H^6 or introduce $H^2\log(H^2)$, etc. [Dorsch, SJH, No '14]

Outline

- modified SM Higgs potential
- Higgs plus singlet
- extra Higgs doublets
- extra colored particles
- summary and conclusions

Modified SM potential

SM + higher-dim. operators

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{M^2}|H|^6$$

Zhang ‘93

Grojean et al. ‘04

maybe related to strong dynamics at the TeV scale, such as technicolor or gravity?

(or simply comes from integrating out extra scalars)

two parameters, (λ, M) ↔ (m_h, M)

λ can be negative → bump because of $|H|^4$ and $|H|^6$

$$\begin{aligned} V_{\rm eff}(\phi,T) = \quad & \frac{1}{2}\left(-\mu^2 + \left(\frac{1}{2}\lambda + \frac{3}{16}g_2^2 + \frac{1}{16}g_1{}^2 + \frac{1}{4}y_t^2\right)T^2\right)\phi^2 \\ & - \frac{g_2^3}{16\pi}T\phi^3 + \frac{\lambda}{4}\phi^4 + \frac{3}{64\pi^2}y_t^4\phi^4\ln\left(\frac{Q^2}{c_F T^2}\right) \\ & + \frac{1}{8M^2}(\phi^6 + 2\phi^4T^2 + \phi^2T^4). \end{aligned}$$

Results for the PT

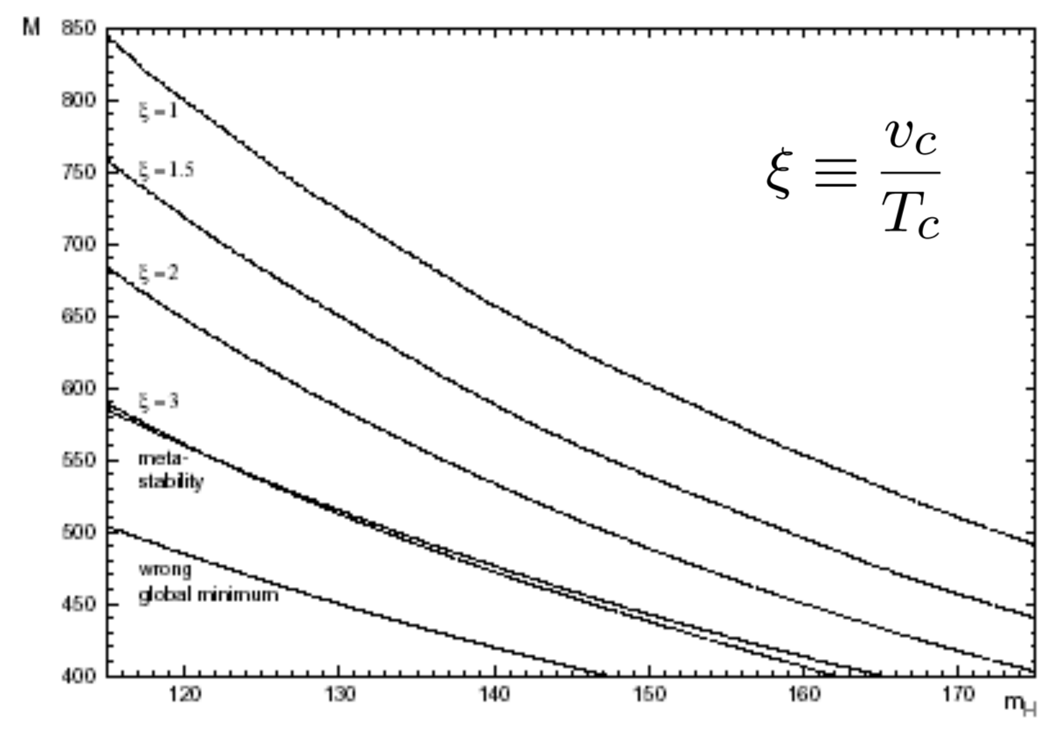
Evaluating the 1-loop

thermal potential:

strong phase transition

for M<850 GeV

up to m_h ~170 GeV



Bödeker, Fromme, S.H., Seniuch ‘04

wall thickness
$2 < L_w T_c < 16$

Similar results, including Higgs cubic terms

Delaunay, Grojean, Wells ‘07

Phenomenology

Grojean, Servant, Wells ‘04

deviations from the SM cubic Higgs

self coupling μH^3

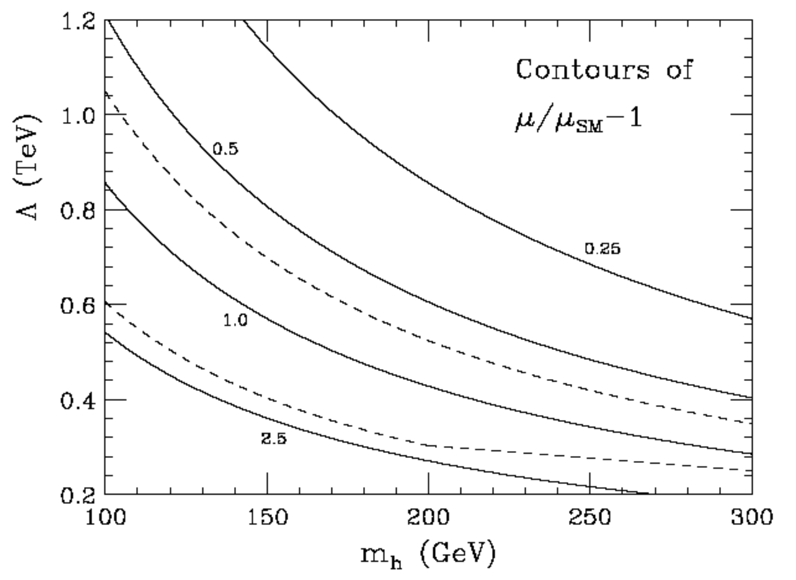
expect order unity deviation!

LHC: order unity sensitivity

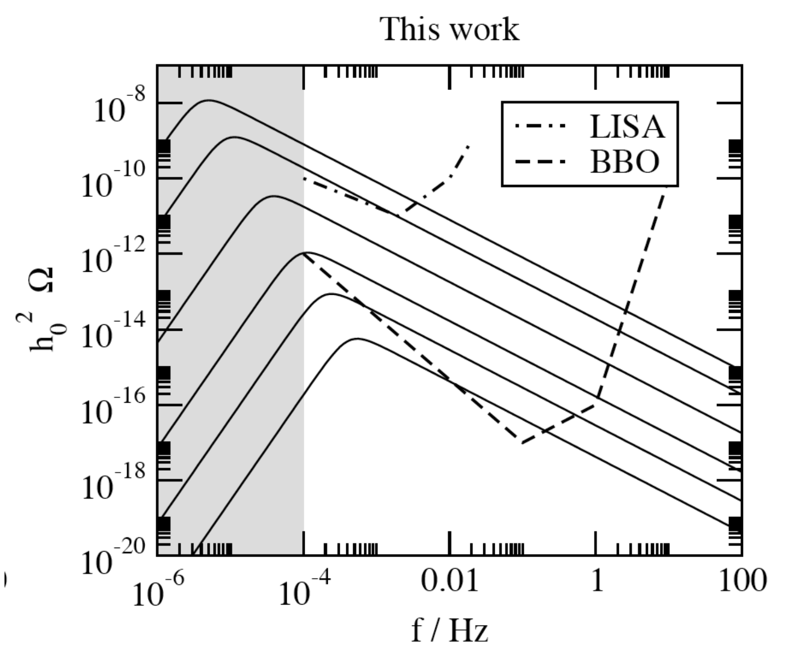
detection by HL-LHC, ILC, TLEP?

find resonances related to the

UV completion?



GW's in the Φ^6 model



T. Konstandin, S.H. ‘08

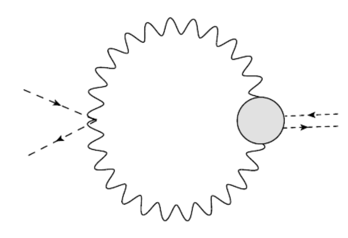
Scale invariant Higgs

Higgs mass stabilized by conformal symmetry, [Abel, Mariotti ’13]

Broken in a hidden sector,

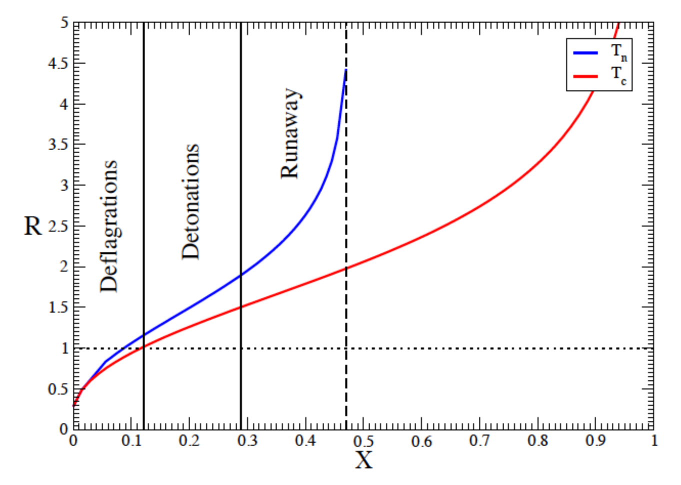
Transmitted to the SM by gauge mediation:

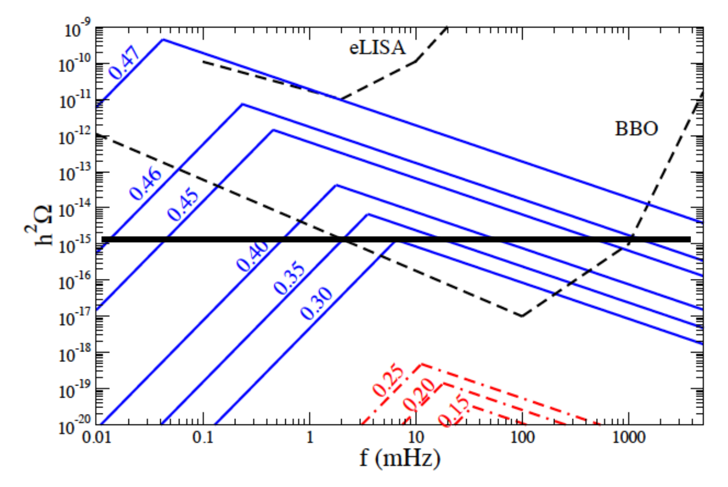
$$\delta V_{\rm eff} \equiv V_0 = -\frac{m_h^2}{4}\, h^2 \left(1 + X \log\left[\frac{h^2}{v^2}\right]\right) + \frac{\lambda}{4}\, h^4$$



$$(\lambda^{hhh}/\lambda^{hhh}_{\rm SM}) - 1 \;=\; 2X/3$$

[Dorsch, SH, No ’14]





Higgs + singlet

The Higgs potential

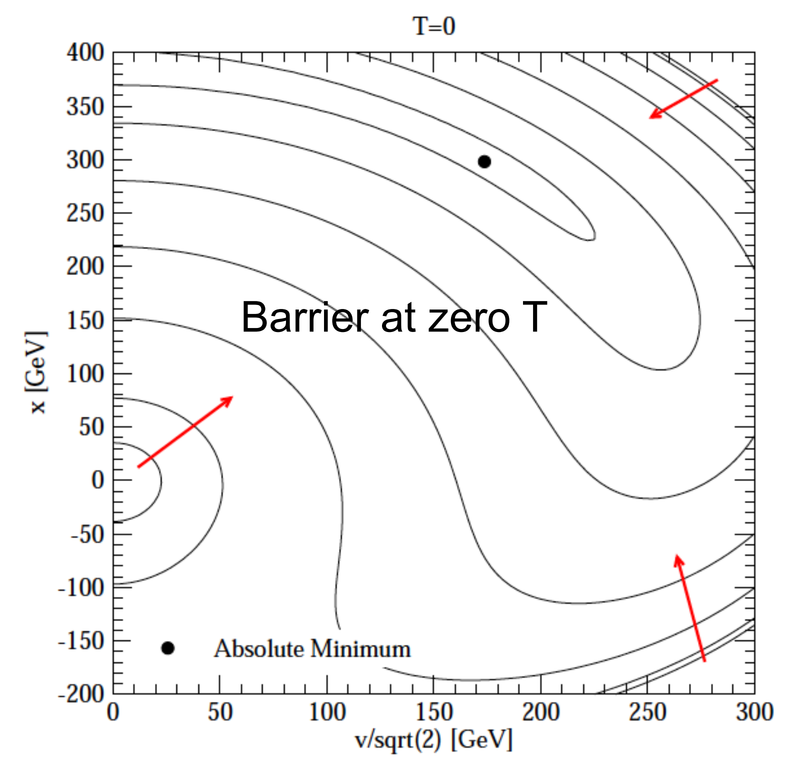
[Profumo, Ramsey-Musolf, Shaughnessy ‘07]

$$V = V_{\rm SM} + V_{\rm HS} + V_{\rm S}$$

$$V_{\rm SM} = -\mu^2 \left(H^\dagger H\right) + \bar{\lambda}_0 \left(H^\dagger H\right)^2$$

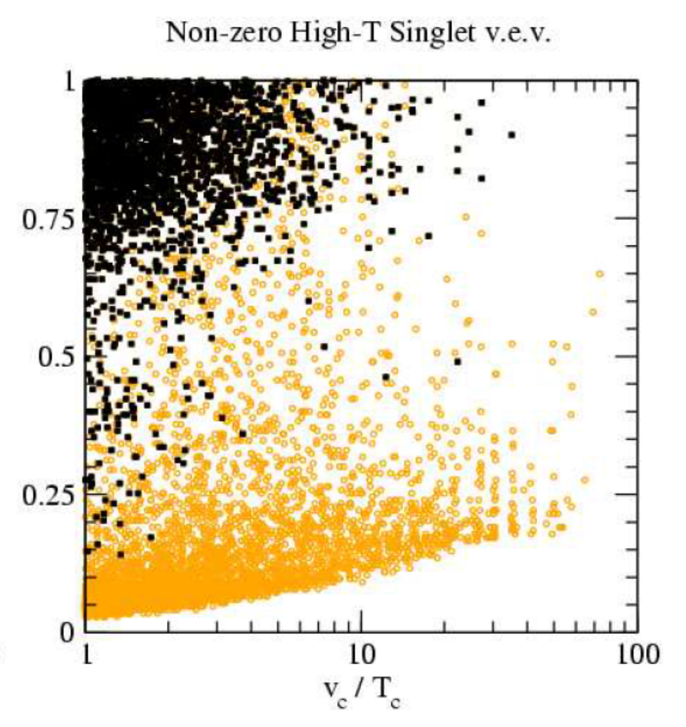
$$V_{\rm HS} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

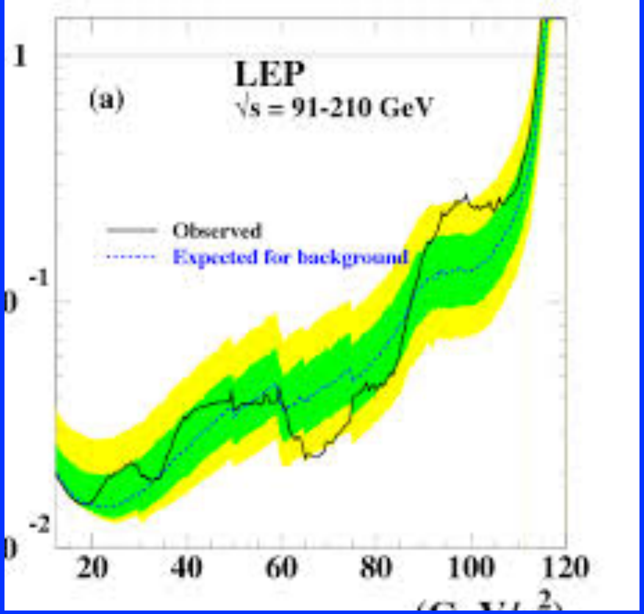
$$V_{\rm S} = \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 \quad ,$$

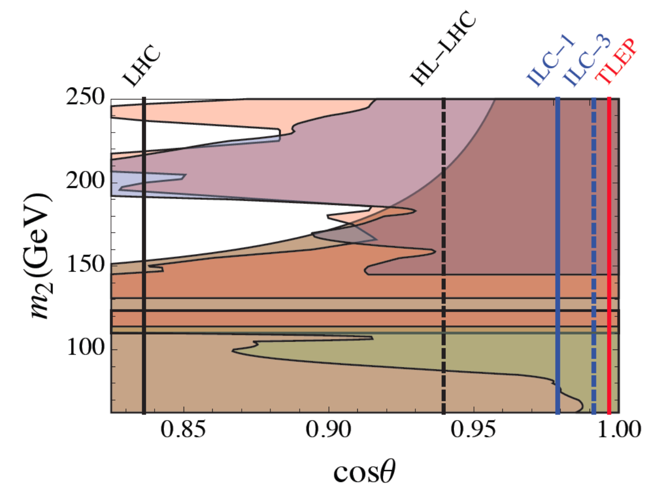


Barrier at zero T

Constraints from Higgs-singlet mixing







One can search for extra scalars, etc.

Also huge literature on singlets in SUSY, eg.

[Kozaczuk, Profumo, Haskins, Wainwright ’14]

The 2HDM

The 2HDM

$$V(H_1,H_2) = \mu_1^2|H_1|^2+\mu_2^2|H_2|^2+\mu_3^2 e^{i\phi}H_1^\dagger H_2 \\ +\lambda_1|H_1|^4+\ldots$$

→ 4 extra physical Higgs degrees of freedom: 2 neutral, 2 charged

→ CP violation, phase Φ (μ_3 breaks Z_2 symmetry softly)

→ there is a phase induced between the 2 Higgs vevs

$$v_1 = \langle H_1\rangle, \qquad v_2 e^{i\theta} = \langle H_2\rangle$$

early work:
Turok, Zadrozny ’91
Davies, Froggatt, Jenkins, Moorhouse ’94
Cline, Kainulainen, Vischer ’95
Cline, Lemieux ‘96

simplified parameter choice:

1 light Higgs m_h → SM-like

3 degenerate heavy Higgses m_H → keeps EW corrections small

The phase transition

Evaluate 1-loop thermal potential:

loops of heavy Higgses generate a cubic term

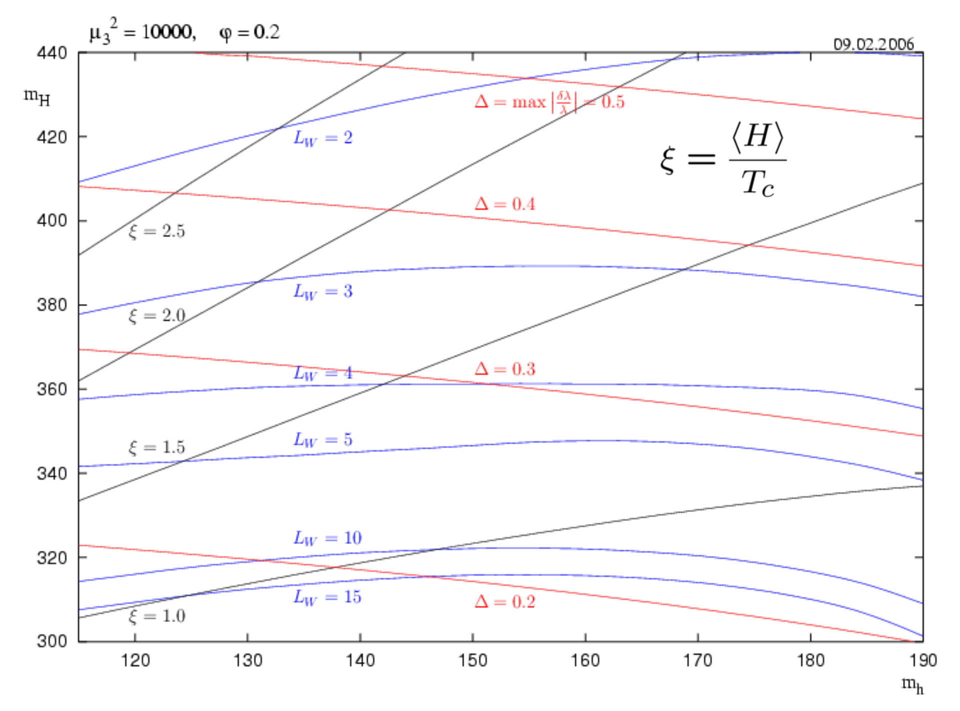
→ strong PT for

m_H>300 GeV

m_h up to 200 GeV

→ PT ~ independent of Φ

→ thin walls only for very strong PT (agrees with Cline, Lemieux ’96)



[Fromme, S.H., Senuich ’06]

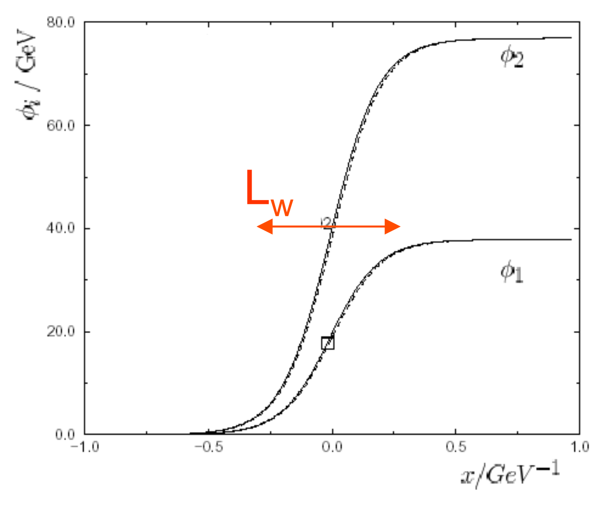
missing: 2-loop analysis of the thermal potential; lattice; wall velocity

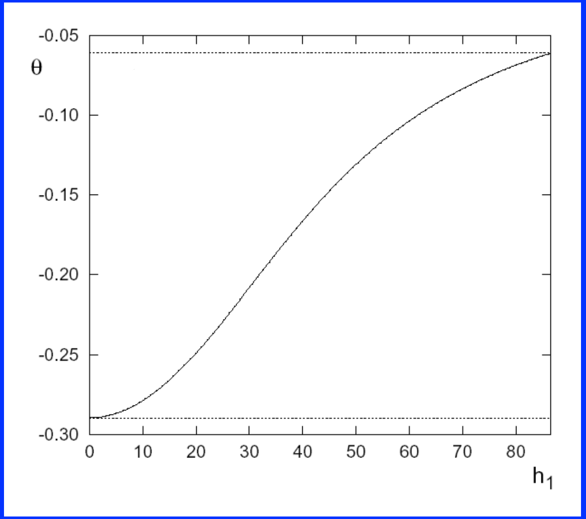
The bubble wall

Solve the field equations with the thermal potential → wall profile $\Phi_i(r)$

kink-shaped with wall thickness L_w

θ becomes dynamical





(numerical algorithm for multi-field profiles, T. Konstandin, S.H. ´06)

The baryon asymmetry

The relative phase between the Higgs vevs, θ, changes along the bubble wall

→ phase of the top mass varies

$\theta_t = \theta/(1+\tan^2\beta)$

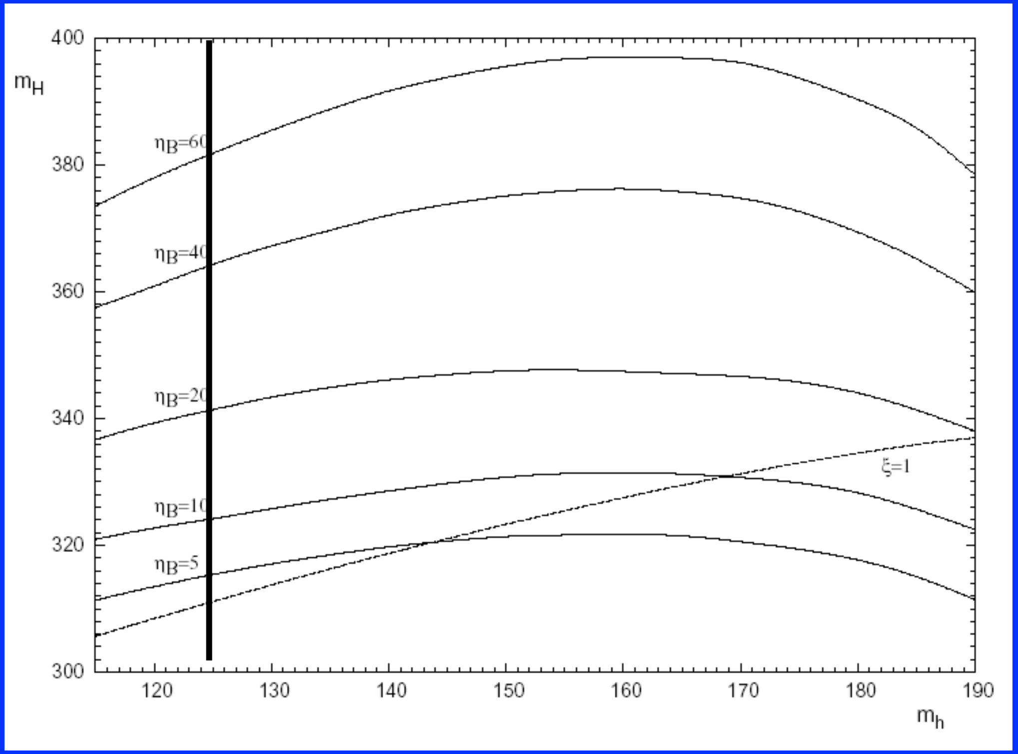
top transport generates a baryon asymmetry, but

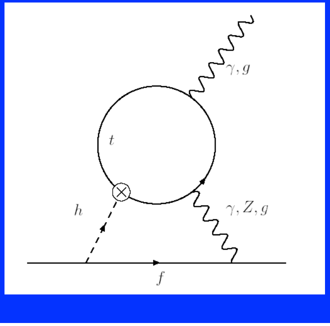
$\tan\beta < 10$ (?)

→ only one phase, so EDMs can be predicted: here

$d_n = 0.1\ 10^{-26} - 7\ 10^{-26}$ e cm

exp. bound: $d_n < 3.0\ 10^{-26}$ e cm





η_B in units of 10^{-11}, $\varphi=0.2$

More general parameter scan

[Dorsch, S.H., No, 2013]

$$\begin{aligned} V_{tree}(\Phi_1,\Phi_2) = &- \mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \frac{\mu^2}{2}\left(e^{i\phi}\Phi_1^\dagger\Phi_2 + H.c.\right) + \\ &+ \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \\ &+ \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + H.c.\right] \end{aligned}$$

Type I or II, softly broken

No CP violation, i.e. Φ=0

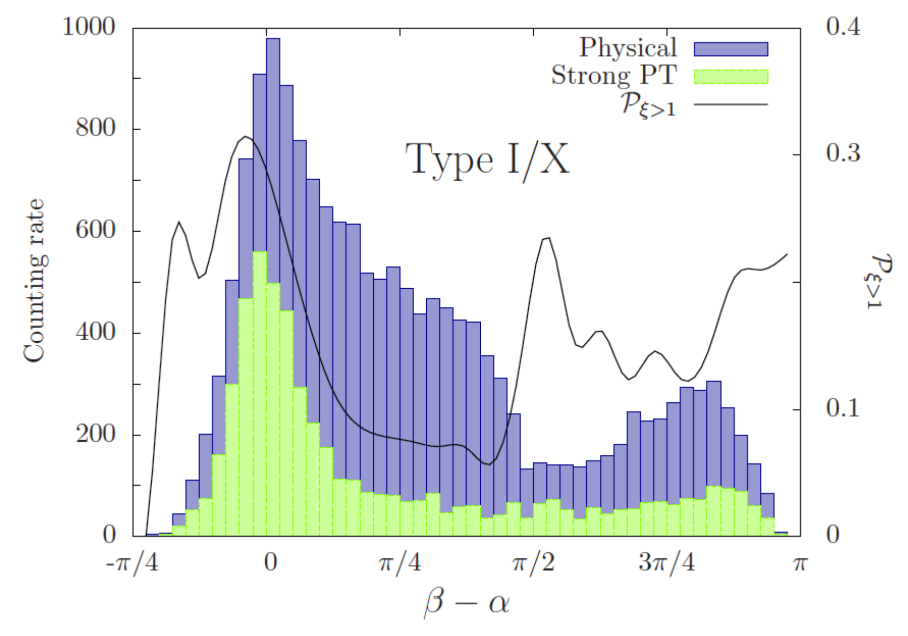
We analyze the thermal 1-loop potential

$$\begin{aligned} 0.4 \leq\ & \tan\beta \leq 10, \\ -\tfrac{\pi}{2} <\ & \alpha\ \leq \tfrac{\pi}{2}, \\ 0\ \text{GeV} \leq\ & \mu \leq 1\ \text{TeV}, \\ 100\ \text{GeV} \leq\ & m_{A^0},\ m_{H^\pm} \leq 1\ \text{TeV}, \\ 150\ \text{GeV} \leq\ & m_{H^0} \leq 1\ \text{TeV}. \end{aligned}$$

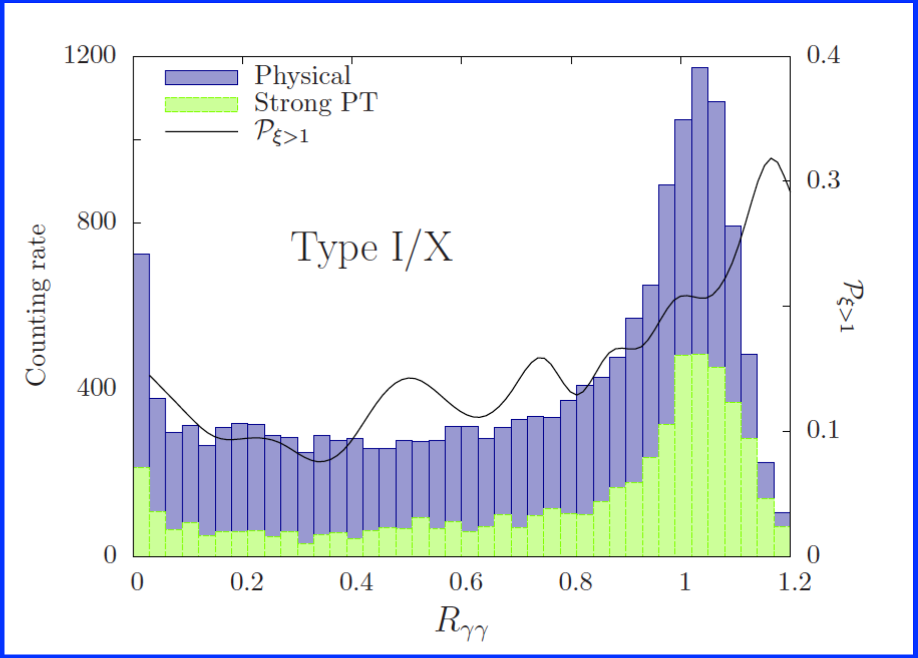
(parameter ranges, m_h=125 GeV)

Constraints: rho-parameter

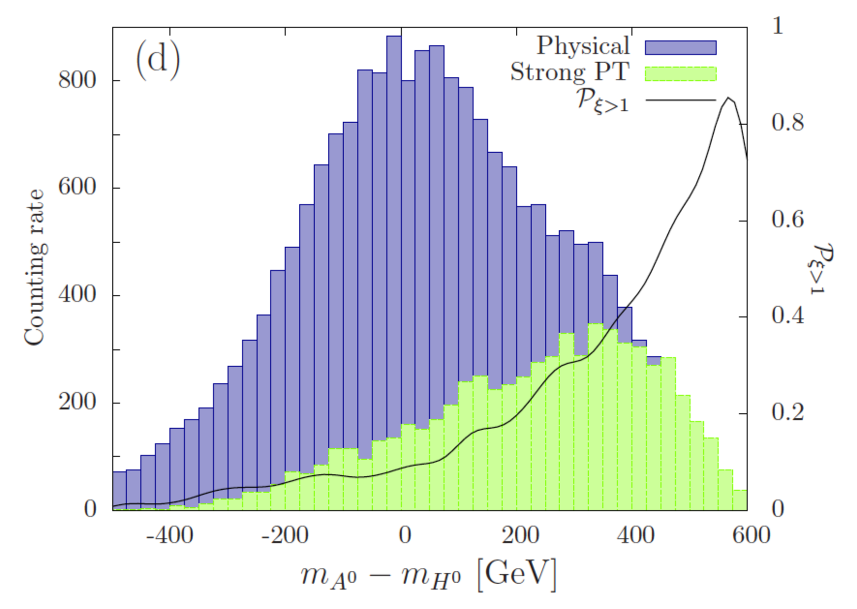
B→ s γ, B-Bbar mixing



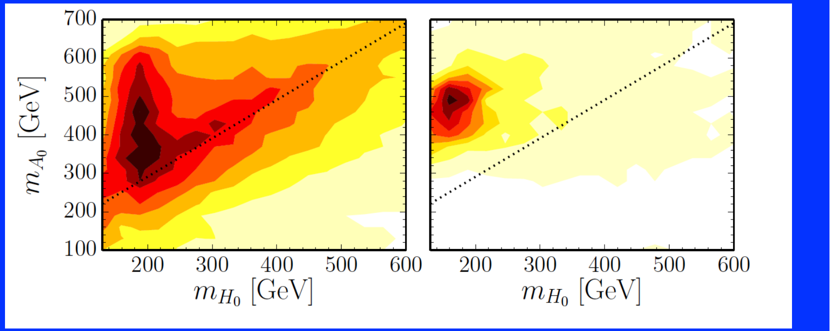
SM like
Higgs?



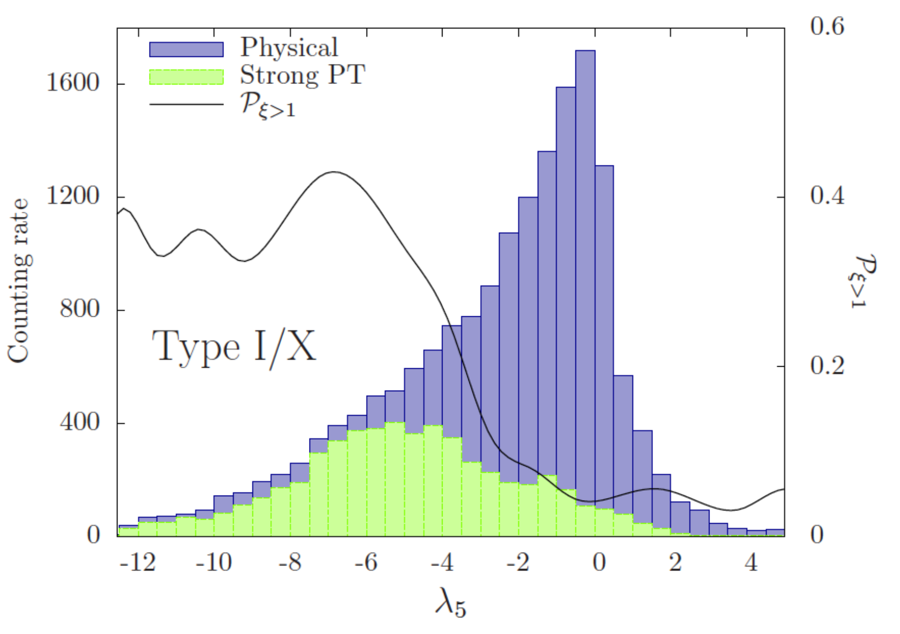
Di-photon channel



Preference for a heavy pseudoscalar



[Dorsch, S.H., Mimasu, No ‘14]



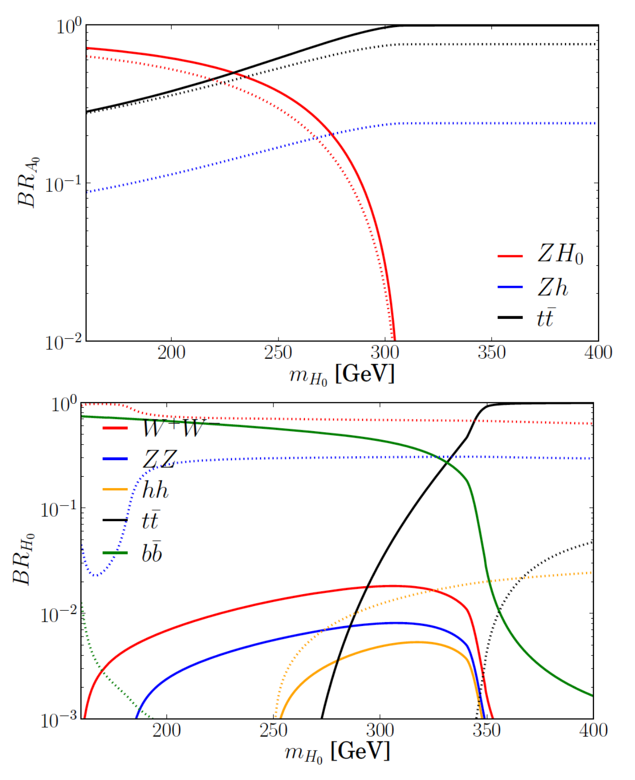
Preference for a large negative λ_5

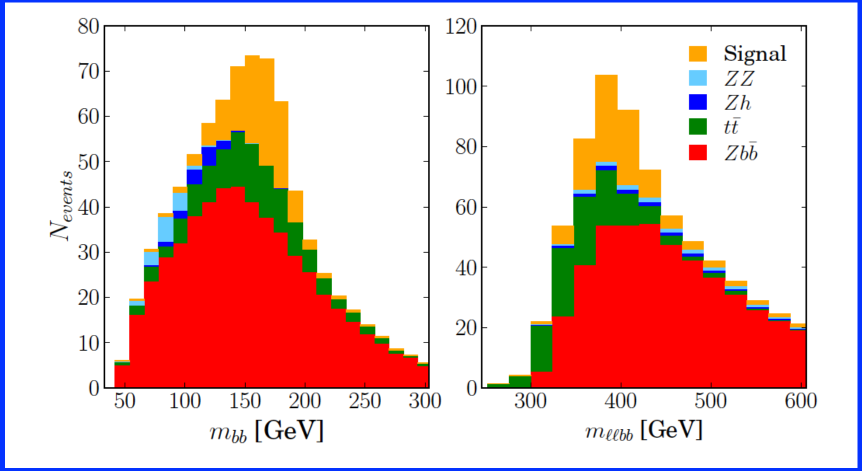
$$\frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + H.c.\right]$$

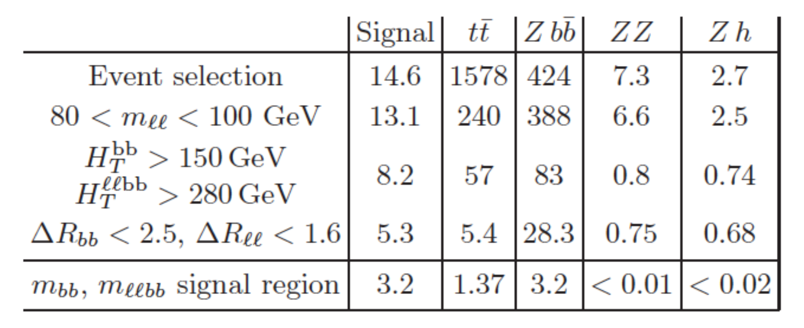
The strong phase transition at LHC

Search for $A_0 \to H_0 Z \to ll\ bb$

[Dorsch, S.H., Mimasu, No ‘14]







	Signal	$t\bar{t}$	$Z\,b\bar{b}$	ZZ	$Z\,h$
Event selection	14.6	1578	424	7.3	2.7
$80 < m_{\ell\ell} < 100$ GeV	13.1	240	388	6.6	2.5
$H_T^{\rm bb} > 150$ GeV $H_T^{\ell\ell {\rm bb}} > 280$ GeV	8.2	57	83	0.8	0.74
$\Delta R_{bb} < 2.5$, $\Delta R_{\ell\ell} < 1.6$	5.3	5.4	28.3	0.75	0.68
m_{bb}, $m_{\ell\ell bb}$ signal region	3.2	1.37	3.2	< 0.01	< 0.02

Discovery needs ~ 40 fb^{-1} (at 14 TeV)

($m^{\pm}$=400 GeV, m_{H_o}=180 GeV)

a strong phase transition in the 2HDM is very much consistent with a SM-like light Higgs

specific predictions for the mass spectrum and certain coupling constants

testable at LHC

Classic: The MSSM

strong PT from stop loops

→ right-handed stop mass ~100 GeV

left-handed stop mass ~1000 TeV

CP violation from varying chargino mixing

resonant enhancement of η for $M_2 \sim \mu$

chargino mass < ~300 GeV

large phases > 0.2 required

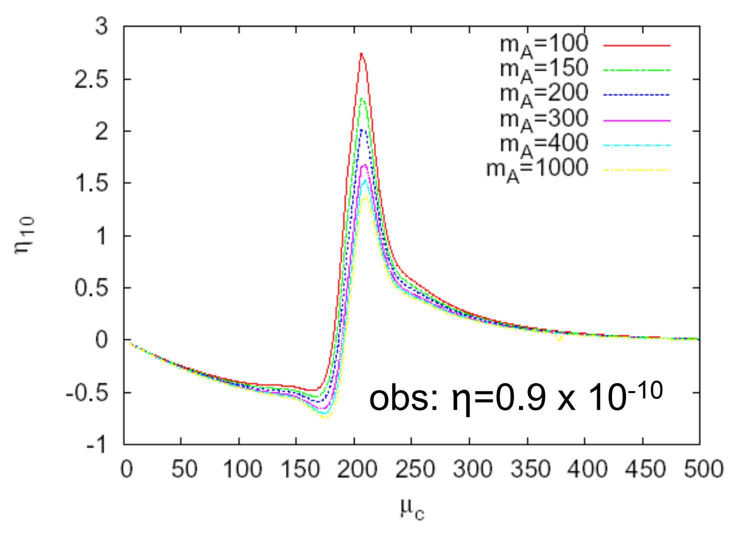
→ 1st and 2nd generation squarks

heavy to keep 1-loop EDMs small

→ "Split SUSY + light stop"

Konstandin, Prokopec, Schmidt, Seco '05

v_w=0.05, M_2=200 GeV, maximal phase



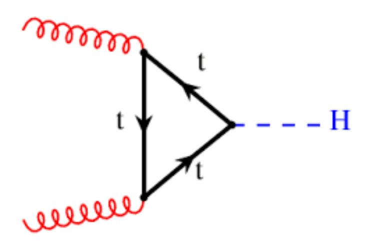
similar but somewhat more optimistic

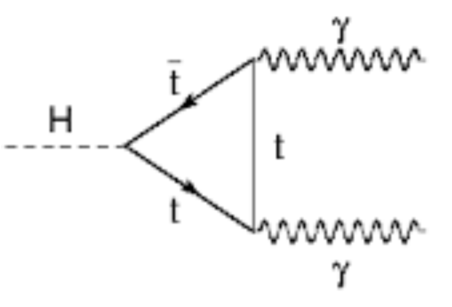
results in Carena, Quiros, Seco, Wagner '02

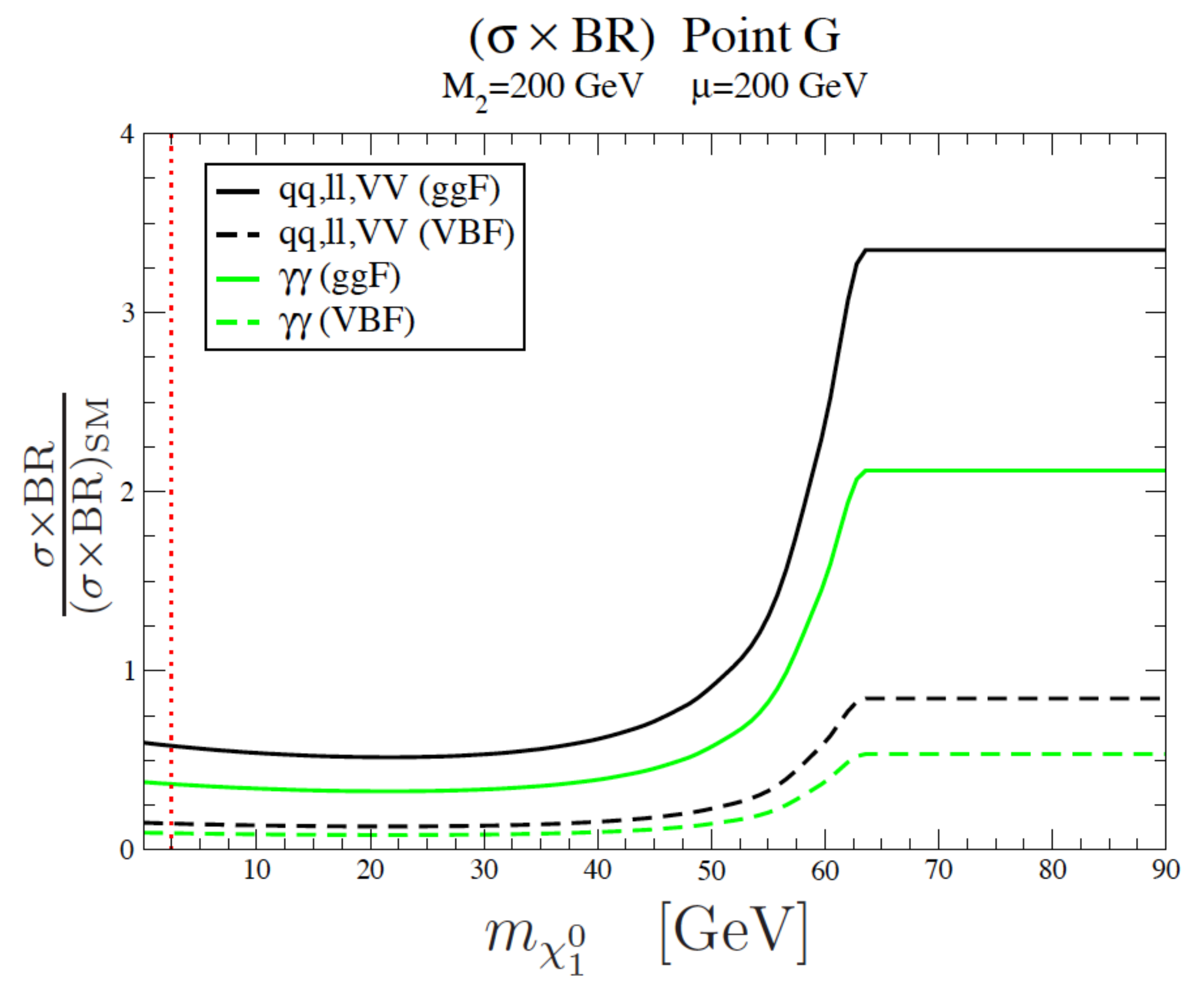
Cirigliano, Profumo, Ramsey-Musolf '06

→ scenario is tightly constrained!

Problem: modified Higgs branching ratios, e.g. into two photons:

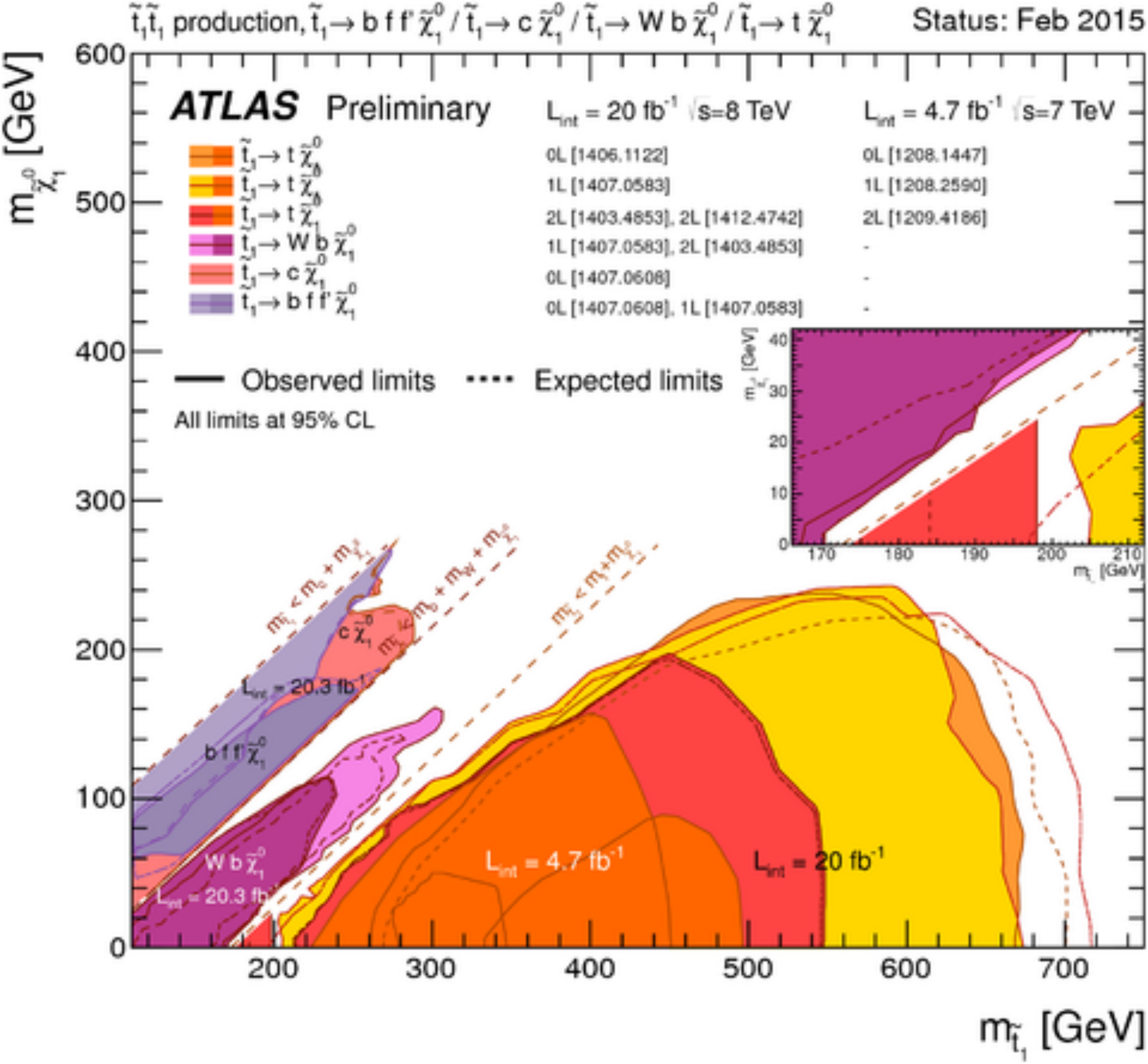






[Carena, Nardini, Quiros,Wagner 2012]

Light stop searches: still loop holes



Summary

Depending on which is the mechanism to induce an EWPT the collider situation is quite different

► modified SM Higgs potential: only deviation in Higgs cubic coupling (difficultto detect!?)

► Higgs + singlet: danger of too large Higgs singlet mixing, searches for extra scalar possible

► extra Higgs doublets: easy to have a SM like Higgs, search for extra Higgs promising

► extra colored states (“stops”): typically disfavored by modified Higgs branching fractions

All eyes now on the LHC!