The hierarchical 2HDM: Probing the EW phase transition at the LHC

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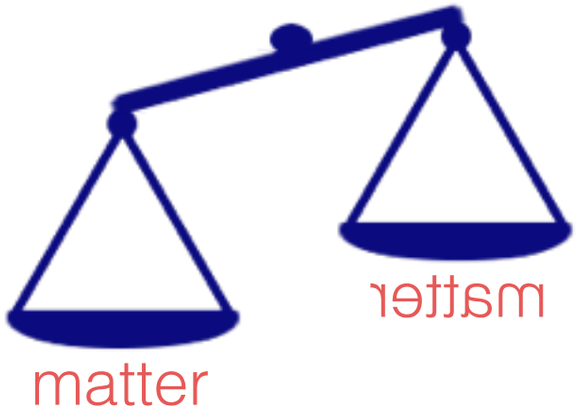
UCL
Université catholique de Louvain

Overview

- Introduction/Motivation
  - Strongly first-order electroweak phase transition (SFOEWPT) as a requirement for successful Baryogenesis
- Study of the Two-Higgs doublet model (2HDM) as a viable candidate
  - Motivation for ‘Hierarchical’ 2HDM
- LHC phenomenology
  - ‘Smoking-gun’ signature of $A_0 \to Z\, H_0$ for SFOEWPT
  - Status of Hierarchical 2HDM in general after Run 1
  - Plenty to come from run Run 2

Introduction



- Can we account for the matter/anti-matter asymmetry of the universe?
- Sakharov conditions (1961) for successful generation of baryonic excess in the early universe
  - C, CP, B-number violating interactions (dynamically generate asymmetry)
  - Occurring out of thermal equilibrium (avoid washout)
- The Standard Model (SM) contains all of the ingredients!
  - Sadly, it doesn't work…
  - Convincing motivation for physics beyond the SM and the nature of EW symmetry breaking, should the two phenomena be related

Close…

- Ingredients for successful Baryogensis can be found in the electroweak (EW) sector and its symmetry breaking
- SM interactions preserve Baryon number, but..
  - At temperatures above the EW scale (v), B-number violating processes (SU(2) sphalerons) are unsupressed ✓

    [Kuzmin, Rubakov & Shaposhnikov; Phys. Lett. B155 (1985) 36]
- Departure from thermal equilibrium can be achieved through a first-order (discontinuous) phase transition (PT)*
  - In the SM, the EWPT is second-order (crossover) for $m_h \gtrsim m_W$ ✗

    [Laine et al.; Phys. Rev. Lett. 77 (1996) 2887-2890]
- Weak interaction predicts CP violation in the quark sector
  - Insufficient (by many orders of magnitude) for desired asymmetry ✗

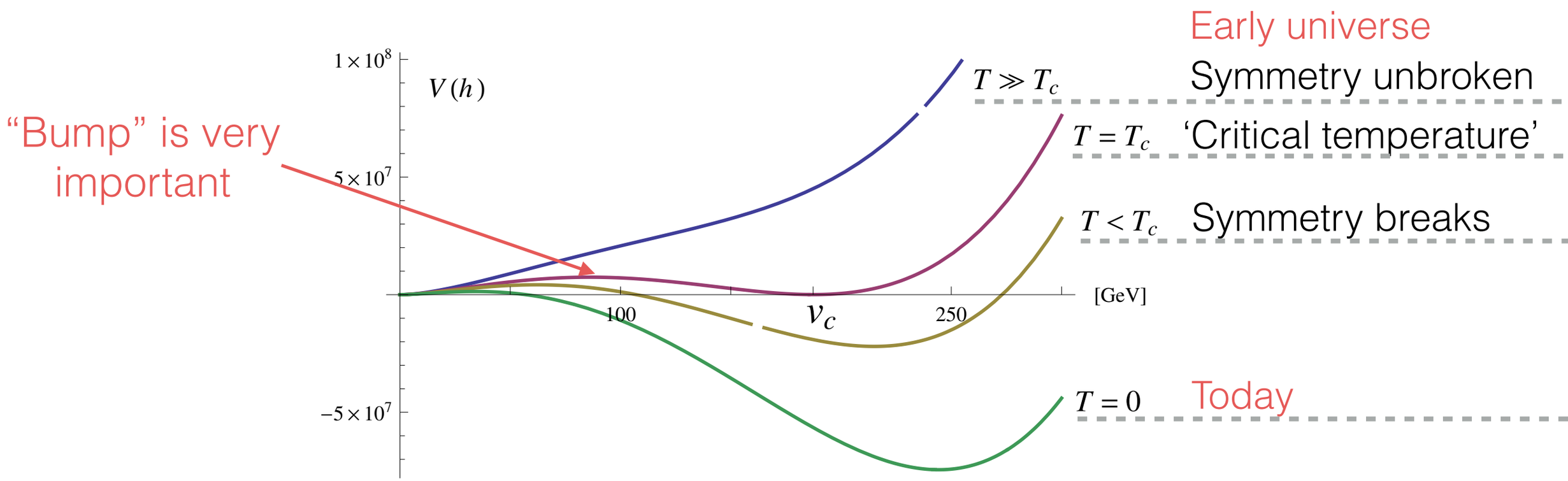
    [Gavela et al.; Nucl. Phys. B430 (1994) 382-426]

*Subject of this talk

EW phase transition

- A **strongly** first-order phase transition is a requirement for EW Baryogenesis

In this scenario, the central figure is the BEH field and the evolution of its potential through temperatures ~ weak scale



K. Mimasu, 21/12/2016

EW phase transition

- Measure of SFOEWPT: $v_c/T_c \gtrsim 1$
- We need the formation of a ‘bump’ or barrier between the trivial and EW minima
  - BEH field tunnels (discontinuously) instead of rolling to the EW vacuum

$$V_{\rm eff}(h,T) = V_0^{\rm tree}(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

- How? let new states modify the scalar potential
  - **Tree-level**: e.g., states mixing with the scalar boson
  - **Loop-level**: modify the zero-temperature effective potential
  - **Thermal**: modify the finite temperature effective potential
  - Any combination of the above

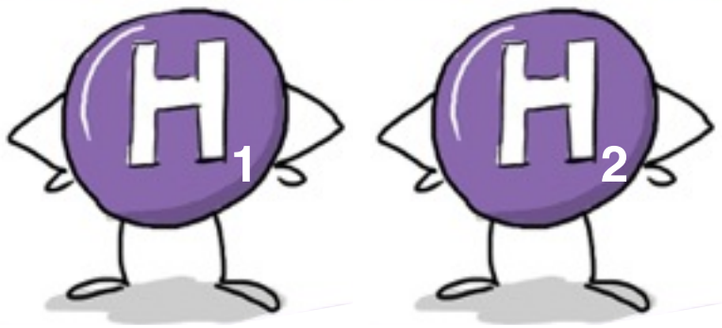
EWPT meets the LHC

- Need: new sector with appreciable couplings to the BEH field and masses not too far from the EW scale
- A SFOEWPT for successful Baryogensis is naturally testable at the LHC!
  - Only **bosonic** states contribute to the desired modifications to the potential in the finite-T effective potential (bump)

  ➡ **Extended scalar sectors**

- Two-Higgs-doublet model (2HDM) is a perfect candidate
  - Exploration of the parameter space realising a SFOEWPT
  - Consequences for the LHC

The 2HDM



- Simple extension of the SM Brout-Englert-Higgs sector
  - Add one more $SU(2)_L$ doublet
  - A limiting case of well-known BSM scenarios: MSSM, composite Higgs,…
- Generalised scalar potential and Yukawa sector
- Both doublets share the role of EW symmetry breaking
- Modification of scalar potential at all levels
  - tree, loop & finite temperature
- Complex parameters in the generalised potential
  - New sources of CP violation

*$\mathbb{Z}_2$: Each fermion couples to only one doublet.
Avoids tree-level flavour changing neutral currents (FCNC)

2HDM: potential

$$V_s'(\Phi_1,\Phi_2) = -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \frac{\mu^2}{2}(\Phi_1^\dagger\Phi_2 + h.c.)$$
$$+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \frac{\lambda_5}{2}\left((\Phi_1^\dagger\Phi_2)^2 + h.c.\right)$$

- We consider the CP conserving potential with a softly broken $\mathbb{Z}_2$-parity*
  - $\Phi = \lambda_{6,7} = 0$ & no spontaneous CP violation
  - 1) for simplicity 2) EWPT is not sensitive to small CPV effects
  - Note: CP violating case is interesting for realisation of Baryogenesis
- 8 parameters, 6 after EWSB (fixing vev and scalar mass)

2HDM: parameters

$\tan\beta$, $\sin(\alpha-\beta)$, m_{H0}, m_{A0}, $m_{H\pm}$, μ^2

- At EW minimum: define $\tan\beta$, the ratio of two vevs (v_2/v_1)
- Scalar field content:
  - ϕ_1: SM BEH (**h**) and Goldstone bosons eaten by W,Z
  - ϕ_2: CP even (**H_0**) and odd (**A_0**) neutral Higgs + charged Higgs (**$H_\pm$**)
- Physical CP even states h, H_0 mix with angle α
  - Gauge interactions of scalar sector defined by $\sin(\alpha-\beta)$
  - $\alpha-\beta=0$ means h interactions are SM-like: **Alignment limit**
- 2HDM types defined by $\mathbb{Z}_2$ assignments of RH fermions

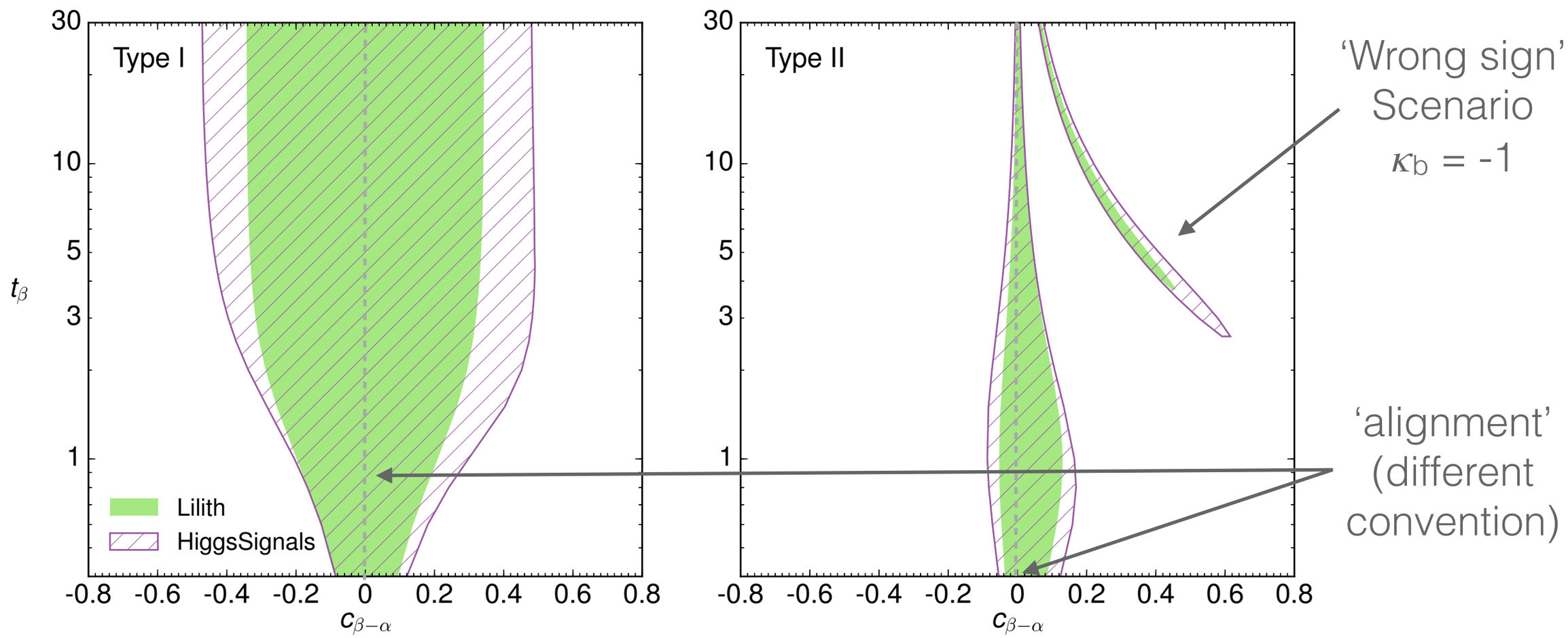
Type	u_R	d_R	e_R
I	$+$	$+$	$+$
II	$+$	$-$	$-$
X	$+$	$+$	$-$
Y	$+$	$-$	$+$

Constraints

- EW precision observables (EWPO): LEP,…
  - W/Z mass relationship affected only at loop level → **T-parameter**
- Flavour changing neutral currents (FCNCs) @ 1-loop
  - Strongest bounds come from b →Xs γ, B_0-$\overline{B}_0$ mixing
  - Constrain the [$m_{H\pm}$, tanβ] plane (**type II: $m_{H\pm} \gtrsim$ 480 GeV**)
- LHC
  - 125 GeV scalar properties constrain [α,β]
  - Direct searches for heavy scalars, dependent on the full parameter space
- Perturbative unitarity & boundedness of potential

The 125 GeV scalar after Run I

- Mixing with the heavier states leads to deviations from SM coupling predictions controlled by tan(β) & cos(α-β)



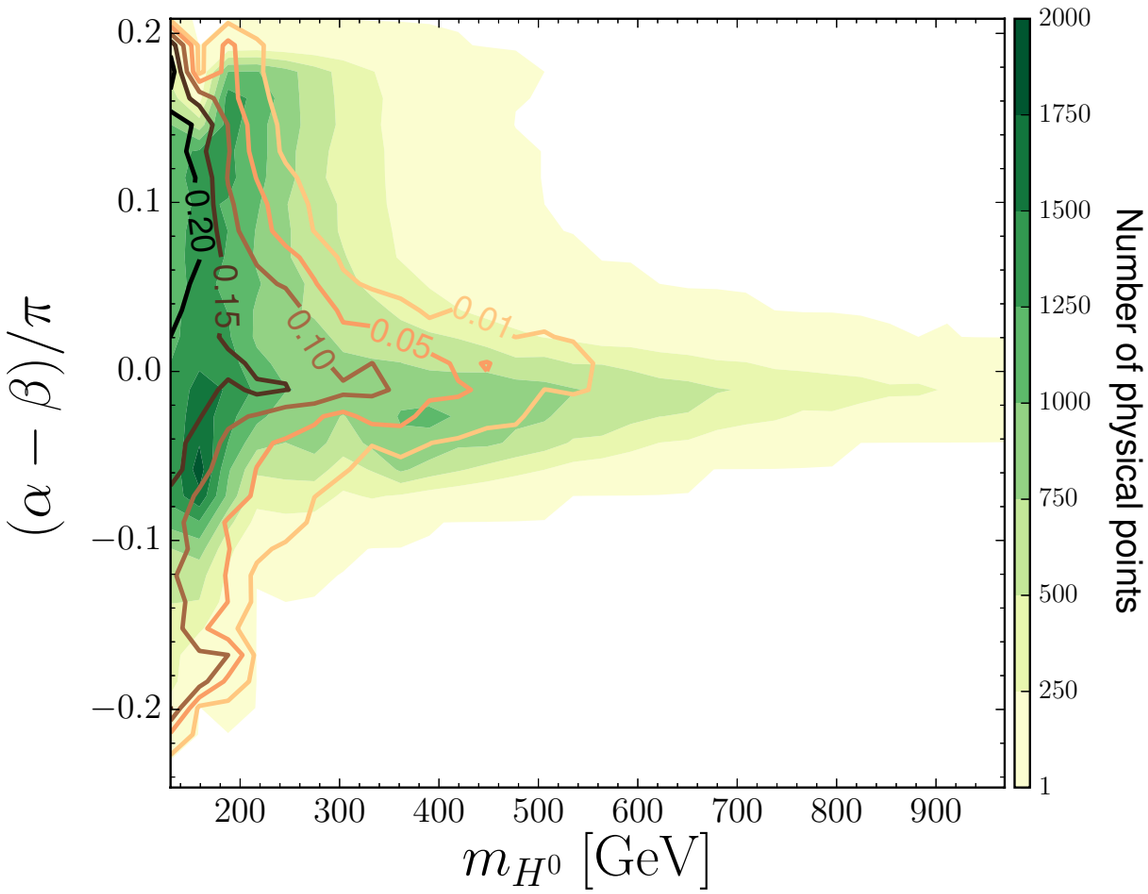
Parameter scan

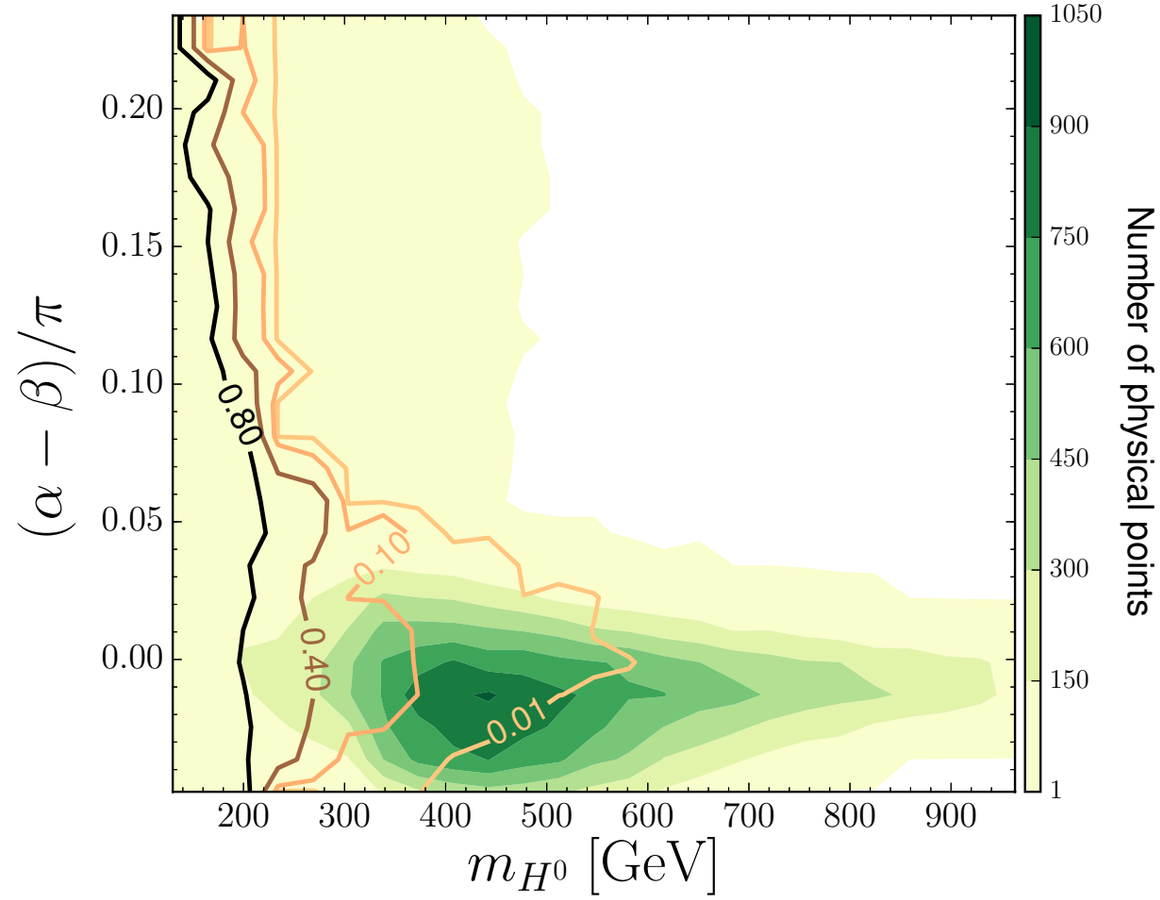
- ~3 x 10^8 points of 2HDM type 1 (EWPT is type insensitive)
- Satisfaction of exp./th. constraints defines 'physical point'
- For each such point, determine the strength of the EW phase transition
  - Critical temperature T_C : the thermal 1-loop effective potential has two degenerate minima at [0, v_C]
  - SFOEWPT declared if **$v_C/T_C > 1$**
- Evaluate the additional effect of requiring a SFOEWPT on previously existing constraints in the 2HDM parameter space

*alignment (α-β~0) = SM-like Higgs boson couplings

Results: alignment

Contours: *ratio* of Physical vs SFOEWPT ~ P(SFOEWPT | Physicality)



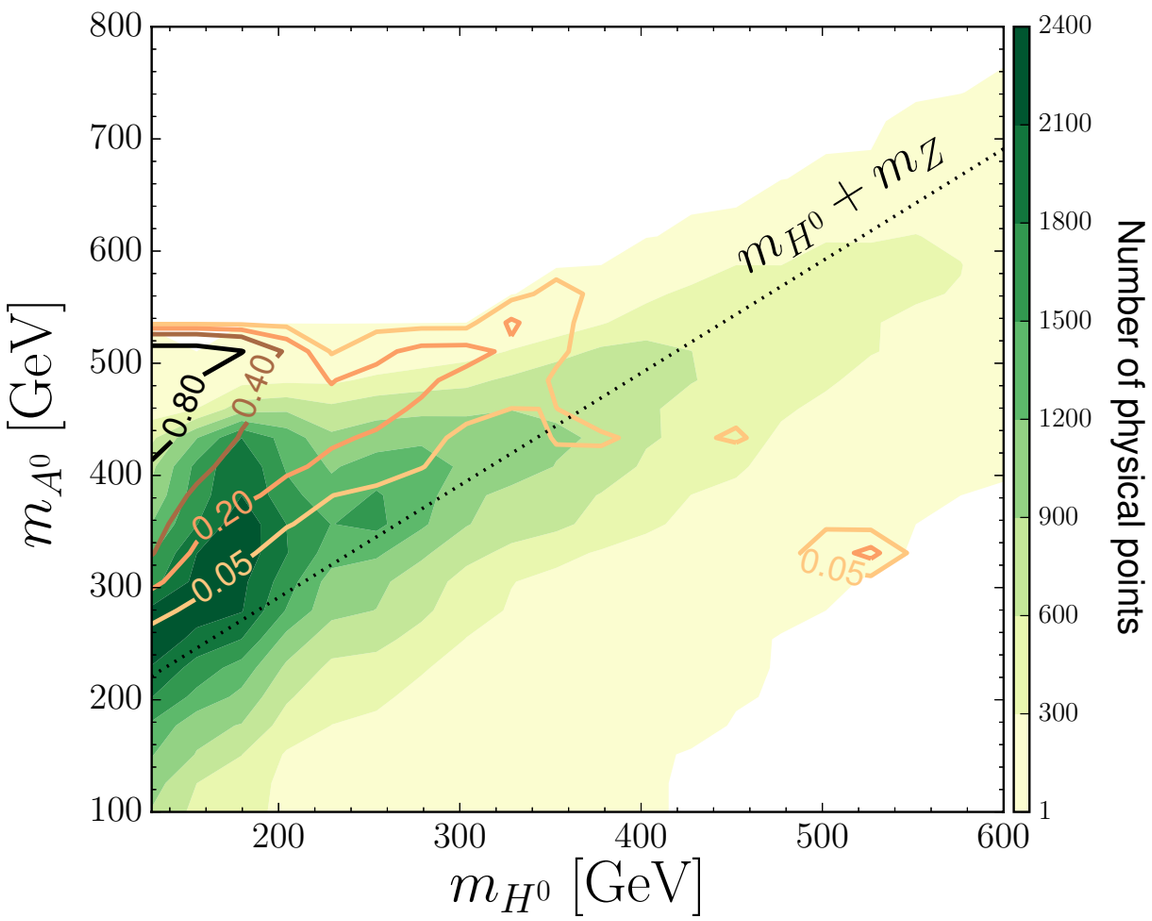


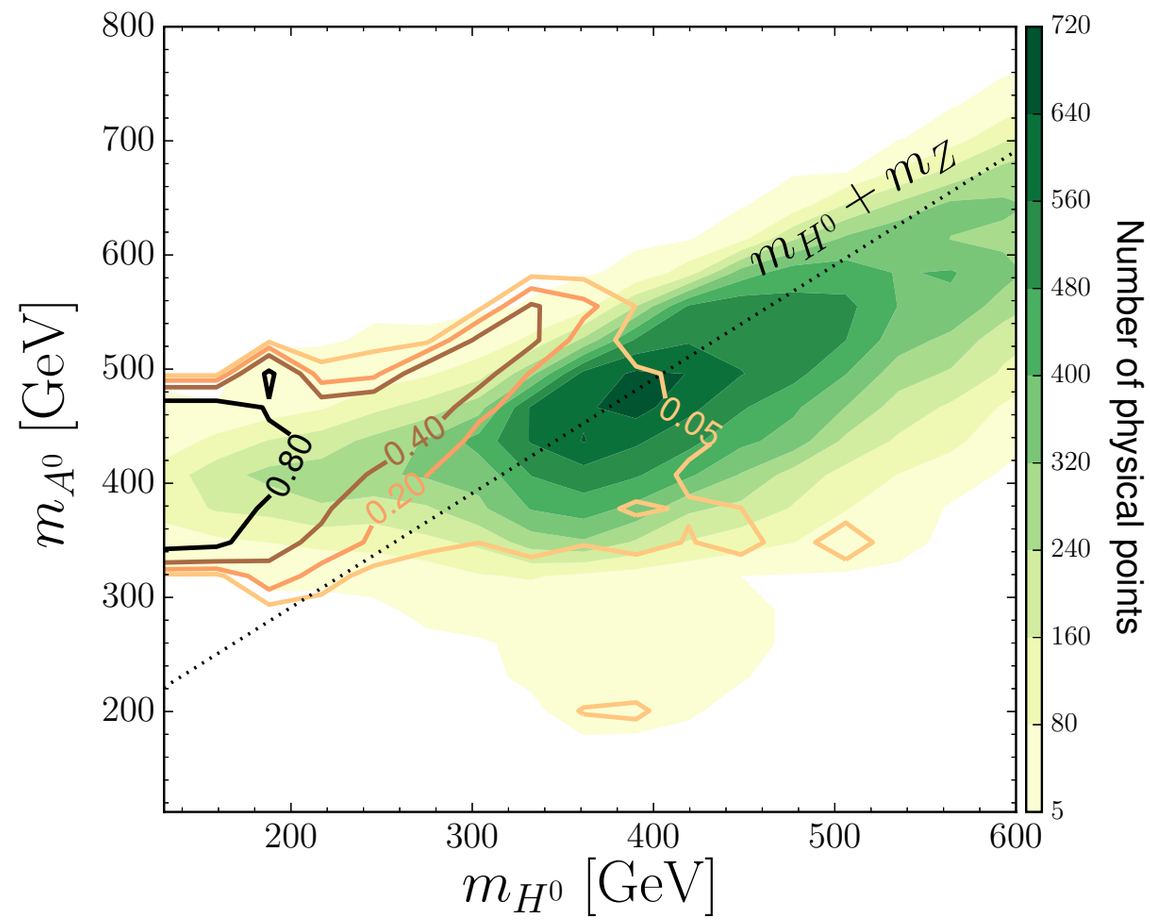
Preference for alignment (from data)

"Light" new CP-even state
More alignment if heavier

Results: mass spectrum

Contours: *ratio* of Physical vs SFOEWPT ~ P(SFOEWPT | Physicality)





Large, positive mass splitting between new heavy CP odd (A_0) and even (H_0) states: > m_Z

Interpretations

- SFOEWPT requirement points to a very specific realisation of the 2HDM… **why?**
- Preference for alignment
  - Away from alignment, both CP even states ‘share’ the vev
  - If the states are heavier in the unbroken phase, PT gets weaker
- Large mass splittings
  - Generically want large self couplings for large effects on the potential
  - Some of these control the splittings, but why $m_{A0} > m_{H0}$?
  - Interplay between physicality constraints for low μ & large λ’s

Interpretations

- Not only a specific realisation but also a very original one
- **Hierarchical** 2HDM
- Not as commonly considered: new states often assumed to be near degenerate
- Points more towards strongly-coupled UV completions for such a scenario
- Unique collider signatures

SFOEWPT at colliders

Close to alignment
Light H_0 < 300 GeV
Heavy A_0 > 400 GeV
Moderate tan β (~few)

Very small deviations of 125 GeV boson properties from SM

$H_0 \to ZZ$, WW, hh & $A_0 \to Zh$ decay modes suppressed

A_0 above top threshold: difficult search to due QCD interference

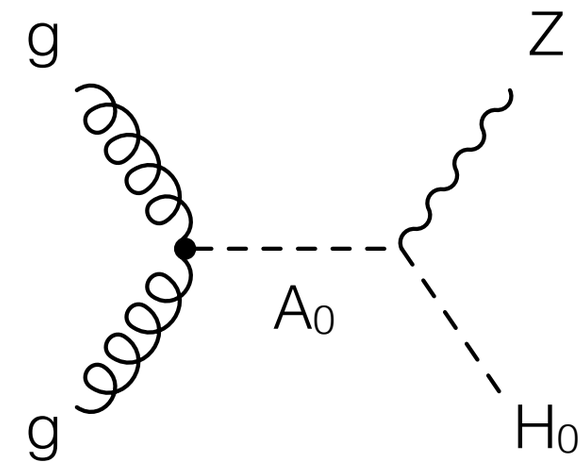
Large splittings open $S_i \to S_j V$
S: scalar (h, A_0, H_0, $H_\pm$)
V: gauge boson ($W_\pm$, Z)

Until last summer, only $A_0 \to Z h$ & $H_0 \to hh$ searches existed

$A_0 \to Z H_0$ enhanced in alignment!

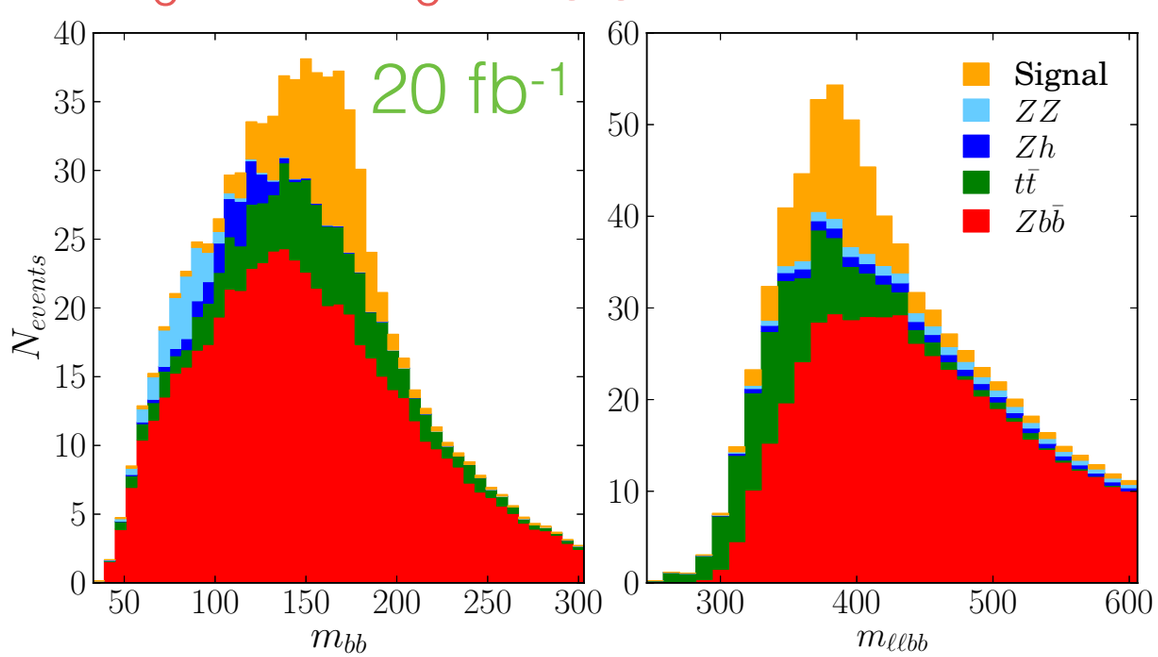
Identified $A_0 \to Z H_0$ as a "smoking gun" SFOEWPT signature in the 2HDM

LHC prospects

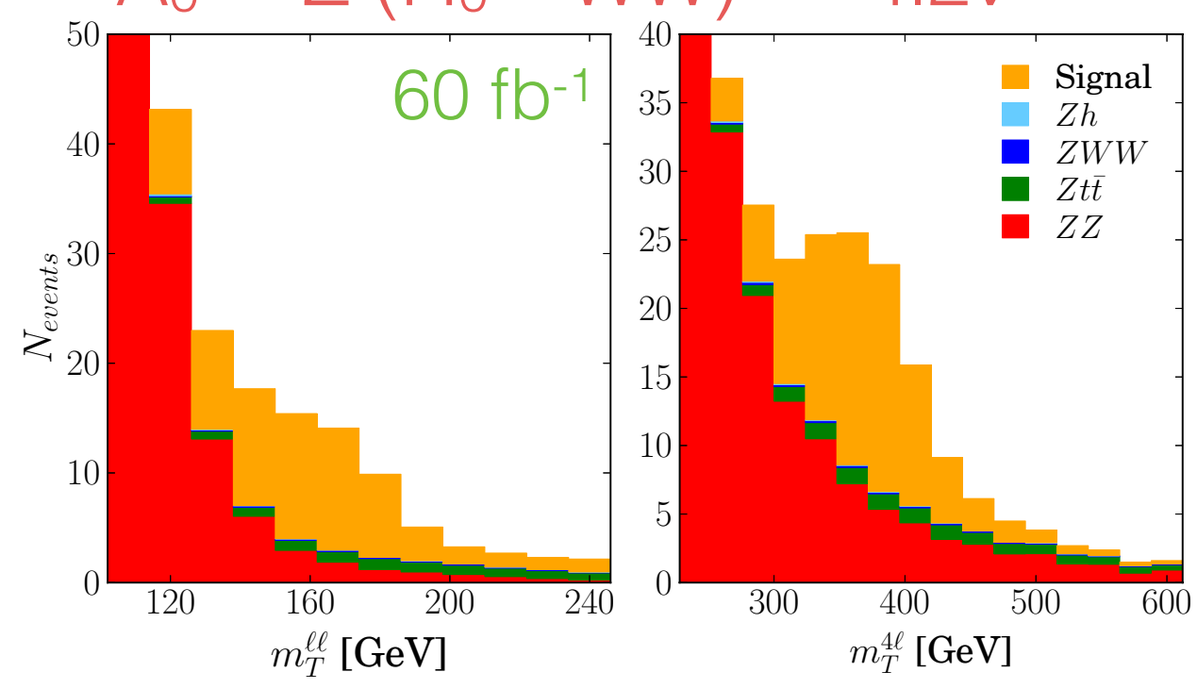


- Performed a detailed analysis & found good prospects for discovering benchmark scenarios at LHC run 2
- Very near & away from alignment within exp. limits

$A_0 \to Z\, H_0 \to bb\ell\ell$



$A_0 \to Z\,(H_0 \to WW) \to 4l2\nu$



One year later…

- A SFOEWPT provides physical motivation for the H2HDM
- Demonstrated a unique & promising LHC signature

Search for H/A decaying into Z and A/H, with Z→ $\ell\ell$ and A/H→ bb or A/H→ $\tau\tau$

The CMS Collaboration

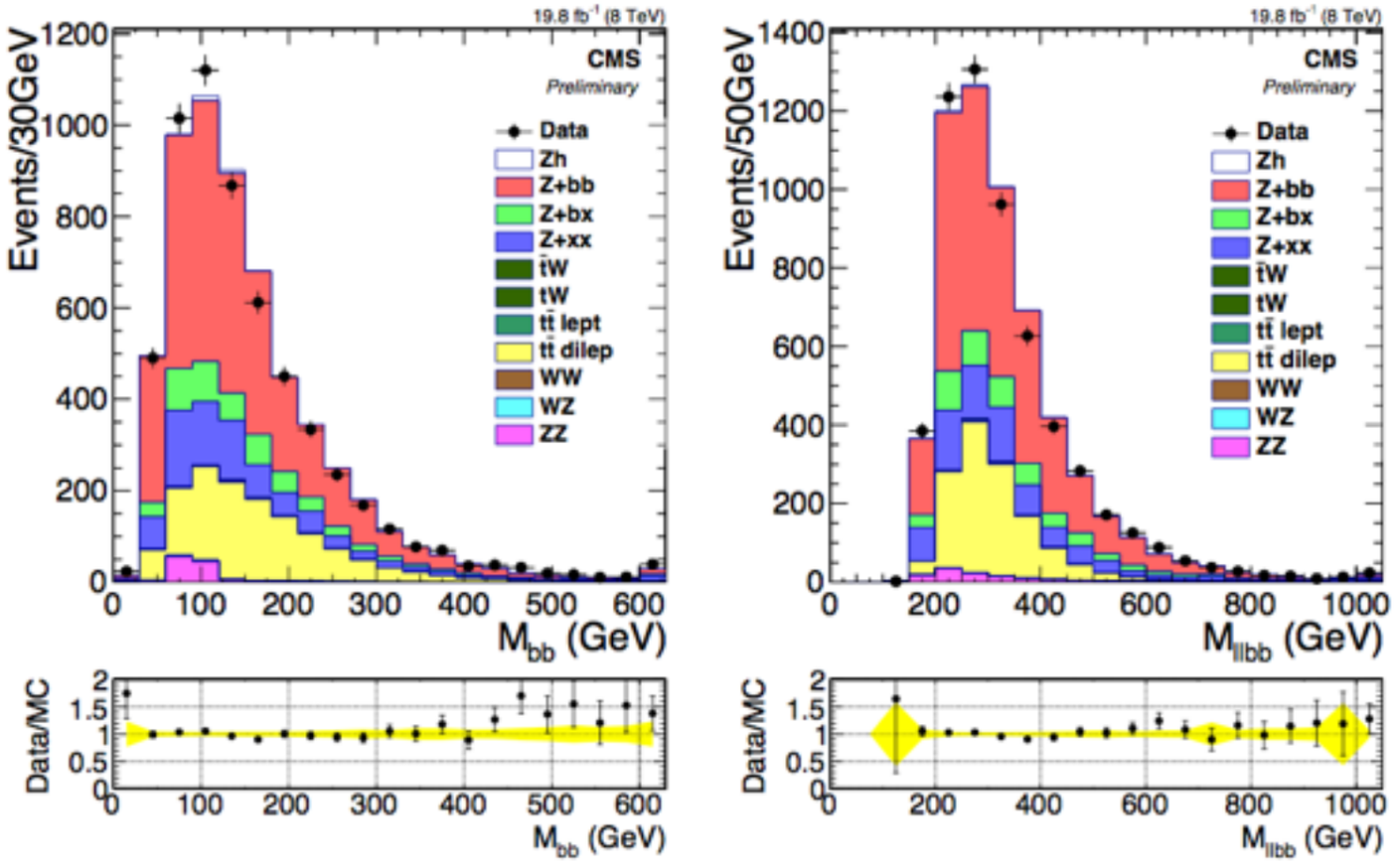
CMS-PAS-HIG-15-001
May 2015

Abstract

A search is performed for a new heavy resonance decaying to a Z boson and a light resonance, where the light resonance decays to either a pair of bottom quarks or a pair of tau leptons and the Z boson decays to two electrons or two muons. The search exploits a data sample collected during 2012 by the CMS experiment at the center-of-mass energy of $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of $\mathcal{L} = 19.8\ \mathrm{fb}^{-1}$. No significant deviation from the standard model expectations is observed and limits are set on benchmark production processes predicted in a model with two Higgs doublets.

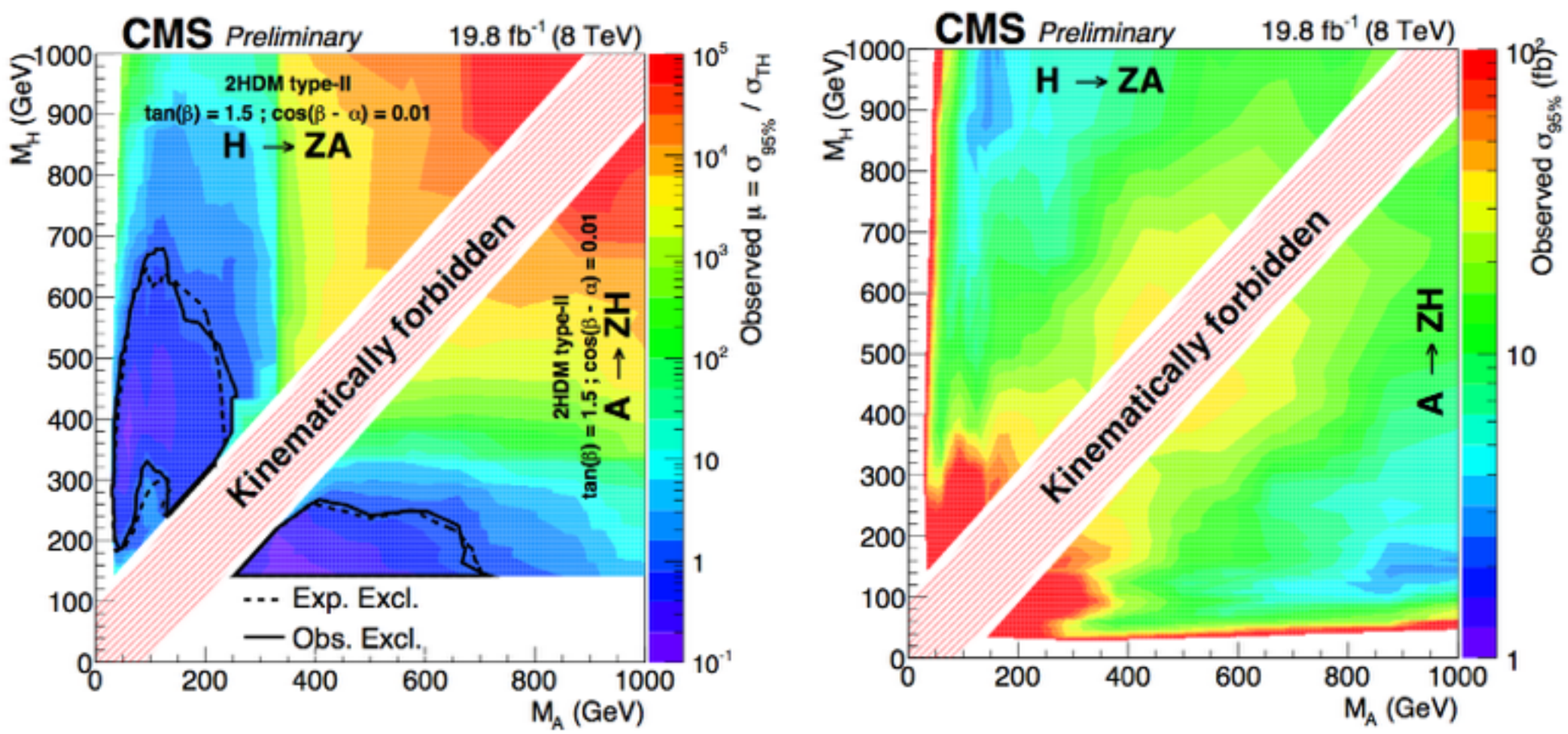
LHC analysis

- To our knowledge, first time that the EW phase transition has been cited as the primary physical motivation for an LHC search



LHC analysis

- Covers both $A_0 \rightarrow Z\, H_0$ & $H_0 \rightarrow Z\, A_0$
- Excludes our alignment benchmark at 8 TeV

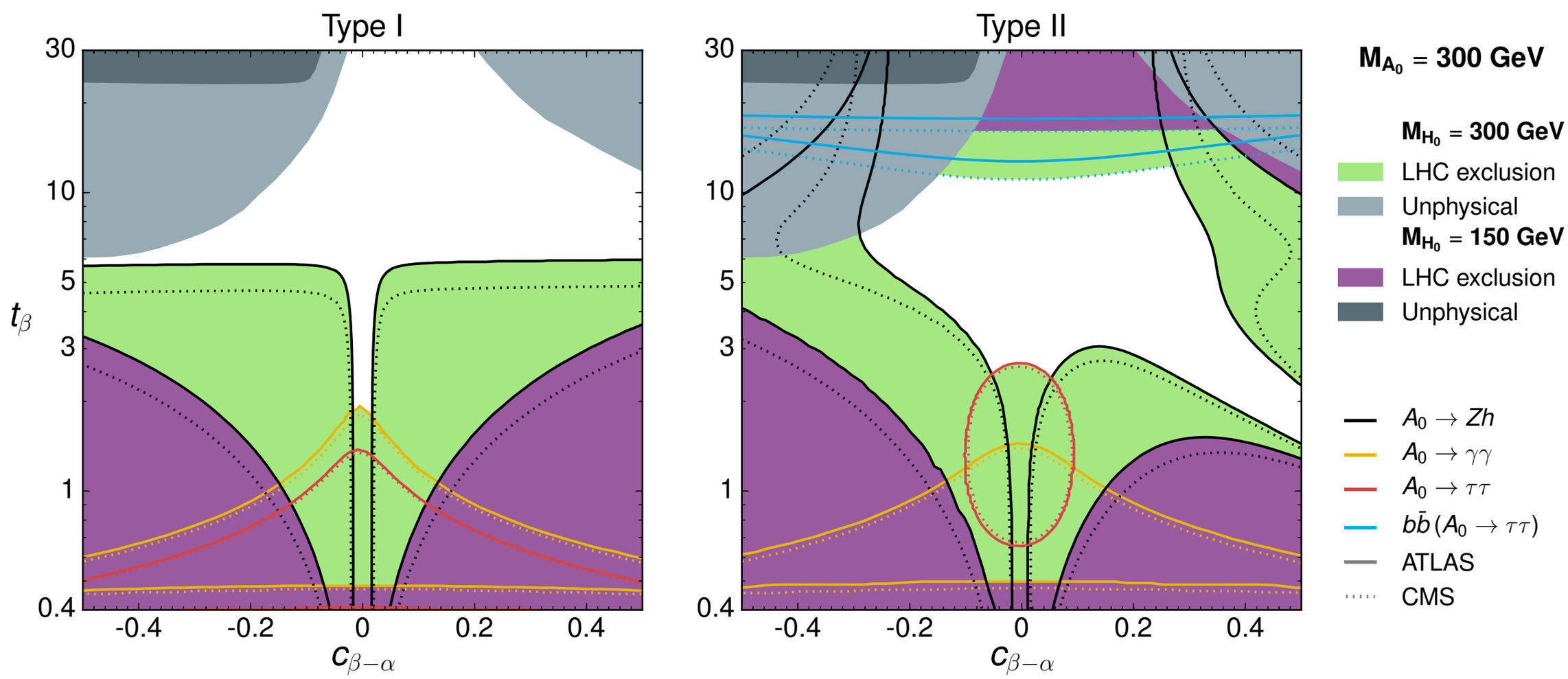


H2HDM after run 1

- Relaxing assumptions about a near-degenerate spectrum alters the picture of existing 2HDM constraints at the LHC
  - Opening up new channels reduces the BR of other decay modes
  - When searched for, these channels can come in and fill gaps
  - A rich phenomenology arises that has not yet been extensively explored
- Explore the effect of a Degenerate vs. Hierarchical 2HDM spectrum on existing constraints
  - **Degenerate:** “classic” scalar resonance searches for heavy states
  - **Split:** “hierarchical” cascade signatures + direct searches for lighter state

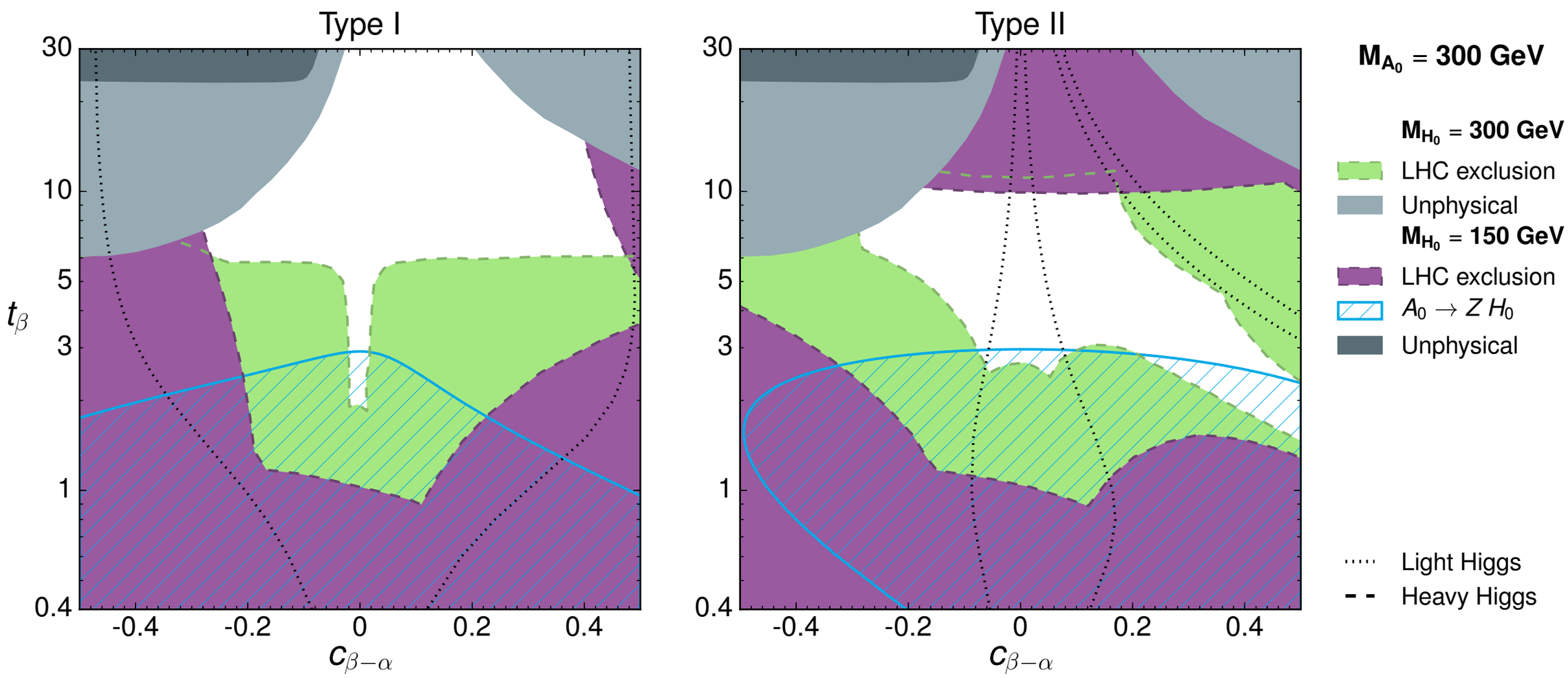
Direct pseudo scalar searches: m_{A0} = 300 GeV

- Strong constraint from **$A_0 \to Z\,h$** search near alignment disappears when splitting is opened
  - Same for diphoton and ditau



Summary: m_{A0} = 300 GeV

- **$A_0 \to Z\, H_0$** search rescues some lost parameter space in the hierarchical case & is more sensitive to alignment
- Constraints in type II completely exclude the wrong sign scenario only in the degenerate case



Run 2

- Strongly coupled UV completion = TeV scale resonances
- A few analyses have been released, just the beginning
- Many final states yet to be searched for in $A_0 \rightarrow Z\ H_0$
  - One hadronically decaying W → 3l2j1v
  - Z decay to neutrinos → 2l + MET (4v) & permutations
  - Tri-Z →4l2j
- Other H2HDM channels
  - Other possible $H_0 \rightarrow Z\ A_0$ signatures
  - $H_0 \rightarrow A_0\ A_0$: could be dominant, as yet unexplored
  - Charged Higgs $H_\pm \rightarrow W_\pm\ H_0(A_0)$ & permutations

Conclusions

- Requirement of a SFOEWPT points to Hierarchical 2HDM
  - Close to alignment, moderate tan β
  - Radically different mass spectrum from usual assumptions
  - New decay channels & smoking gun signature of $A_0 \to Z\, H_0$
- Thanks to EW Baryogensis, H2HDM is now very relevant
- Many new signatures to cover
- Fill the gaps left in the collider limits 2HDM parameter space when moving from a degenerate to a hierarchical spectrum
- Stay tuned

BACKUP

2HDM: general

$$\mathcal{L}_y = -\bar{F}_L(\Gamma_1\Phi_1 + \Gamma_2\Phi_2)f_R + \cdots$$

$$\begin{aligned} V_s(\Phi_1,\Phi_2) = & -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \frac{\mu^2}{2}(e^{i\phi}\Phi_1^\dagger\Phi_2 + h.c.) \\ & + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) \\ & + \left\{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \Big(\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\Big)(\Phi_1^\dagger\Phi_2) + h.c.\right\} \end{aligned}$$

- Yukawa interactions = potentially dangerous FCNCs
  - Can't simultaneously diagonalise Yukawas
  - Solution: $\mathbb{Z}_2$ parity → each fermion only couples to one doublet
- Generalised potential
  - New mass scales, μ_1, μ_2 & μ (=soft $\mathbb{Z}_2$ breaking mass + phase Φ)
  - New self couplings, of which $\lambda_{6,7}$ can be complex (CP violation)

See also [G. C. Dorsch, S. J. Huber, J. M. No; JHEP 1310 (2013) 029]

The 2HDM & EWPT

- Restrict ourselves to Type I in our analysis
  - All fermions couple to the same doublet
  - No lower bound on $H_\pm$ mass from flavour constraints
- EWPT is largely insensitive to 2HDM type
  - By convention, dominant fermionic coupling (top) is always the same
  - Models mainly differ in experimental constraints
- We perform a large parameter scan
  - Investigate the viable 2HDM parameter space for a SFOEWPT
  - Incorporating the latest experimental constraints
  - Theoretical contraints on perturbative unitarity & boundedness from below

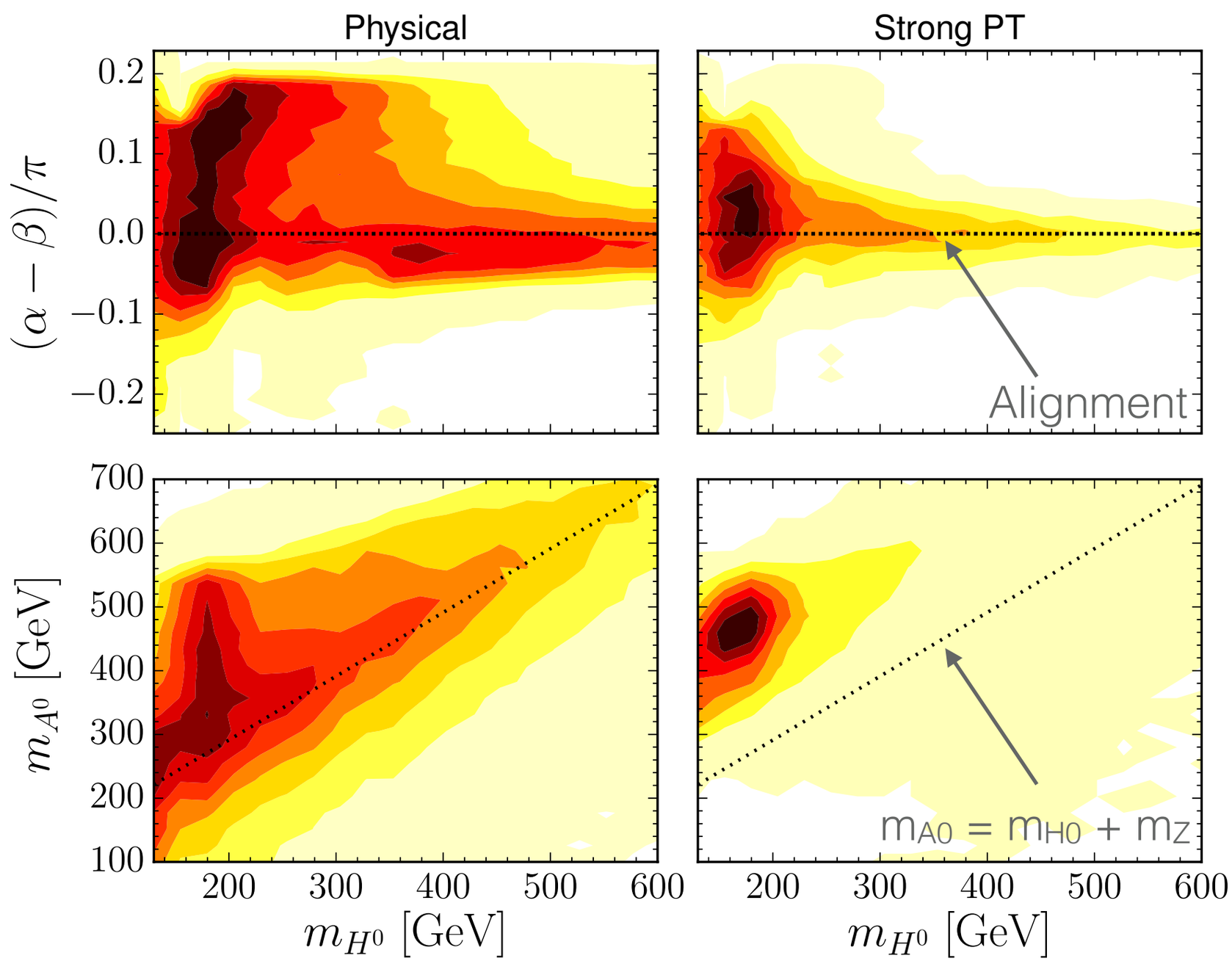
The 2HDM & EWPT

- Size of parameter space motivates a scan
- Developed a numerical code combining experimental & physicality constraints
  - Interfaced with 2HDMC, HiggsBounds/HiggsSignals
  - Ensure (1-loop) stability & (tree-level) perturbative unitarity
  - EWPO constraints
  - Light Higgs properties from LHC, Tevatron (signal strengths)
  - Direct searches from LEP, Tevatron & LHC
  - Flavour constraints

3 x 10^8 points

Results

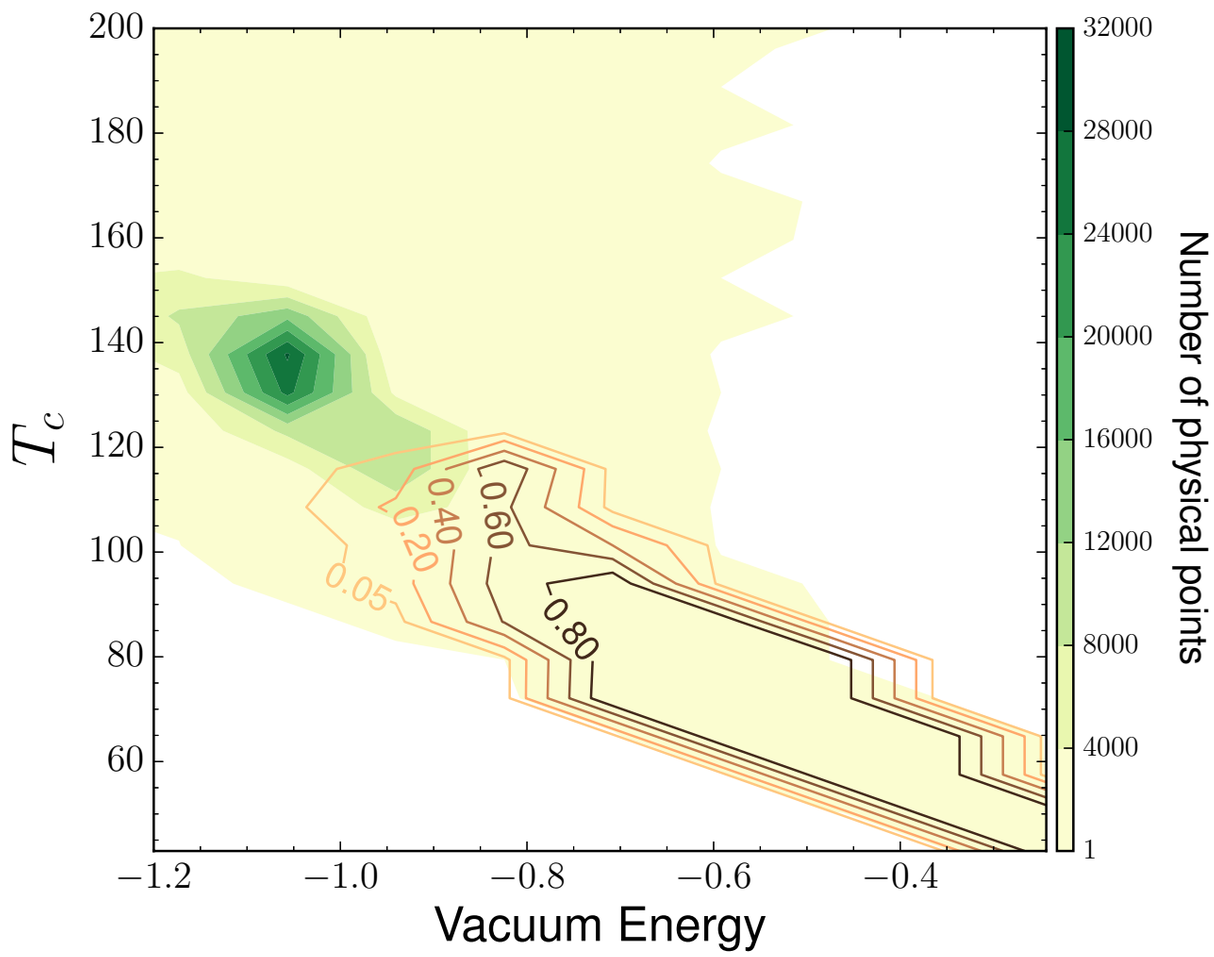
Pass physicality constraints

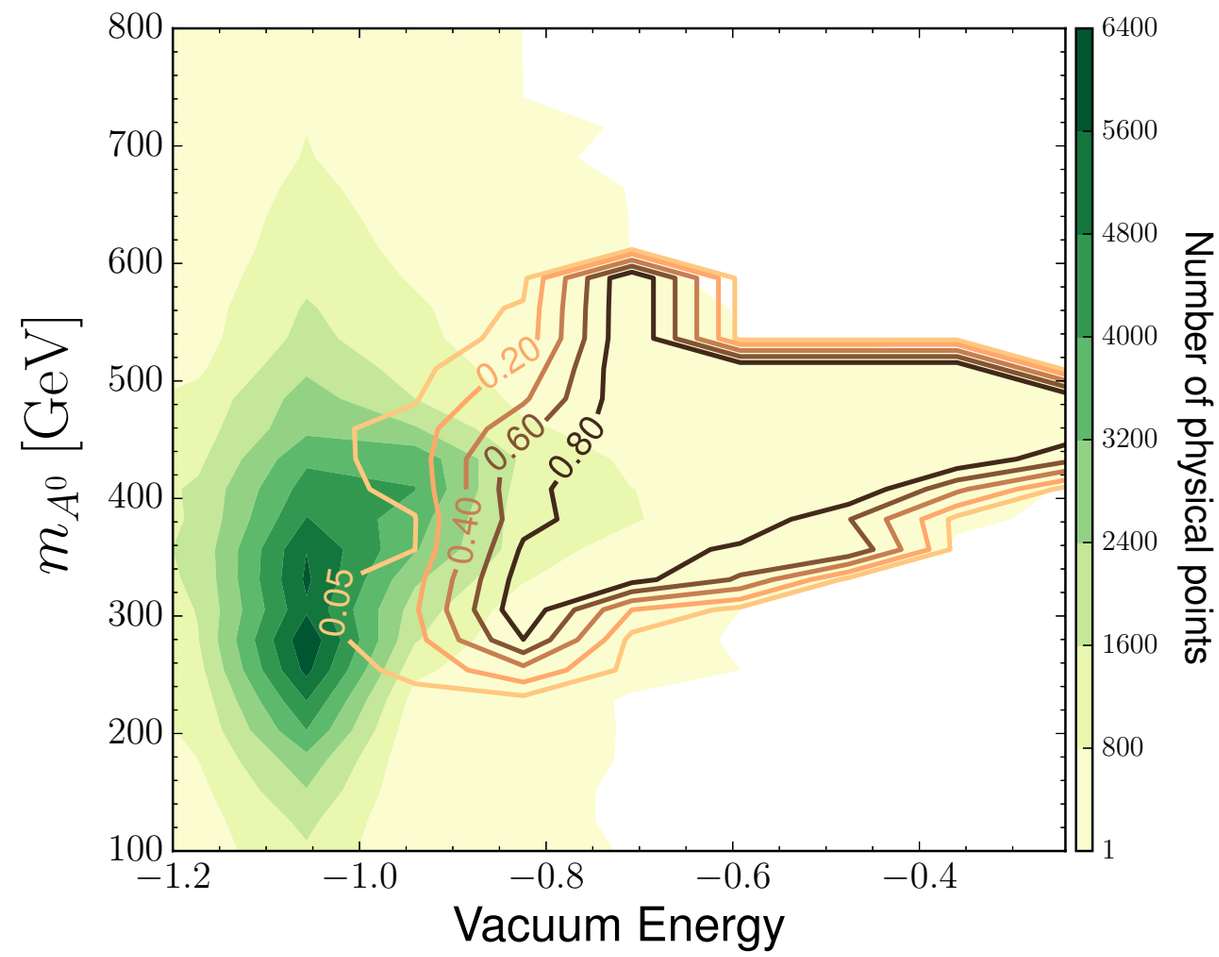


Predict SFOEWPT

Results

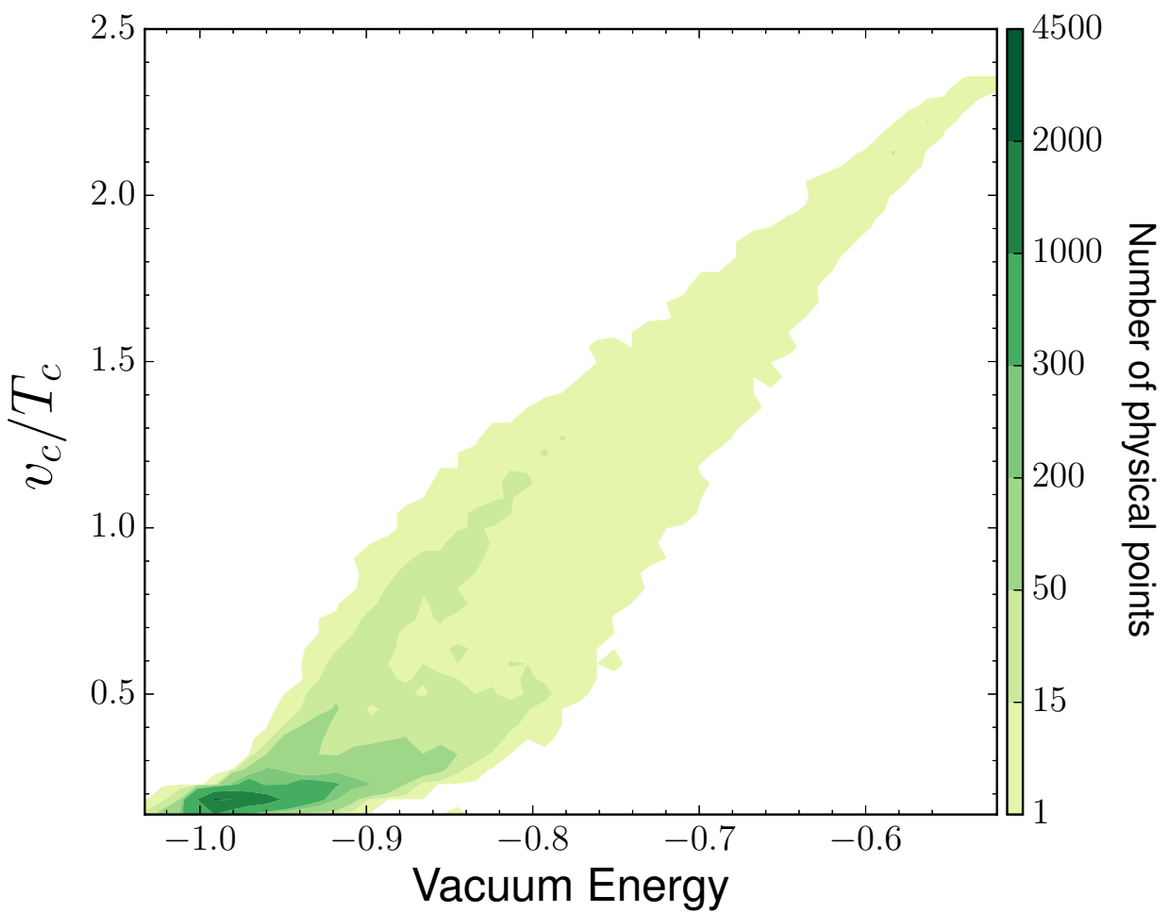
Lifting of the EW vacuum: Zero temperature, 1-loop effect

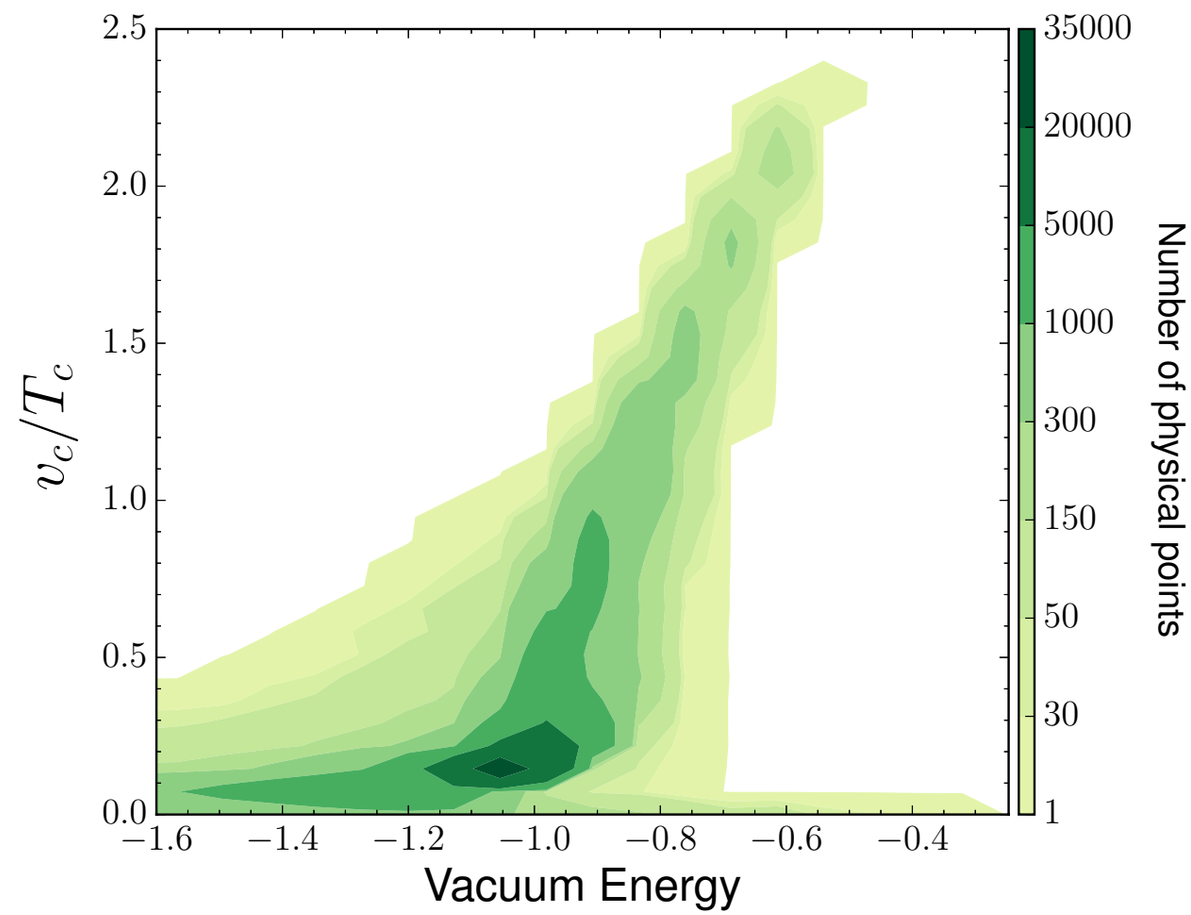




Results

Strongly correlated to the PT strength!
Forthcoming publication…





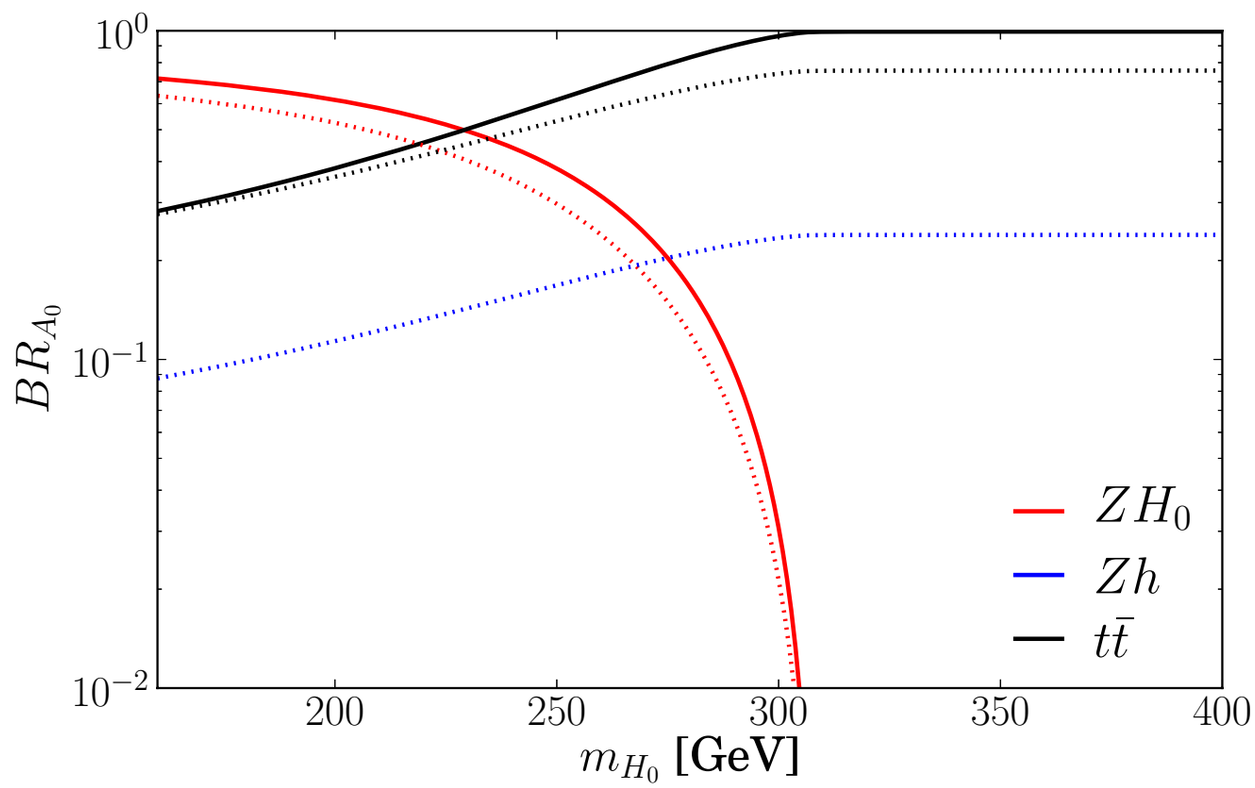
$A_0 \rightarrow Z\, H_0$ benchmarks

- Choose benchmarks compatible with ‘physicality’ and SFOEWPT requirements
  - Consider alignment limit & departure from alignment
  - Search strategy governed by decay mode of H_0

mH_0 = 180 GeV
mA_0 = 400 GeV
$mH_\pm$ = 400 GeV

$\tan\beta = 2$
μ =100 GeV
α-β = 0.001π (A)
α-β = 0.1π (B)

A_0 decays



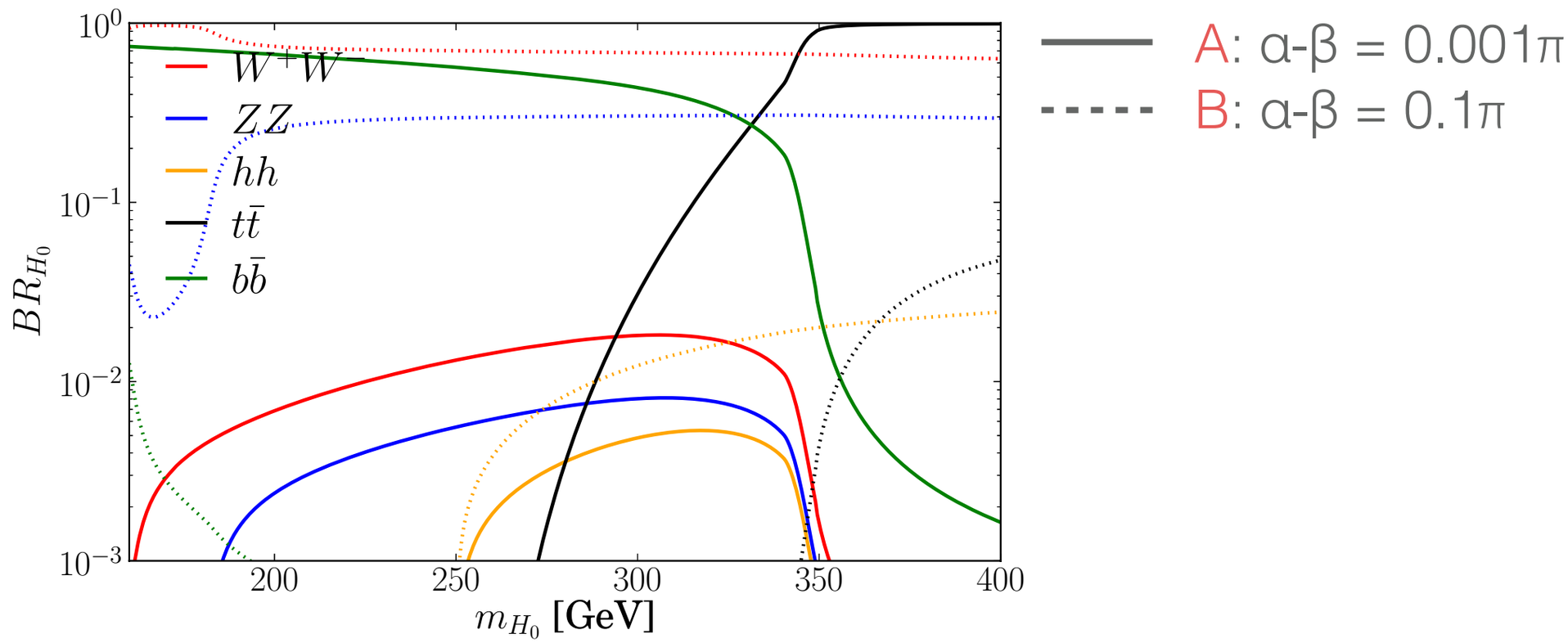
mA_0 = 400 GeV

A: α-β = 0.001π

B: α-β = 0.1π

- Competing decay channels are tt and $W_{\pm}H_{\mp}$
  - tt depends on $(\tan\beta)^{-2}$
  - Availability of charged Higgs decay depends on $m_{H\pm}$
  - Choose mH_0 degenerate for simplicity, presence of other decay will ~ halve BR(Z H_0)

H_0 decays



- Clear preference for bb and WW in A & B respectively
  - hh depends on μ and could be more important for other choices
  - Choose leptonic modes for Z & W for simplicity
  - A: bbll final state & B: 4l2v final state

LHC analysis

- FeynRules implementation of Type I 2HDM
- Generated signal & backgrounds with MadGraph5_aMC@NLO
  - Pythia for parton shower & hadronisation
  - Delphes for detector simulation
- Cut & count analyses to extract signal vs. background
  - NLO k-factors used for signal & background predictions
  - Obtained from literature for backgrounds, used SusHi for signal
- Looked at 13 TeV LHC prospects
  - Suspected that 8 TeV data might be sensitive to this parameter space

$A_0 \rightarrow Z\, H_0 \rightarrow bbll$

k-factor:	1.6	1.5	1.4	-	-
	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
$H_T^{\mathrm{bb}} > 150$ GeV $H_T^{\ell\ell\mathrm{bb}} > 280$ 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

σ(fb)

- Cut flow
  - Z-mass window for leptons
  - Cuts on total H_T, with & without leptons
  - ΔR of bb and ll systems

See also [B. Coleppa, F. Kling, S.Su; JHEP 1409 (2014) 161]

$A_0 \rightarrow Z\, H_0 \rightarrow bbll$

- Main backgrounds: Zbb, tt, ZZ, Zh
- Simple event selection
  - Anti-kT jets, R=0.6
  - 2 b-tags within $|\eta|<2.5$
  - Parametrised tagging efficiency as per *[CMS-PAS-BTV-13-001]*
  - 2 isolated, same-flavour leptons
  - Lepton $|\eta|<2.5(2.7)$ for electrons(muons)
  - Leading lepton pT > 40 GeV
  - Sub-leading lepton pT > 20 GeV

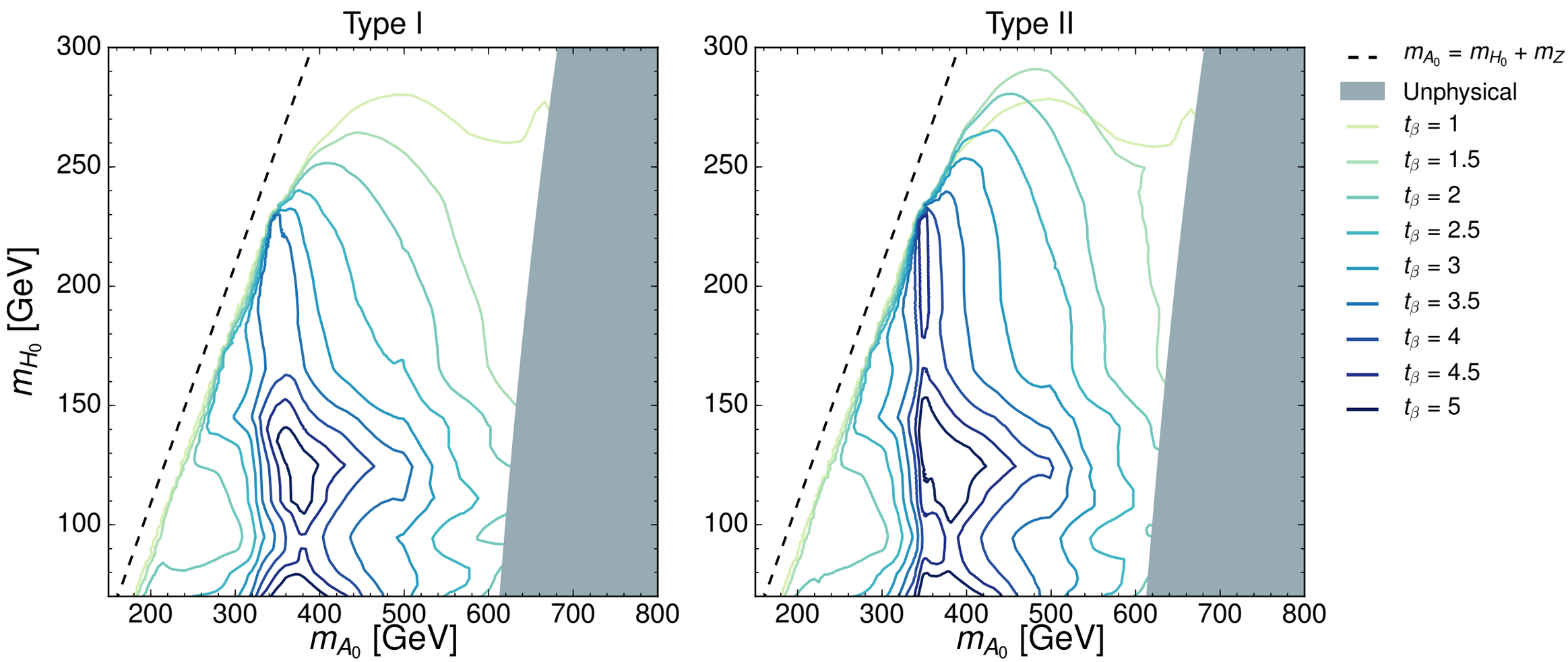
See also [B. Coleppa, F. Kling, S.Su; arXiv:1404.1922]

$A_0 \rightarrow Z\, H_0 \rightarrow llWW \rightarrow 4l2\nu$

- Away from alignment, this is a promising channel
- $A_0 \rightarrow Z\, H_0 \rightarrow llZZ \rightarrow 4l2j$ also powerful
- Main background: $ZZ \rightarrow 4l$ + rare processes: Ztt, Zh, ZWW
- Similar selection to bbll analysis
  - 4 isolated leptons in same-flavour pairs, $p_T > 20$ GeV
  - Leading lepton $p_T > 40$ GeV
  - Z-mass window for one pair as in bbll case
- No further selection required
  - Other handles if needed e.g. ΔR & Z-veto on other ll system

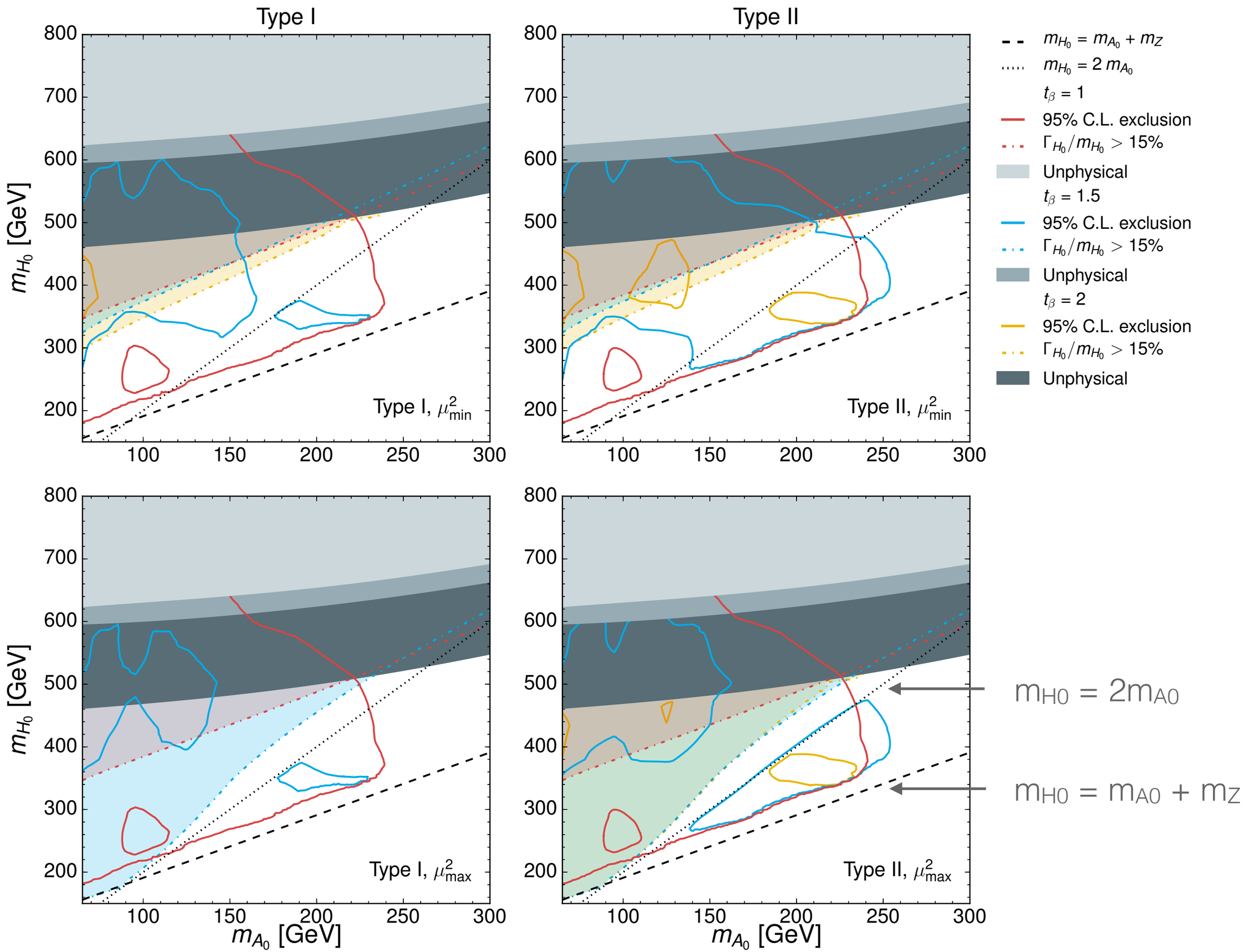
CMS-PAS-HIG-15-001: $A_0 \rightarrow Z\, H_0 \rightarrow bbll$

- In alignment limit, constraints depend only on tan(β)
  - Potential contribution from charged Higgs to diphoton BR of H_0 not included as it depends on the full set of 2HDM parameters



$H_0 \rightarrow Z A_0 \rightarrow bbll$

- Production rate a bit smaller
- Physicality constraints punish this splitting more severely and depend on tan(β)
- Same issue with μ^2 this time controlling the $H_0 \rightarrow A_0 A_0$ decay for which there is currently no direct search
- The width of the H_0 increases rapidly in this region
  - Saturates the maximum 15% width assumption used in the analysis



K. Mimasu, 21/12/2016