EW phase transition in a hierarchical 2HDM

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[arXiv:1405.5537]

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Introduction

- Our *raison d'être* (during this workshop): strongly first-order electroweak phase transition (SFOEWPT)
  - A convincing motivation for physics beyond the SM
  - Need new bosonic states to alter the Higgs potential
  - Extended scalar sectors
- Two Higgs Doublet Model (2HDM)
  - New neutral, charged scalar states ✓
  - Possible new source of CP violation ✓ (Baryogenesis)
  - Unique collider signatures ✓

The 2HDM

- Simple extension of the SM Higgs sector
  - One more $SU(2)_L$ doublet
  - A limiting case of well-known BSM scenarios: MSSM, composite Higgs,…
- Generalised scalar potential and Yukawa sector
  - For the latter, a $\mathbb{Z}_2$ symmetry typically imposed to avoid strong constraints from Flavour-Changing Neutral Currents (FCNC)
- Both doublets share the role of EW symmetry breaking
- Complex parameters in the generalised potential
  - CP violation

The 2HDM

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

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

- Yukawa interactions
  - Cannot simultaneously diagonalise both Yukawa matrices →FCNC
- 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)
  - $\lambda_{6,7}$ explicitly break $\mathbb{Z}_2$ parity

The 2HDM

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

- We consider the CP conserving, $\mathbb{Z}_2$-symmetric potential
  - $\Phi = \lambda_{6,7} = 0$ & no spontaneous CP violation
  - 1) for simplicity 2) phase transition is not sensitive to small CPV effects
  - CP violating case is interesting from a baryogenesis point of view
- 8 parameters, 6 after EWSB (fixing vev and Higgs mass)

The 2HDM

- EW minimum defines tan β, the ratio of two vevs
- Scalar field content:
  - ϕ_1: SM Higgs (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(α-β)
  - Convention: α-β=0 means h interactions are SM-like: ***Alignment***
- 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)
  - $SU(2)_L$ doublets preserve custodial symmetry of EW vacuum
  - W/Z mass relationship affected only at loop level → T-parameter
- FCNCs
  - Strongest bounds come from b →Xs γ, B_0-$\overline{B}_0$ mixing
  - Constrain the [$m_{H\pm}$, tanβ] plane (type II: $m_{H\pm}$ > 380 GeV)
- LHC
  - Light Higgs properties constrain [α,β]
  - Direct searches for heavy scalars, dependent on the full parameter space

The 2HDM & EWPT

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

- Restrict ourselves to Type I
  - 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
- Our goal:
  - Investigate the viable 2HDM parameter space for a SFOEWPT
  - Incorporate latest experimental constraints
  - Connect with new LHC signatures

The 2HDM & EWPT

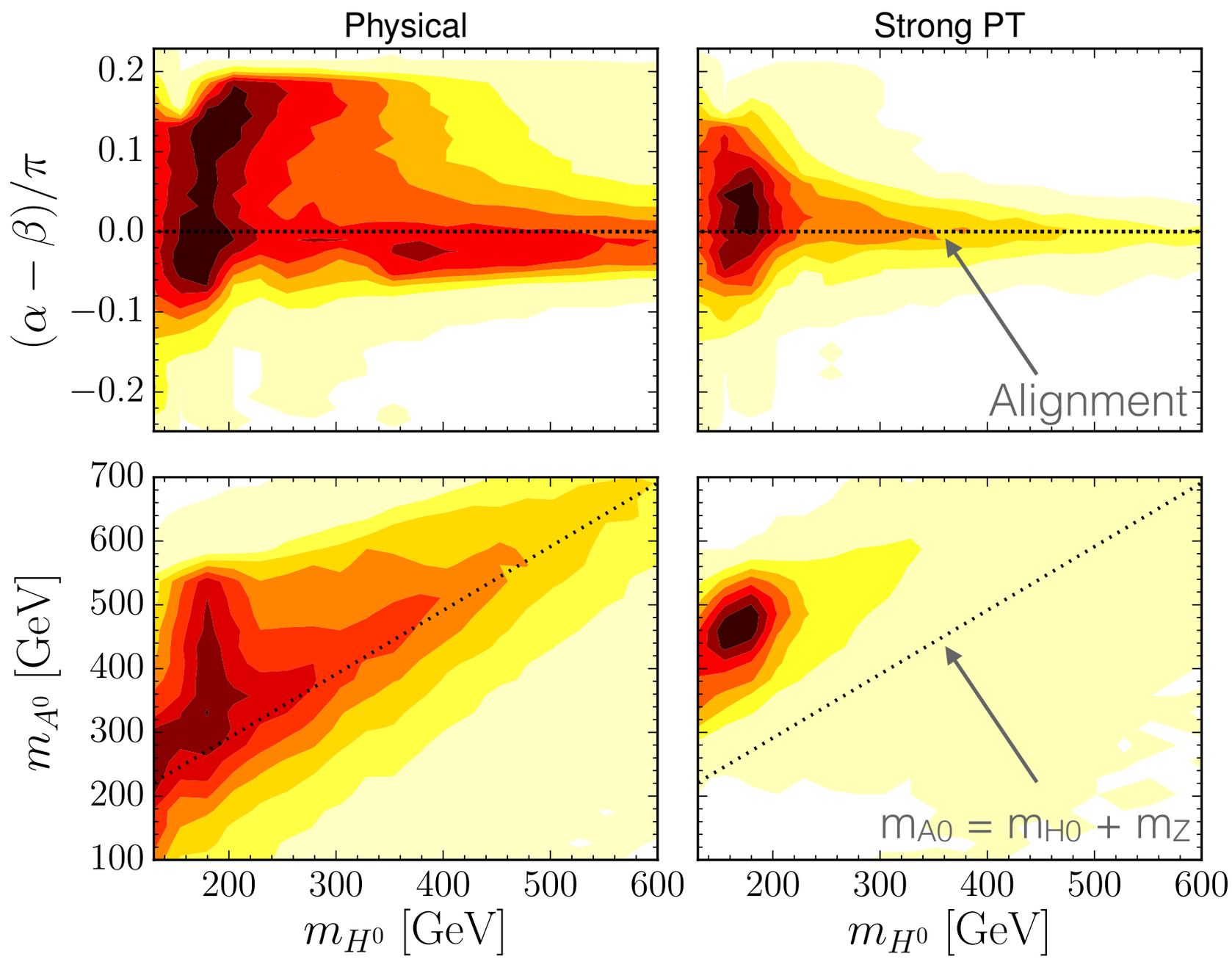
- Size of parameter space motivates a scan
- Developed a numerical code combining experimental & physicality constraints
  - Interfaced with 2HDMC, HiggsBounds/HiggsSignals
  - Ensure (1-loop) stability & (tree-level) perturbative unitarity
  - EWPO constraints
  - Light Higgs properties from LHC, Tevatron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

Parameter scan

- Satisfaction of the above defines a ‘physical point’
- For each physical point, determine the strength of the EW phase transition
  - Point at which the thermal 1-loop effective potential has two degenerate minima at [0, v_C]
  - Defines critical temperature T_C
  - SFOEWPT declared if $v_C/T_C > 1$
- Evaluate the additional effect of requiring of a SFOEWPT on the previously existing constraints in the 2HDM parameter space

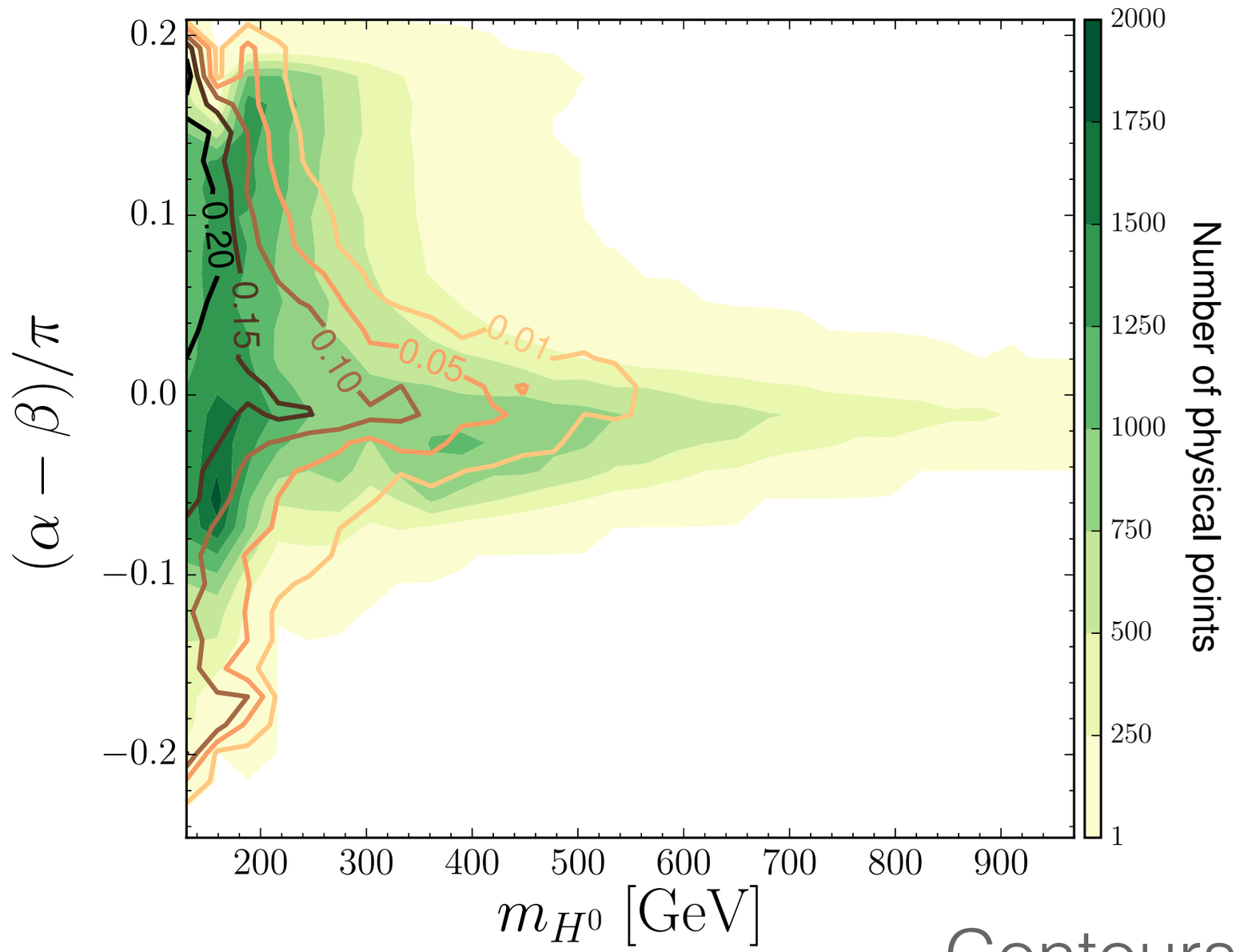
Results

Pass physicality constraints



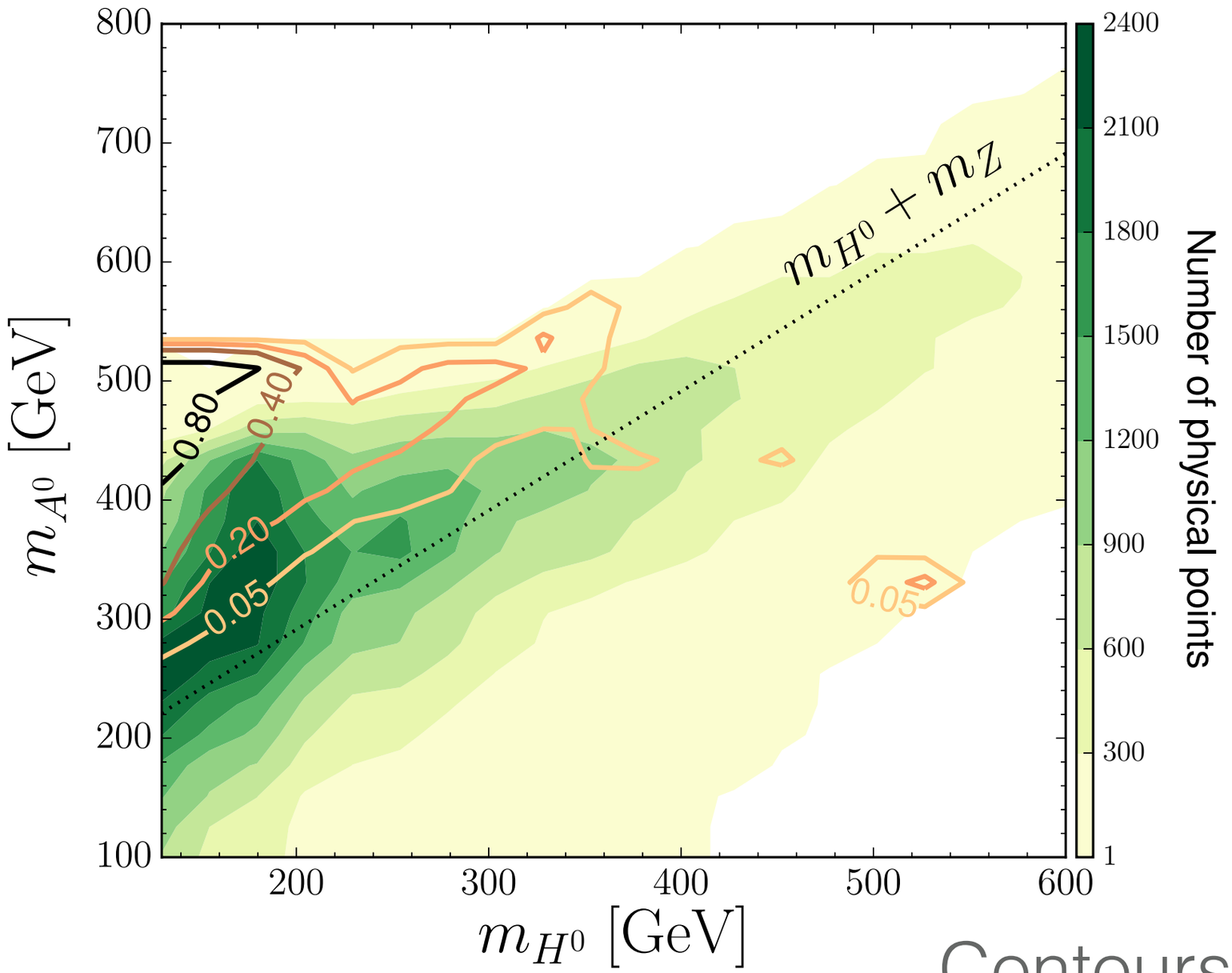
Predict SFOEWPT

Results



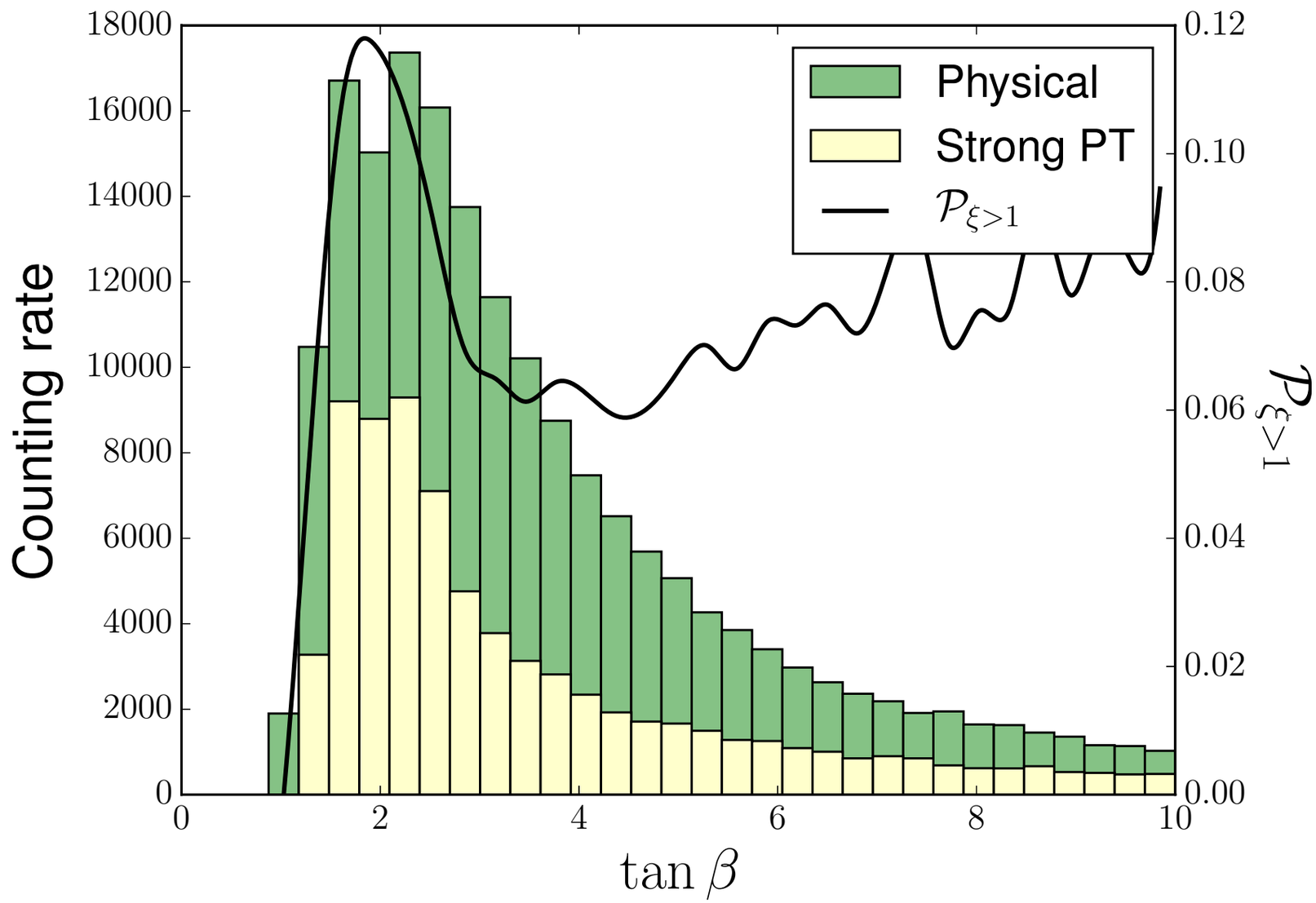
Contours: *ratio* of Physical vs SFOEWPT

Results



Contours: *ratio* of Physical vs SFOEWPT

Results



Black curve: *ratio* of Physical vs SFOEWPT

Observations

- Preference for alignment limit
  - α-β ~ 0
  - Imposed by experimental constraints
  - Maintained by SFOEWPT requirement
- Moderate tan β (scan only went up to 10)
- Mass splitting (~v) between A_0 and H_0
  - Relatively light H_0 (m_{H0} < 300 GeV)
  - Heavy A_0 (m_{A0} > 300 GeV)
  - As m_{H0} increases, range of α-β decreases

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
  - See G. Dorsch’s thesis

Interpretations

- Not only a specific realisation but also a very original one
- ‘Hierarchical’ 2HDM
- Majority of analyses are quite ‘SUSY-oriented’
  - v, μ set the scale of the states, λ’s drive the splittings
  - Gauge origin of the self-couplings in SUSY
  - Near degenerate spectrum with splittings ≪ v
- Points more towards strongly-coupled UV completions for such a scenario
- Unique collider signatures!

H2HDM at Colliders

- Summary
  - Large (≥ v) mass splittings are strongly preferred
  - Heavy A_0 (≳300 GeV), Lighter H_0 (≲ 300 GeV)
  - Close to alignment (SM-like 125 GeV Higgs)
  - Moderate tan β
- Heavy CP-even Higgs searches focus on WW, ZZ, ff channels
- CP-odd searches:
  - WW/ZZ forbidden for A_0 in CP conserving scenario
  - Only fermionic (very difficult if mA0 > 2mt!)

H2HDM at Colliders

- Large splittings open $S_i \rightarrow S_j V$
  - S: scalar (h, A_0, H_0, $H_\pm$), V: gauge boson ($W_\pm$, Z)
  - Often assumed to be kinematically forbidden
  - Until this summer, only $A_0 \rightarrow Z\, h$ & $H_0 \rightarrow hh$ searches existed
- 'Smoking gun' for the SFOEWPT: $A_0 \rightarrow Z\, H_0$
  - Not alignment suppressed ~ $\cos(\alpha-\beta)$
  - In contrast to $A_0 \rightarrow Z\, h$ ~ $\sin(\alpha-\beta)$
- Determine the LHC prospects for this signature

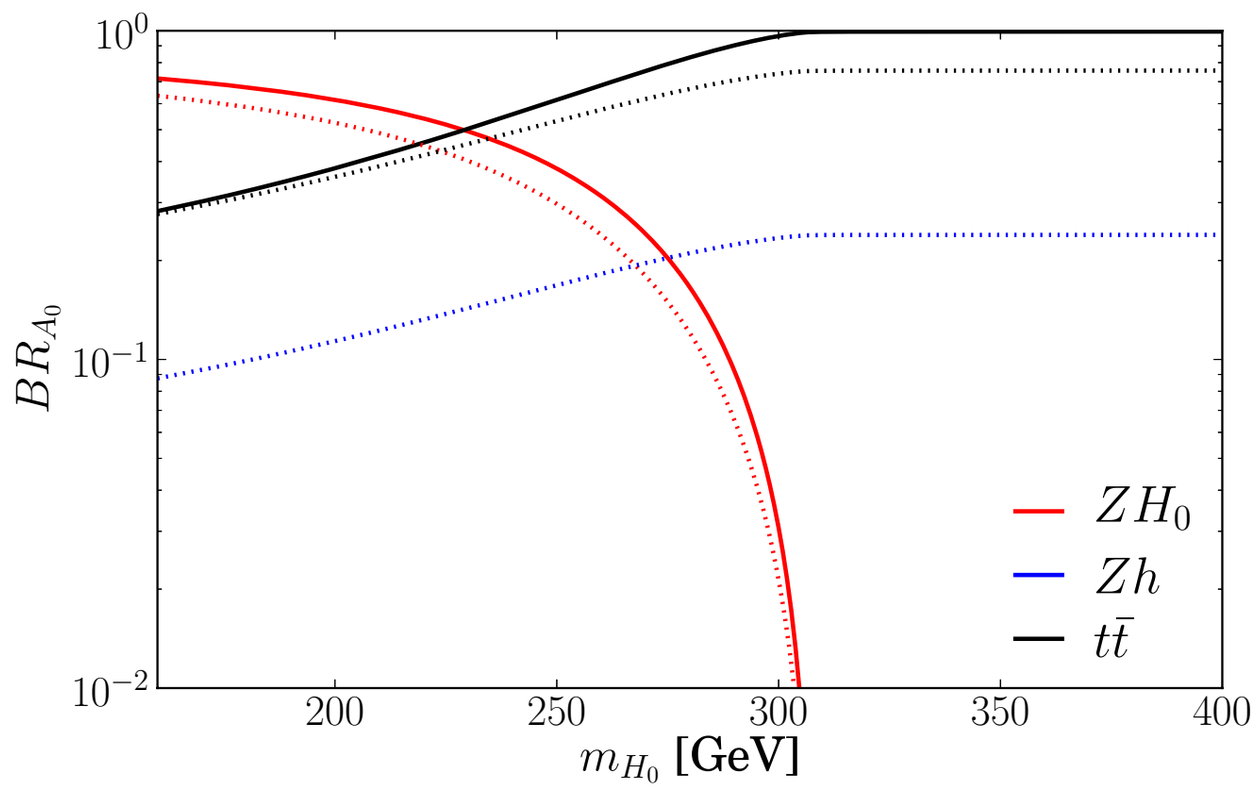
$A_0 \rightarrow Z\, H_0$ benchmarks

- 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



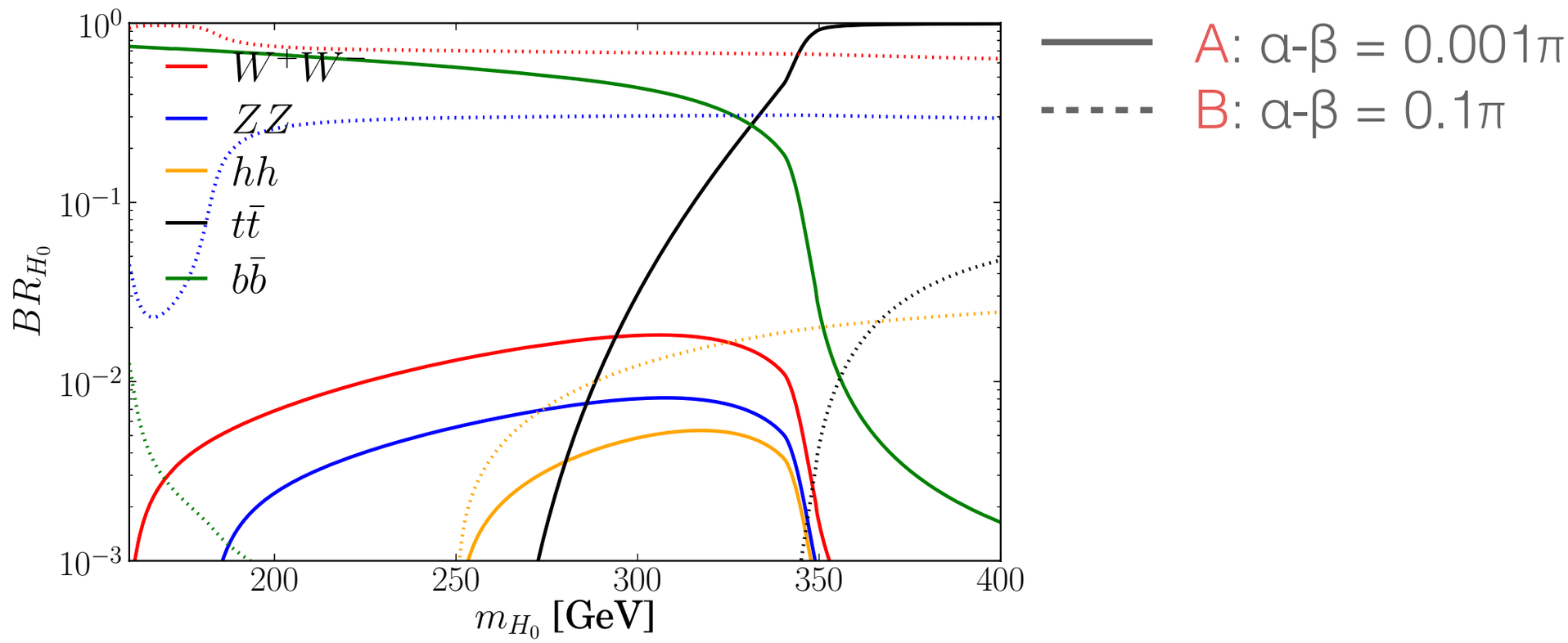
mA_0 = 400 GeV

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 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

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 |η|<2.5
  - Parametrised tagging efficiency as per *[CMS-PAS-BTV-13-001]*
  - 2 isolated, same-flavour leptons
  - Lepton |η|<2.5(2.7) for electrons(muons)
  - Leading lepton pT > 40 GeV
  - Sub-leading lepton pT > 20 GeV

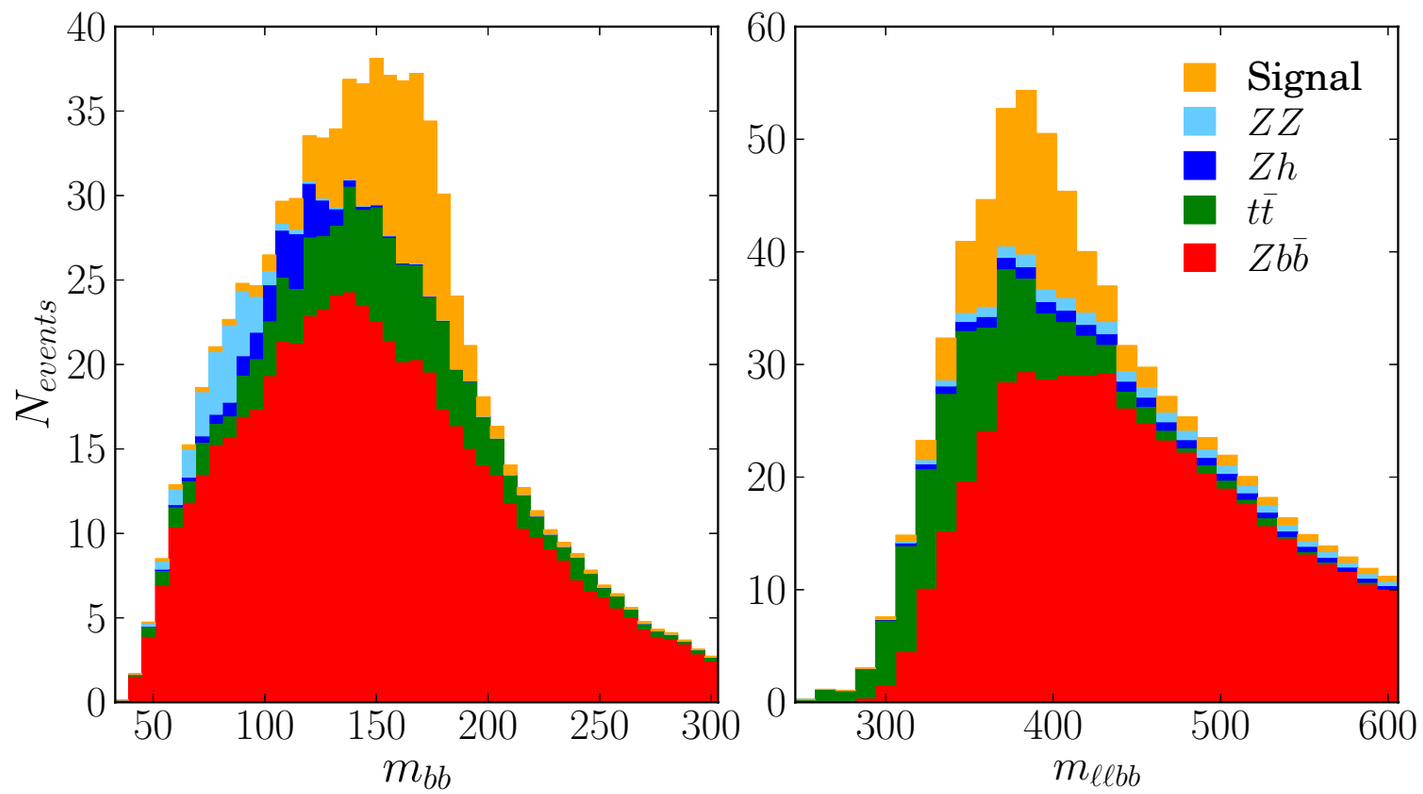
$A_0 \rightarrow Z\, H_0 \rightarrow bbll$

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

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



13 TeV LHC
L= 20 fb^{-1}

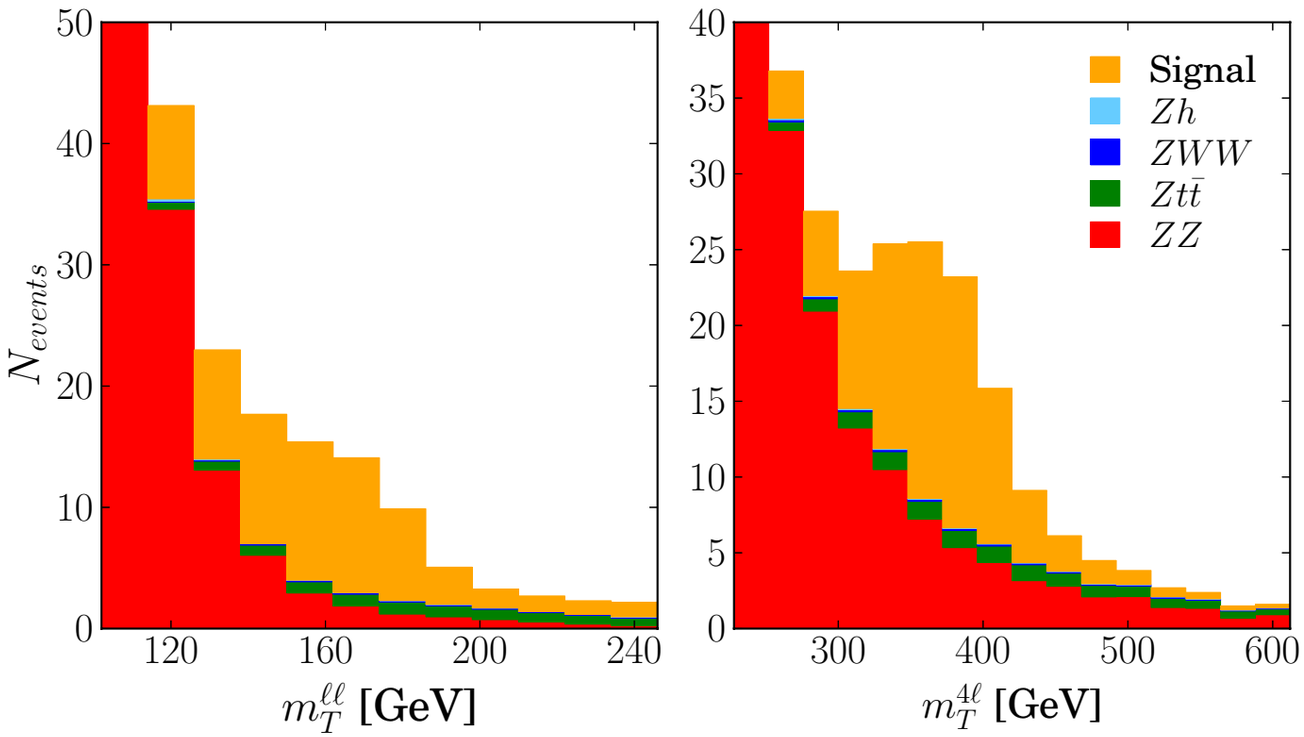
- Final observables: invariant mass of bb and bbll systems
  - Energy losses expected due to finite resolution & imperfect reconstruction
  - m_{bb} within (m_{H0} - 20) ± 30 GeV & m_{bbll} within (m_{A0} - 20) ± 40 GeV
  - Statistics only significance of 5σ for 20 fb^{-1}
  - Assuming 10% uncertainty (CLs) →40 fb^{-1}

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

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



13 TeV LHC
L= 60 fb^{-1}

$$(m_T^{\ell\ell})^2 = (\sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \not{p}_T)^2 - (\vec{p}_{T,\ell\ell} + \vec{\not{p}}_T)^2$$

$$m_T^{4\ell} = \sqrt{p_{T,\ell'\ell'}^2 + m_{\ell'\ell'}^2} + \sqrt{p_{T,\ell\ell}^2 + (m_T^{\ell\ell})^2}$$

- Transverse mass variables:
  - mT4l > 290 GeV → sig = 0.88fb, bkg = 1.39 fb
  - Statistics only significance of 5σ for 60 fb^{-1}
  - Assuming 10% uncertainty → 200 fb^{-1}

Low background situation!
Investigate reducible backgrounds further

LHC analysis

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

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

The CMS Collaboration

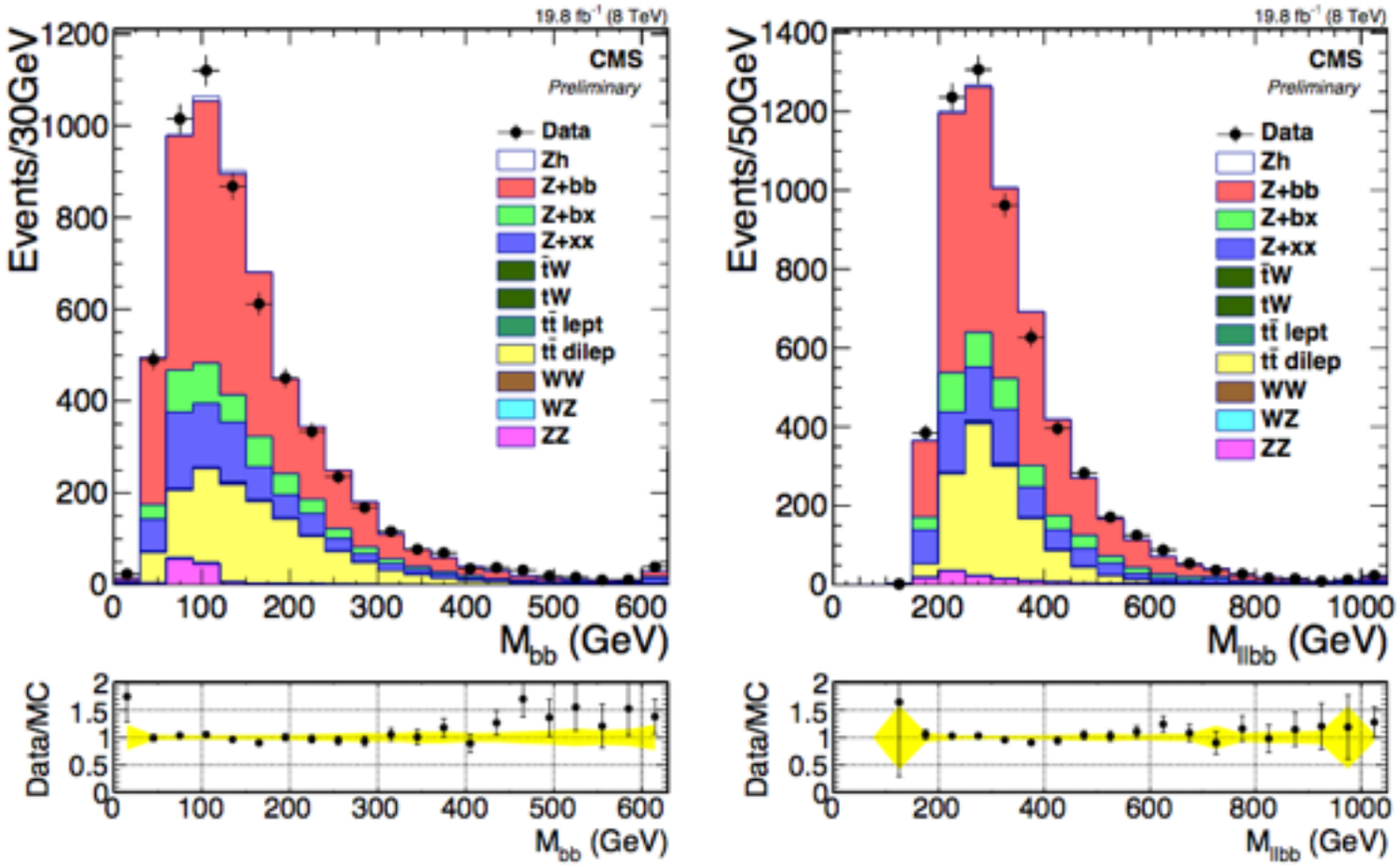
CMS-PAS-HIG-15-001
May 2015

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.

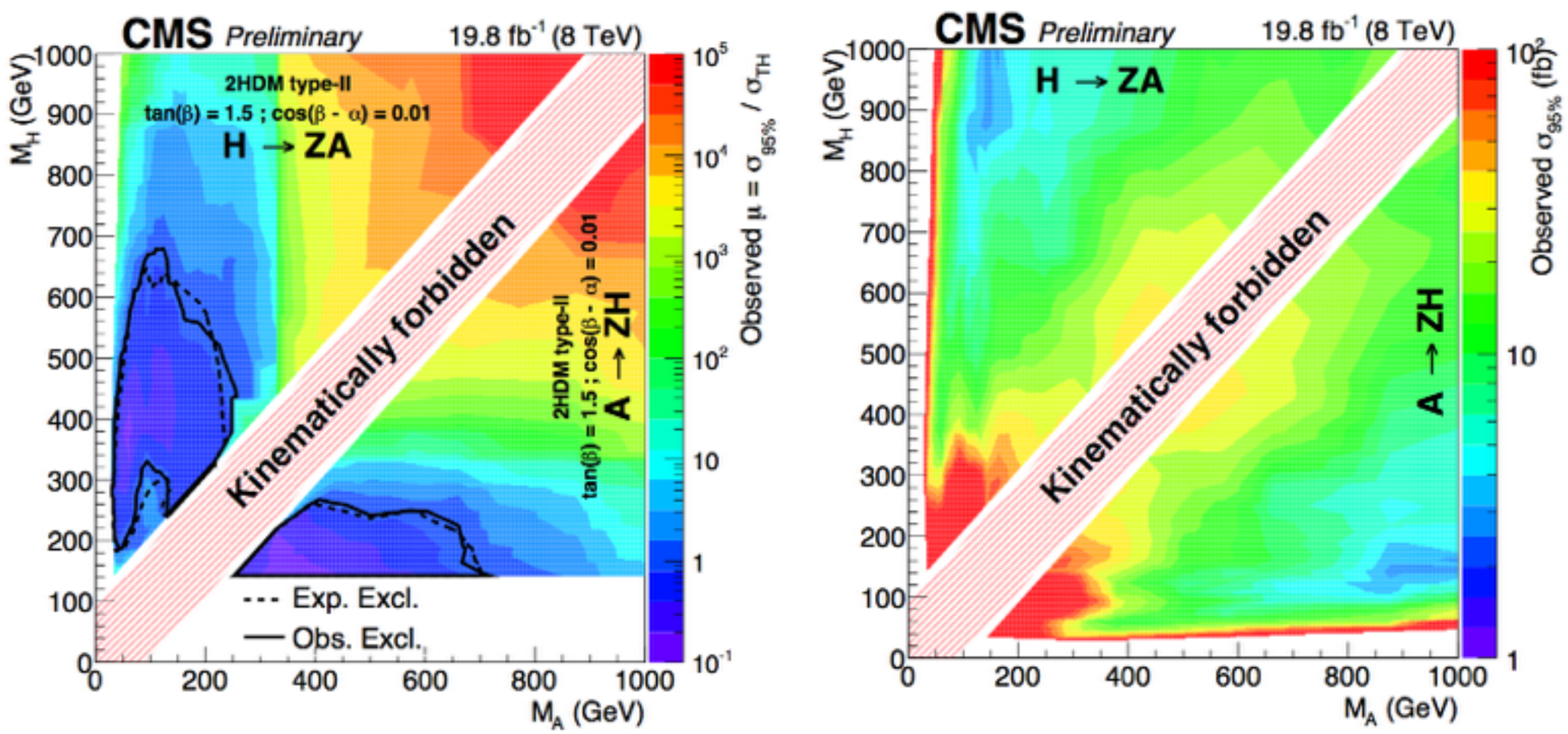
LHC analysis

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



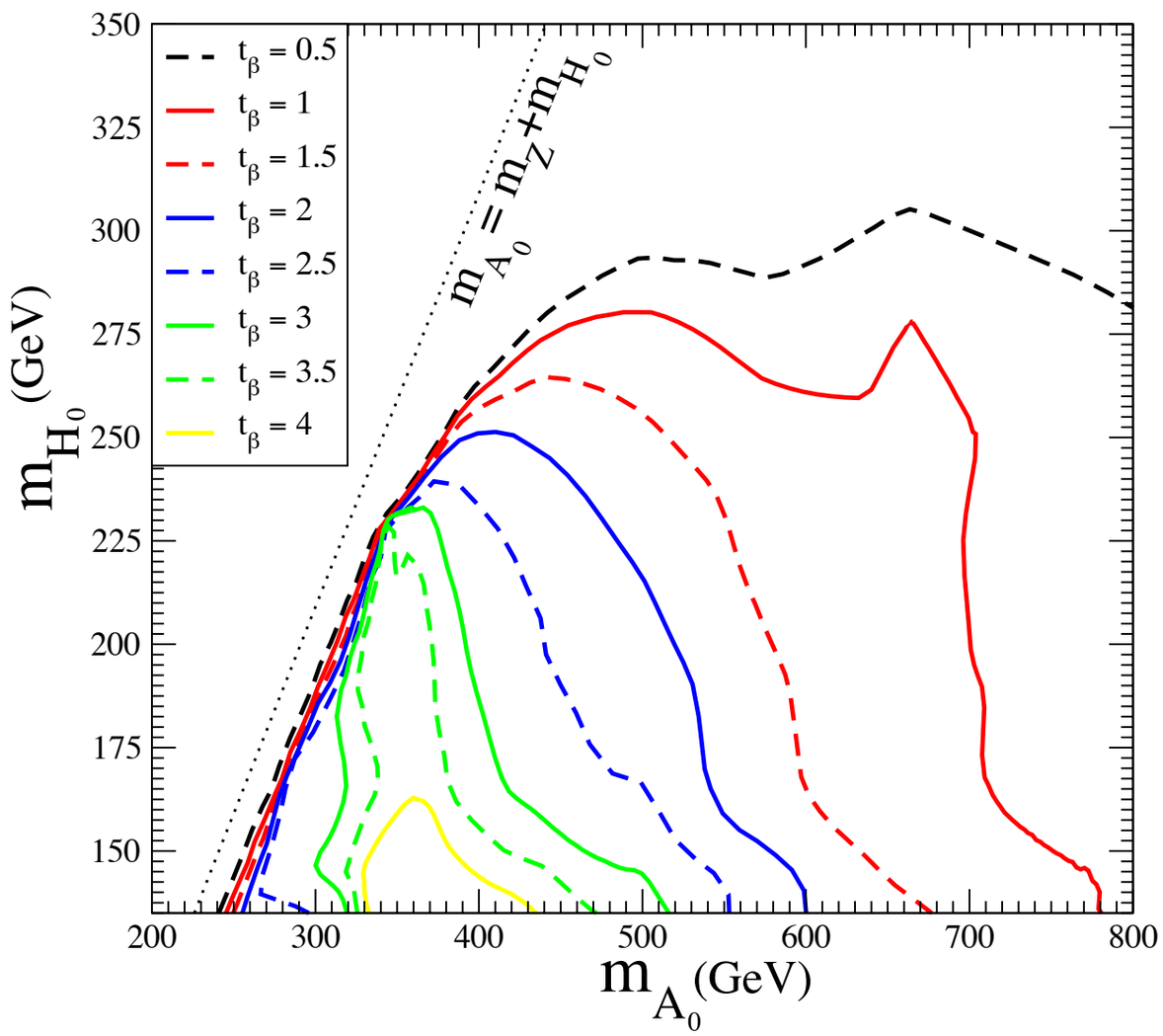
LHC analysis

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

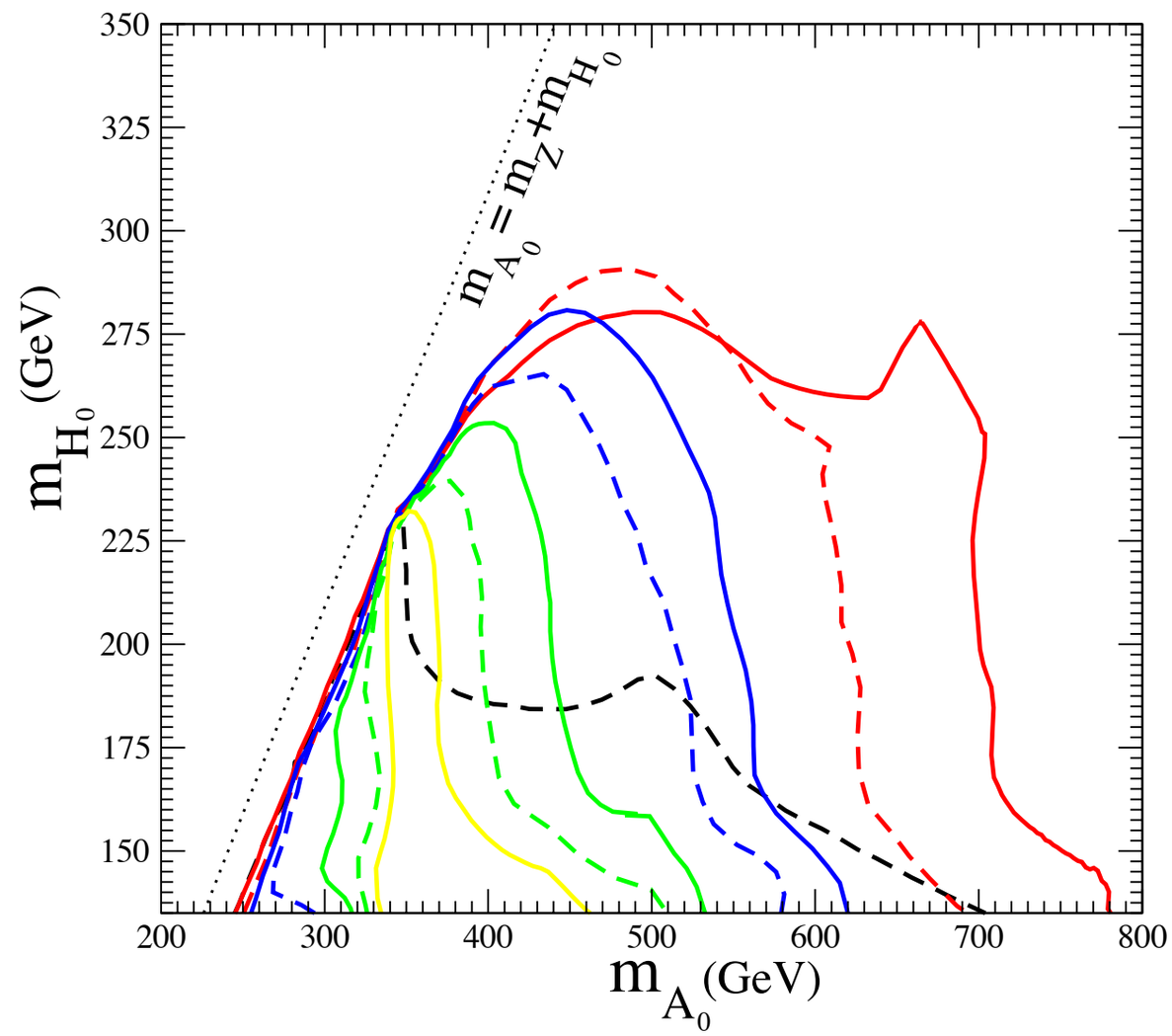


LHC analysis

Type I



Type II

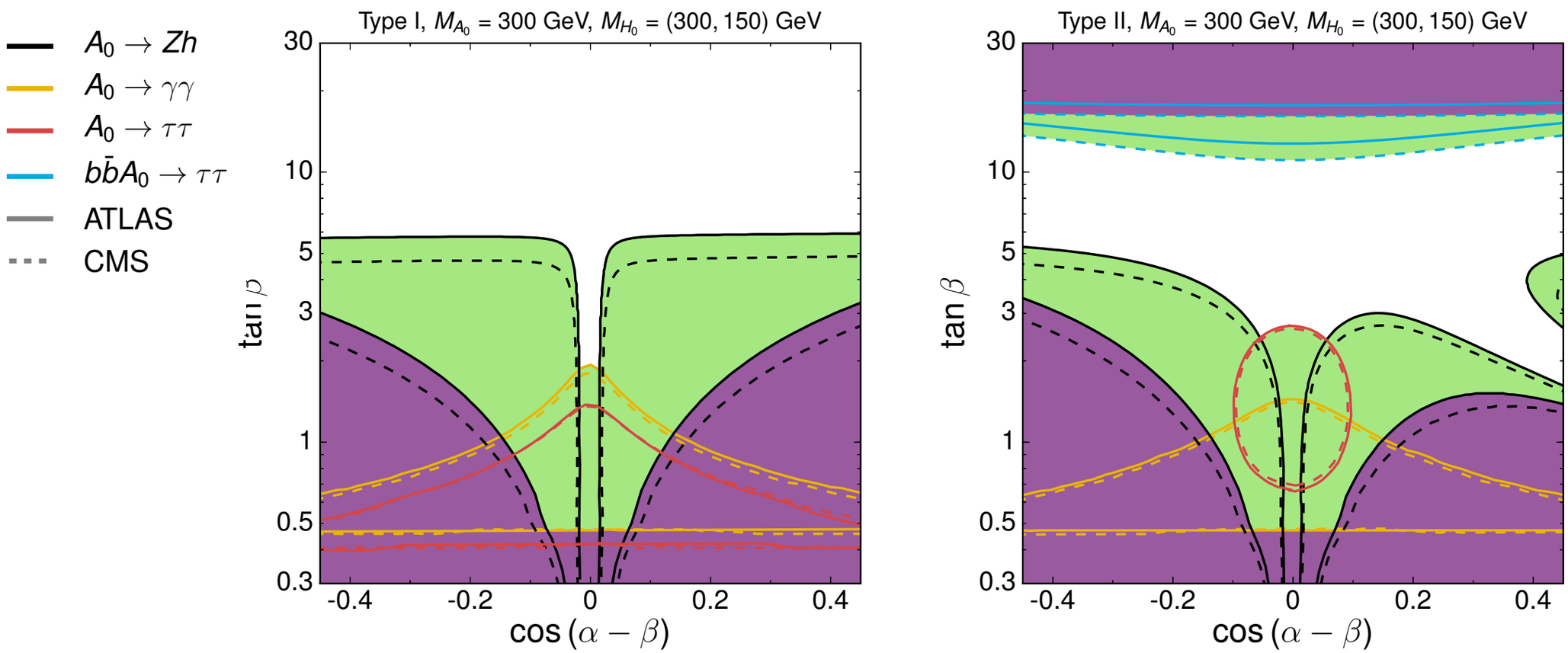


Future

- H2HDM is already being constrained by the LHC
- 13 TeV & future colliders will significantly improve limits
  - Strongly coupled UV completion = TeV scale composite resonances
- Many processes yet to be searched for
  - 4l2v final state
  - One hadronically decaying W → 2l2j2v
  - Z decay to neutrinos → 2l + MET (4v) & permutations
  - Tri-Z →4l2j
  - Other possible H_0 → Z A_0 signatures
  - Charged Higgs decays *[B. Coleppa, F. Kling, S.Su; JHEP 1412 (2014) 148]*

Further motivation

- Relaxing assumptions about a near-degenerate spectrum alters the picture of existing 2HDM constraints at the LHC
  - Opening up these new channels reduces the BR of other decay modes

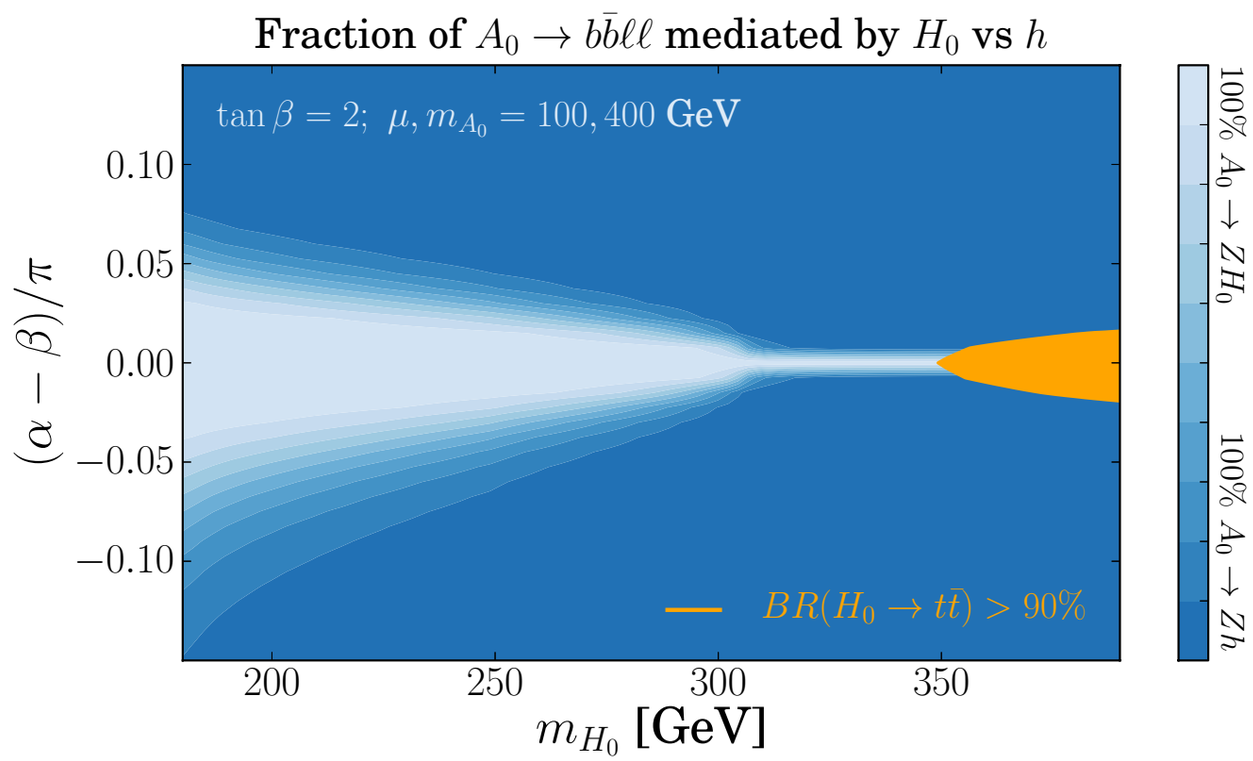


Conclusions

- 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 $A_0 \rightarrow Z\, H_0$
- 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: bigger paper in the pipeline

BACKUP

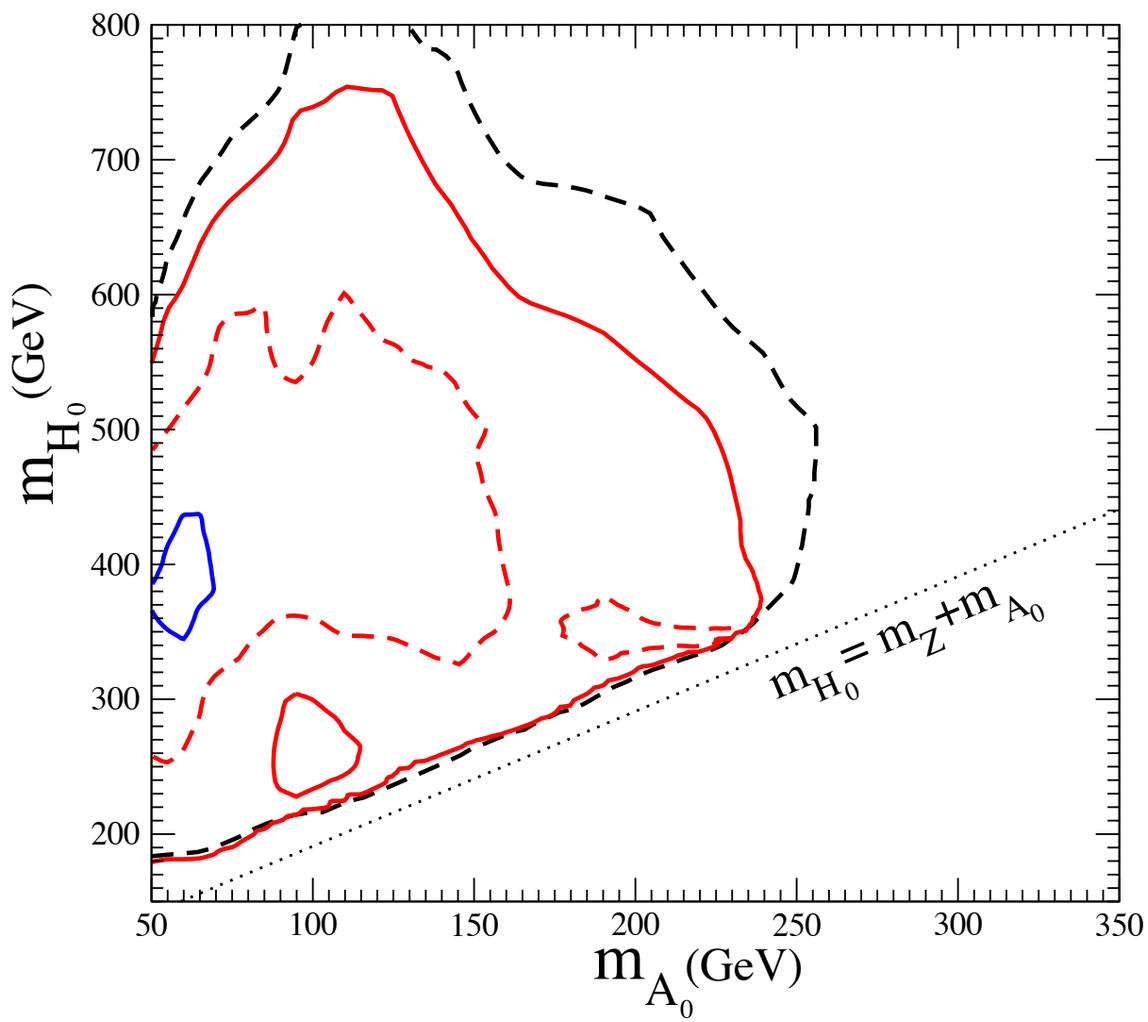
bbll final state



- SM Higgs production & $A_0 \to Z\,h$ can have this final state
  - Resonant production ≫ off-shell SM associated production
  - Near alignment $A_0 \to Z\,h$ is suppressed

LHC analysis

Type I



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