Discovering a cosmologically motivated 2HDM at the LHC via $A_0 \rightarrow Z\ H_0$

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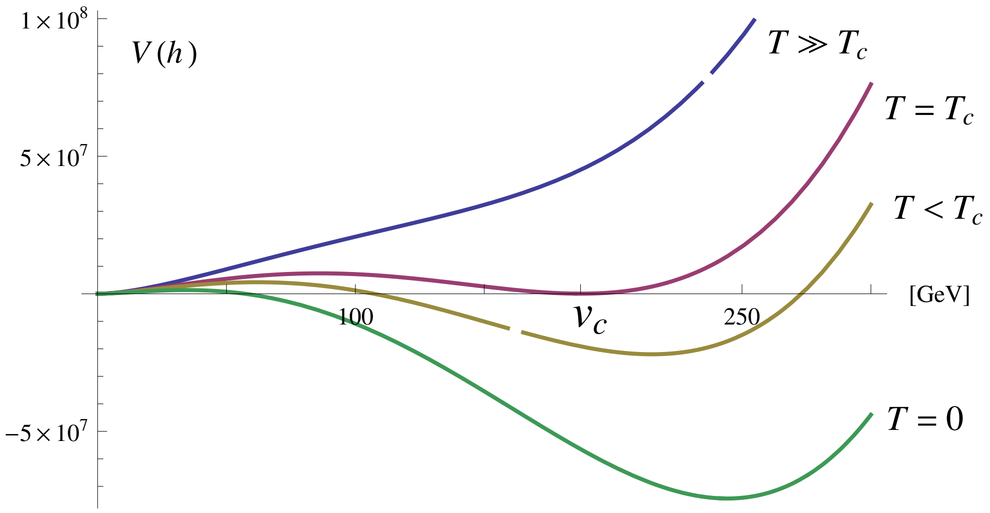
Overview

- Introduction/Motivation
  - Strongly first order electroweak phase transition (EWPT) and Baryogenesis
  - 2HDM as a viable candidate to provide this EWPT
- LHC phenomenology
  - The 'smoking gun' signature of $A_0 \rightarrow Z H_0$
  - Motivating the search in the $b\bar{b}ll$ and $WWll \rightarrow 4l\ 2\nu$ channels
  - Detailed, detector level analysis of two benchmark scenarios at the LHC
  - Promising discovery prospects, both with current data and the upcoming run
- Conclusion & Outlook

EW phase transition

- The Standard Model is unable to account for the baryon asymmetry of the universe
- Sakharov conditions: C, CP, B violating interactions occurring out of thermal equilibrium in the early universe
  - B violating interactions unsuppressed at temperatures above EW scale ✓
  - EW phase transition (PT) must be first order (discontinuous) in order for the generated asymmetry to not be washed out.
  - SM predicts a second order phase transition for $m_h \geq m_W$ ✗
  - Insufficient CP violation ✗



EW phase transition

- A strongly first order PT is a requirement for EW baryogenesis
- It is natural to focus on extending the bosonic sector due to their contributions to the thermal effective potential
- The Two Higgs Doublet Model (2HDM) can provide this
  - Adds new bosonic degrees of freedom which contribute in a way that is conducive to a strong first order EWPT
  - Potentially new sources of CP violation
  - One of the simplest extensions to the scalar sector of the SM
  - Testable at the LHC
  - Provides a connection between cosmology and collider physics

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

The 2HDM

- Add one $SU(2)_L$ scalar doublet to the SM
- Simple, well motivated extension of the Standard Model
  - Scalar sector of the SM is the source of many of its potential issues regarding naturalness, hierarchy problem, vacuum stability etc.
  - The Brout-Englert-Higgs mechanism can be seen as a minimal parametrisation for the generation of mass and the unitarisation of vector boson scattering
  - Arises in well known BSM scenarios (i.e. MSSM, composite Higgs)
- Leads to a generalised scalar potential + Yukawa sector
  - Z_2 symmetry imposed to avoid tree level FCNCs
- Both doublets can share the role of EW symmetry breaking
- Complex parameters in the potential → CP violation
  - We have considered the CP violating case for simplicity
  - Not important for phase transition but clearly relevant for subsequent baryogenesis

The 2HDM

- CP conserving, softly broken Z_2-symmetric potential
  - 8 free parameters

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

- EW minimum defines tanβ, the ratio of the vevs
  - Mixing angle rotating to a basis where one field gets the whole vev
- Φ'_1: SM Higgs, h, and 3 Goldstone bosons eaten by W and Z
- Φ'_2
  - Upper component - charged scalar states: $H^\pm$
  - Lower component - two additional neutral (CP even and odd) states: H_0, A_0

The 2HDM

- CP even scalar states, h and H_0, will mix with angle α, assume the lightest of the two should correspond to the recently observed Higgs-like state with mass m_h=125 GeV
- Minimisation conditions and mass matrix diagonalisation
  - Trade parameters in the potential for physical masses and mixing angles
  - Leaving 6 free parameters: m_{H0} , m_{A0} , $m_{H^\pm}$, μ , α , tanβ
- Gauge interactions of the scalar sector are characterised by the quantities sin(α-β) and cos(α-β); α-β=0 means light Higgs is SM-like
- Yukawa interactions determined by the parity assignments of RH fermions
  - By convention parity of up type quark matches that of Φ_2
  - MSSM corresponds to Type II

Type	u_R	d_R	e_R
I	+	+	+
II	+	−	−
X	+	+	−
Y	+	−	+

2HDM and the EWPT

- We focus on the type I 2HDM
  - All fermions couple to the same doublet
  - No lower bound on the charged Higgs mass from flavour constraints
- EWPT insensitive to the 2HDM model type
  - By convention, the top quark always couples to the same doublet and is the only fermion with appreciable couplings to the scalar sector
  - Other fermionic contributions to the thermal effective potential are negligible
  - Only experimental constraints differ between model types
- We investigate the viable 2HDM parameter space for a strong EW phase transition
  - Incorporate experimental constraints
  - Link to potential LHC signatures

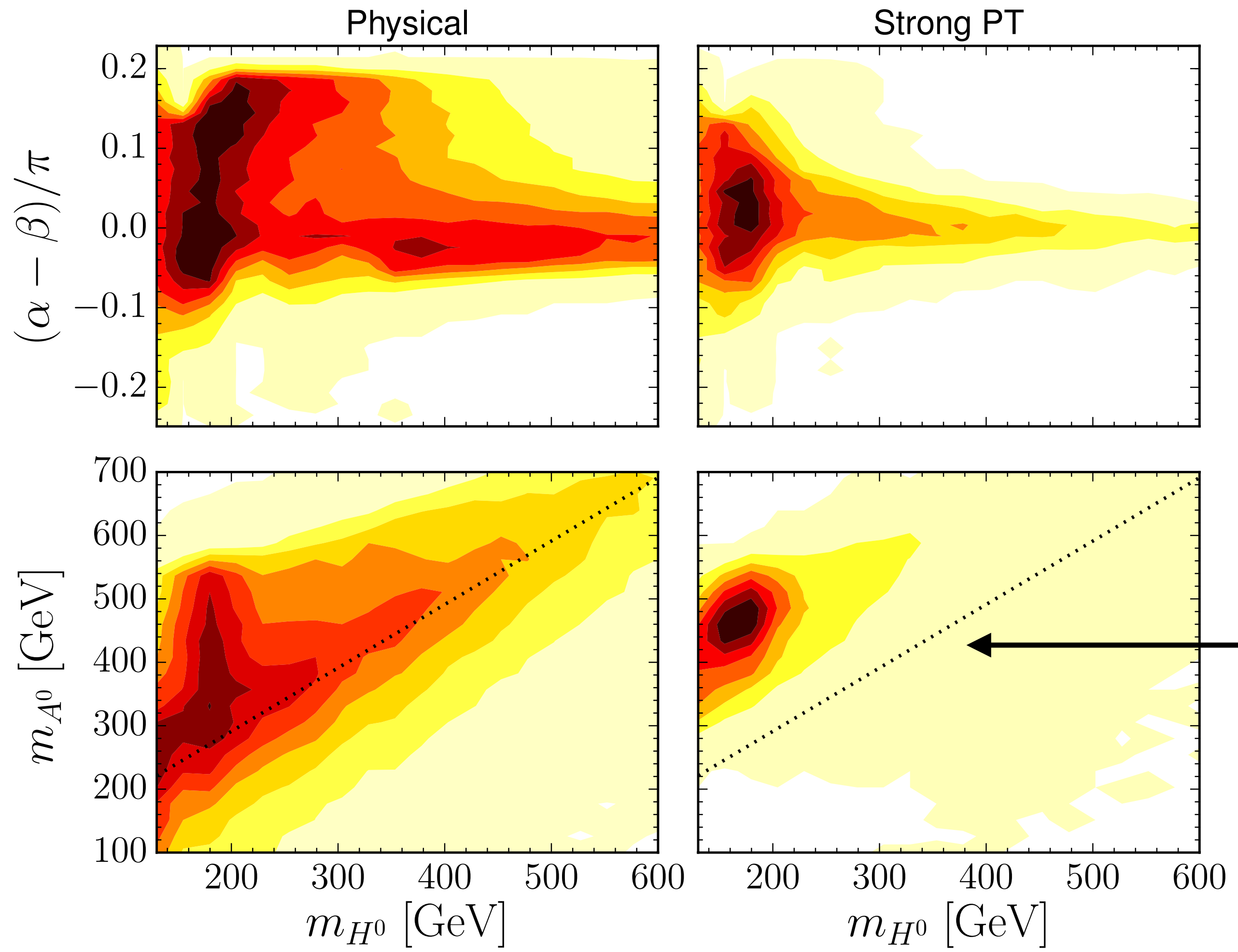
2HDM and the EWPT

- Parameter space large enough to motivate scan
- Numerical code interfaced with 2HDMC and HiggsBounds/HiggsSignals
  - Select points that satisfy tree-level unitarity, perturbativity
  - EW precision constraints
  - Collider bounds from light Higgs data and heavy scalar searches
  - Direct exclusions from LEP, Tevatron & LHC (NWA)
  - Higgs signal strength measurements from Tevatron & LHC as of March 2014
  - Flavour constraints from $b \to s\gamma$ taken into account
  - Cross check limits on α and $\tan\beta$ from a global fit of light Higgs properties performed in *[C.-Y. Chen, S. Dawson M. Sher; PRD 88 (2013) 015018]*
- Satisfaction of the above conditions defines a 'physical' point

2HDM and the EWPT

- The strength of the EWPT is evaluated for each physical point
  - Point at which the thermal 1-loop effective potential has two degenerate minima at 0 and v_C → critical temperature T_C
  - Strong PT determined by $v_C / T_C > 1$

Pass physicality constraints

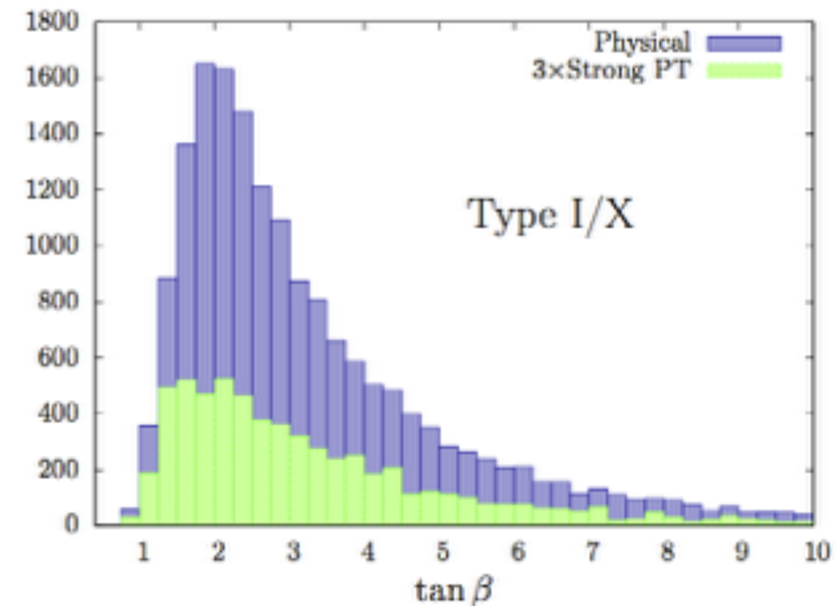


Predict strong, first order transition

$m_A = m_H + m_Z$

2HDM and the EWPT

- SM-like light Higgs is preferred
  - low α-β and moderate tanβ
  - Mass splitting ~ v between A_0 and H_0,
  - m_{A_0} > 300 GeV



- Alignment limit
  - Naturally preferred by experimental constraints
- Reinforced by strong first order PT requirement
  - As m_{H_0} increases, the range of preferred α-β narrows
  - Away from the alignment limit (α-β=0), both CP even scalar states 'share' the EW vev and participate in the EWPT
  - PT gets weaker as these states become heavier

2HDM and the EWPT

- Requiring a strong first order EWPT points to a very different kind of 2HDM than commonly considered
- Typical analyses are relatively 'SUSY-oriented'
  - Near-degenerate spectrum
- Dimensionful parameters, v and mu, set the scale
  - Scalar mass splittings are driven by the self couplings, λ_i
  - e.g. in SUSY these are typically much less than v, decreasing as the overall scale increases
  - A preference for substantial splittings points towards strongly coupled theories as UV completions of such a scenario

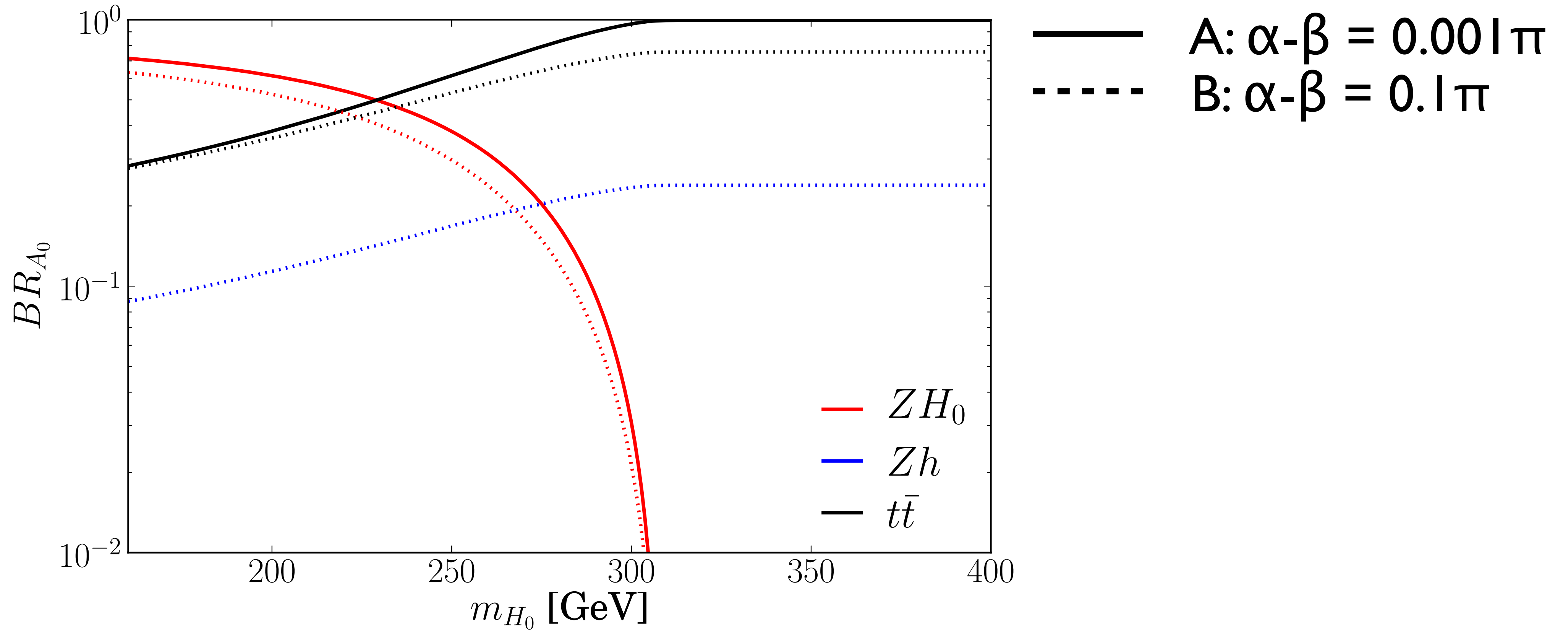
Pheno consequences

- Large splittings are preferred, along with a heavy CP-odd scalar state, relatively light 2nd CP even state and a SM-like Higgs
- Opens new decay channels not previously considered
  - Heavy Higgs searches focus mostly on gauge bosons decay modes (WW, ZZ)
  - These channels are not permitted for the A_0 by CP
  - Difficult to look for in t, b final states
  - Pseudoscalar searches are currently limited to $A_0 \rightarrow Zh$, $\tau\tau$
- Most importantly, the $S_i \rightarrow VS_j$ opens
  - V is a vector boson ($W^{\pm}$, Z) and S_i is another heavy scalar (A_0,H_0,$H^{\pm}$)
  - These channels are typically assumed to be kinematically forbidden

Pheno consequences

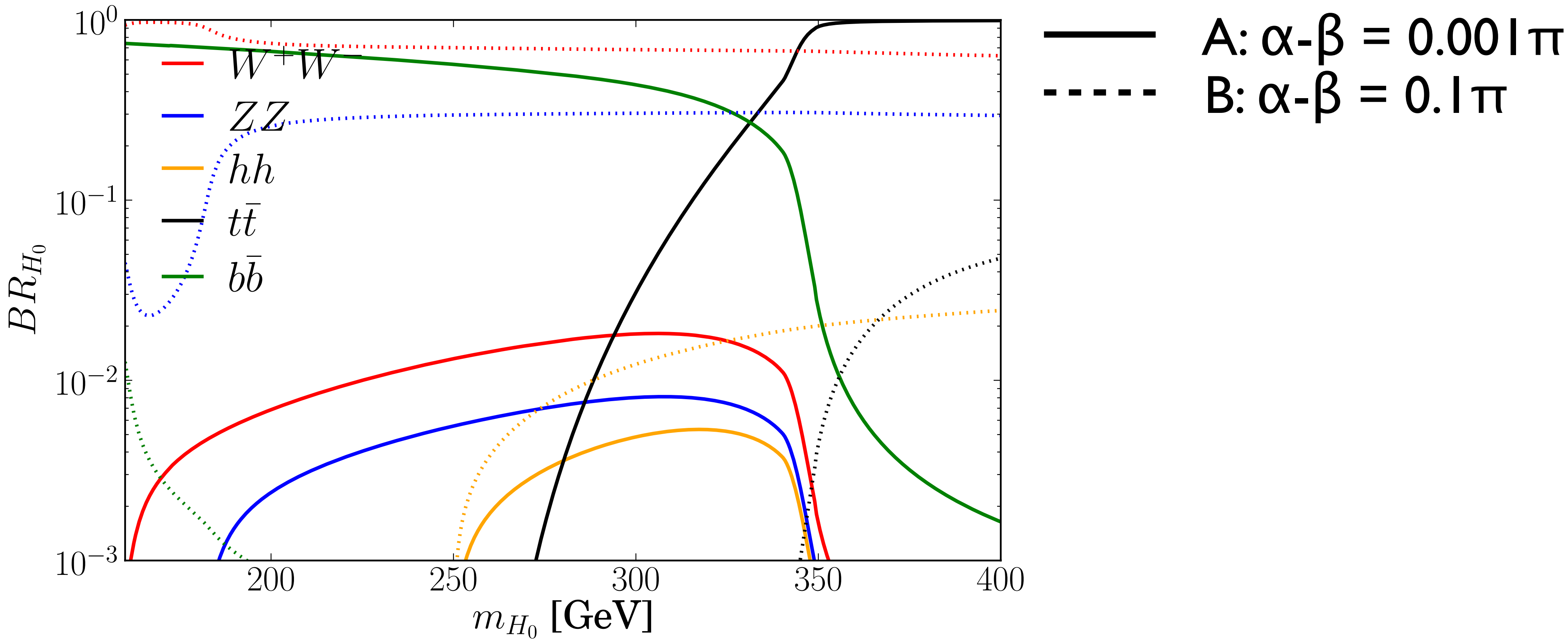
- Heavy pseudoscalar points to $A_0 \to ZH_0$
  - Coupling is not affected in the alignment limit ~ $\cos(\alpha-\beta)$
  - In contrast, $A_0 \to Zh$ vanishes, like gauge boson couplings to H_0 ~ $\sin(\alpha-\beta)$
- Determine the LHC discovery prospects of this type of model
  - Choose benchmarks with parameters compatible with a strong first order EWPT and physicality requirements including direct searches
- $m_{H_0} = 180$, $m_{A_0} = 400$, $m_{H^{\pm}} = 400$, $\mu = 100$ [GeV]
  - $\tan\beta = 2$ controls the $gg \to A_0$ production rate via top couplings
  - Focus on both the aligned and non-aligned scenarios i.e. $\alpha-\beta = 0.001\pi, 0.1\pi$
  - The search strategy is then dictated by the preferred decay mode of H_0

A_0 decay modes



- Other competing decay channels are $t\bar{t}$ and $W^{\pm}H^{\mp}$
  - The $t\bar{t}$ channel goes as $(\tan\beta)^{-2}$
  - Availability of $W^{\pm}H^{\mp}$ depends on $m_{H^{\pm}}$
  - EWPO constrain the charged Higgs to be close in mass to one or the other heavy scalar
  - We choose to have it pair with A_0 and close the channel for simplicity
  - Its presence will roughly halve BR(ZH_0)

H_0 decay modes



- Clear preference for bb and WW in the respective scenarios
  - hh decay mode increases with μ and can dominate when kinematically available (more difficult to satisfy constraints)
  - We considered leptonic decays of Z and W
  - A: $b\bar{b}ll$ final state
  - B: WWll →4l 2ν final state

LHC analysis

- The type I 2HDM was implemented using FeynRules
  - Including an effective dimension-5 operator for production via gluon fusion
- Signal + backgrounds generated using Madgraph5_aMC@NLO
  - Events passed on to Pythia for parton showering and hadronisation
  - Delphes used for LHC detector simulation
- Perform a ‘cut and count’ analysis on a small set of kinematical variables to extract the signal over the background
  - Use NLO k-factors for signal and dominant backgrounds to approximate the most significant radiative corrections
  - Obtained from literature for backgrounds, used SusHi for signal

$A_0 \to ZH_0 \to b\bar{b}ll$

- Given the potential sensitivity already at 7 and 8 TeV, one should expect that the 13 TeV run be promising
  [B. Coleppa, F. Kling, S.Su; arXiv:1404.1922]
- Main irreducible backgrounds are $Zb\bar{b}$, $t\bar{t}$, ZZ and Zh
- Straightforward event selection
  - Anti-k_T jets with distance parameter R=0.6
  - 2 b-tagged jets; $|\eta| < 2.5$
  - Tagging efficiency modelled as a function of p_T and η as per *[CMS-PAS-BTV-13-001]*
  - 2 isolated, same flavour leptons (within a cone of 0.3); $|\eta| < 2.5(2.7)$ for electrons (muons)
  - $P_T^1 > 40$ GeV, $P_T^2 > 20$ GeV

$A_0 \to ZH_0 \to b\bar{b}ll$

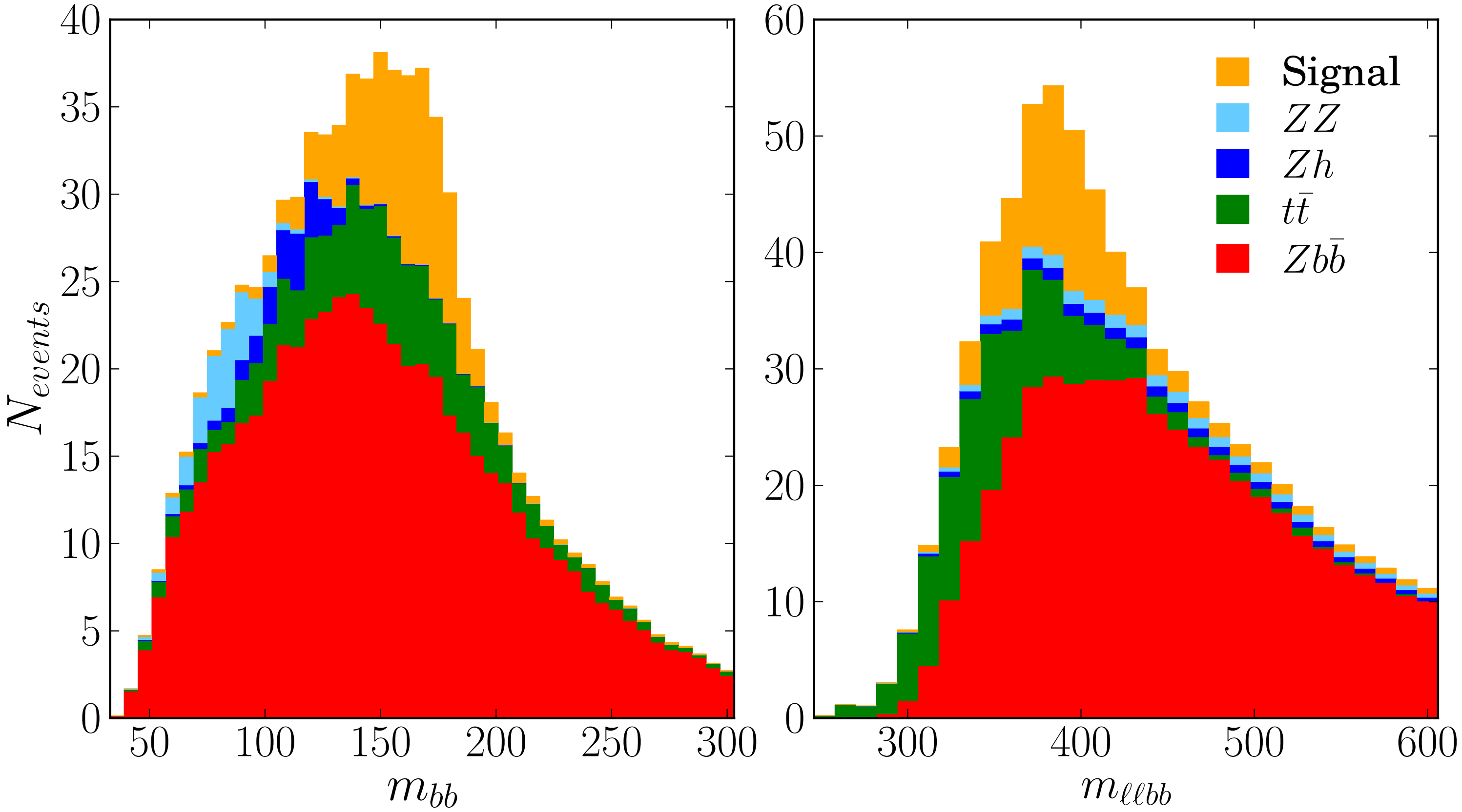
k-factor:	1.6	1.5	1.4	-	-
	Signal	$t\bar{t}$	$Z\,b\bar{b}$	ZZ	$Z\,h$
Event selection	14.6	1578	424	7.3	2.7
$80 < m_{\ell\ell} < 100$ GeV	13.1	240	388	6.6	2.5
$H_T^{\rm bb} > 150$ GeV, $H_T^{\ell\ell{\rm bb}} > 280$ GeV	8.2	57	83	0.8	0.74
$\Delta R_{bb} < 2.5$, $\Delta R_{\ell\ell} < 1.6$	5.3	5.4	28.3	0.75	0.68
m_{bb}, $m_{\ell\ell bb}$ signal region	3.2	1.37	3.2	< 0.01	< 0.02

- Kinematical cuts
  - Leptons should reconstruct m_Z
  - 2 cuts on total $H_T = \Sigma P_T$, with and without the leptons
  - $\Delta R^2 = \Delta\eta^2 + \Delta\Phi^2$ between $b\bar{b}$ and ll

$A_0 \to ZH_0 \to b\bar{b}ll$

- Observables: invariant masses of the $b\bar{b}$ and the $b\bar{b}ll$ systems
  - Energy losses due to imperfect reconstruction and finite resolution occur
  - m_{bb} within $(m_{H0} - 20) \pm 30$ GeV; m_{bbll} within $(m_{A0} - 20) \pm 40$ GeV
  - Statistical-only significance of 5 with L=20 fb^{-1}
  - Assuming 10% uncertainty on background (CLs) → L=40 fb^{-1}

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



WWll→4l 2ν

- Away from the alignment limit, $b\bar{b}ll$ will be dominated by A→Zh but altogether quite low due to the small BR(Zh)
- WWll is one of the most promising channels to look in this limit (tri-Z →4l 2j has also been shown to be powerful)
- Main background is ZZ → 4l + rare: Ztt, Zh and ZWW
- Employ similar selection to $b\bar{b}ll$ analysis
  - 4 isolated leptons in SF pairs; $|\eta| < 2.5(2.7)$ for electrons (muons)
  - $P_T^1>40$ GeV, $P_T^{2,3,4}>20$ GeV
  - Require one pair to reconstruct the Z mass as in $b\bar{b}ll$
- No further selection required
  - Other handles such as ΔR or a Z-veto on the remaining lepton pair could reduce the background more but were deemed unnecessary

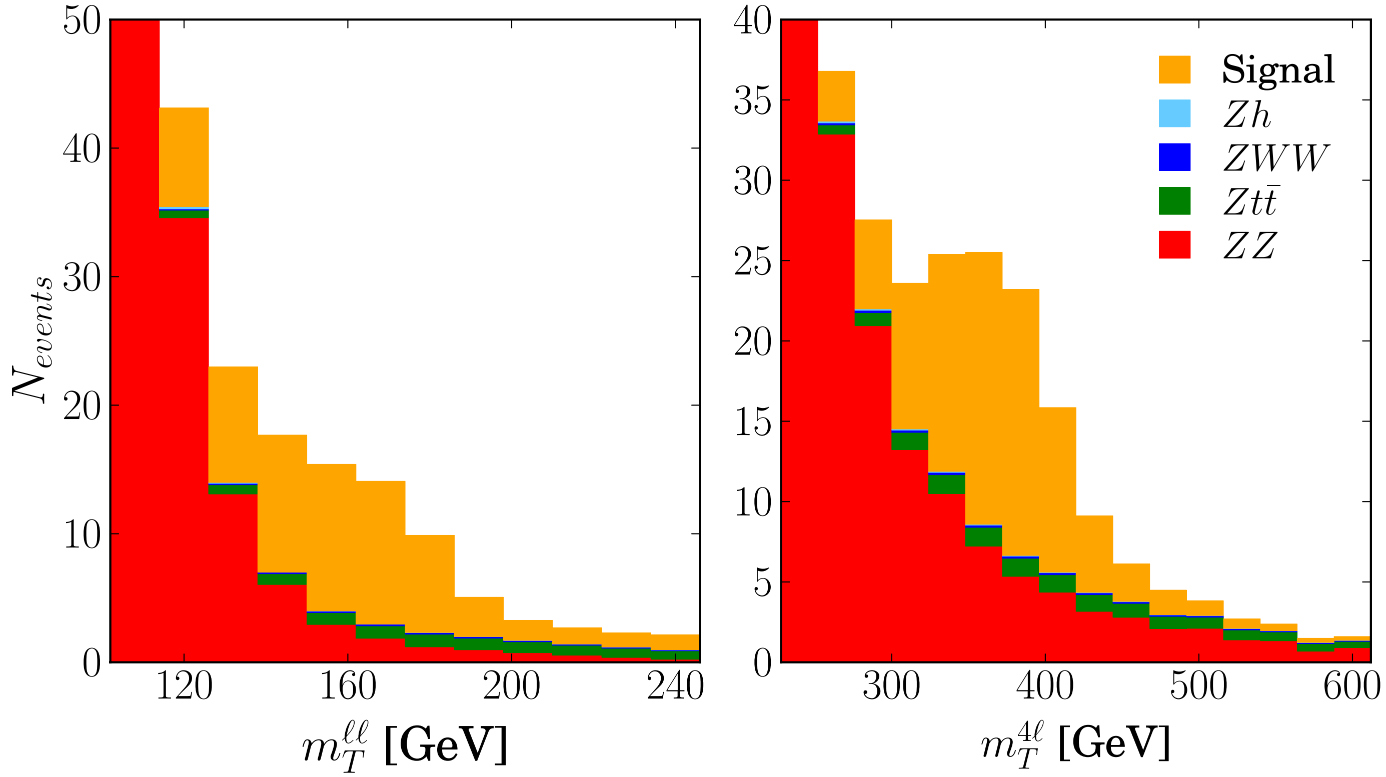
WWll→4l 2ν

- Signal - 0.93, fb ZZ- 5.6 fb, all rare - 0.25 fb post selection
- Since there are two neutrinos, some information about their momenta (even transverse) cannot be fully deduced
  - Construct transverse mass variables that should be sensitive to the two scalar masses

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

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

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



$WWll \rightarrow 4l\ 2\nu$

- A single cut on $m^{4l} > 260$ GeV allows for signal extraction
- Signal 0.88 fb vs bkg 1.39 fb
- Statistics-only significance of 5 is reached with 60 fb^{-1} of data
- Incorporating the 10% background uncertainty increases this to 200 fb^{-1}
- Very low background situation
  - May be prudent to investigate reducible backgrounds further
- Overall promising prospects at the early stages of the new LHC run

Conclusion

- The 2HDM is a simple, testable extension of the SM that has the capacity to provide the strong first order phase transition required by EW baryogenesis
- Explored the parameter space employing current experimental and theoretical constraints finding that a strong EWPT prefers
  - SM like Higgs + Heavy A_0,
  - Large mass splitting ~ v between A_0 and H_0
- This points to a very particular type of 2HDM with a 'smoking gun' signature of $A_0 \rightarrow ZH_0$
- Described a detector-level analysis of two possible final states preferred in and out of alignment
  - Simple 'cut and count' method
  - Allows for discovery at the early stages of LHC run 2

Outlook

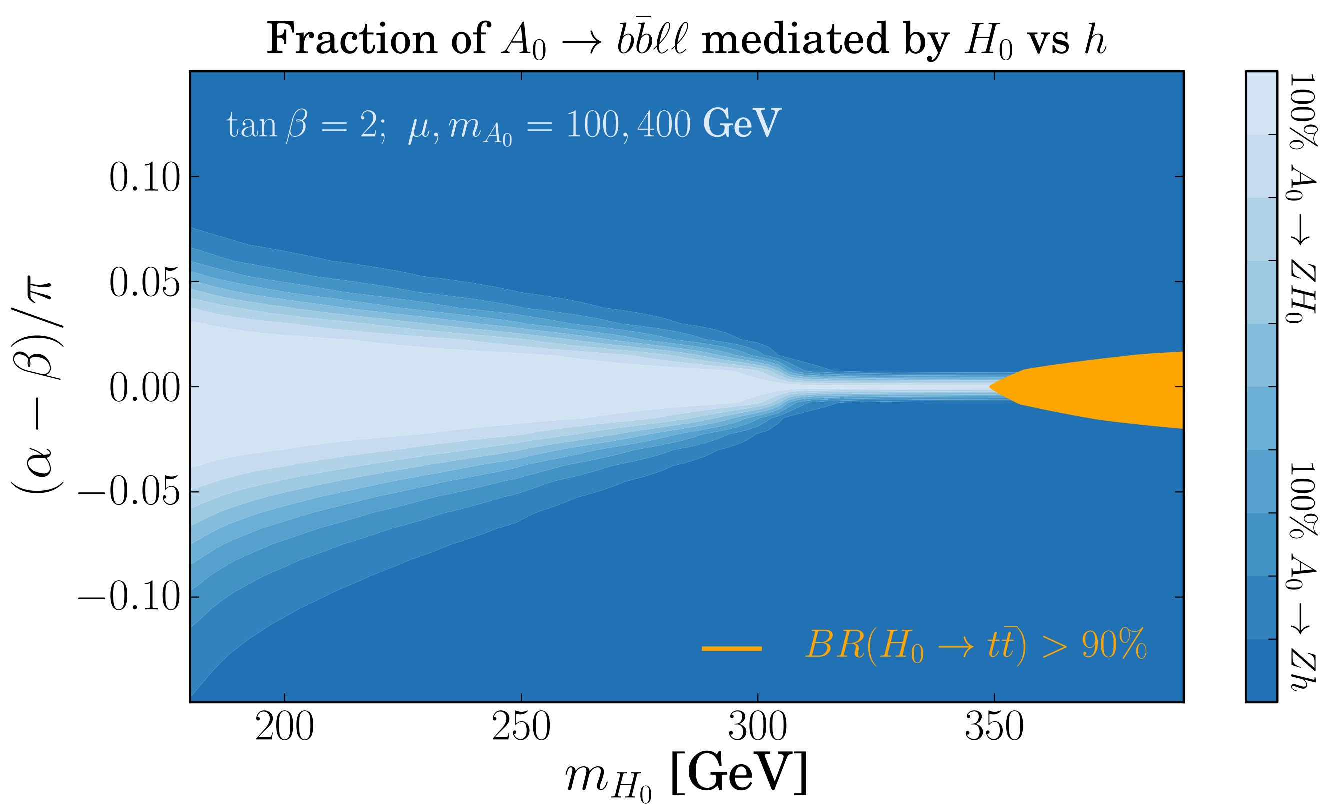
- A nice connection between cosmology and testable LHC phenomenology
  - These results motivate taking this search seriously at the LHC
- We aim to extend this work beyond the analysis of two benchmark points
  - Aim for the LHC sensitivity in the m_A-m_H plane
- Further investigate the sensitivity of current data to this model
  - Fully reinterpret the light Higgs analyses to obtain extra constraints on parameter space
  - 4 lepton + MET (SUSY)
- Include the $A_0 \to H^{\pm}W^{\mp}$ channel
- Include CP violation
- Two-loop thermal effective potential

Thank you

Experimental limits

- EW precision observables
  - Additional $SU(2)_L$ doublets automatically preserve the custodial symmetry of the EW vacuum
  - W/Z mass relationship preserved at tree level
  - At loop level, mass splittings between the scalar states induce contributions to the T parameter
- FCNCs
  - Strongest bounds come from $B \to X_S \gamma$ and B_0-$\overline{B}_0$ mixing
  - Constrains the $m_{H^\pm}$, $\tan\beta$ plane (Type II: $m_{H^\pm} > 360$ GeV)
- LHC
  - Measurements of the properties of the newly observed Higgs will constrain the mixing angles
  - Searches of additional scalar states will also provide bounds dependent on the full set of parameters

$b\bar{b}ll$ final state



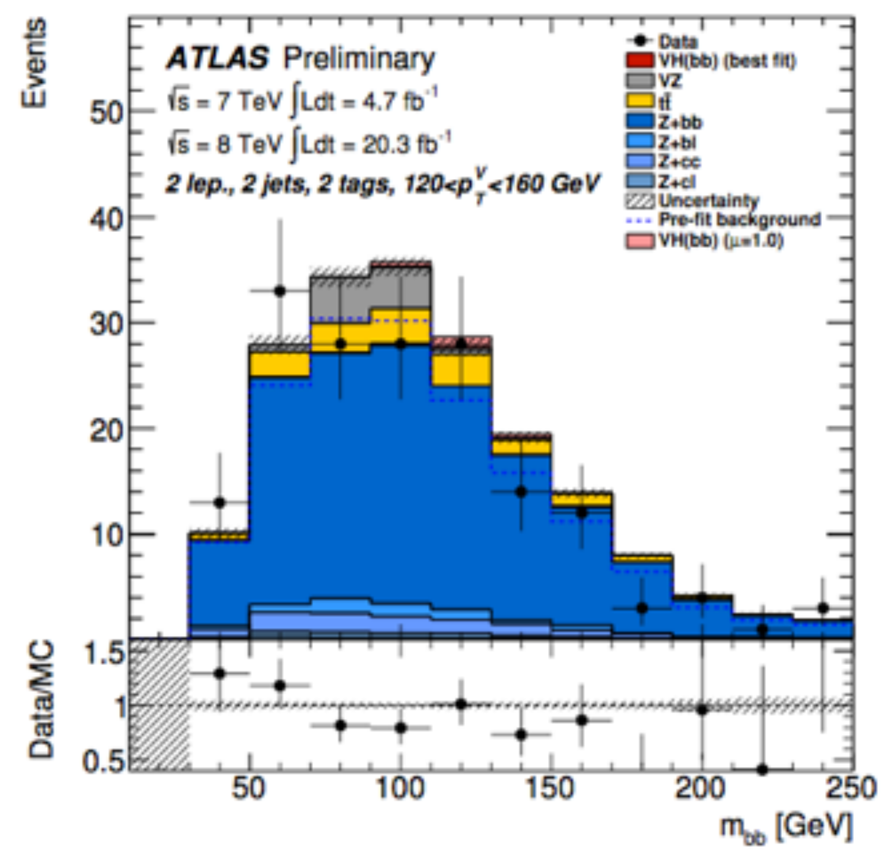
- Both SM Higgs production and $A_0 \to Zh$ can have same final states
  - For the SM, associated ≪ resonant production
  - In the regions of interest $A_0 \to Zh$ is suppressed by a combination of the pseudoscalar and SM Higgs BRs
  - An initial contamination of < few % can be discarded considering that our signal region targets heavier objects

LHC analysis

- Higgs properties are being measured in a variety of production mechanisms: current data may already be sensitive to the signatures of this model
- Considered current 8 TeV LHC data in one analysis for bbll
- At 14 TeV, determined the required luminosity to achieve a statistical significance of 5
  - Statistical uncertainties only: $S/\sqrt{(S+B)}$
  - Assuming a 10% total uncertainty on the background expectation, marginalised over as a nuisance parameter using the CLs method

$A_0 \rightarrow ZH_0 \rightarrow b\bar{b}ll$

- Search for the $b\bar{b}$ decay mode of the SM Higgs produced in association with a W or Z *[ATLAS-CONF-2013-079]*
  - Defines signal regions according to number of leptons, additional jets
  - Splits them according to the p_T of the ll system (no $m_{b\bar{b}}$ requirement)
  - Global fit extracts the background normalisations and signal strength of a SM Higgs with mass 125 GeV
- p_T^{ll} in our signal set by m_{A_0}-m_{H_0}
  - Heavy A_0 means the signal will predominantly populate the boosted kinematical region
  - Low backgrounds and SM Higgs expectation
  - Reproducing the analysis and using the most powerful signal region gives a statistical-only significance close to 3



$A_0 \to ZH_0 \to b\bar{b}ll$