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

G. C. Dorsch, S. J. Huber, K. Mimasu, J. M. No

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University of Sussex

Overview

- Introduction/Motivation
  - Strongly first order electroweak phase transition (EWPT) and Baryogenesis
  - 2HDM as a viable candidate to provide this EWPT
- Study
  - 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
  - Very promising discovery prospects, both with current data and the upcoming run
- Conclusion & Outlook

EW phase transition

- The SM 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 ✗
- A strongly first order PT is a requirement for EW baryogenesis
  - The 2HDM is able to provide this, in adding new bosonic degrees of freedom which contribute to the thermal effective potential in a way that is conducive to a strong first order EWPT
  - New sources of CP violation
  - A simple extension to the scalar sector of the SM, testable at the LHC
  - Provides a connection with cosmology and collider physics

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

The 2HDM

- We consider the softly broken, Z_2-symmetric 2HDM
- For simplicity, we do not consider CP-violation (future work)
- Introduces along with the SM Higgs boson, h:
  - A pair of charged scalars, $H^\pm$
  - An additional CP-even and CP-odd neutral scalar, H_0 and A_0
- 8 free parameters in the scalar potential
  - Trading for physical masses and mixing angles leaves 6
  - m_{H_0}, m_{A_0}, $m_{H^\pm}$, μ, α, $\tan\beta$
- Gauge interactions of the scalar sector are characterised by the quantities $\sin(\alpha-\beta)$ and $\cos(\alpha-\beta)$
  - Convention: $\alpha-\beta=0$ means light Higgs is SM-like
  - Differs from usual definition by $\pi/2$

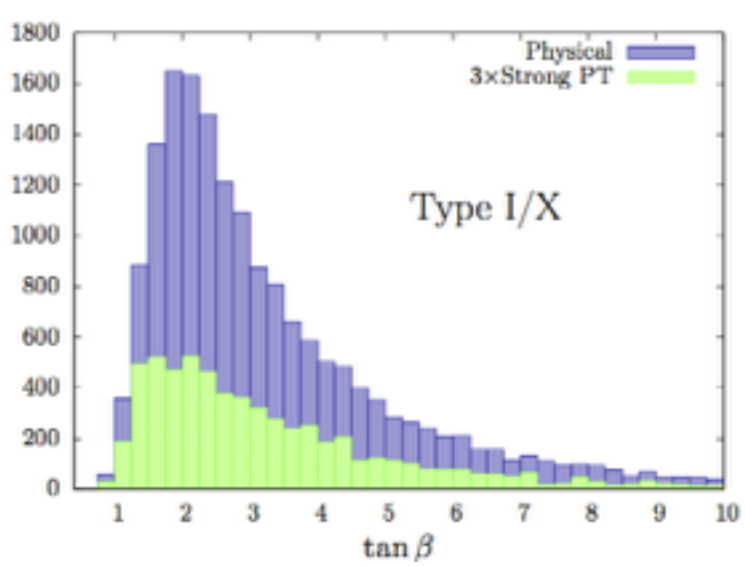
Type	u_R	d_R	e_R
I	$+$	$+$	$+$
II	$+$	$-$	$-$
X	$+$	$+$	$-$
Y	$+$	$-$	$+$

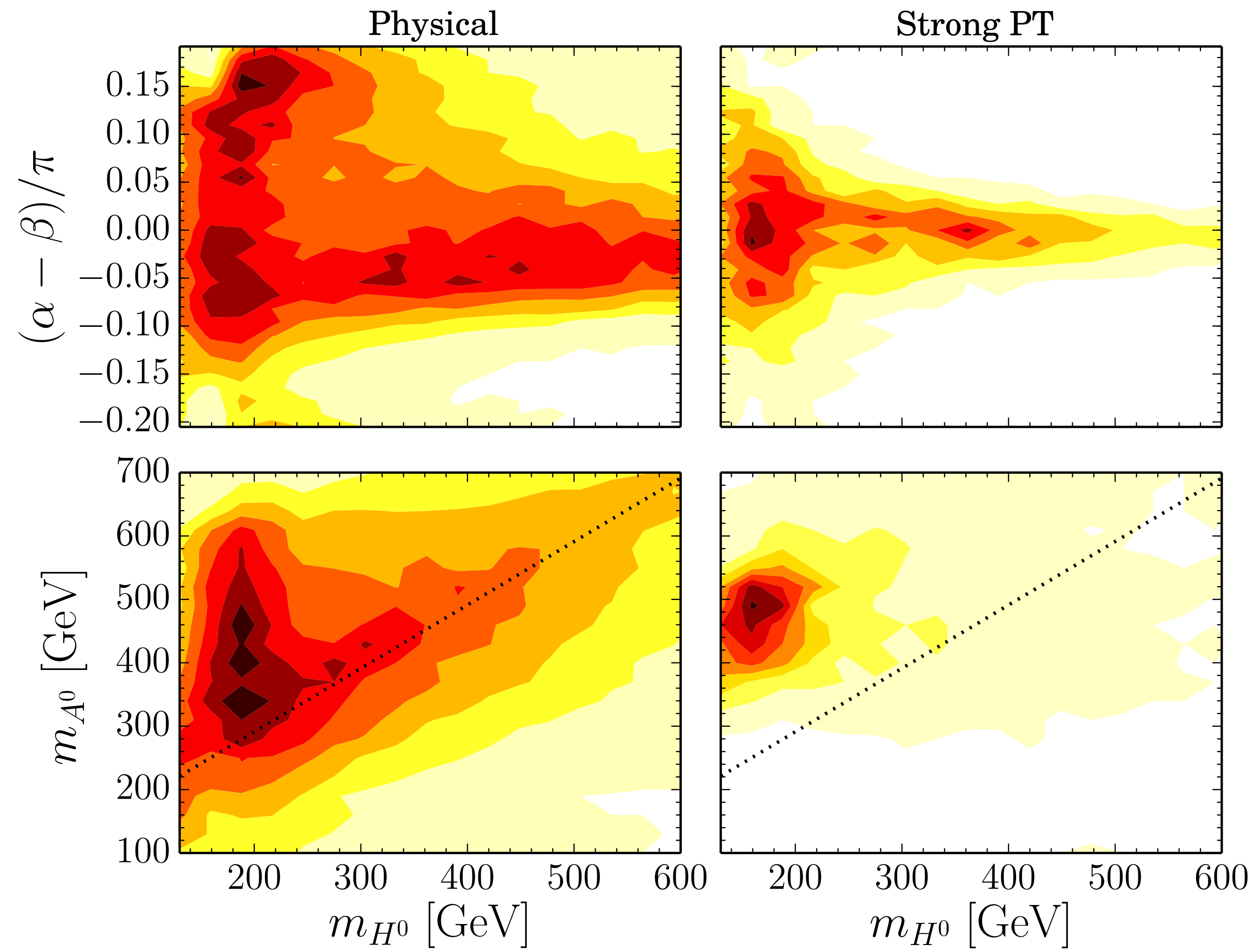
2HDM and the EWPT

- We focus on the type I 2HDM
  - All fermions couple to the same doublet
  - EWPT is insensitive to the type of 2HDM since, by convention, the top quark always couples to the same doublet and is the only fermion with appreciable couplings to the scalar sector
  - No lower bound on the charged Higgs mass from flavour constraints
  - Only experimental constraints will differ between model types
- Study of the characteristics of the EWPT in 2HDM scenarios
  - The parameter space is large enough to motivate a Monte Carlo scan
  - Numerical code interfaced with 2HDMC and HiggsBounds
    - Select points that satisfy tree-level unitarity, perturbativity, EW precision constraints and collider bounds
    - Stability of the potential is checked at 1 loop: EW minimum is the global minimum
  - Flavour constraints from $b \to s\gamma$ taken into account
  - We also impose 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 $v_C / T_C > 1$
- Physical points vs strong PT
  - Prefers SM-like light Higgs
  - Low α-β and moderate tanβ
  - Mass splitting ~ v between A_0 and H_0
  - m_{A_0} > 300 GeV





2HDM and the EWPT

- Preference for a SM-like Higgs is naturally less constrained given the present outcome of measurements of the Higgs properties
  - As m_{H0} 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

- Requiring a strong first order EWPT points to a very different kind of 2HDM than commonly considered
  - Typical analyses and studies tend to be SUSY-oriented
  - The two dimensionful parameters, v and μ, set the scale
  - 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 to strongly coupled theories as UV completions of such a scenario

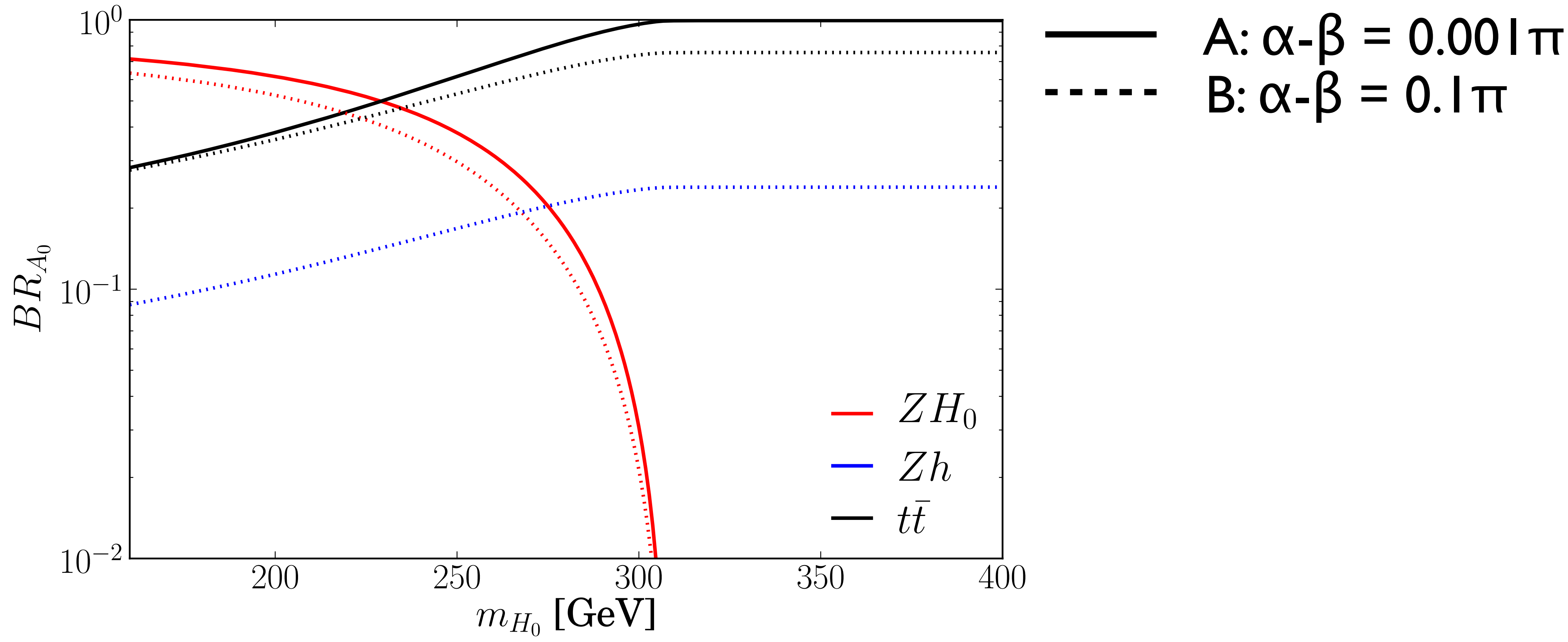
Pheno consequences

- 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 (some constraints from τs)
  - 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 kinematically forbidden in models such as SUSY where mass splittings originate from gauge couplings and do not exceed $\sim m_Z$

Pheno consequences

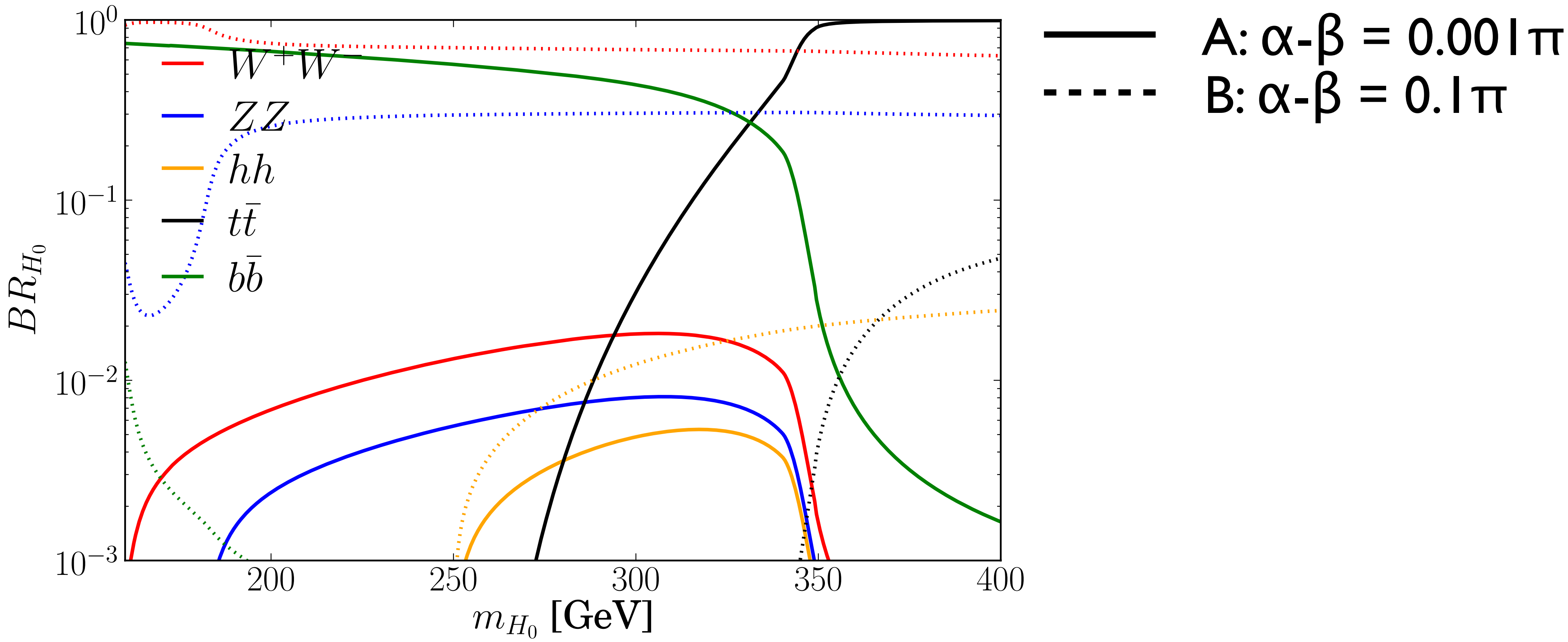
- Heavy pseudoscalar points to $A_0 \rightarrow ZH_0$
  - Coupling is not affected in the alignment limit ~ $\cos(\alpha-\beta)$
  - In contrast, $A_0 \rightarrow Zh$ vanishes, like gauge boson couplings to H_0 ~ $\sin(\alpha-\beta)$
- Determine the LHC discovery prospects of this type of model
  - Choose 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, μ=100 [GeV]
  - $\tan\beta$=2 controls the $gg \rightarrow A_0$ 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)
  - Leptons are nice and clean, with lower backgrounds than hadronic channels
  - Require 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@MLO
  - 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
- 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 20% total uncertainty on the background expectation, marginalised over as a nuisance parameter

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

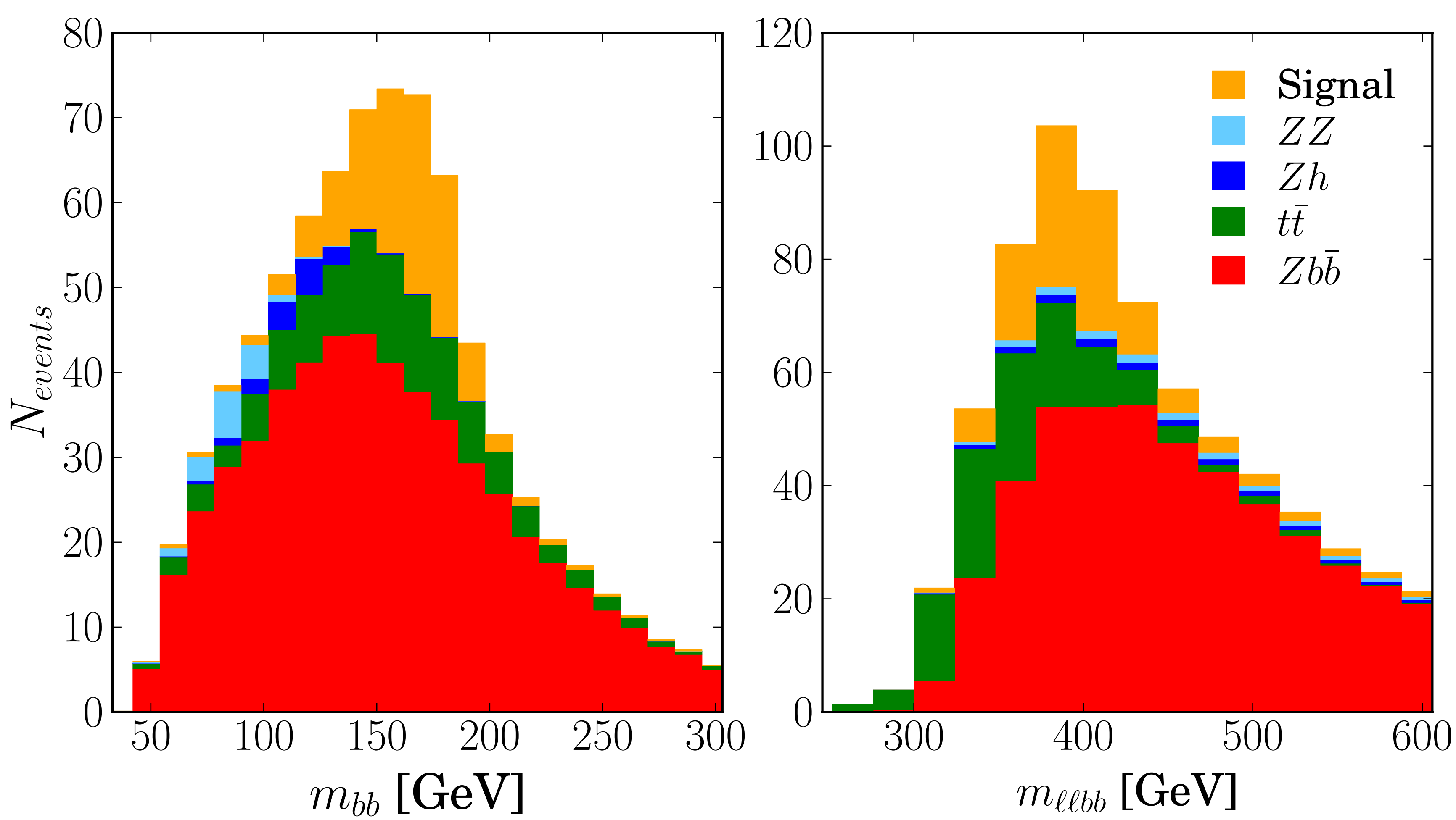
- Given the potential sensitivity already at 7 and 8 TeV, one should expect that the 13 TeV run be promising
  [B. Coleppa, F. Kling, S.Su; arXiv:1404.1922]
- Main irreducible backgrounds are $Zb\bar{b}$, $t\bar{t}$, ZZ and Zh
- Straightforward signal selection
  - Anti-k_T jets with distance parameter R=0.6
  - 2 b-tagged jets; $|\eta| < 2.5$
  - 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
- Kinematical cuts
  - Leptons should reconstruct m_Z
  - Cuts on total $H_T = \Sigma P_T$
  - $\Delta R^2 = \Delta\eta^2 + \Delta\Phi^2$ between $b\bar{b}$ and ll

	Signal	$t\bar{t}$	$Z\,b\bar{b}$	ZZ	$Z\,h$
k-factor:	1.6	1.5	1.4	-	-
Event selection	14.6	1578	424	7.3	2.7
$80 < m_{\ell\ell} < 100$ GeV	13.1	240	388	6.6	2.5
$H_T^{bb} > 150$ GeV $H_T^{\ell\ell bb} > 280$ 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

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

- 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)±30 GeV; m_{bbll} within (m_{A0} - 20)±40 GeV
  - Statistical-only significance of 5 with L=20 fb^{-1}
  - Assuming 20% uncertainty on background expectation increases L to 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 $b\bar{b}ll$
- LO cross sections for signal, ZZ and combined rare backgrounds are 0.93, 5.6 and 0.25 fb after selection
- No further selection required
  - Other variables such as ΔR or a Z-veto on the remaining lepton pair could reduce the background more but were deemed unnecessary

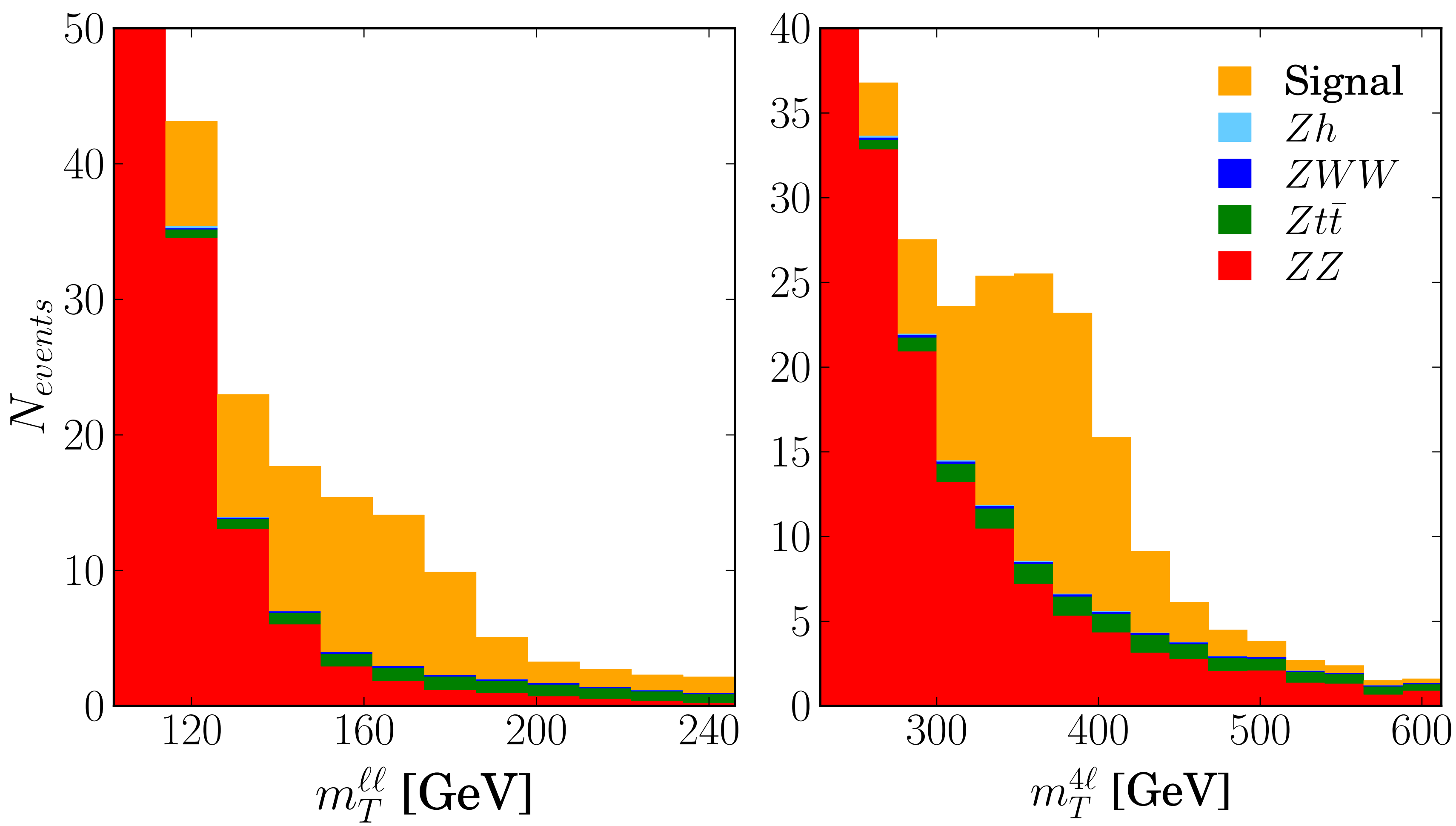
WWll→4l 2ν

- 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→4l 2ν

- A single cut on m^{4l} > 260 GeV allows for signal extraction
- Statistics-only significance of 5 is reached with 40 fb^{-1} of data
- Incorporating the 20% background uncertainty increases this to 60 fb^{-1}
- Almost background-free situation
  - May be prudent to investigate reducible backgrounds further
- Overall promising prospects at the very early stages of the new LHC run

Conclusion

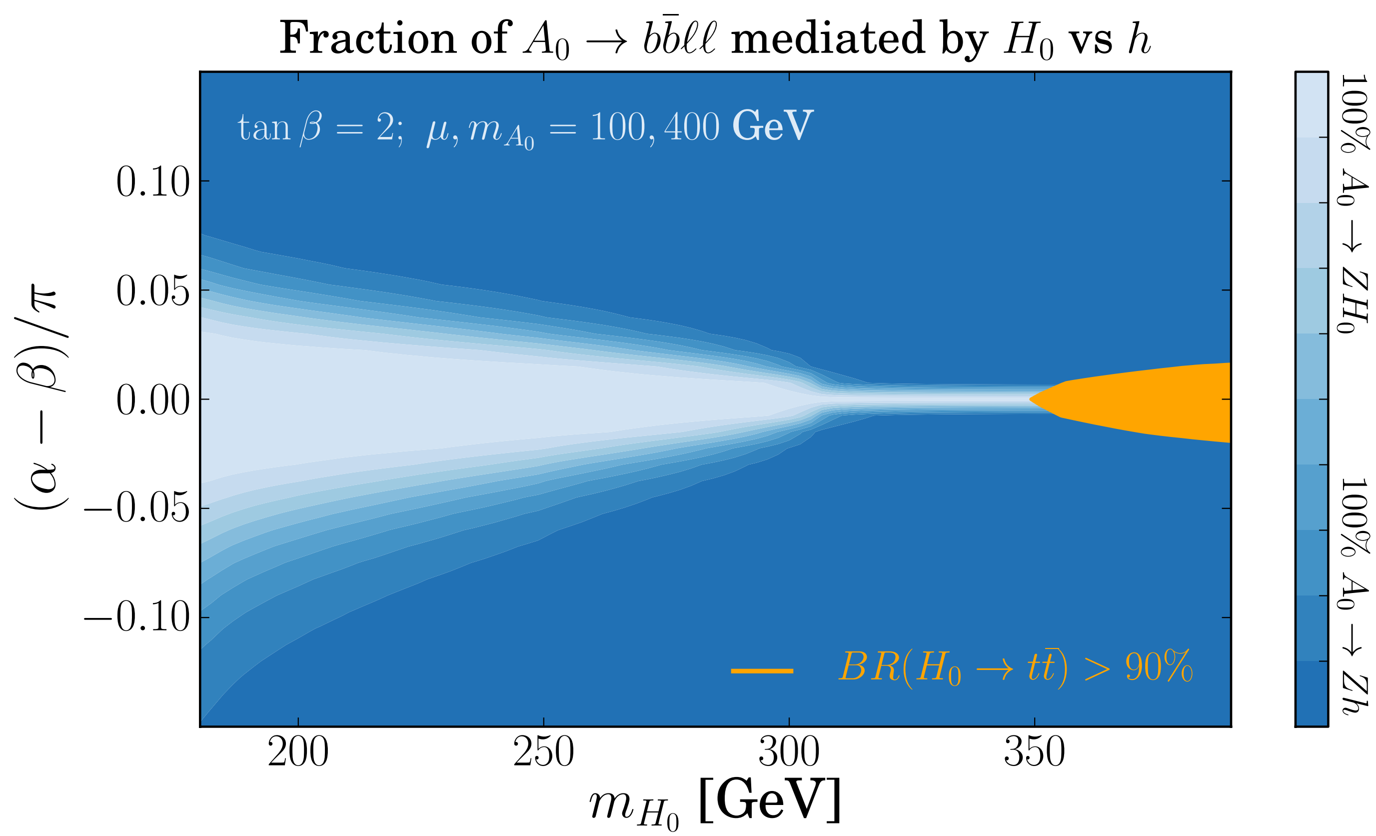
- The 2HDM is a simple, testable extension of the SM that has the capacity to provide the strong first order phase transition required by EW baryogenesis
- Explored the parameter space employing current experimental and theoretical constraints finding that a strong EWPT prefers
  - Heavy A_0
  - SM like Higgs
  - 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 $A_0 \rightarrow ZH_0$
- Current data could already be sensitive to this signature
- Described a detailed detector-level analysis of two possible final states preferred by a pair of benchmark points
  - Simple 'cut and count' method
  - Allows for discovery at the very early stages of the 14 TeV LHC run

Outlook

- These results very much motivate taking this search seriously at the LHC
- We aim to extend this work beyond the analysis of two benchmark points
- Further investigate the sensitivity of current data to this model
  - Reinterpret the light Higgs searches
- Include the $A_0 \to H^{\pm}W^{\mp}$ channel
- Include CP violation

Thank you

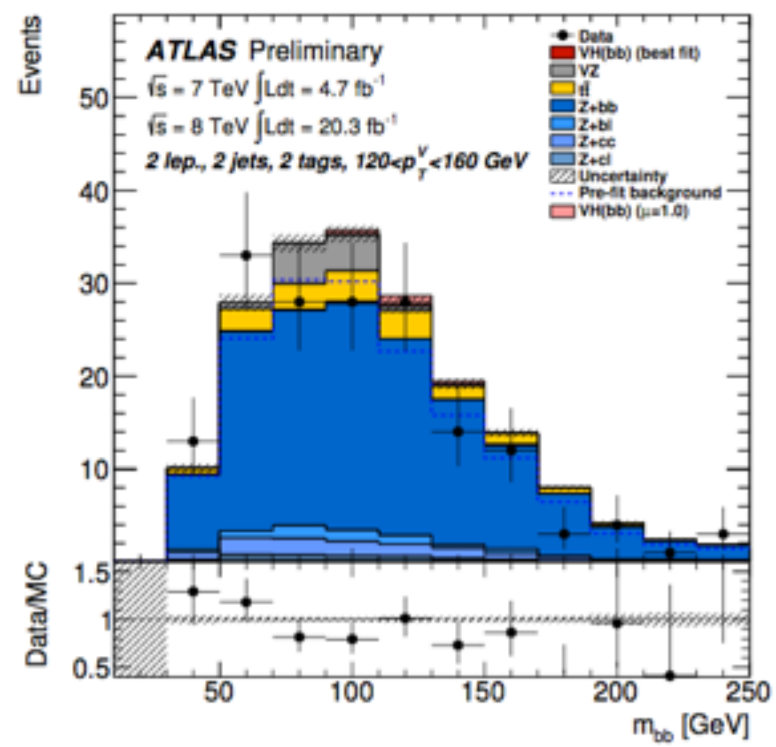
H_0 decay modes



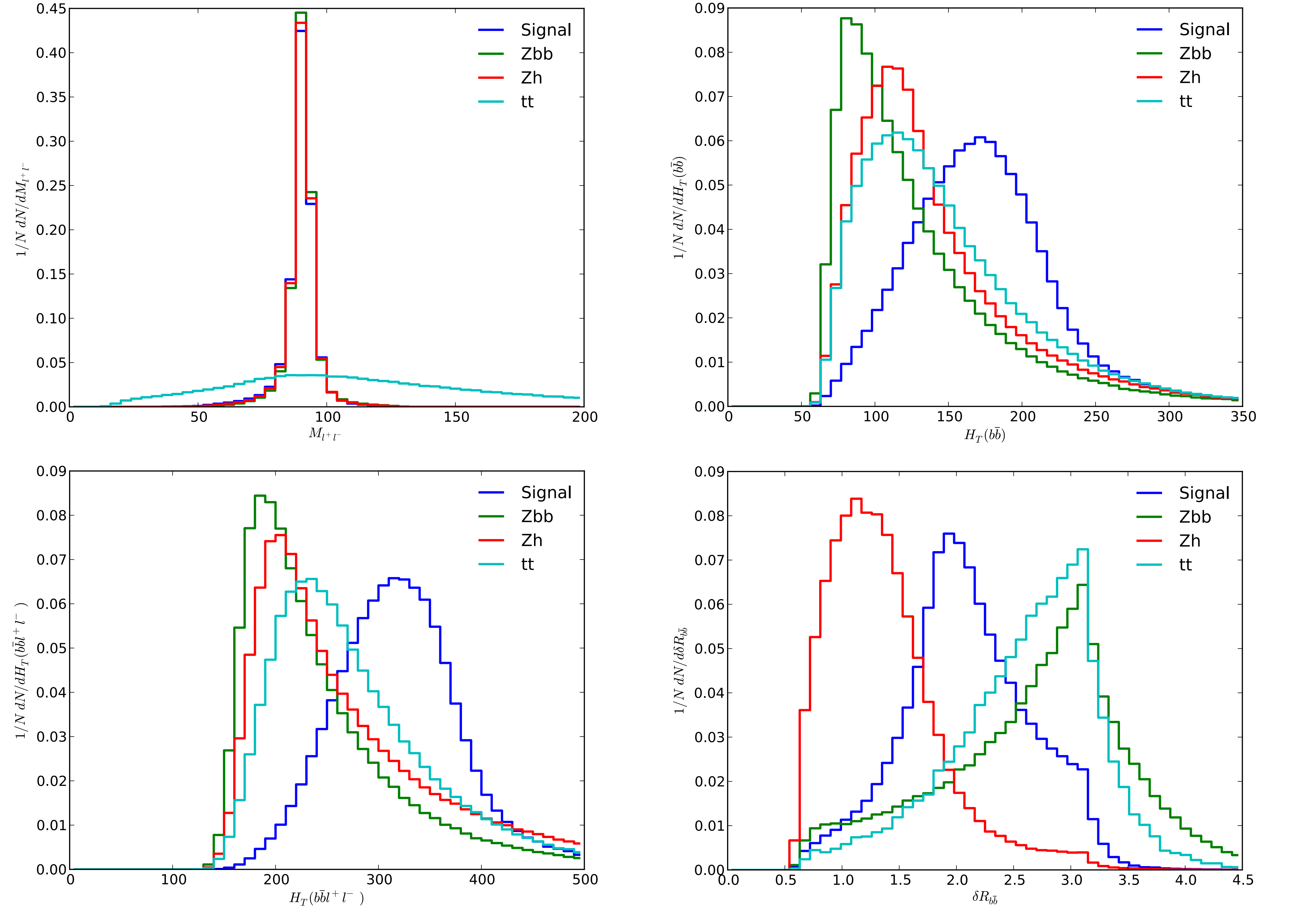
- Both SM Higgs production and $A_0 \to Zh$ can have same final states
  - Associated ≪ resonant production
  - In the regions of interest this signal will be suppressed by a combination of the pseudoscalar and SM Higgs BRs
  - An initial contamination of < few % can be discarded considering that our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

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

- Higgs properties are being measured in a variety of production mechanisms: current data may already be sensitive to the signatures of this model
- In particular, a 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 $b\bar{b}$ 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^{bb} in our signal set by m_{A0}-m_{H0}
  - 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
  - Further investigation warranted!



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



Experimental limits

- EW precision observables
  - Additional scalar $SU(2)_L$ doublets (and trivially singlets) automatically preserve the custodial symmetry of the EW vacuum
  - At tree level, the relationship between the W and Z masses is preserved
  - At loop level, mass splittings between the scalar states induce contributions that can be constrained
  - It turns out that the Peskin-Takeuchi T parameter is the most strongly constraining of these
- FCNCs
  - Strongest bounds come from $B \to X_S \gamma$ and B_0-$\overline{B}_0$ mixing
  - Leptonic couplings do not play a role, grouping types I/X and II/Y
  - 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 parameters α and $\tan\beta$
  - Searches of additional scalar states will also provide bounds dependent on the full set of parameters

The 2HDM

- Minimal, 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
  - 2HDM = addition of one $SU(2)_L$ scalar doublet
  - Arises in well known BSM scenarios (i.e. MSSM, composite Higgs)
- Adding a new scalar doublet leads to a generalised scalar potential + Yukawa sector with many new parameters where both doublets can share the role of EW symmetry breaking

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

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

The 2HDM

- Extended Yukawa interactions can lead to potentially dangerous FCNCs at tree-level
  - The diagonalisation of the mass matrix after EW symmetry breaking does not permit the simultaneous diagonalisation of the two Yukawa matrices
  - The simplest solution is to constrain the model by a Z_2 parity, limiting each fermion type (u,d,e) to have Yukawa interactions with one of the two doublets: $\Phi_1 \to -\Phi_1$; $\Phi_2 \to \Phi_2$
- Presence of complex parameters and phases (λ_5 ,λ_6, λ_7,Φ) allows for additional explicit CP violation
- CP can also be spontaneously violated by a relative phase between the vacuum expectation values of the two fields
- The μ, λ_6 and λ_7 terms in V_s explicitly violate the Z_2 symmetry
  - Considering the CP conserving case to start with, for simplicity and only allowing for the parity to be softly broken i.e. by a dimensionful parameter sets λ_6, λ_7 and Φ to 0
  - The CP violating case is certainly interesting from a cosmological and phenomenological point of view but is left for future work

The 2HDM

- CP conserving, softly broken Z_2 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 vevs
  - Can be interpreted as a mixing angle rotating to a basis where one field behaves like the SM doublet (v = 174 GeV)

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v\cos\beta \end{pmatrix}; \quad \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v\sin\beta \end{pmatrix} \quad \xrightarrow{\beta} \quad \langle\Phi_1'\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}; \quad \langle\Phi_2'\rangle = 0$$

- 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