Probing the EW Phase Transition via Exotic Higgs Decays at LHC

J.M.N, M. Ramsey-Musolf, arXiv:1310.6035

G. Dorsch, S. Huber, K. Mimasu, J.M.N, to appear.

Jose Miguel No (Sussex U.)

Unlocking the Higgs Portal
Amherst, UMass, May 2nd 2014

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The EW Symmetry Breaking Agenda:

What is the Specific Nature of the EWSB Sector?

- ⇨ Anomalous/SM-like Higgs Couplings?
- ⇨ Elementary/Composite Higgs?
- ⇨ One/Several Higgs Boson(s)?
- ⇨ Measurement of Higgs Potential?

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⇨ Cosmology of EWSB?

Sakharov Conditions for Baryogenesis:

B Violation (Sphalerons)

C, CP Violation

Departure from Equilibrium ⇨ The EW Phase Transition

EW Scale Origin of Matter-Antimatter Asymmetry in Universe?

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Sakharov Conditions *for* *Baryogenesis*:

B Violation (Sphalerons)
C, CP Violation
Departure from Equilibrium ⇨ The EW Phase Transition

In the SM **(** m_h **= 125 GeV)** EW Phase Transition Smooth CrossOver

K. Kajantie, M. Laine, K. Rummukainen, M. Shaposhnikov, Phys. Rev. Lett. ***77*** *(1996) 2887*

1^{st} Order EW Phase Transition possible in Extended EWSB Sectors

HowTo Probe Nature of EW Phase Transition in EWSB Sectors?

HOWTO Probe Nature of EW Phase Transition in EWSB Sectors?

Extended

at LHC

What Can Collider Searches Tell us about the EW Phase Transition?

HowTo Probe Nature of EW Phase Transition in EWSB Sectors?

Extended

at LHC

What Can the EW Phase Transition Tell us about Collider Searches?

❶ Identify (possible) Patterns Leading to 1st Order EW Phase Transition

❷ Extract *LHC* signatures Characteristic of such Patterns

"To find it, you need to know where to look for"

HowTo Develop a Search Strategy for Extended EWSB Sectors with a Strong EW Phase Transition at LHC?

Singlet - Extended EWSB Scalar Sectors

➔ *Scalar Higgs Portal*

R. Schabinger, J. Wells, Phys. Rev. ***D72*** *(2005) 093007*
B. Patt, F. Wilczek, hep-ph/0605188

$|H|^2$ unique Lorentz & Gauge Invariant term w. $d<4$

SM + Real Scalar Singlet **S**

$$V(H,S) = -\mu^2 \, |H|^2 + \lambda \, |H|^4 + \frac{b_2}{2} S^2 + \frac{b_4}{4} S^4 + \frac{a_1}{2} S|H|^2 + \frac{a_2}{2} S^2|H|^2 + \frac{b_3}{3} S^3$$

Scenarios w. Scalar Singlets can Lead to Strong 1st Order EW Phase Transition

S. Profumo, M. Ramsey-Musolf, G. Shaughnessy, JHEP ***0708*** *(2007) 010*
V. Barger, P. Langacker, M. McCaskey, M. Ramsey-Musolf, G. Shaughnessy, Phys. Rev. ***D79*** *(2009) 015018*
J. R. Espinosa, T. Konstandin, J. M. N, M. Quiros, Phys. Rev. ***D78*** *(2008) 123528*
J. R. Espinosa, T. Konstandin, F. Riva, Nucl. Phys. ***B854*** *(2012) 592*

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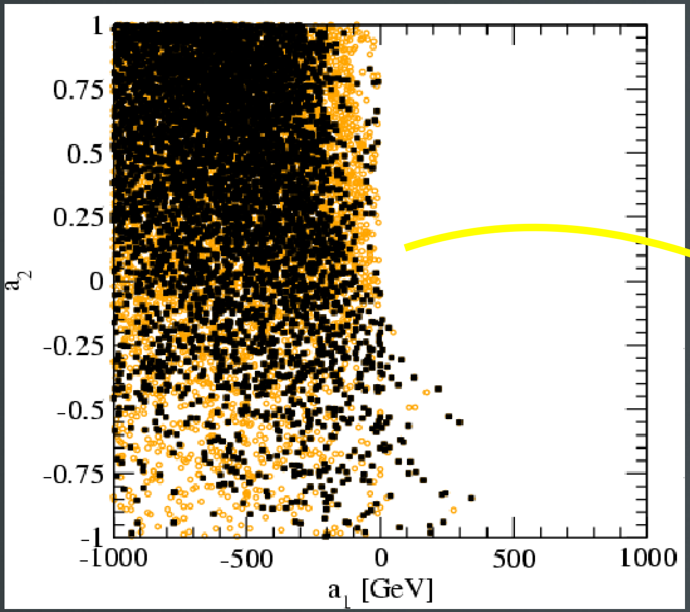
Singlet-Doublet Mixing

h_1 (m_1 = 125 GeV) h_2 (m_2) θ_m



A Strong EW Phase Transition strongly prefers $a_1 < 0$ (Mixing)

*S. Profumo, M. Ramsey-Musolf, G. Shaughnessy, JHEP **0708** (2007) 010*

Singlet – Extended EWSB Scalar Sectors

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HowTo Map the EW Phase Transition to LHC?

Singlet - Extended EWSB Scalar Sectors

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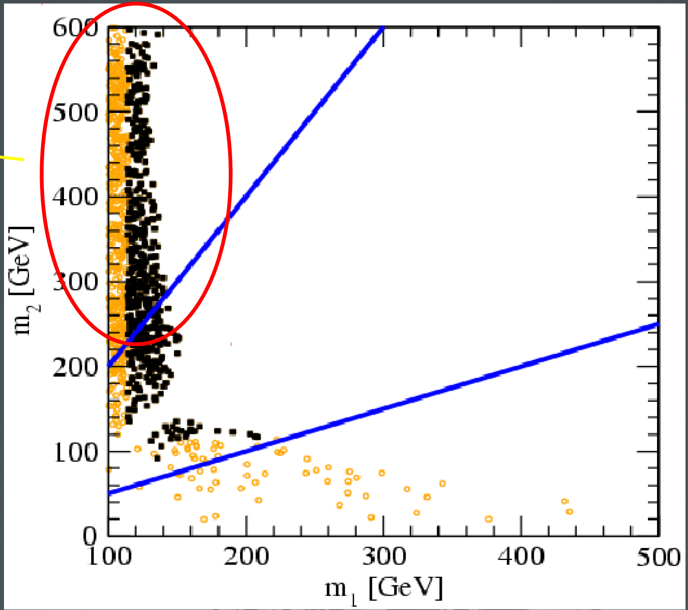


Decay Channel $h_2 \rightarrow h_1\, h_1$

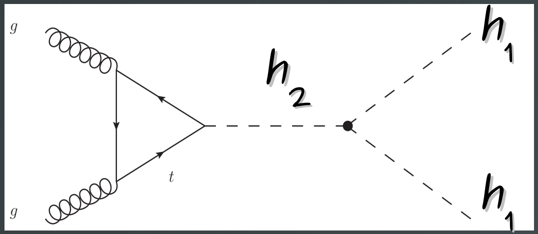
$$\lambda_{211} = b_3 s_\theta^2 c_\theta + a_2 v s_\theta (c_\theta^2 - s_\theta^2/2) + \frac{a_1}{4} c_\theta (c_\theta^2 - 2s_\theta^2) - 3\lambda v c_\theta^2 s_\theta$$

S. Profumo, M. Ramsey-Musolf, G. Shaughnessy, JHEP ***0708*** *(2007) 010*

Singlet - Extended EWSB Scalar Sectors

125 GeV (Resonant) Higgs Pair Production at LHC

M. Dolan, C. Englert, M. Spannowsky, Phys. Rev. ***D87*** *(2013) 5, 055002*
J. Cao, Z. Heng, L. Shang, P. Wan, J. M. Yang, JHEP ***1304*** *(2013) 134*
J. M. N, M. Ramsey-Musolf, arXiv:1310.6035 [hep-ph].



Potential Discovery Mode for h_2

(if $h_2 \rightarrow Z\,Z$ Suppressed)

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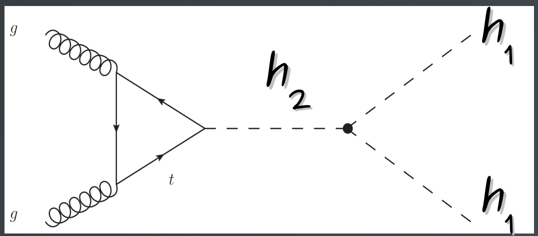
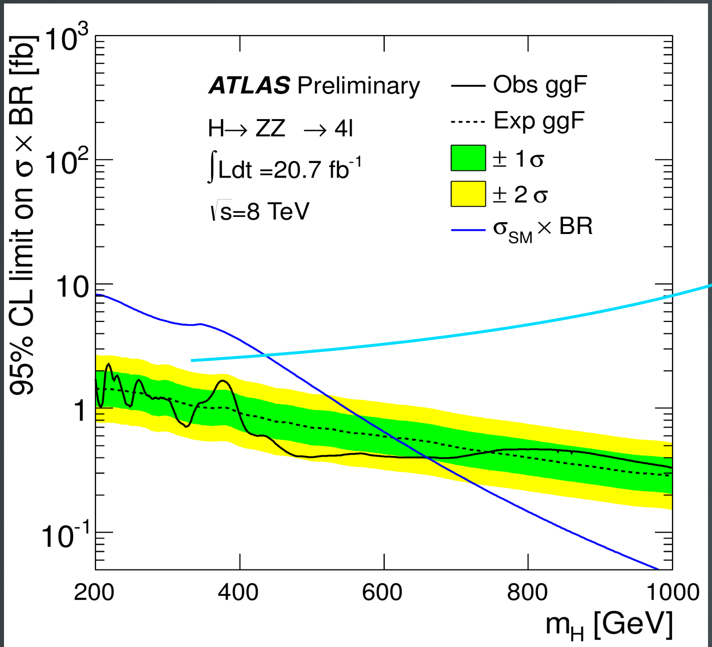


Potential Discovery Mode for h_2

(if $h_2 \to Z\,Z$ Suppressed)



ATLAS-CONF-2013-013

Possible to Evade Direct Searches:

⇨ Suppressed Production (Singlet Admixture)

⇨ Suppressed $Br(h_2 \to Z\,Z)$

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Constraints:

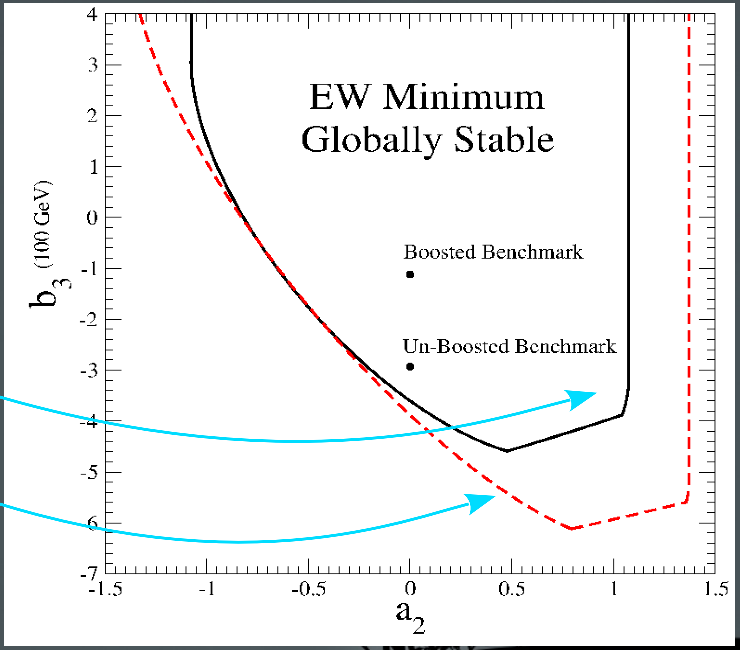
- ➔ *125 GeV Higgs Couplings* (LHC) → $(C_\theta)^2 \geq 0.66$ at 95% C.L.
- ➔ *Direct Heavy Higgs Searches* (LHC)
- ➔ *EW Precision Observables*

See Peter Winslow's Talk

- ➔ *Vacuum Stability*

$(C_\theta)^2 = 0.66$, $m_2 = 270$ GeV , $b_4 = 1$

$(C_\theta)^2 = 0.66$, $m_2 = 370$ GeV , $b_4 = 1$



Searching for Resonant Di-Higgs at LHC

$$p\,p \rightarrow h_2 \rightarrow h_1\, h_1 \rightarrow \bar{b}b\tau^+\tau^-$$

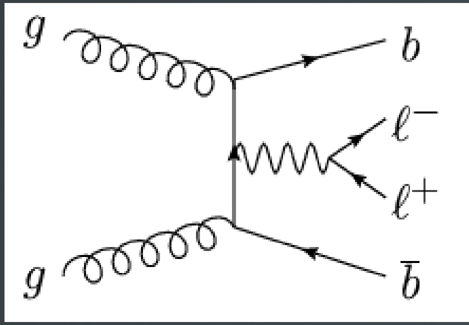
Classify according to Leptonic/Hadronic Nature of each τ*-Decay*

Benchmark Scenarios:

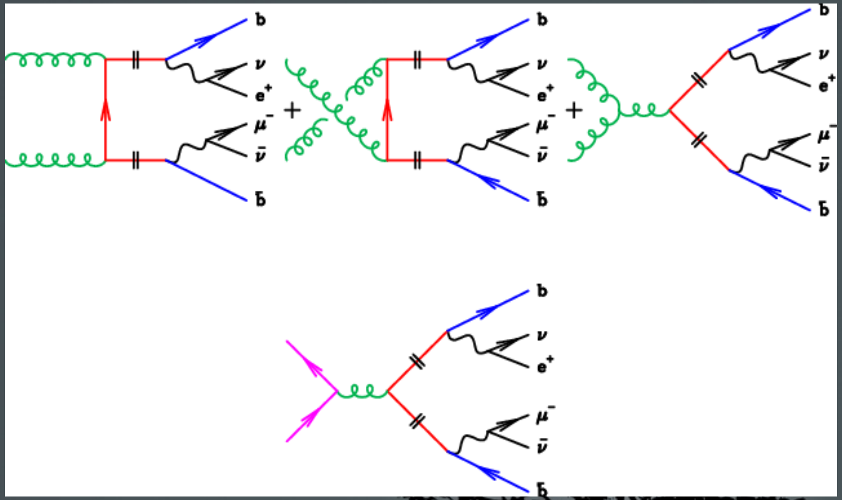
- Un-Boosted: $(c_\theta)^2 = 0.66$, $m_2 = 270$ GeV , $\lambda_{211} = 325$ GeV
- Boosted: $(c_\theta)^2 = 0.66$, $m_2 = 370$ GeV , $\lambda_{211} = 325$ GeV

Main SM Backgrounds:

$Z\,\bar{b}b$



$\bar{t}\,t$



Searching for Resonant Di-Higgs at LHC

$$p\, p \rightarrow h_2 \rightarrow h_1\, h_1 \rightarrow \bar{b}b\tau^+\tau^-$$

Reconstructing both 125 GeV Higgses → m_{bb} $m_{\tau\tau}$

... but τ-Decay involves missing Energy

$m_{\tau\tau}$ Reconstruction Algorithms:

⇨ Collinear approximation

R. Ellis, I. Hinchliffe, M. Soldate, J. J. van der Bij, Nucl. Phys. **B297** (1988) 221.

$$x_{1,2} = \frac{p_{1,2}^{\rm vis}}{p_{1,2}^{\rm vis} + p_{1,2}^{\rm mis}}$$

$$p_1^{\rm mis} = \frac{\sin(\phi_2^{\rm vis}) E_{Tx}^{\rm miss} - \cos(\phi_2^{\rm vis}) E_{Ty}^{\rm miss}}{\sin(\theta_1^{\rm vis}) \sin(\phi_2^{\rm vis} - \phi_1^{\rm vis})}$$

$$p_2^{\rm mis} = \frac{\cos(\phi_1^{\rm vis}) E_{Ty}^{\rm miss} - \sin(\phi_1^{\rm vis}) E_{Tx}^{\rm miss}}{\sin(\theta_2^{\rm vis}) \sin(\phi_2^{\rm vis} - \phi_1^{\rm vis})}$$

$$m_{\tau\tau}^{\rm coll} = \frac{m_{\tau\tau}^{\rm vis}}{\sqrt{x_1\, x_2}}$$

⇨ Missing Mass Calculator

A. Elagin, P. Murat, A. Pranko, A. Safonov, Nucl. Instrum. Meth. **A654** (2011) 481

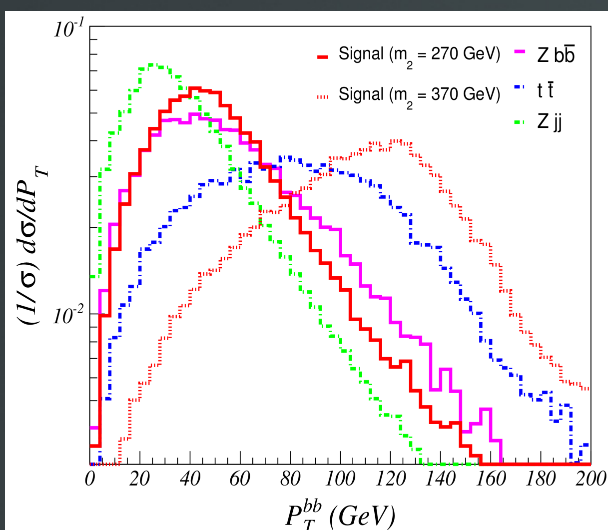
Searching for Resonant Di-Higgs at LHC

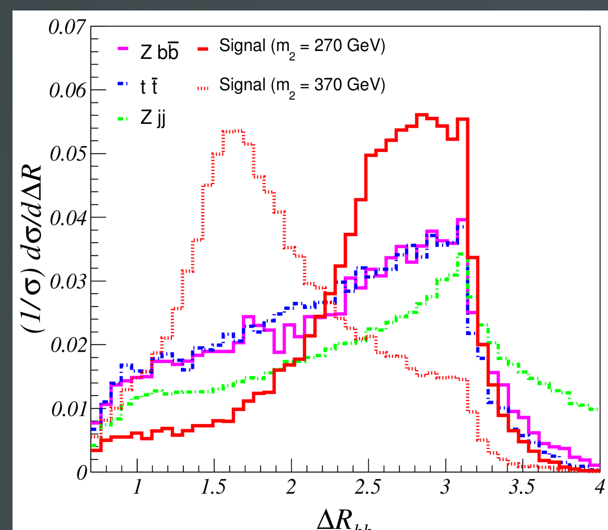
$$p\ p \to h_2 \to h_1\ h_1 \to \bar{b}b\tau^+\tau^-$$

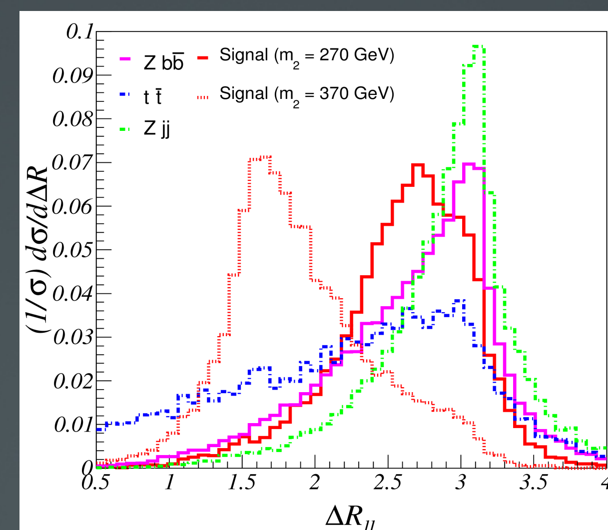
Event Generation → MadGraph 5 + Pythia + PGS/Delphes

Leptonic Mode: $\tau_{lep}\tau_{lep}$

Un-Boosted vs Boosted







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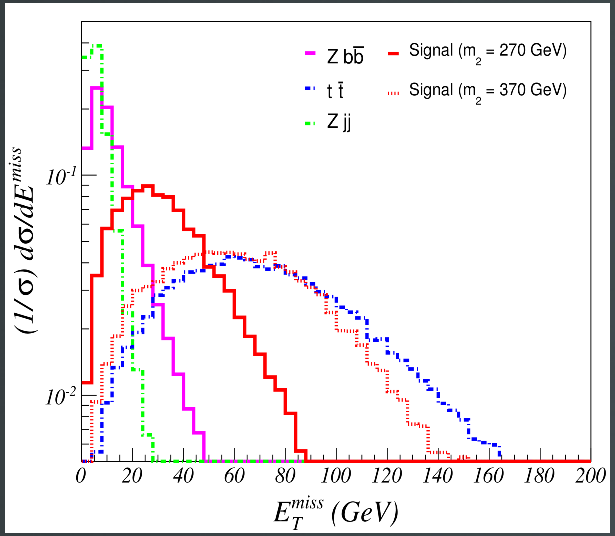
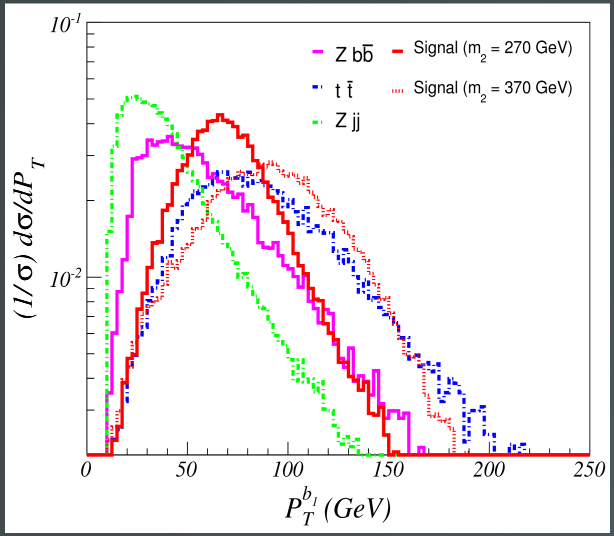
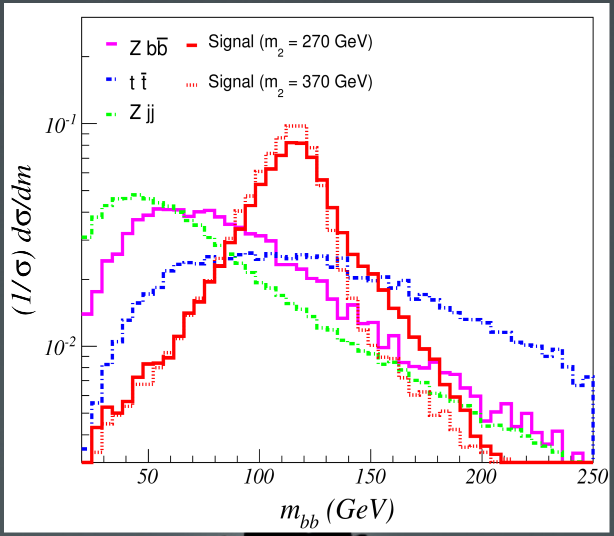






Searching for Resonant Di-Higgs at LHC

Leptonic Mode: $\tau_{lep}\tau_{lep}$

Un-Boosted

	$h_2 \to h_1 h_1$	$t\bar{t}$			$Z\,b\bar{b}$	$Z\,jj$
	$b\bar{b}\tau_{\rm lep}\tau_{\rm lep}$	$b\bar{b}\ell\ell$	$b\bar{b}\ell\tau_{\rm lep}$	$b\bar{b}\tau_{\rm lep}\tau_{\rm lep}$	$b\bar{b}\ell\ell + b\bar{b}\tau_{\rm lep}\tau_{\rm lep}$	$jj\ell\ell + jj\tau_{\rm lep}\tau_{\rm lep}$
Event selection	7.47	11209	4005	289	8028	1144
$\Delta R_{bb} > 2.1$, $P_{T,b_1} > 45$ GeV, $P_{T,b_2} > 30$ GeV	4.46	5585	2013	145	2471	153
h_1-mass: 90 GeV $< m_{bb} <$ 140 GeV	3.12	1073	405	30	880	47
Collinear x_1, x_2 Cuts	2.34	438	164	14.1	248	18
$\Delta R_{\ell\ell} > 2$, $H_T^{\rm lept} <$ 120 GeV	2.08	226	82	7.9	200	16.7
30 GeV $< m_{\ell\ell}\,(m_{e\mu}) <$ 75 (100) GeV	1.86	136	49	5.7	11.6	0.95
h_1-mass: 100 GeV $< m_{\tau\tau}^{\rm coll} <$ 150 GeV	1.05	32.5	11.4	1.63	3.24	0.24
$E_T^{\rm miss} <$ 50 GeV	0.89	10.5	3.37	0.56	3.03	0.23
h_2-mass: 230 GeV $< m_{bb\tau\tau}^{\rm coll} <$ 300 GeV	0.81	1.19	0.39	0.12	0.86	0.09

$S/\sqrt{B} \sim 5 \to L \sim 150\ fb^{-1}$

Boosted

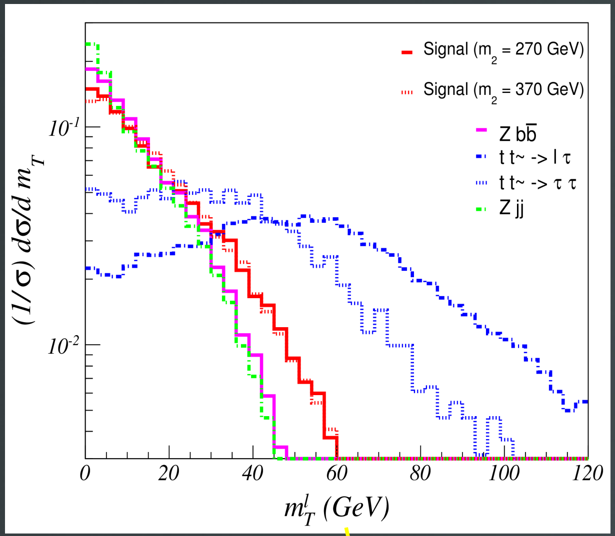
	$h_2 \to h_1 h_1$	$t\bar{t}$			$Z\,b\bar{b}$	$Z\,jj$
	$b\bar{b}\tau_{\rm lep}\tau_{\rm lep}$	$b\bar{b}\ell\ell$	$b\bar{b}\ell\tau_{\rm lep}$	$b\bar{b}\tau_{\rm lep}\tau_{\rm lep}$	$b\bar{b}\ell\ell + b\bar{b}\tau_{\rm lep}\tau_{\rm lep}$	$jj\ell\ell + jj\tau_{\rm lep}\tau_{\rm lep}$
Event selection	4.24	11209	4005	289	8028	1144
$\Delta R_{bb} < 2.2$, $P_{T,b_1} > 50$ GeV, $P_{T,b_2} > 30$ GeV	2.38	3356	1202	85	1166	35
h_1-mass: 90 GeV $< m_{bb} <$ 140 GeV	1.89	1396	512	36	452	12
$\lvert\vec{P}_T^{bb}\rvert >$ 110 GeV	1.35	719	264	19	208	4.9
Collinear x_1, x_2 Cuts	1.09	293	107	8.8	58	1.86
$\Delta R_{\ell\ell} < 2.3$, $H_T^{\rm lept} <$ 120 GeV	0.80	120	45	4.2	9	0.14
30 GeV $< m_{\ell\ell}\,(m_{e\mu}) <$ 75 (100) GeV	0.70	85	30	2.45	1.51	0.019
h_1-mass: 100 GeV $< m_{\tau\tau}^{\rm coll} <$ 150 GeV	0.60	30	11	0.96	0.24	0.003
25 GeV $< E_T^{\rm miss} <$ 90 GeV	0.42	18	6.2	0.60	0.18	0.003
h_2-mass: 330 GeV $< m_{bb\tau\tau}^{\rm coll} <$ 400 GeV	0.32	3.25	1.08	0.11	0.025	$<$ 0.001

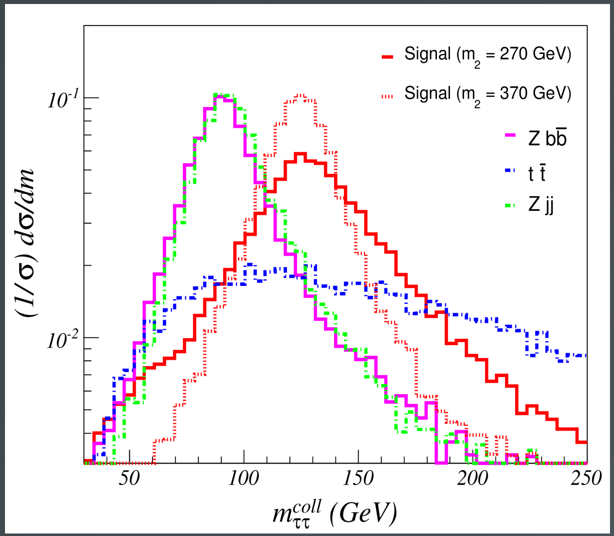
$S/\sqrt{B} \sim 5 \to L \sim 1000\ fb^{-1}$

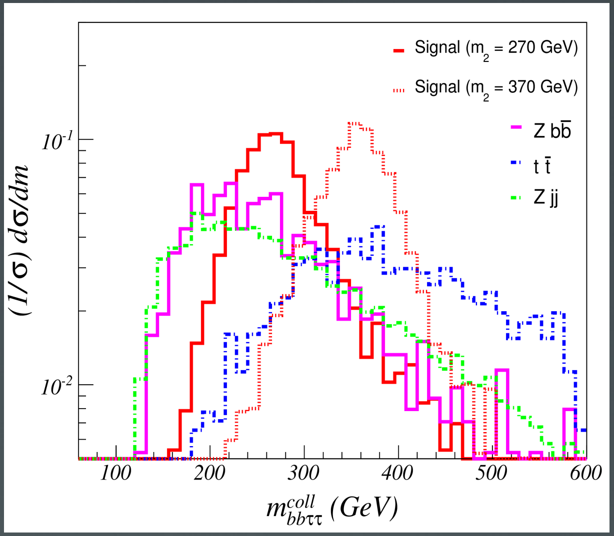
Searching for Resonant Di-Higgs at LHC

$$p\,p \rightarrow h_2 \rightarrow h_1\, h_1 \rightarrow \bar{b}b\tau^+\tau^-$$

SemiLeptonic Mode: $\tau_{lep}\tau_{had}$







$$m_T^\ell = \sqrt{2 p_T^\ell E_T^{\rm miss}(1 - \cos\phi_{\ell,{\rm miss}})}$$

Searching for Resonant Di-Higgs at LHC

SemiLeptonic Mode: $\tau_{lep}\tau_{had}$

Un-Boosted

	$h_2 \to h_1 h_1$	$t\bar{t}$		$Z\,b\bar{b}$	$Z\,jj$
	$b\bar{b}\tau_{\rm lep}\tau_{\rm had}$	$b\bar{b}\ell\tau_{\rm had}$	$b\bar{b}\tau_{\rm lep}\tau_{\rm had}$	$b\bar{b}\tau_{\rm lep}\tau_{\rm had}$	$jj\tau_{\rm lep}\tau_{\rm had}$
Event selection	19.17	5249	762	601	98
$\Delta R_{bb} > 2.1$, $P_{T,b_1} > 45$ GeV, $P_{T,b_2} > 30$ GeV	11.45	2639	384	188	10.8
h_1-mass: 90 GeV $< m_{bb} <$ 140 GeV	8.00	531	80	69	3.68
Collinear x_1, x_2 Cuts	4.81	209	36.4	41.6	2.41
$\Delta R_{\ell\tau} > 2$	4.10	129	23.1	26.5	2.03
$m_T^\ell < 30$ GeV	3.44	30.9	11.1	24.4	1.90
h_1-mass: 110 GeV $< m_{\tau\tau}^{\rm coll} <$ 150 GeV	1.56	4.97	2.05	4.92	0.38
$E_T^{\rm miss} < 50$ GeV	1.37	3.31	0.87	4.29	0.36
h_2-mass: 230 GeV $< m_{bb\tau\tau}^{\rm coll} <$ 300 GeV	1.29	0.39	0.17	1.21	0.13

$S/\sqrt{B} \sim 5 \to L \sim 50\ fb^{-1}$

Boosted

	$h_2 \to h_1 h_1$	$t\bar{t}$		$Z\,b\bar{b}$	$Z\,jj$
	$b\bar{b}\tau_{\rm lep}\tau_{\rm had}$	$b\bar{b}\ell\tau_{\rm had}$	$b\bar{b}\tau_{\rm lep}\tau_{\rm had}$	$b\bar{b}\tau_{\rm lep}\tau_{\rm had}$	$jj\tau_{\rm lep}\tau_{\rm had}$
Event selection	10.73	5249	762	601	98
$\Delta R_{bb} < 2.2$, $P_{T,b_1} > 50$ GeV, $P_{T,b_2} > 30$ GeV	6.02	1576	223	85	2.46
h_1-mass: 90 GeV $< m_{bb} <$ 140 GeV	4.77	672	94	31.5	0.84
$\lvert\vec{P}_T^{bb}\rvert > 110$ GeV	3.42	345	49	13.9	0.33
Collinear x_1, x_2 Cuts	2.31	136	22.3	8.38	0.22
$\Delta R_{\ell\tau} < 2.3$	1.71	68	11.1	4.31	0.055
$m_T^\ell < 30$ GeV	1.46	18.4	5.64	4.02	0.051
h_1-mass: 110 GeV $< m_{\tau\tau}^{\rm coll} <$ 150 GeV	1.05	4.2	1.26	0.30	0.003
25 GeV $< E_T^{\rm miss} <$ 90 GeV	0.76	2.93	0.75	0.23	0.002
h_2-mass: 330 GeV $< m_{bb\tau\tau}^{\rm coll} <$ 400 GeV	0.63	0.60	0.15	0.026	< 0.001

$S/\sqrt{B} \sim 5 \to L \sim 100\ fb^{-1}$

(1/2) Summary

$h_2 \rightarrow h_1 h_1$ as Probe of Higgs Portal & EW Phase Transition

Promising at LHC in bbττ Final State with 100 - 200 fb^{-1}

Other Final States?

bbbb
bbWW
bbγγ
...

Interplay between $h_2 \rightarrow h_1 h_1$ & $h_2 \rightarrow Z Z$?

(1/2) Summary

$h_2 \to h_1 h_1$ *as Probe of Higgs Portal & EW Phase Transition*

Promising at LHC in bb$\tau\tau$ Final State with 100 - 200 fb^{-1}

Other Final States?

bbbb
bbWW
bb$\gamma\gamma$
...

Interplay between $h_2 \to h_1 h_1$ & $h_2 \to Z Z$?

HowTo *Map the EW Phase Transition in Higgs Portal to LHC...*

Extended EWSB Scalar Sectors

➔ *2 Higgs Doublet Model*

HowTo Develop a Search Strategy for 2HDMs with a Strong EW Phase Transition at LHC?

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m_H m_A $m_{H^\pm}$ t_β α-β μ

Extended EWSB Scalar Sectors

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What Regions Lead to a Strong EW Phase Transition in 2HDM?

*G. Dorsch, S. Huber, J. M. N., JHEP **1310** (2013) 029*

G. Dorsch, S. Huber, K. Mimasu, J. M. N., To Appear

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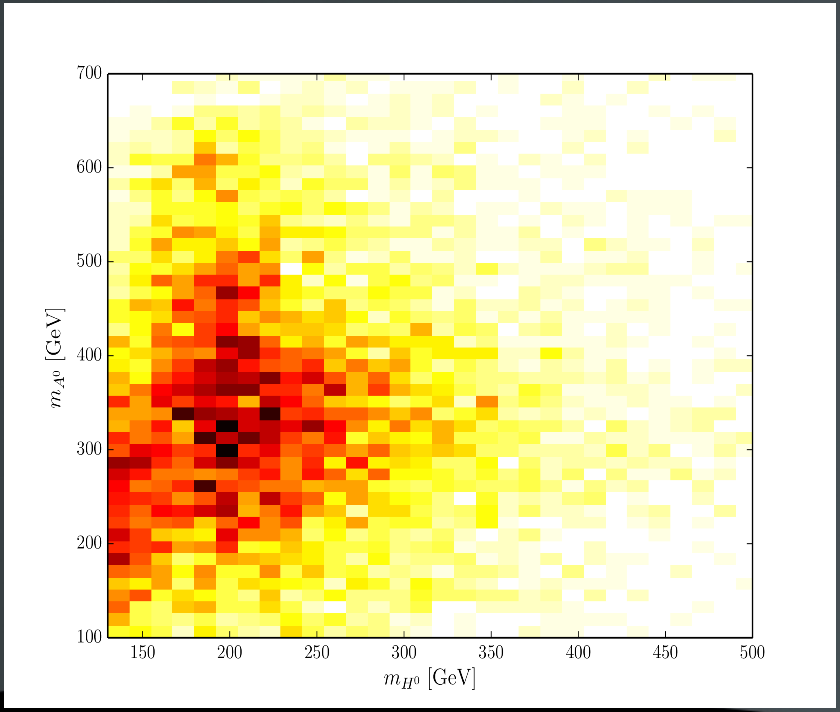

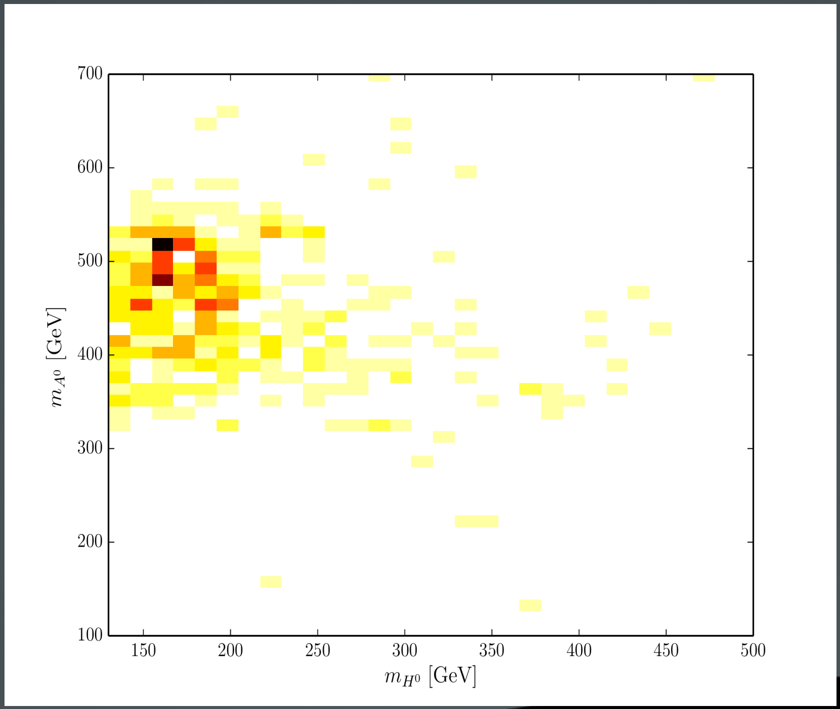

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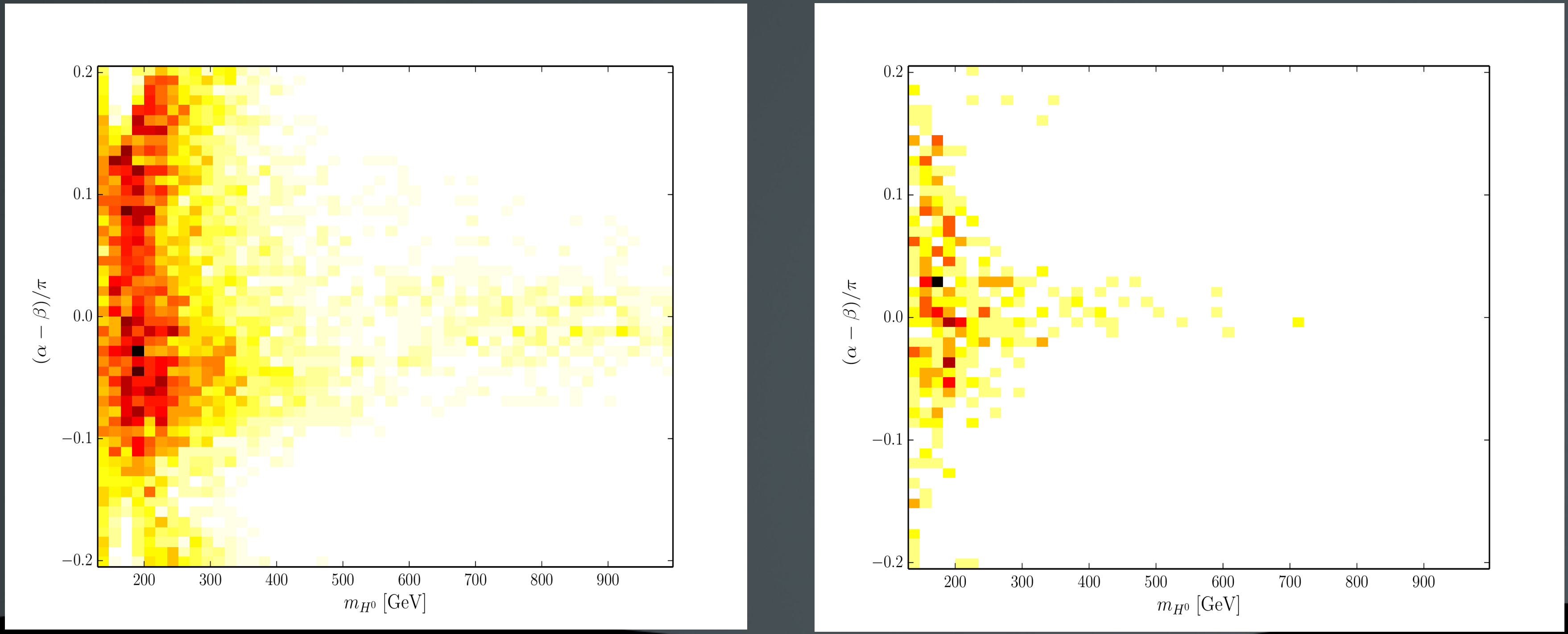

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m_H m_A $m_{H^\pm}$ t_β α-β μ

⇨ $m_A > 350$ GeV

⇨ $m_A - m_H \sim v$

⇨ $\alpha \sim \beta$

(for light H_0, $\alpha \neq \beta$ possible)

⇨ *moderate* t_β $(t_\beta \sim 1 - 5)$

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Decay Channel $A_0 \to Z\ H_0$

B. Coleppa, F. Kling, S. Su, arXiv:1404.1922 [hep-ph]
G. Dorsch, S. Huber, K. Mimasu, J. M. N., To Appear

⇨ $\alpha \sim \beta$

(for light H_0, $\alpha \neq \beta$ possible)

Decay Channel $A_0 \to Z\ h$ suppressed

⇨ moderate t_β ($t_\beta \sim 1 - 5$)

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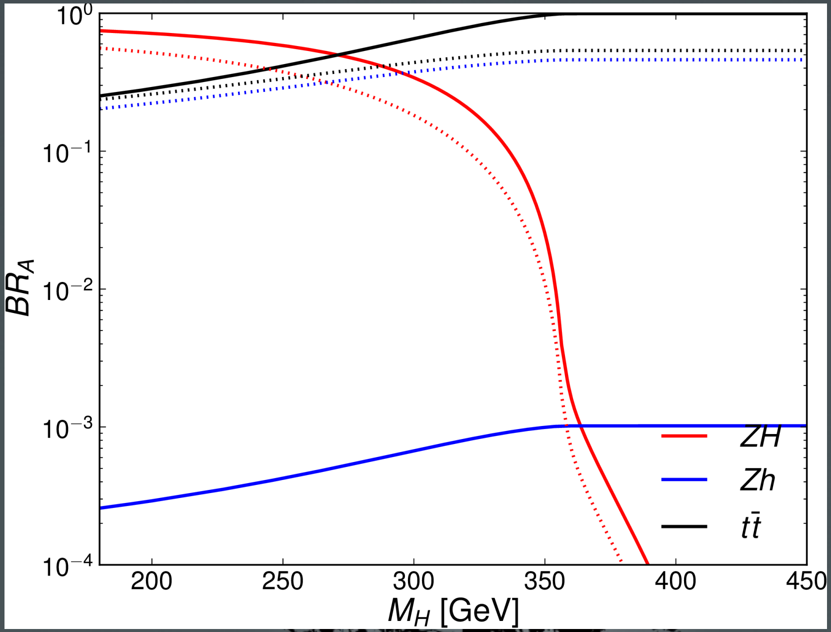

$m_A = m_{H^\pm} = 450$ GeV $t_\beta = 2$
$(\alpha-\beta)/\pi = 0.005$ (0.15) $\mu = 100$ GeV

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m_H m_A $m_{H^\pm}$ t_β $\alpha-\beta$ μ

What Final States to Search For at LHC?

$(\alpha-\beta)/\pi = 0.005 \rightarrow \bar{b}b\,\ell^+\ell^-$

$(\alpha-\beta)/\pi = 0.15 \rightarrow W^+W^-\,\ell^+\ell^-$

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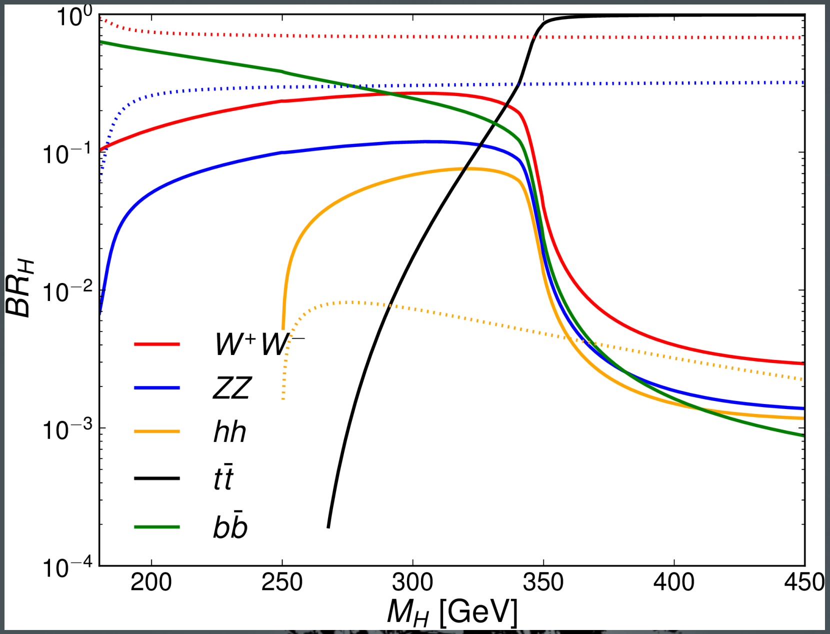

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m_H $\quad m_A$ $\quad m_{H^\pm}$ $\quad t_\beta$ $\quad \alpha\text{-}\beta$ $\quad \mu$

What Final States to Search For at LHC?

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B. Coleppa, F. Kling, S. Su, arXiv:1404.1922 [hep-ph]
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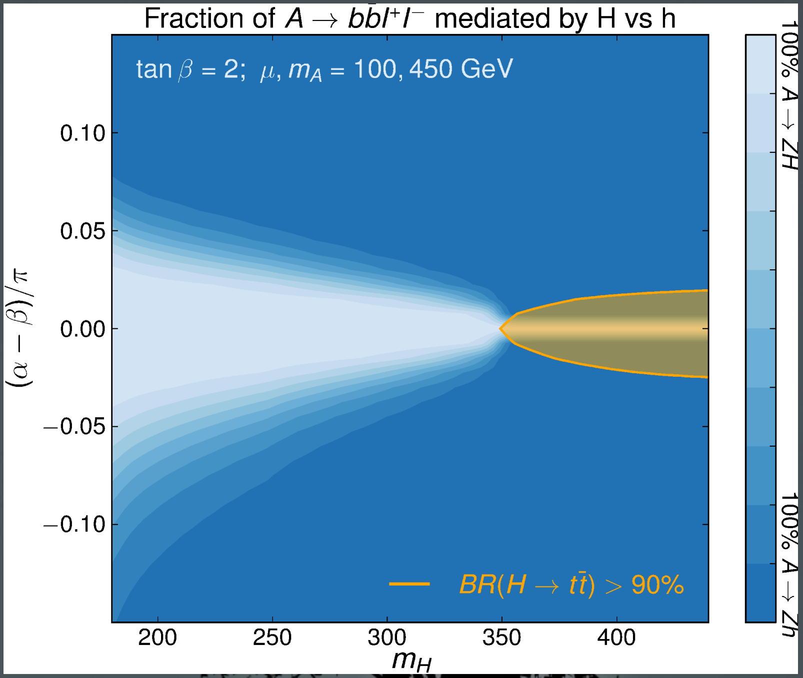
Searches for $bb\ell\ell$ on $A_0 \rightarrow Z\, h$ are suppressed for a Strong EW Phase Transition



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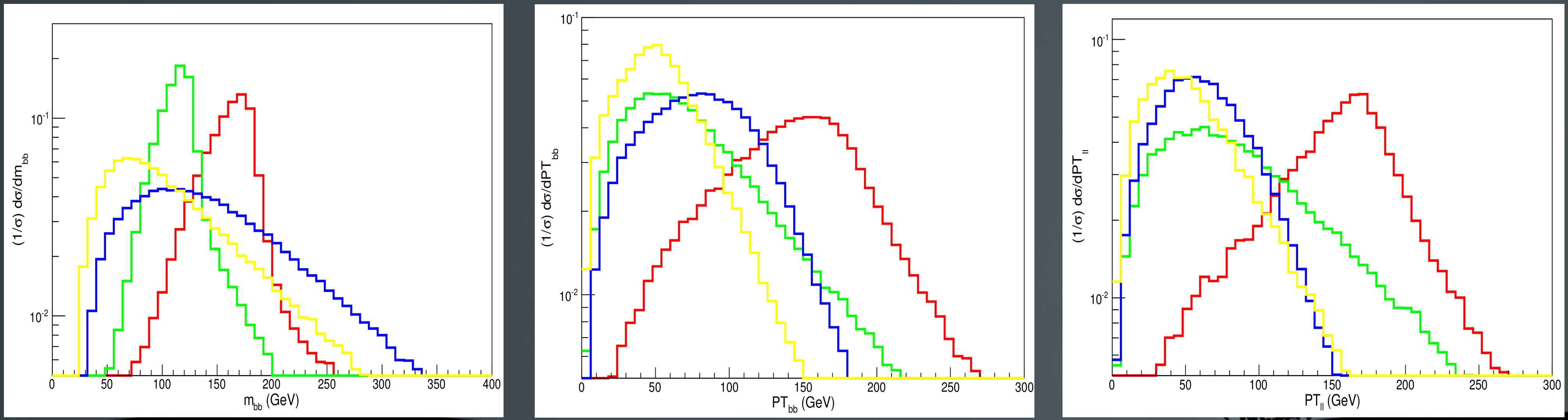
Search Mode: $\bar{b}b\ \ell^+\ell^-$



Summary

What Can EW Phase Transition / Collider Searches Tell About Collider Searches / EW Phase Transition ?

$\Downarrow$

HowTo Develop a Search Strategy for Extended EWSB Sectors with a Strong EW Phase Transition at LHC?

<u>Singlet Higgs Portal:</u> $h_2 \to h_1\, h_1$ vs $h_2 \to Z\, Z$

Other Signals for $m_{h_2} < 250$ GeV? $h_1 \to h_2\, h_2$?

<u>2HDM:</u> $A_0 \to Z\, H_0$