

Physics Beyond the SM with Higgs

CmF RA3 Kick-off

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UNIVERSITÄT **BONN**

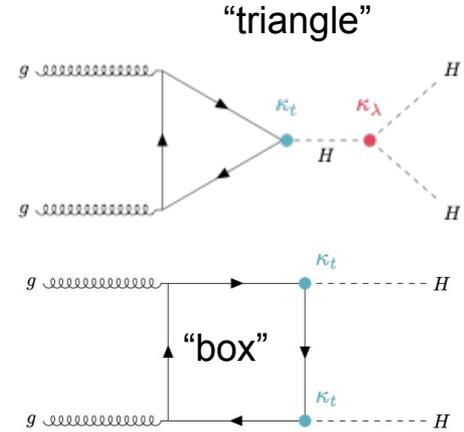
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Ongoing Projects

Non-resonant Di-Higgs production

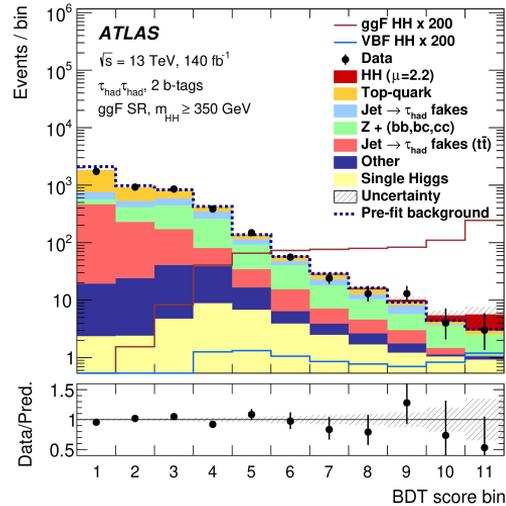
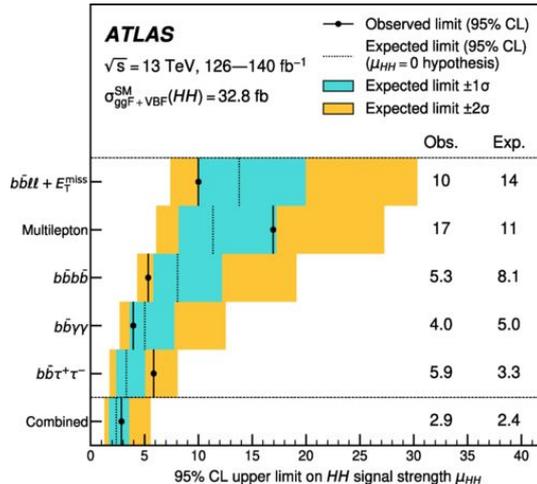
- Main goal: measure the Higgs self-coupling
 - Ultimate probe of the scalar sector
 - BSM physics via non-SM Higgs self-coupling values or resonant HH production
- Currently we are searching for $HH \rightarrow bb\tau\tau$ with Run 2 + 2022-2023 Run 3 data set
 - Identification of fake tau-leptons
 - $H \rightarrow \tau\tau$ mass reconstruction



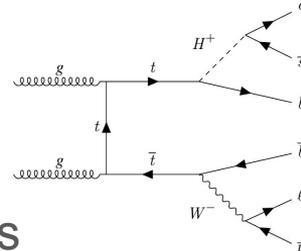
$HH \rightarrow XX$

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

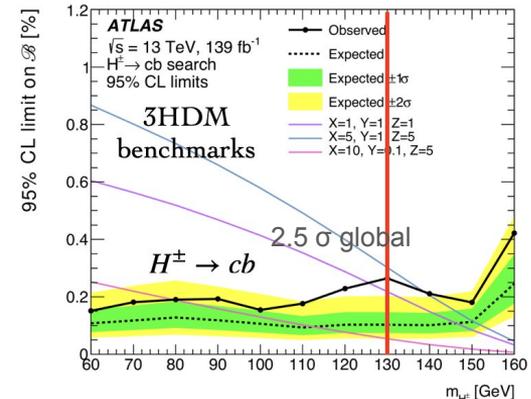
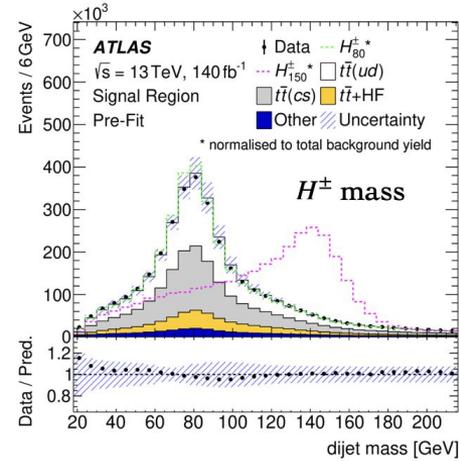
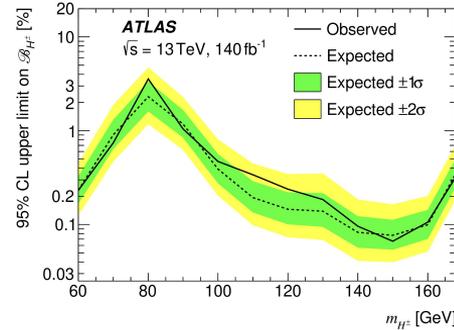
multilepton



Charged Higgs searches: $H^+ \rightarrow cs$

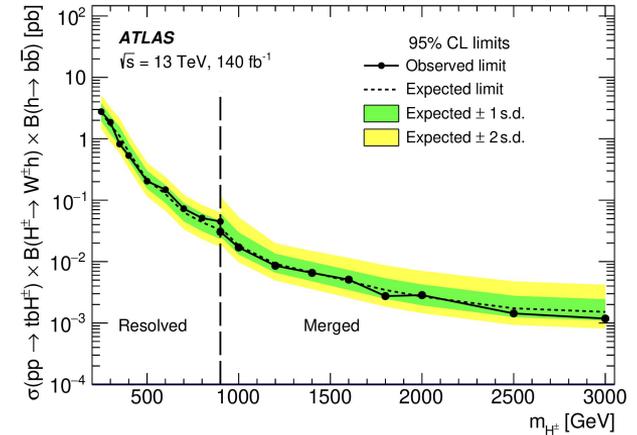
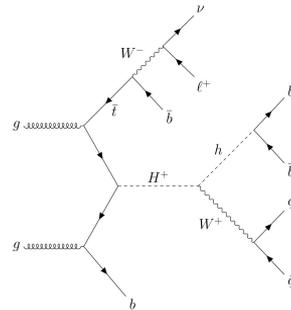
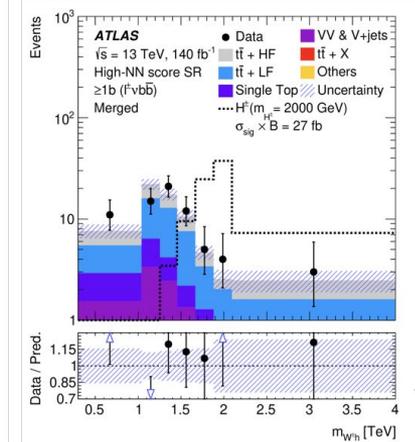
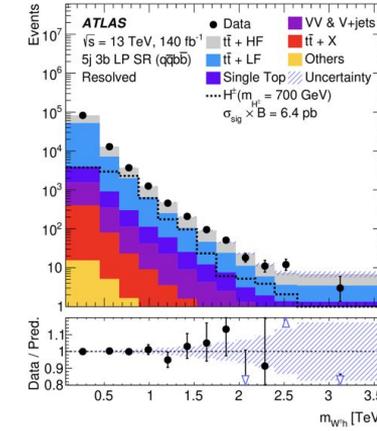


- 2HDM and MSSM motivated
- Sizeable BR at high $\tan\beta$ and low H^+ masses
- Analysis strategy:
 - Lepton + jets final state
 - Fully reconstructed $t\bar{t}$ system (likelihood)
 - Final discriminant: BDT score
 - Cover charged Higgs mass range 60 -168 GeV
- Dominated by systematics
- We published a paper with the full Run 2 data set
- Current search focus on Run 3 and includes cs and cb final states: [kick-off](#)
 - SPANet to reconstruct $t\bar{t}$ system



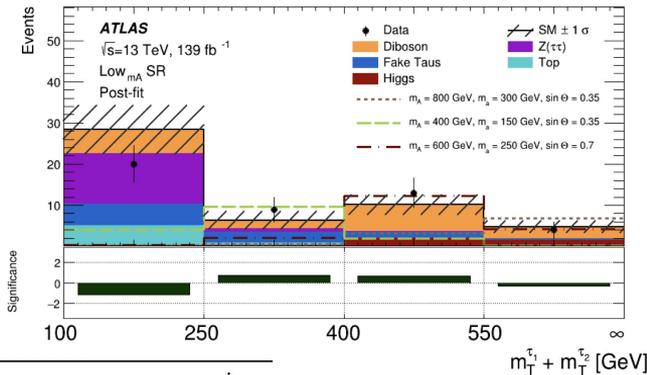
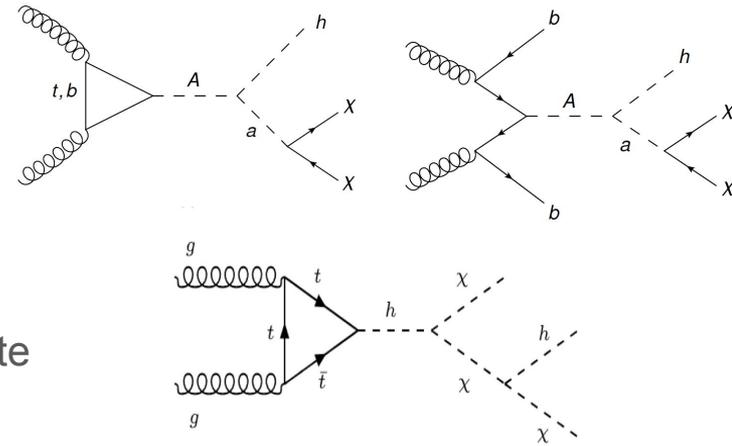
Charged Higgs searches: $H^+ \rightarrow Wh, h \rightarrow bb$

- First LHC search in the $H^+ \rightarrow Wh, h \rightarrow bb$ channel with 125 GeV h
 - Target both resolved and merged W and h decays \rightarrow **Xbb tagger**
 - $H^+ \rightarrow lvbb$ and $H^+ \rightarrow qqbb$ channels
- Final observable: reconstructed charged Higgs mass
 - BDT to correctly assign particles to reconstruct H^+
- Main backgrounds (tt and $V+jets$) corrected using data in dedicated control regions

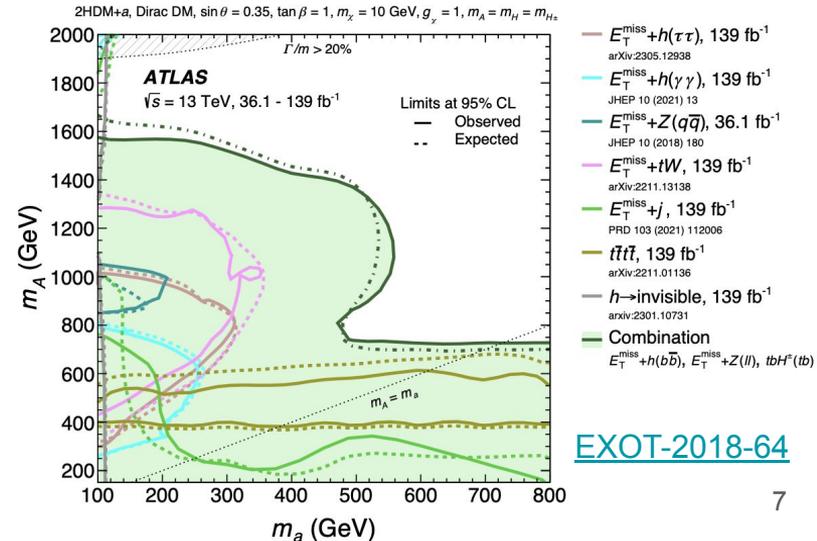


Mono-Higgs $H \rightarrow \tau\tau + \text{MET}$

- Various BSM models justify the search:
 - 2HDM+a Type I [[2404.05704](#)]
 - Axion-like particles and sterile neutrinos [[2412.08212](#)]
 - Higgs portals [[2012.07822](#)]
- Run 2 search focused on 2 hadronic τ 's + MET final state
 - Sensitive at low MET, low m_A part
 - 2HDM+a interpretations, fermionic dark matter
- Run 3 search goals:
 - Focus on new BSM models/benchmarks
 - Interested in HH+MET search as well



$$m_T^{\tau i} = \sqrt{2p_T^{\tau i} E_T^{\text{miss}} (1 - \cos \Delta\phi(\tau_i, p_T^{\text{miss}}))}$$



EXOT-2018-64

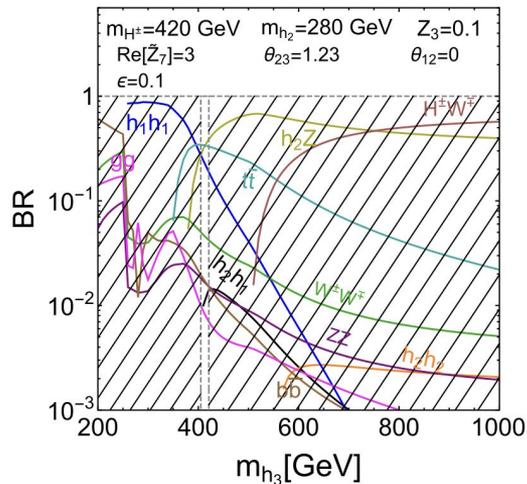
Future Projects within CmF

Higgs and CP Violation

- CKM phase is so far the only source of the **CP violation** in the SM
 - CP-odd Higgs hypothesis is strongly disfavored experimentally but the observed Higgs boson could be a mixture of CP-even and CP-odd states \Rightarrow another possible source of CP violation
- **Extended Higgs sector** (e.g. 2HDM) provides room for **CPV Higgs couplings**
 - Complex mass and coupling parameters could lead to CPV (e.g. C2HDM)
- Indirect probes of CPV couplings:
 - electron EDM
 - Higgs rate measurements
- Direct probes of CPV couplings:
 - Higgs distributions, e.g. $h \rightarrow ZZ^*$, WW^* or $t\bar{t}(h \rightarrow \gamma\gamma)$, $h \rightarrow \tau\tau$
 - **additional Higgs bosons: neutral scalars h_1, h_2, h_3 can lead to CPV signatures**

CPV Higgs couplings benchmarks

- Due to experimental constraints, the CPV couplings are expected to be small \Rightarrow HL-LHC
- Main production channel:
 - $\sigma(gg \rightarrow h_2) \sim 5.8$ pb, $\sigma(gg \rightarrow h_3) \sim 2.7$ pb at 13 TeV
- Event rates @ HL-LHC [Phys. Rev. D 105 \(2022\) 035009](#)
 - $pp \rightarrow h_3 \rightarrow h_1 h_1 Z \sim 20$ k events
 - $pp \rightarrow h_3 \rightarrow h_1 ZZ \sim 200$ k events
 - $pp \rightarrow h_2 \rightarrow h_1 h_1 \sim 40$ k events
 - $pp \rightarrow h_2 \rightarrow h_1 Z \sim 900$ k events



Mass of additional Higgs bosons is close to the EW scale
New triple boson final states not studied at the LHC yet

\Rightarrow Connection to RA2 and RA4

\Rightarrow RA3: EFT fits will constrain the allowed parameter space

Flavourful Two Higgs Doublet Models

- Break flavour universality
- Generate (some) mass hierarchies

Example: $\mathcal{L} = \bar{f}YfH + \bar{f}Y'fH'$

125 Higgs (h) Additional
Higgses
(H, A, H[±])

$$\mathcal{M} = vY + v'Y'$$

$$(\mathcal{M}_0 + \Delta\mathcal{M})$$

Altmannshofer et al [1507.07927](#)
Ghosh et al [1508.01501](#)

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m_e & \mathcal{O}(m_e) & \mathcal{O}(m_e) \\ \mathcal{O}(m_e) & m_\mu & \mathcal{O}(m_\mu) \\ \mathcal{O}(m_e) & \mathcal{O}(m_\mu) & \mathcal{O}(m_\mu) \end{pmatrix}$$

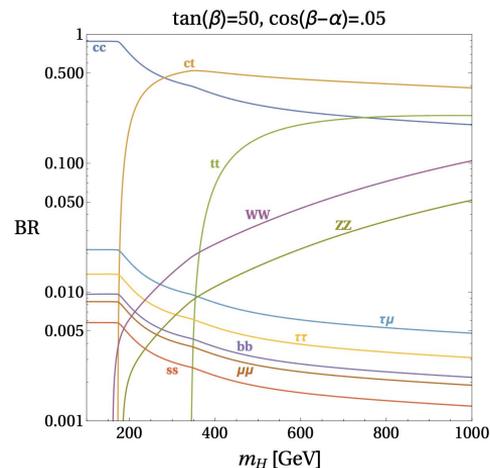
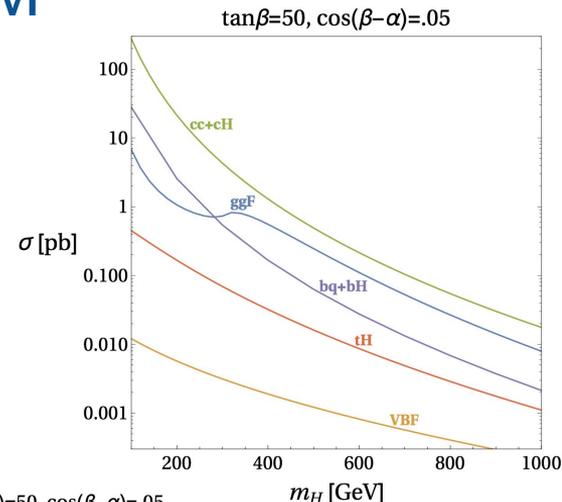
Analogue structure in the quark sector

- Hierarchies obtained though $v \gg v'$
- Allows flavour violating Higgs boson decays

Heavy Higgs signatures of Flavourful 2HDM

Altmannshofer et al [1610.02398](#)

- Top-charm resonances:
 - $pp \rightarrow H \rightarrow tc$
 - **$pp \rightarrow t(c)H, H \rightarrow tc$**
→ Interesting channel to cover
- Tau- μ resonances:
 - $pp \rightarrow t(c)H, H \rightarrow \tau\mu$
- Light di-jet resonances:
 - $pp \rightarrow t(c)H, H \rightarrow cc$
- Charm-bottom and charm-strange resonances:
 - $pp \rightarrow H^+ \rightarrow cs, cb$ above and below the top threshold
→ Expertise in our group



Additional topics for discussion

Composite Higgs

Why is the **Higgs boson** so **light**?

- Mass is not protected by symmetries like for fermions (chiral symmetry) or vector bosons (gauge symmetry)

Either **New Physics** appears at a **scale Λ** or there has to be a “**fine-tuning**”

→ One possible solution: **Compositeness**

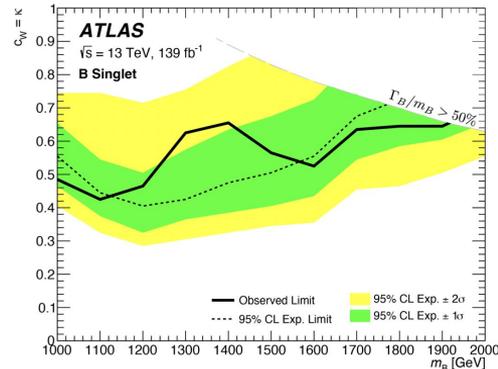
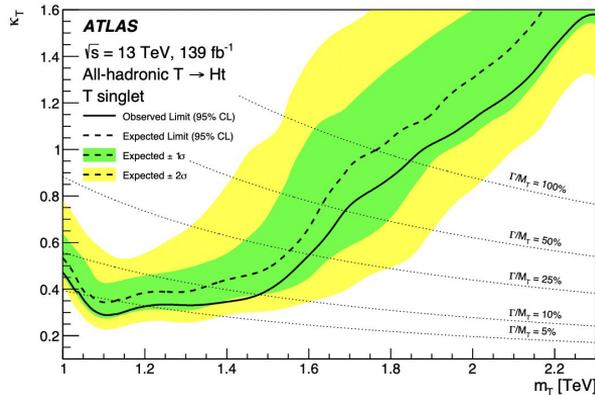
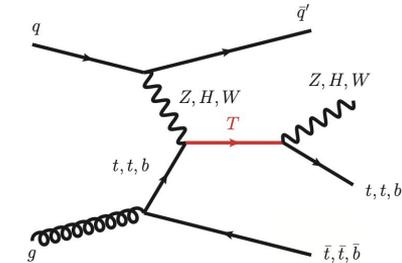
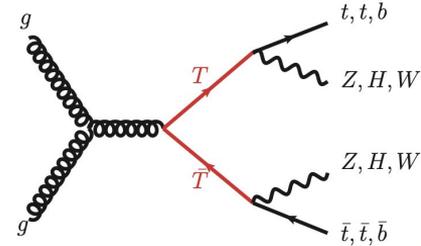
- Higgs is not an elementary particle
 - No true hierarchy problem beyond the scale of compositeness

⇒ **New strong interaction** at the scale of ~ 10 TeV

- Indirect searches: precision EW, Higgs, Top
- Direct searches: fermionic and bosonic resonances

Fermionic resonances: Vector-Like Quarks

- **VLQ pair production:** model independent, relevant at low mass
- **VLQ single production:** model dependent couplings, PDF-favoured at high masses
- Masses below ~ 1 TeV are excluded for any BR combination of pair produced B and T quarks
- Our group is interested in **VLQ single production**
 - $T \rightarrow Ht$, $B \rightarrow Hb$ hadronic final states & boosted $H \rightarrow bb$ topology
 - Multilepton $T \rightarrow Zt$ or $B \rightarrow Zb$ is most sensitiv channel in Run 2



BACKUP

Extended Higgs Sector Models

Additional Singlet

- Simplest extension, S: real singlet scalar
- Higgs portal \rightarrow connection to dark sector
- Free parameters: mass of S, mixing angle α
- Couplings inherited from SM Higgs suppressed by $\sin \alpha$

Additional Singlet + Doublet

- 2HDM extended with a complex singlet
- Additional CP-odd/even scalars wrt 2HDM
- Example: next-to-minimal supersymmetric SM (NMSSM)

Additional Doublet

- Two Higgs Doublet Models (2HDM): additional SU(2) doublet
- Required by SUSY
- Free parameters: masses of additional states, mixing angle α , ratio of two VEVs $\tan \beta$
- 5 physical scalar states: two neutral CP-even (H, h), one neutral CP-odd (A) and two charged (H^\pm)
- Alignment limit $\cos(\beta - \alpha) \rightarrow 0$: $h \equiv h_{125}$
- Yukawa couplings:

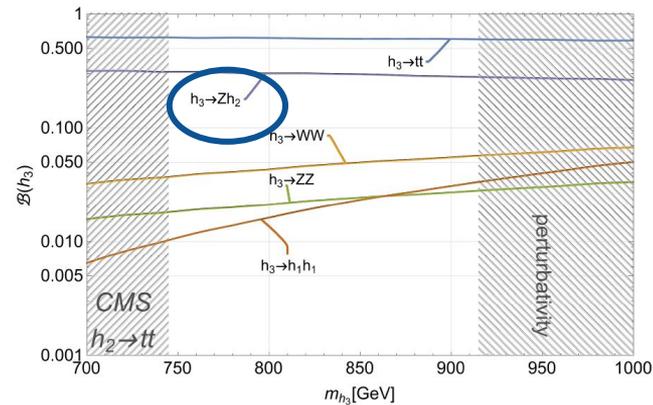
$$\lambda_f^{SM} = \frac{\sqrt{2}}{v} m_f, \quad \lambda_f^{BSM} = \frac{n_f}{\tan \beta} \lambda_f^{SM}$$

	Type-I	Type-II	Type-L	Type-F
η_u	1	1	1	1
η_d	1	$-\tan^2 \beta$	1	$-\tan^2 \beta$
η_l	1	$-\tan^2 \beta$	$-\tan^2 \beta$	1

Heavy Higgs CPV signatures

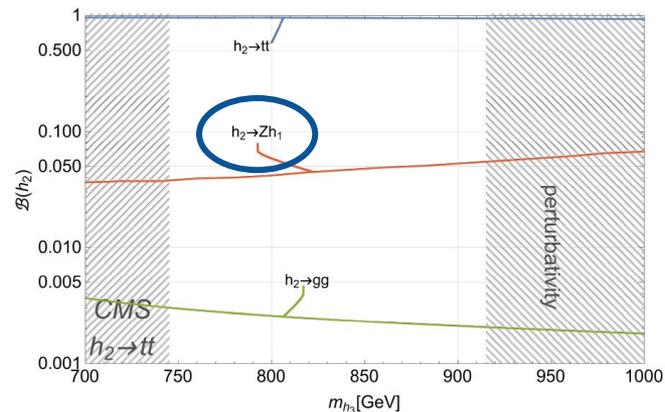
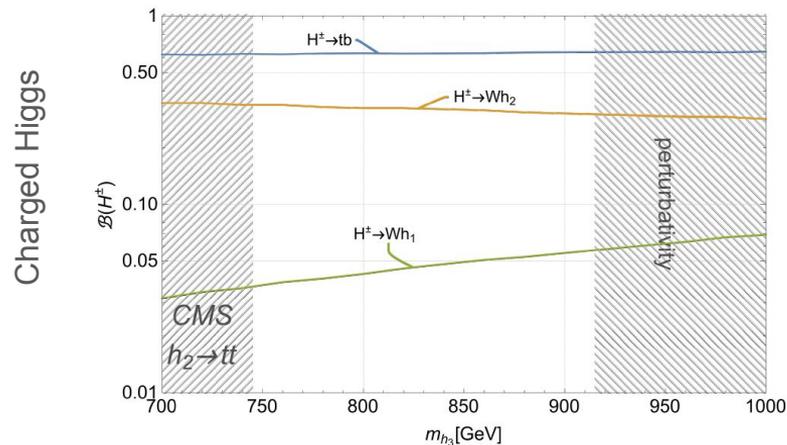
Examples of CPV signatures (S. Gori, N. Hamer [thesis](#)):

- $h_3 \rightarrow h_2 Z, h_2 \rightarrow h_1 Z$
- $h_3 \rightarrow h_2 h_1$



Not allowed in CP conserving scenario

2HDM Type 2 benchmark from [thesis](#)
not excluded by EW precision tests, Higgs
rates measurements and electron EDM



HH + MET

H coupling to a dark sector (H as portal particle) open up possibility of H + MET

- H \rightarrow invisible well covered, e.g. [arXiv:1809.06682](https://arxiv.org/abs/1809.06682)
- H + invisible (on-going PhD. thesis in Bonn)
- HH + invisible: several scenarios, interest in Bonn