Constraining electroweak baryogenesis with searches for heavy Higgs bosons

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(on behalf of the ATLAS collaboration)

Corfu 2023 - Workshop on Standard Model and Beyond

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

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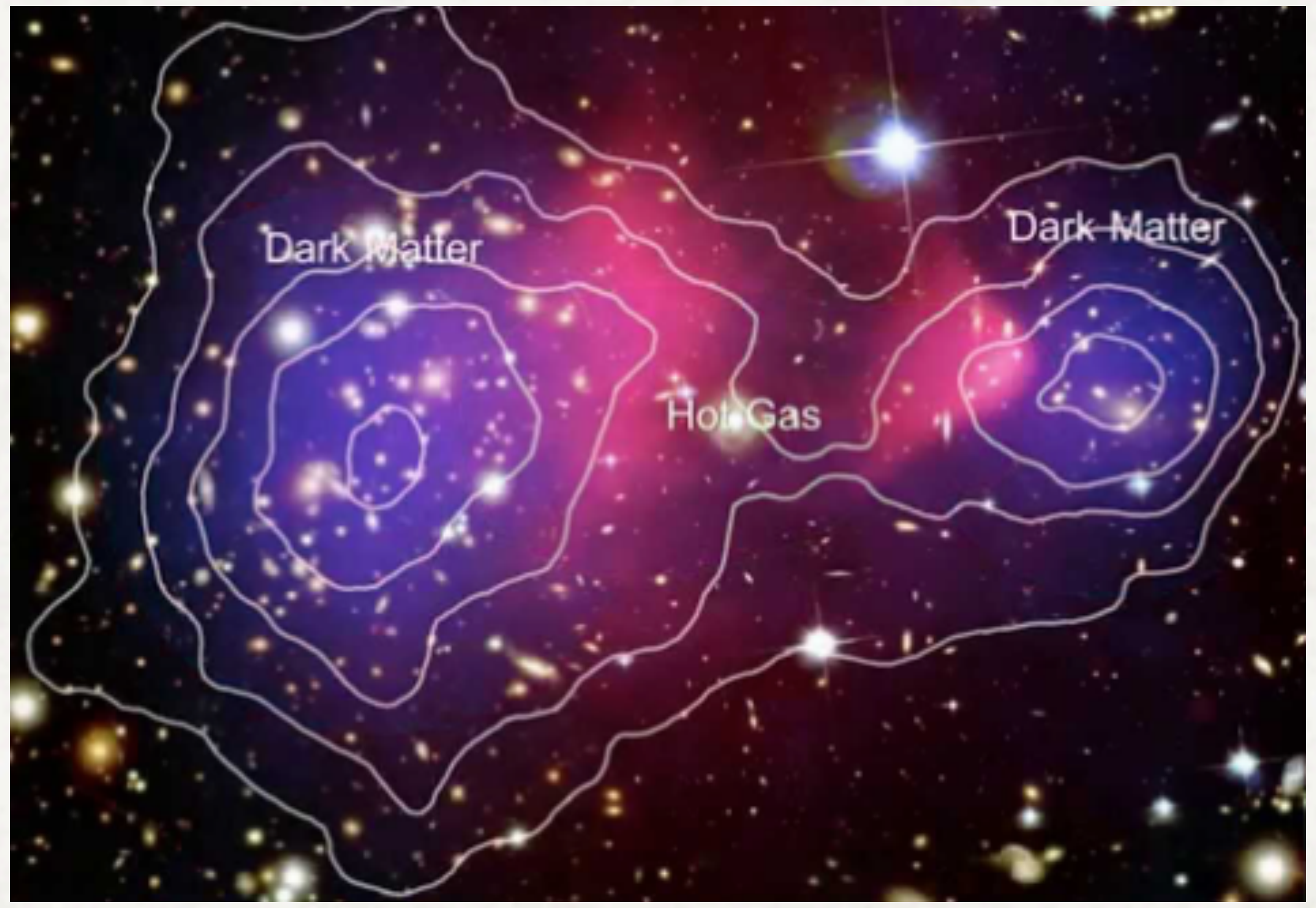
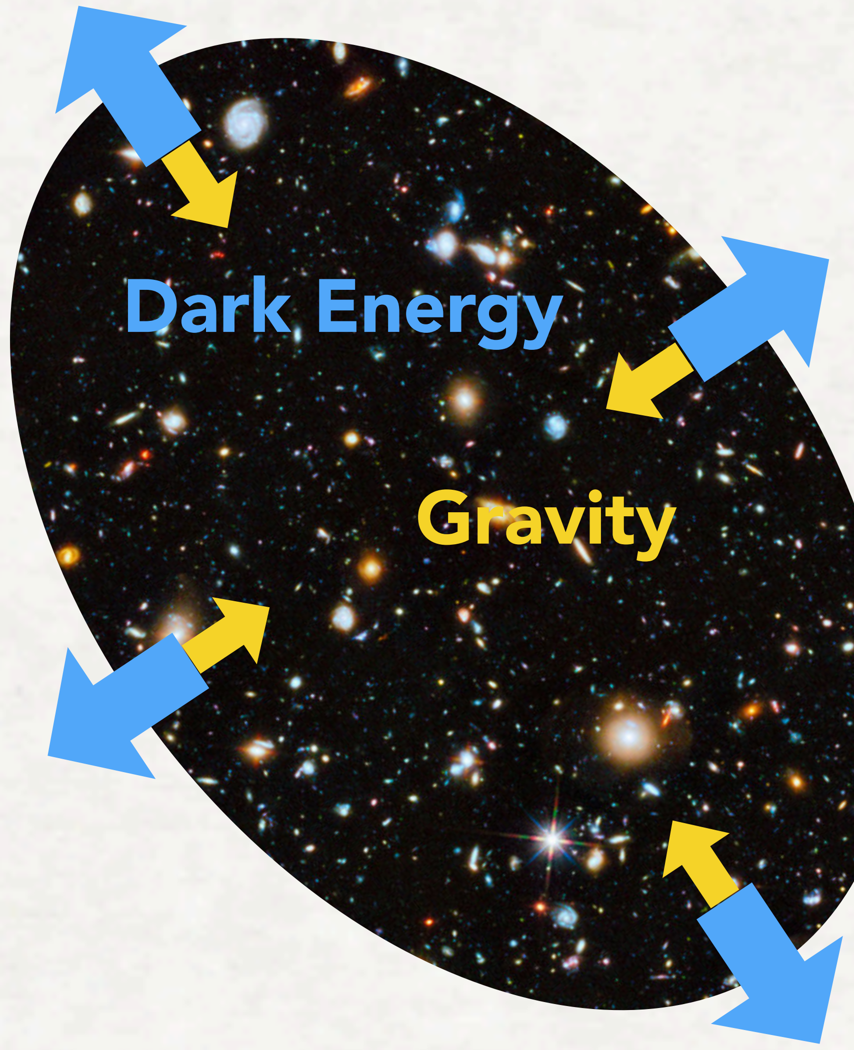
Open questions in particle physics & cosmology

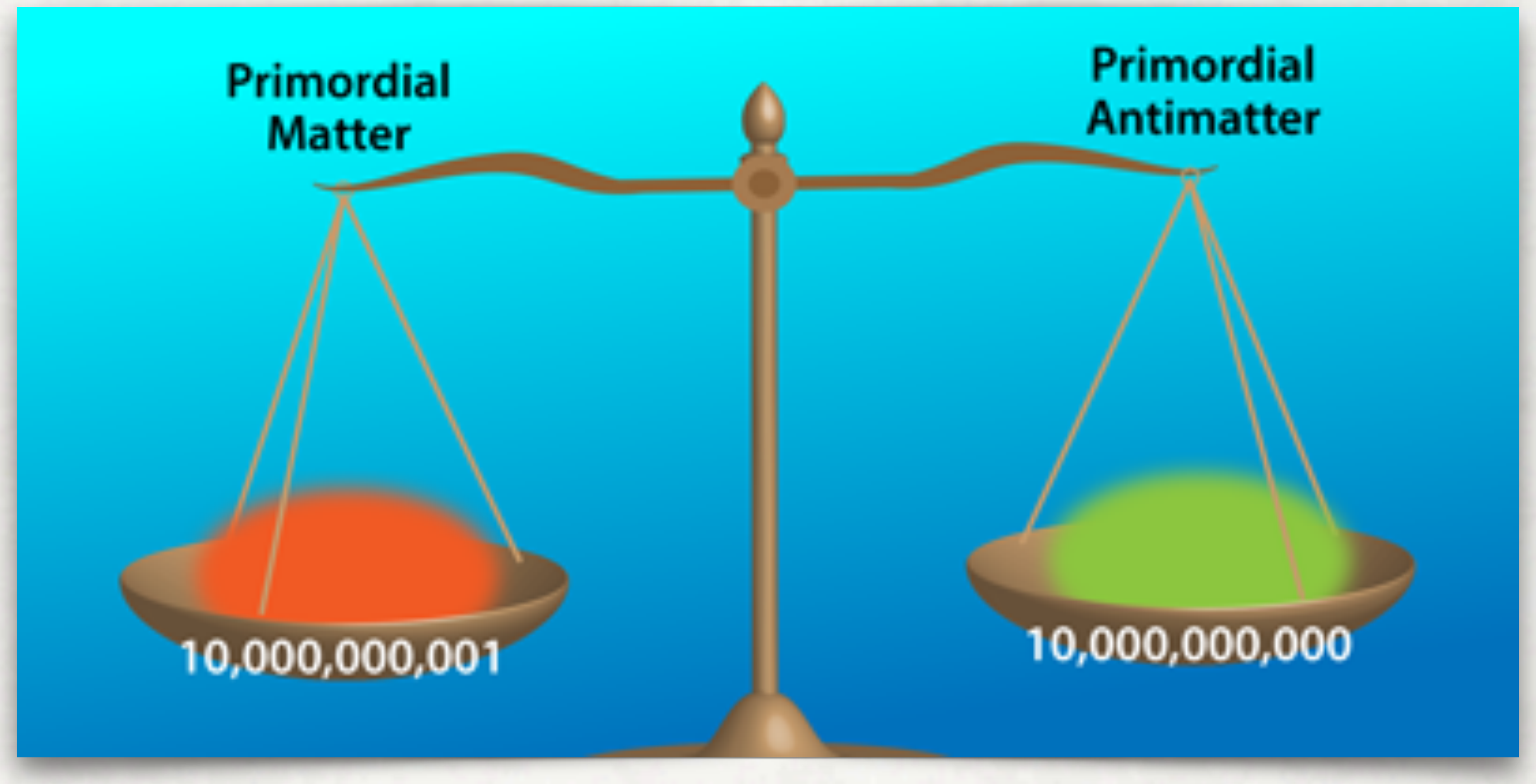
Dark Matter



Dark Energy



Baryon Asymmetry



+ are these related to the Higgs sector?

The Higgs-cosmology connection

1. **Higgs** sector can mediate **Dark Matter** interactions
   - ➡ see my talk in Corfu 2022

Kuzmin, Rubakov, Shaposhnikov, PLB 155 (1985) 36
Shaposhnikov, NPB 287 (1987) 757 (1987)
Nelson, Kaplan, Cohen, NPB 373 (1992) 453

SA, Brandt, Haisch Symmetry 2021, 13 (12)

SA, Haisch SciPost Phys. 13 (2022) 1

…

2. **Higgs** portal ↔ scalar **Dark Energy**
   - ➡ maybe Corfu 2024?

Bezrukov, Shaposhnikov, PLB 659 (2008) 703

Burrage et al, JCAP 11 (2018) 036

SA, Burrage, Englert, 2304.08118

…

3. **Higgs (EWSB) can trigger baryogenesis**
   - ➡ today's talk

Silveira, Zee, PLB 161 (1985) 136
Ipek et al, Phys. Rev. D 90 (2014) 055021
Bell et al, JCAP 03 (2017) 015
Berlin et al, JHEP 06 (2014) 078
Duerr et al, JHEP 09 (2016) 042
…

Outline

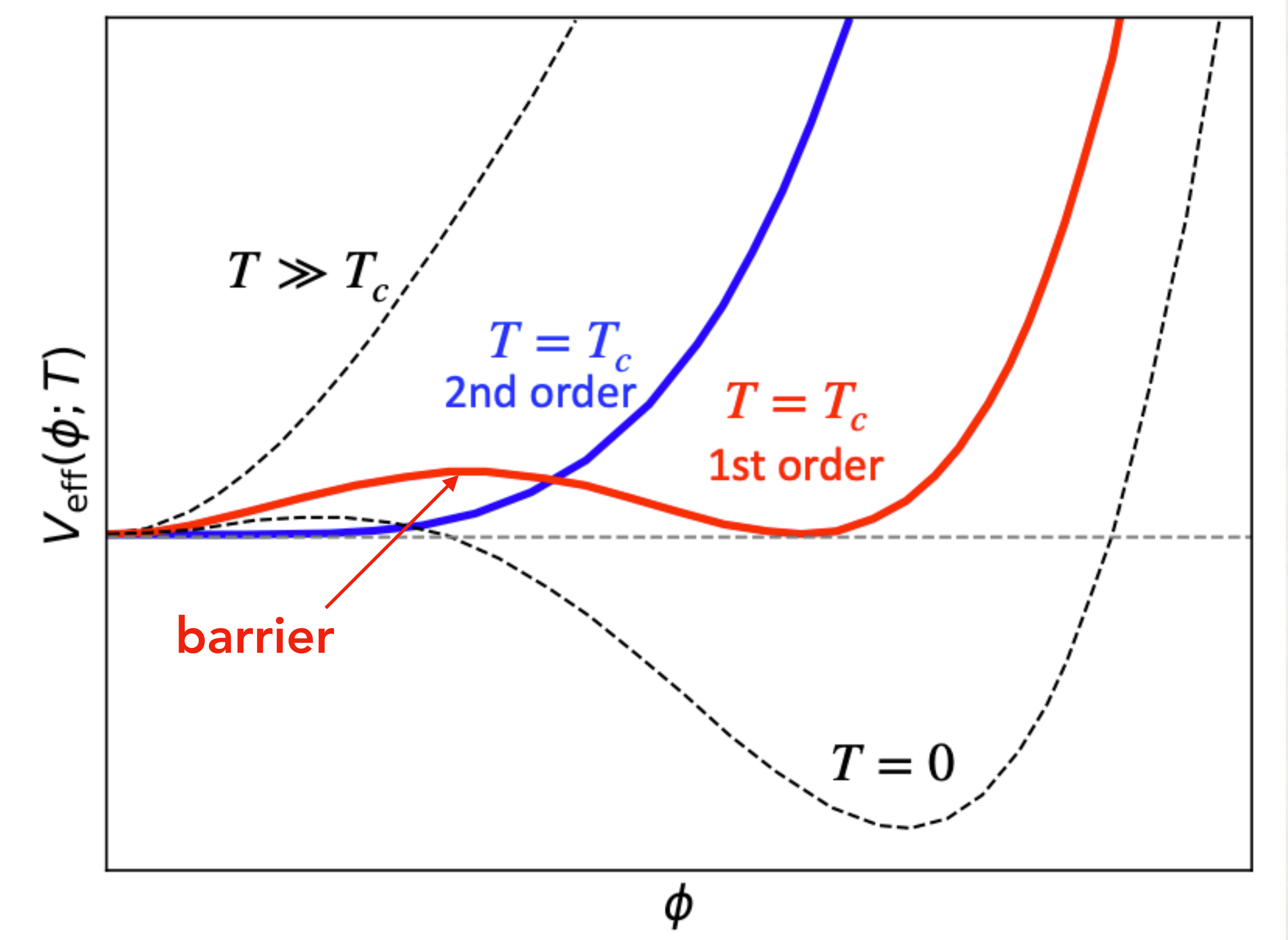
1. **Pheno overview**: how can EWSB trigger baryogenesis?
2. **Previous experimental searches**
3. **New searches in ATLAS** [ATLAS-CONF-2023-034]
   - H decays to top quarks
   - H decays to bottom quarks

Baryogenesis - general conditions

1. **B violation**
   - ✓ Exists in SM: sphalerons
   - $\Delta(B+L) \neq 0$ transitions when $\langle \phi \rangle = 0$
   - Exponentially suppressed when $\langle \phi \rangle \neq 0$

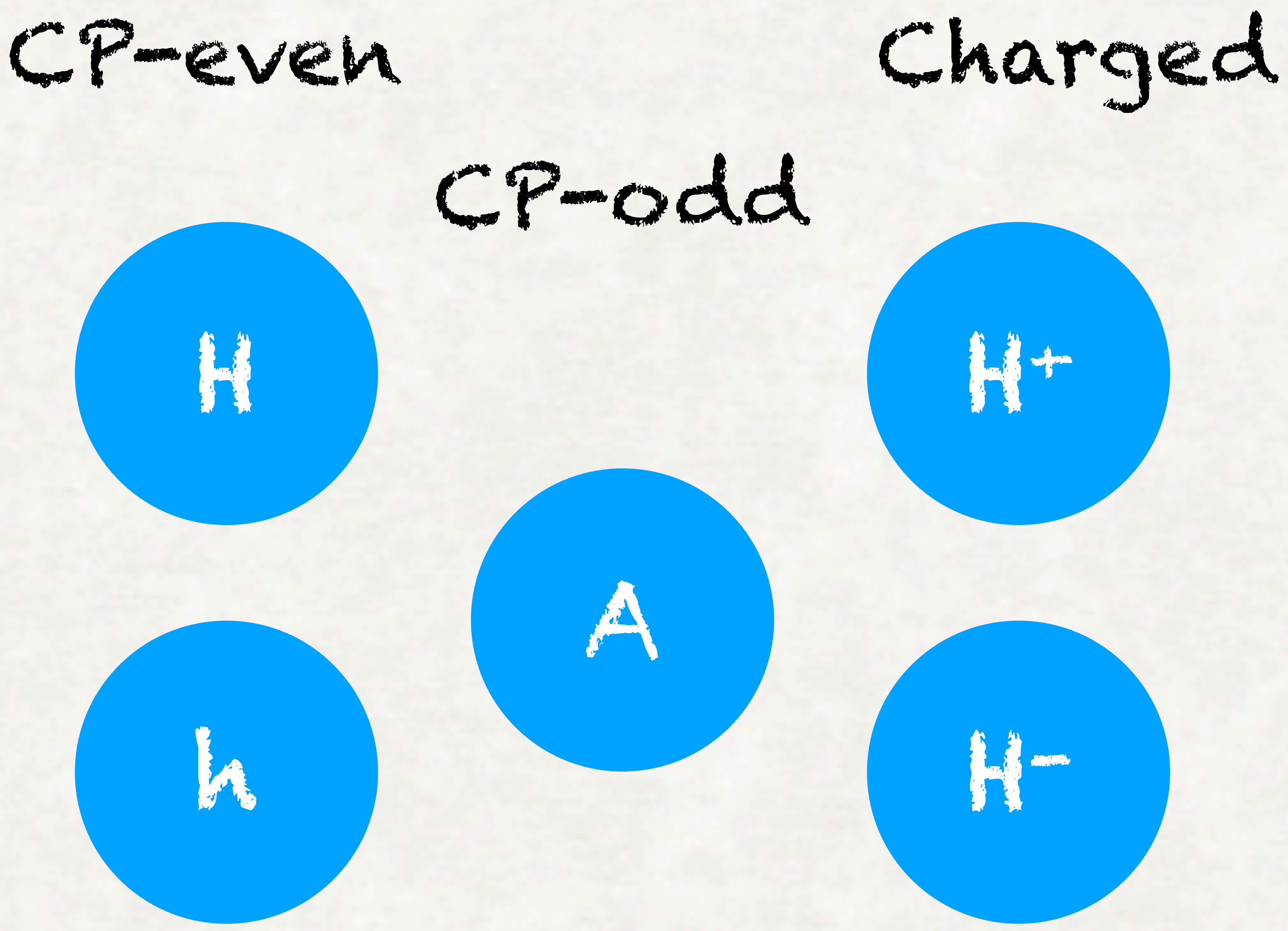
2. **C/CP violation**
   - ◉ Not enough from weak interactions - need new sources
   - ➡ extended Higgs sectors

3. **Non-equilibrium**
   - ◉ Does not exist in SM
   - Depends on form of effective Higgs potential at T_c - need 1st order phase transition
   - ➡ extended Higgs sectors



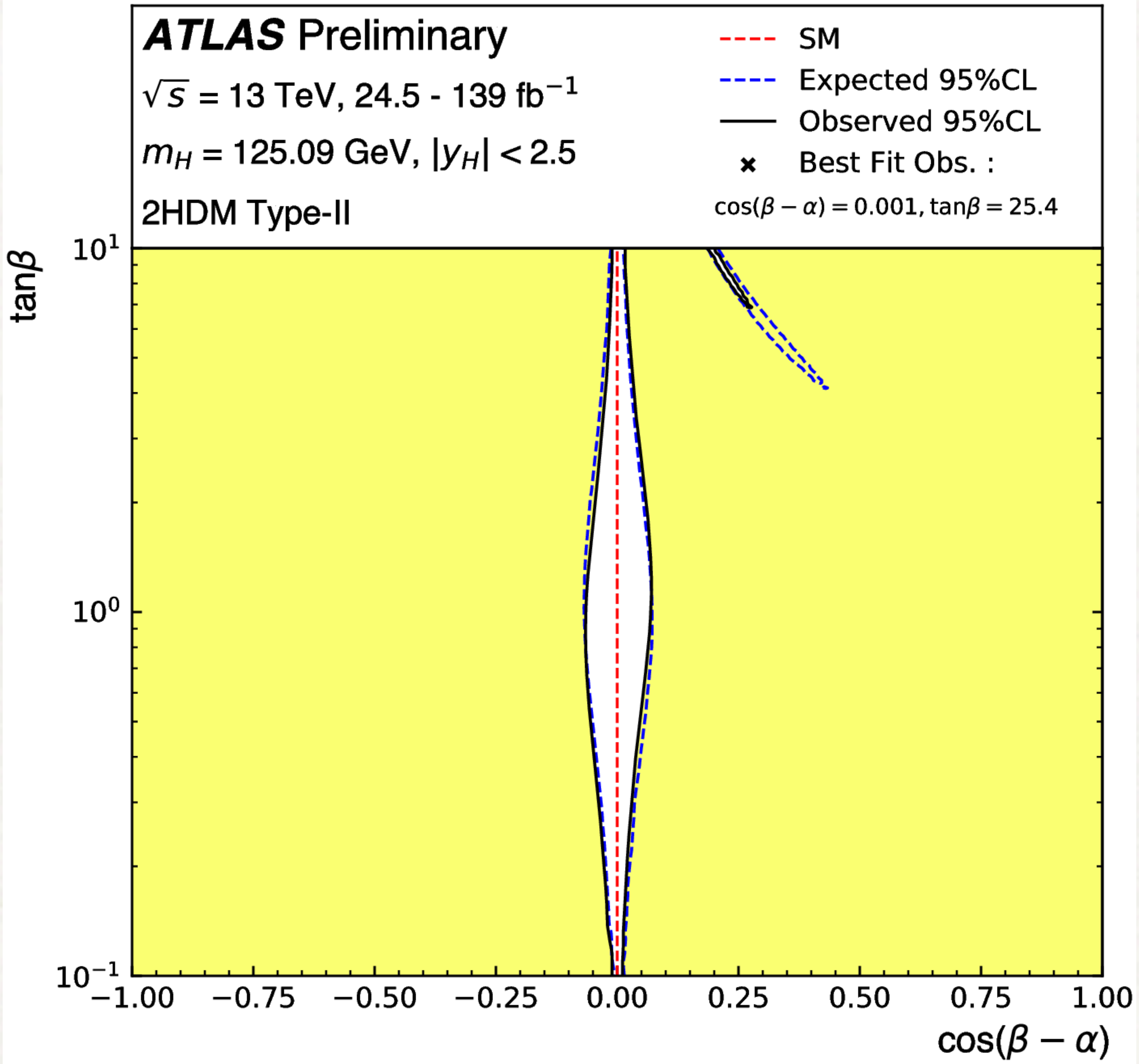
The 2 Higgs Doublet Model

- related to other models (e.g. axion, MSSM, ...)
- 5 Higgs bosons
- Free parameters:
  m_A, m_H, $m_{H\pm}$
  α: mixing between H, h
  tan**β**: ratio of vacuum expectation values
- Different Yukawa structures (Type I,II,...)
  suppressed/enhanced couplings to fermions
- Alignment limit: cos(β-α)=0
  h has the same couplings as the SM Higgs

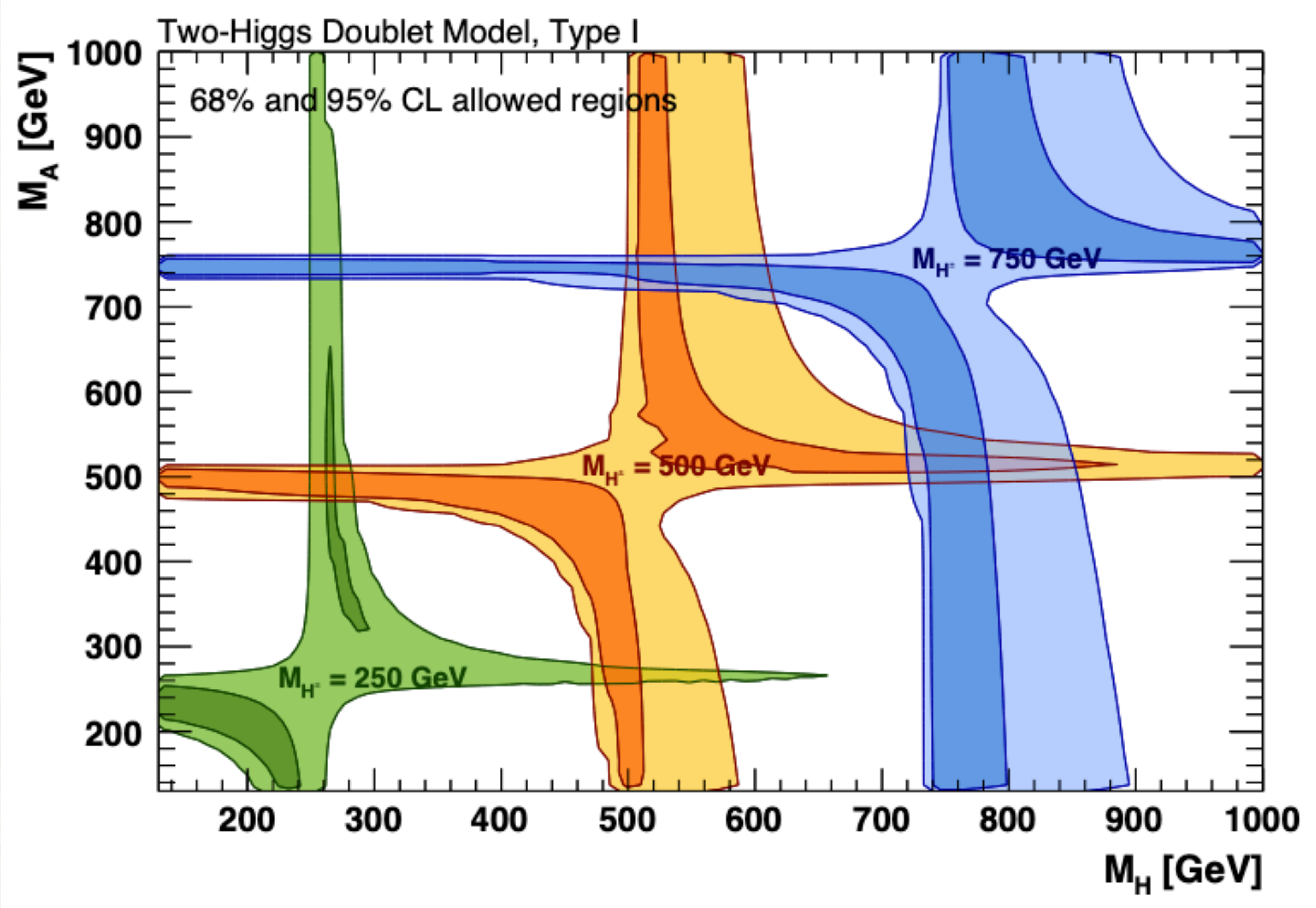


Branco et al, Phys.Rept. 516 (2012) 1
Rompotis, Ferrari, Symmetry 2021,13,2144

Existing constraints



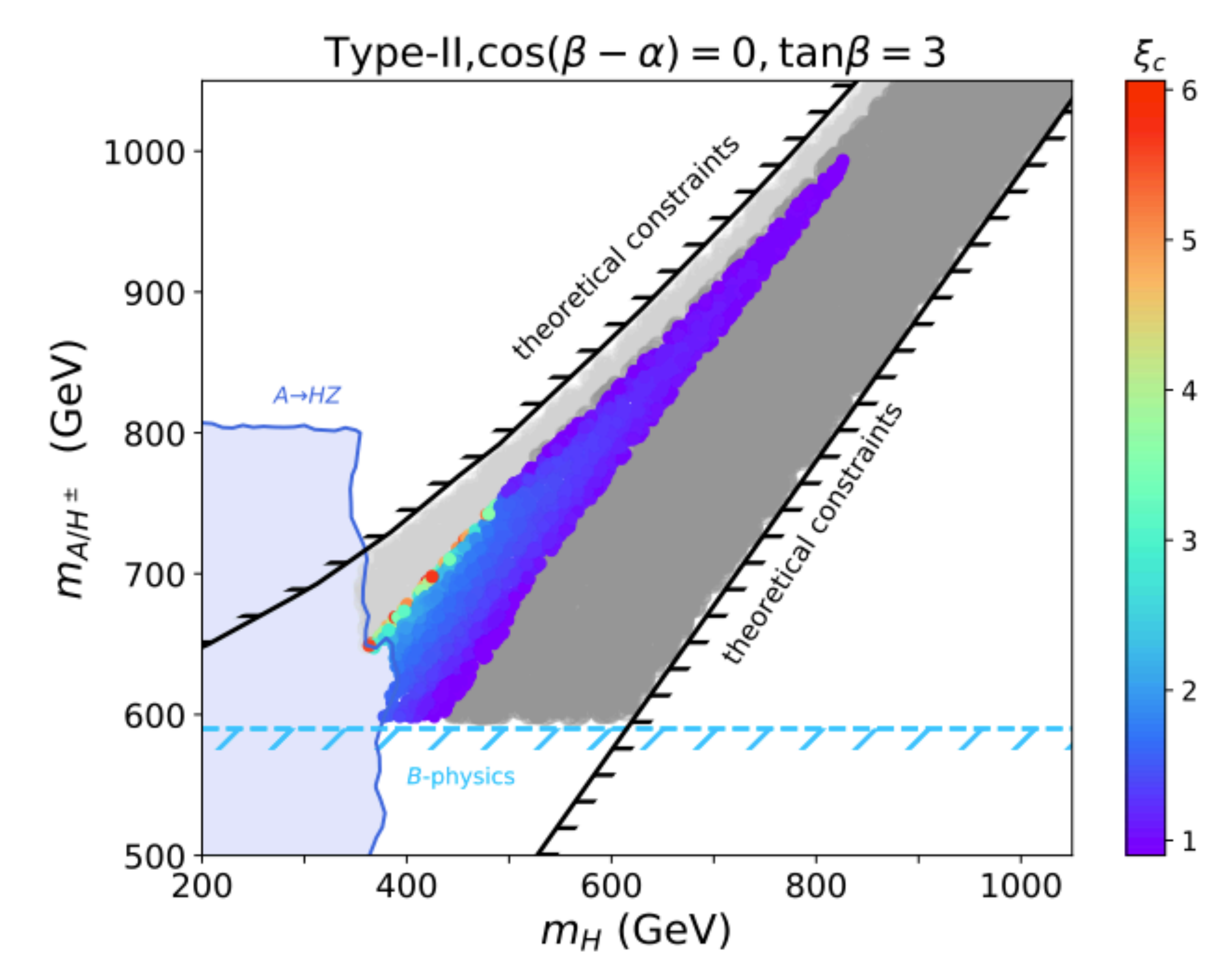
ATLAS-CONF-2021-053



Gfitter, EPJC 78 (2018) 675

- Higgs coupling measurements: we are close to alignment limit
- H± must be degenerate with A or H, but $m_A - m_H$ **can be big!**

What is needed for baryogenesis in 2HDM?

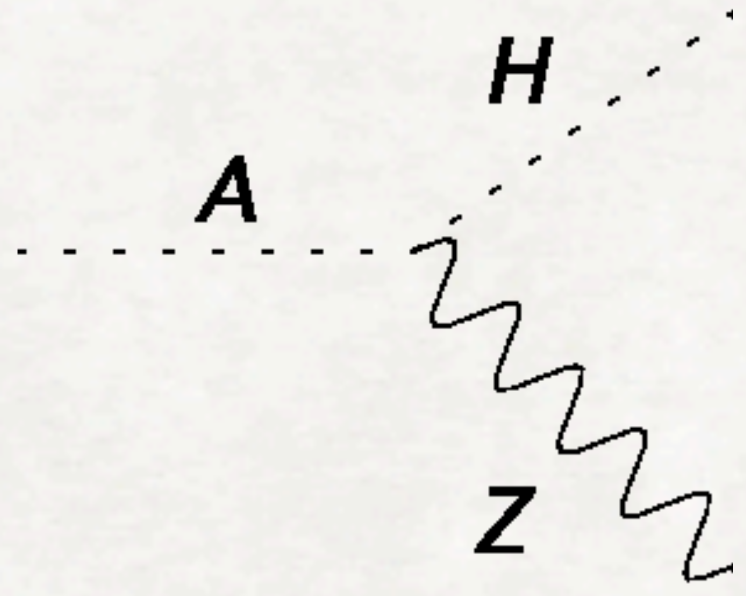


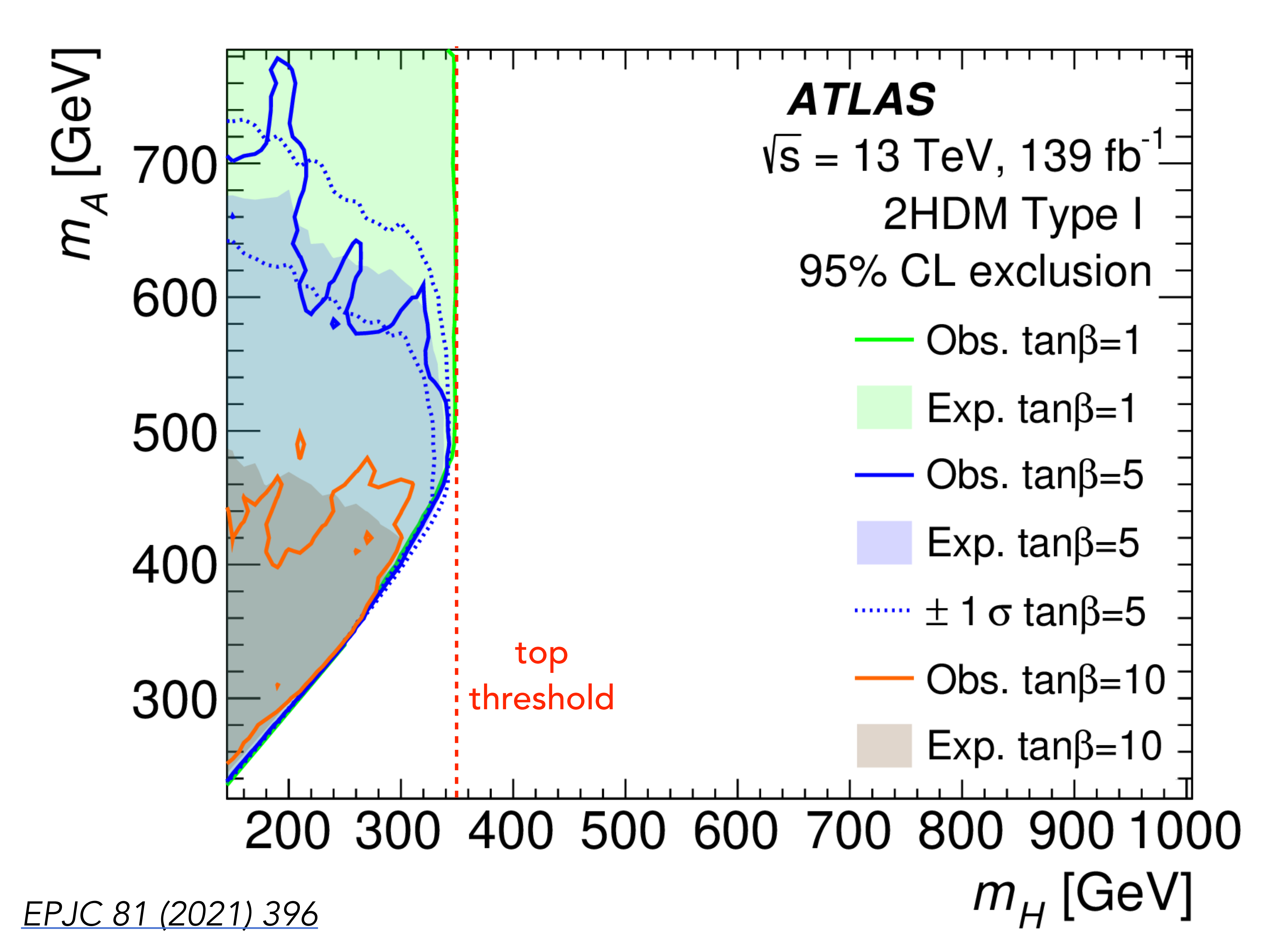
Su, et al, JHEP 04 (2021) 219

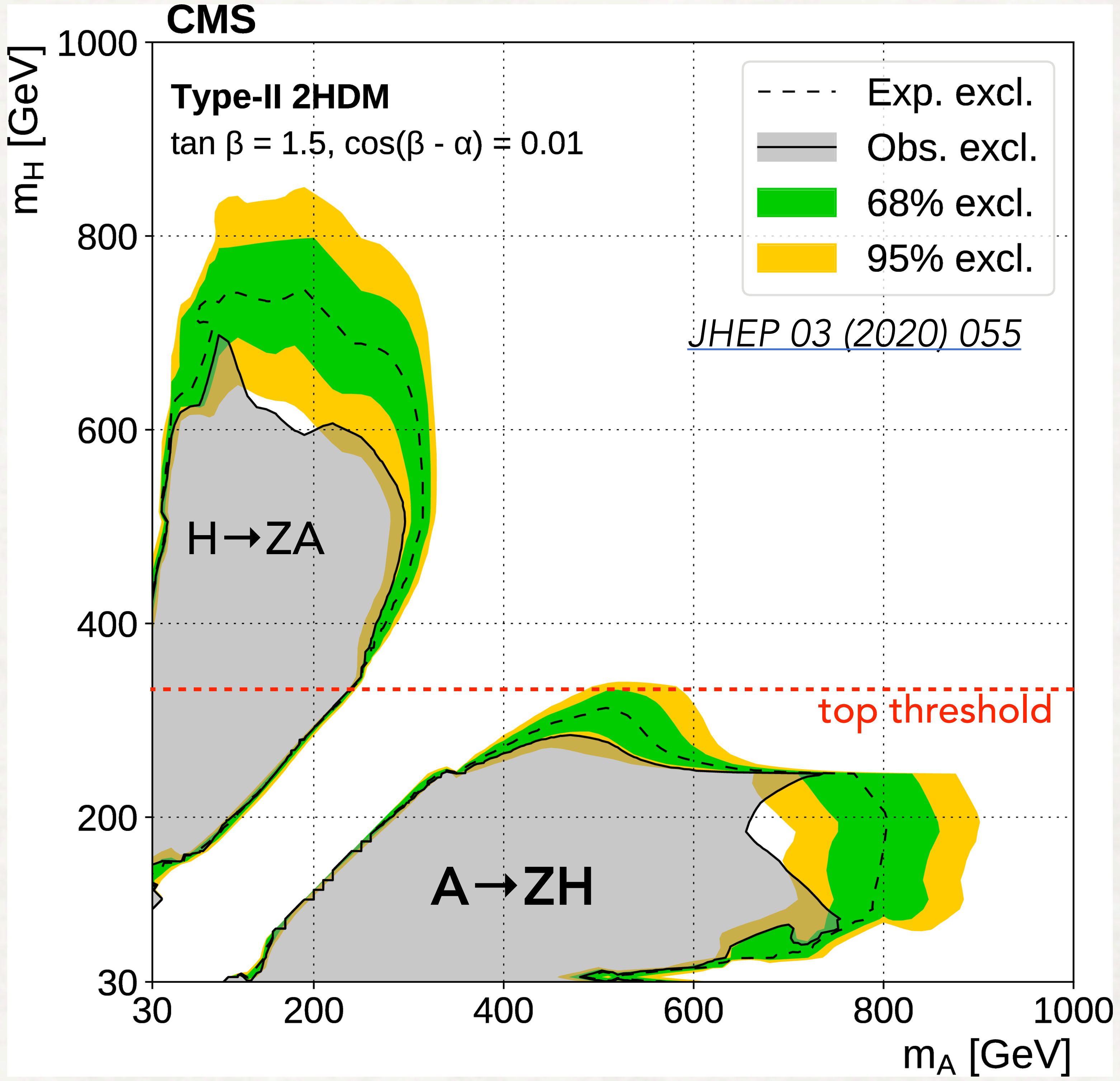
- For baryogenesis to occur $m_A - m_H$ **mass splitting is needed**
- Generally A should not be too heavy and $m_A - m_H \simeq 200$ GeV favoured

➡ **Search for two heavy Higgs** bosons with a **large mass splitting** with masses up to about **1 TeV**

Previous searches for A→ZH





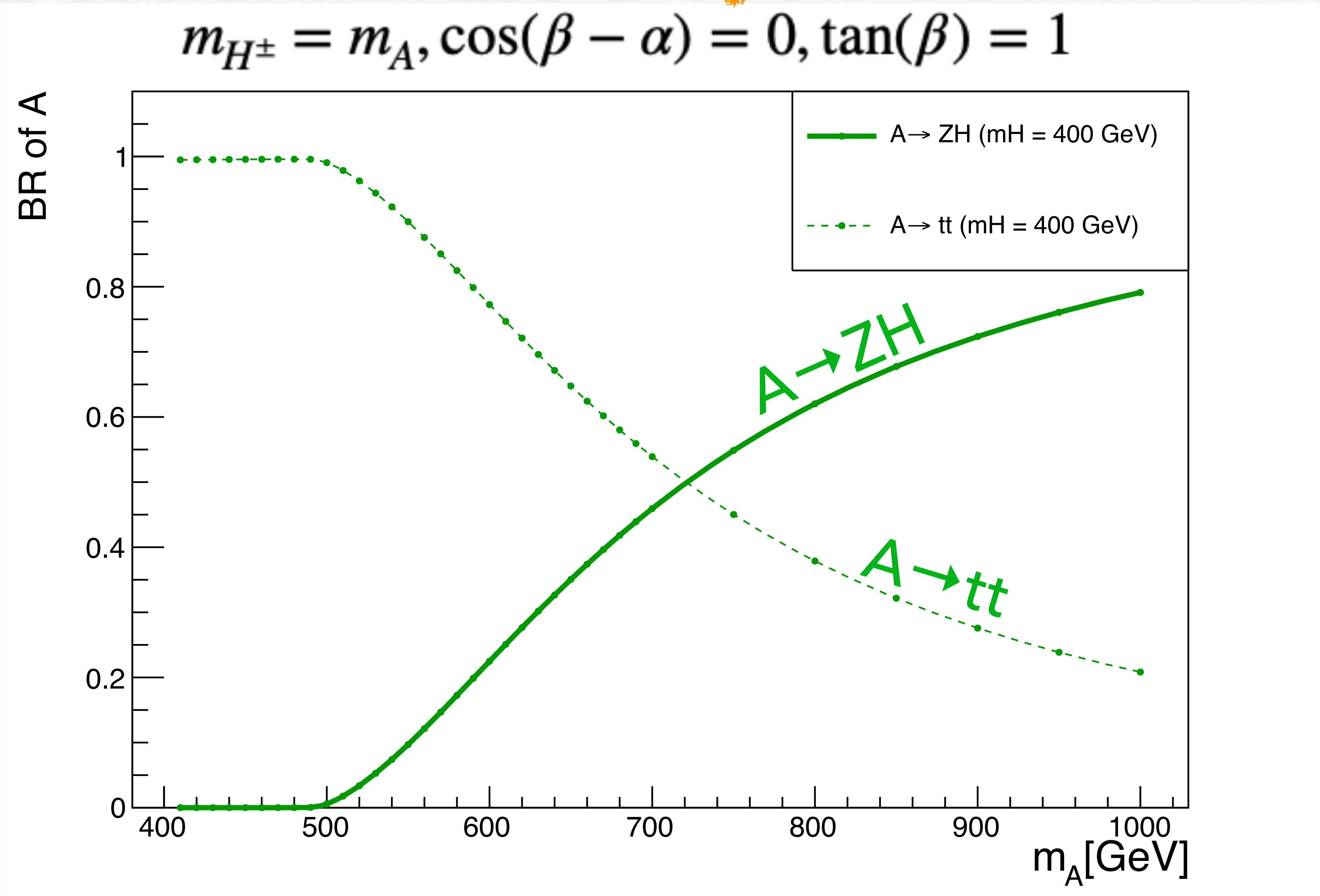


- $H \to b\bar{b} + Z(\ell\ell)$ [ATLAS & CMS]: sensitivity stops at top threshold
- $H \to \tau\tau$ [CMS]: much less sensitive than $H \to b\bar{b}$
- $H \to WW$ [ATLAS]: not sensitive when $\cos(\beta - \alpha) = 0$
- $H \to hh$ [ATLAS] : can probe high m_H but not sensitive when $\cos(\beta - \alpha) = 0$

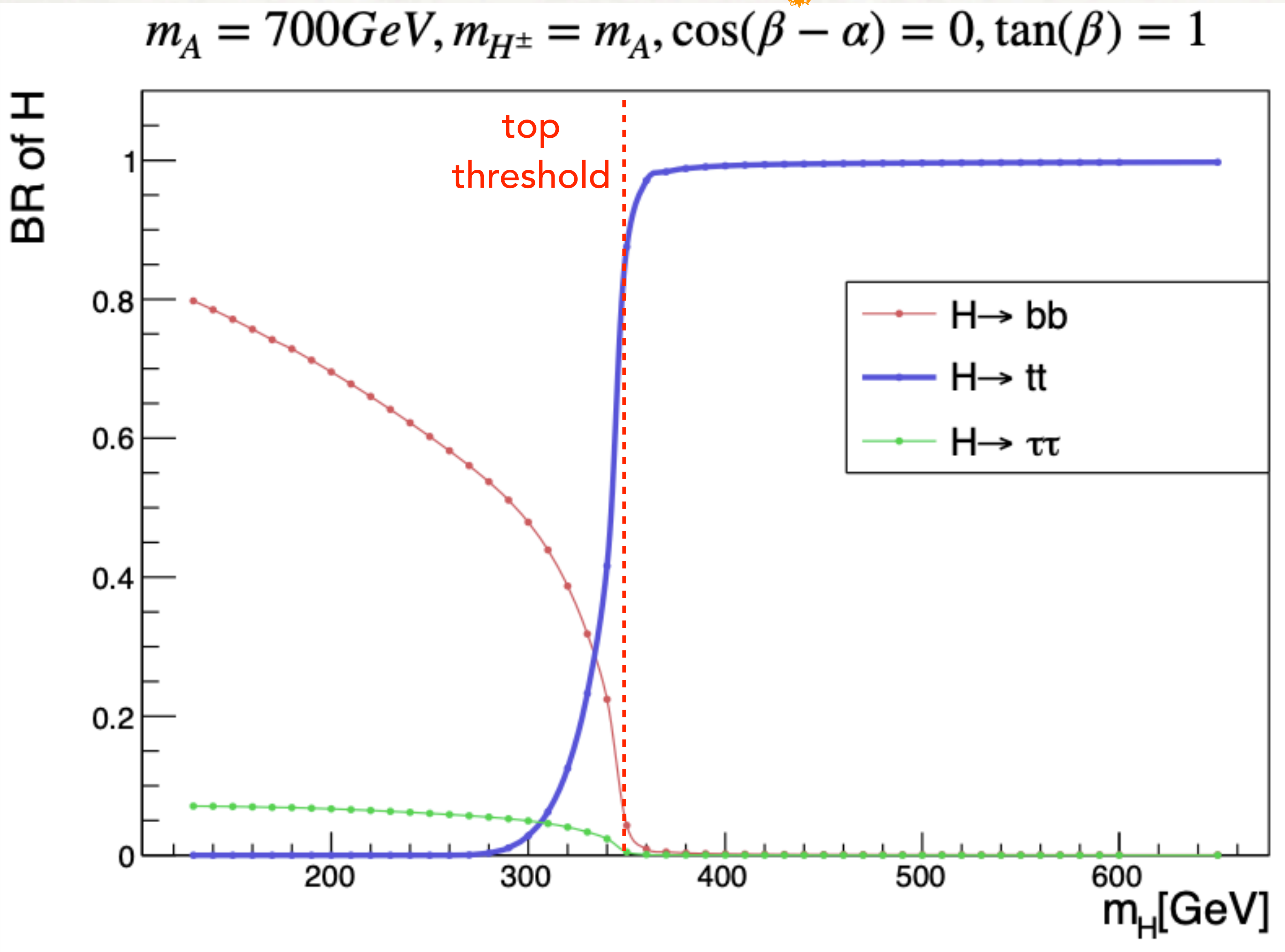
➡ None of these could probe $m_H > 350$ GeV in the alignment limit

How to extend the covered phase space

A decay



H decay



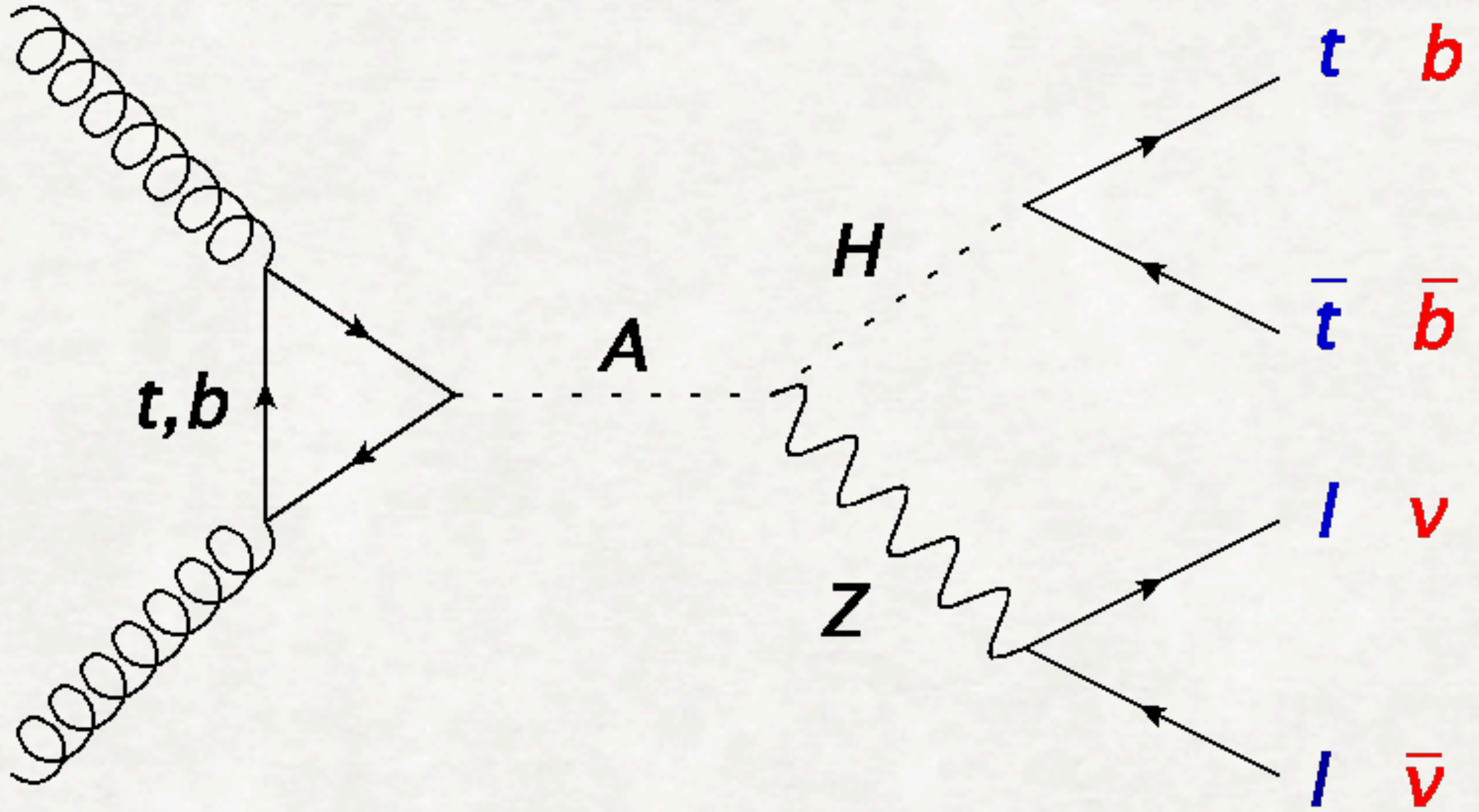
- $A \to ZH$ dominates when $m_A - m_H \gtrsim 250$ GeV
- $H \to b\bar{b}$ dominant below top threshold
- $H \to t\bar{t}$ dominant above top threshold

➡ $A \to Z(\ell\ell)H(t\bar{t})$ to cover the region $m_H > 350$ GeV

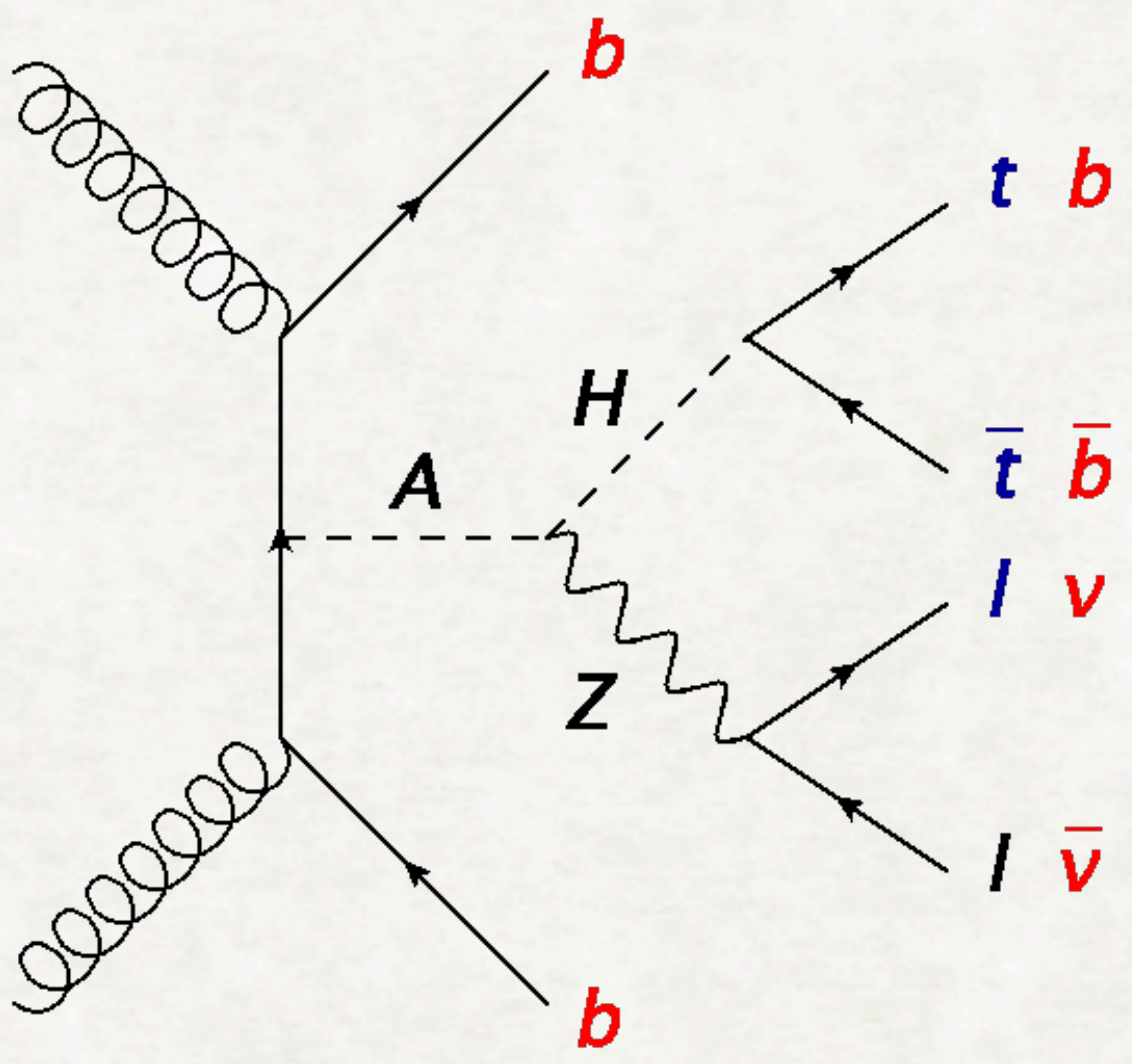
➡ $A \to Z(\nu\bar{\nu})H(b\bar{b})$ to cover the region with $m_H < 350$ GeV at high m_A (complementary to $\ell\ell b\bar{b}$)

Production modes

ggF



bbA



- Note - for Type-II 2HDM (MSSM-like)
  - $g_{At\bar{t}} \sim g_{Ht\bar{t}} \sim 1/\tan\beta$
  - $g_{Ab\bar{b}} \sim g_{Hb\bar{b}} \sim \tan\beta$

➡ $H \to t\bar{t}$ channel generally probes lower $\tan\beta$ than $H \to b\bar{b}$

➡ 2 production modes with different sensitivity to $\tan\beta$

Experimental analyses

ATLAS-CONF-2023-034

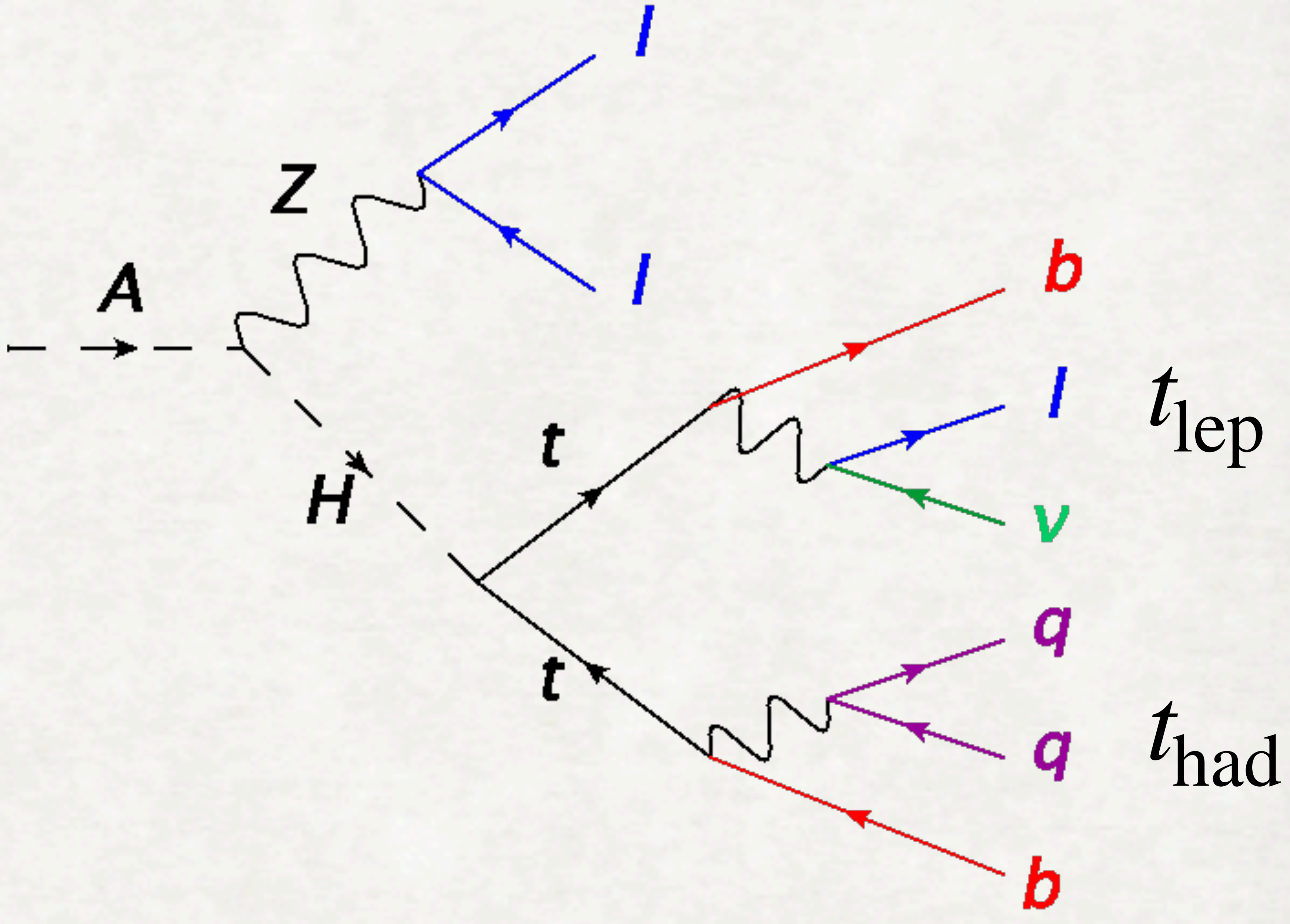
The lltt final state

- Use semi-leptonic top decays
  - relatively high BR
  - only one $\nu \rightarrow$ better m_t resolution than di-lepton

- 3 leptons, 2 b-jets, 2 light-jets (from W), moderate E_T^{miss}

- Reconstruction:
  - Z-candidate: $e^+e^-/\mu^+\mu^-$ pair with mass closest to m_Z
  - t_{lep} = lepton + closest b-jet + E_T^{miss}
  - t_{had} = 2 light-jets with mass closest to m_W + remaining b-jet

➡ fit $\Delta m = m(t\bar{t}Z) - m(t\bar{t})$ in bins of $m(t\bar{t})$



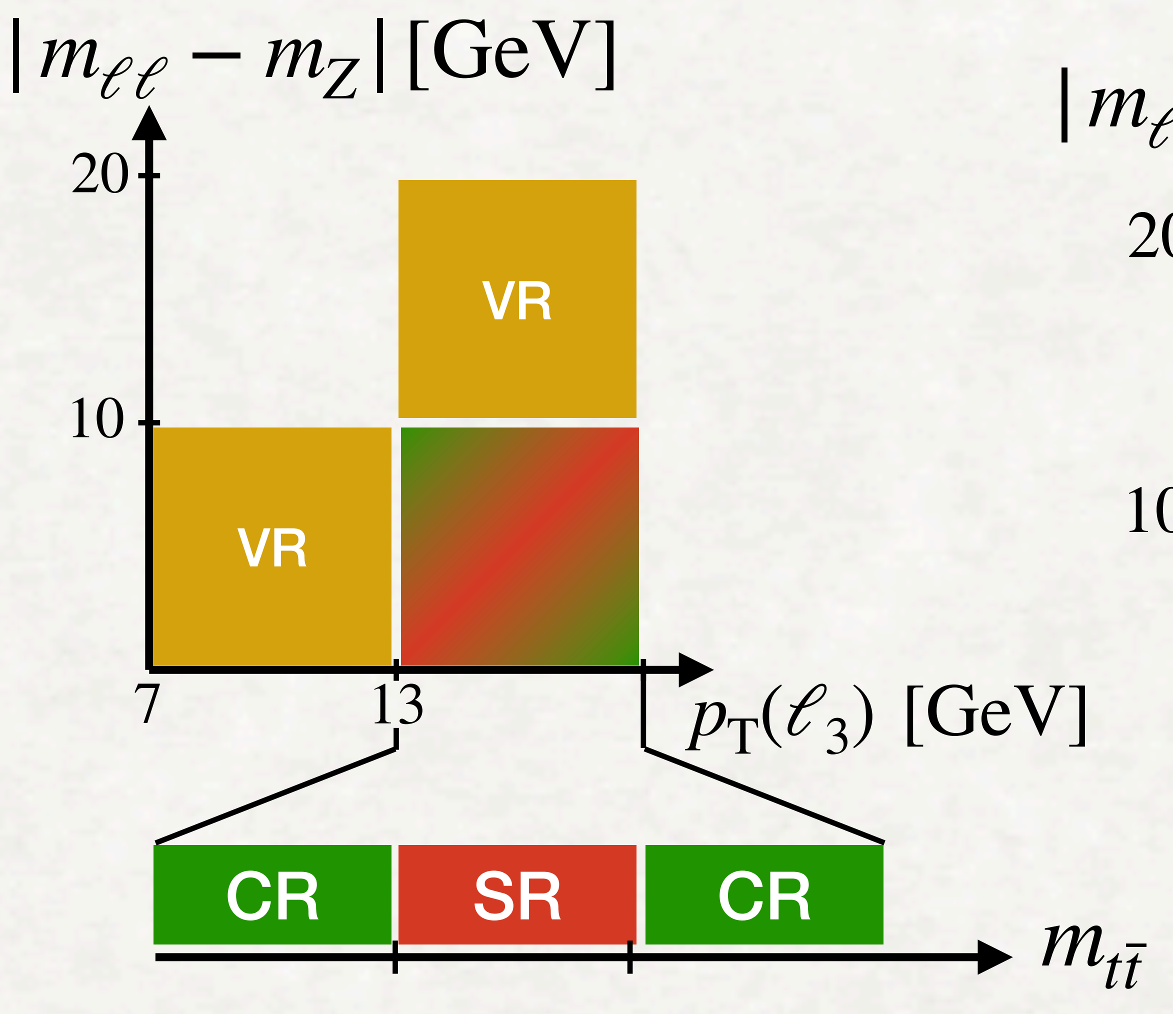
Signal and control regions

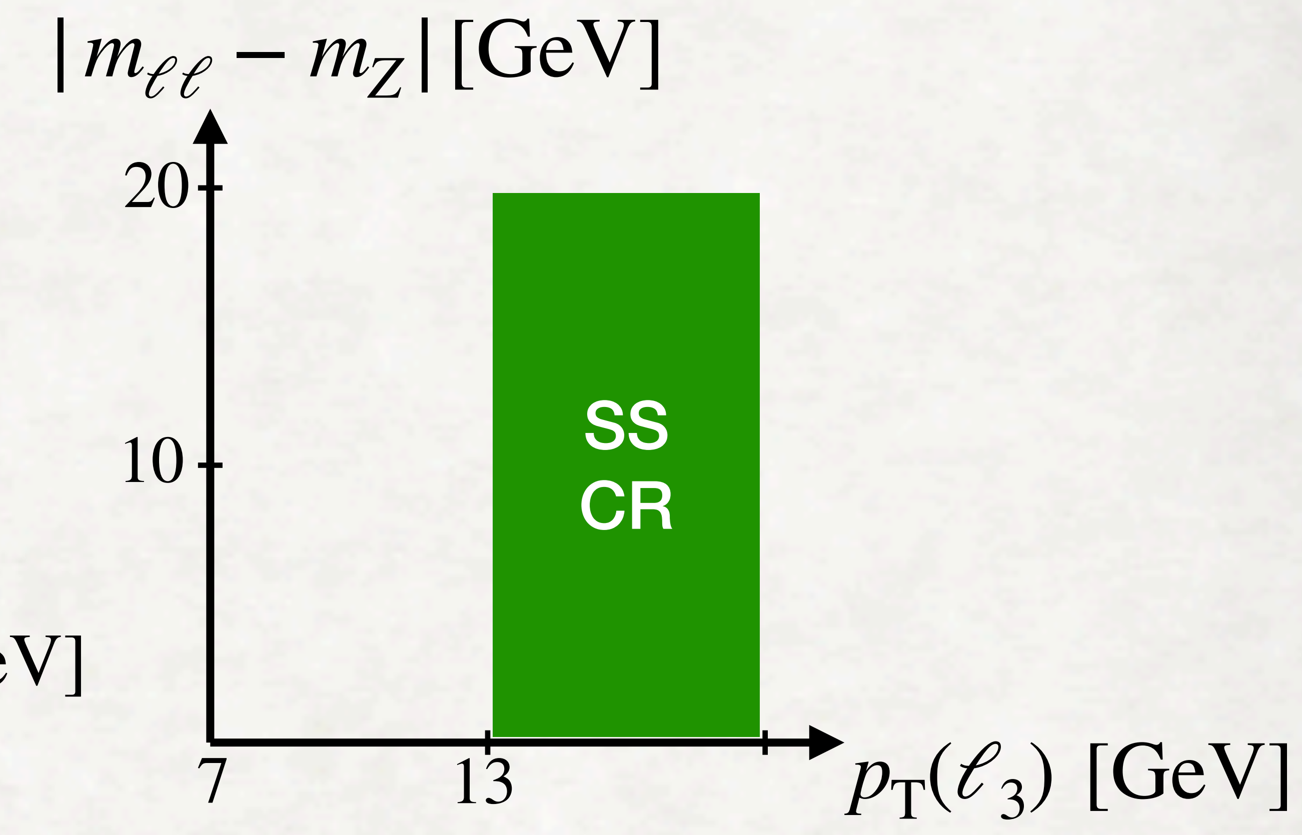
- Backgrounds constrained by profile likelihood fit using control regions defined using $\{p_T(\ell_3), m(\ell\ell), m(t\bar{t})\}$ cuts

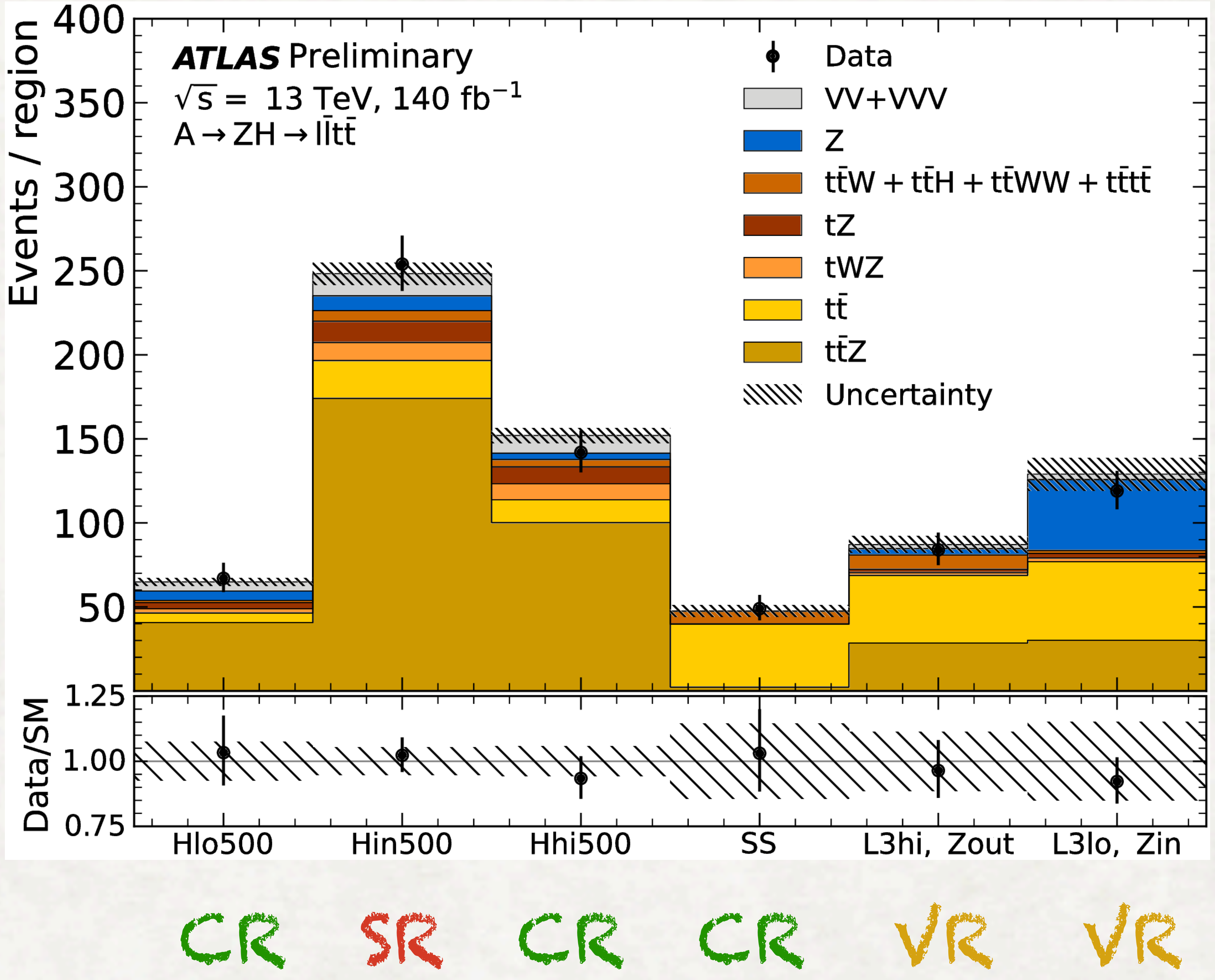
- Major backgrounds:
    - $t\bar{t}Z$: irreducible but no resonant $t\bar{t}$ - constrained from $m(t\bar{t})$ side-band regions
    - $t\bar{t}$+fake lepton : use region with same-sign leptons

- 1-bin fit in control regions

- Sliding $m(H)$ window used to define SR
    - multi-bin fit in SR

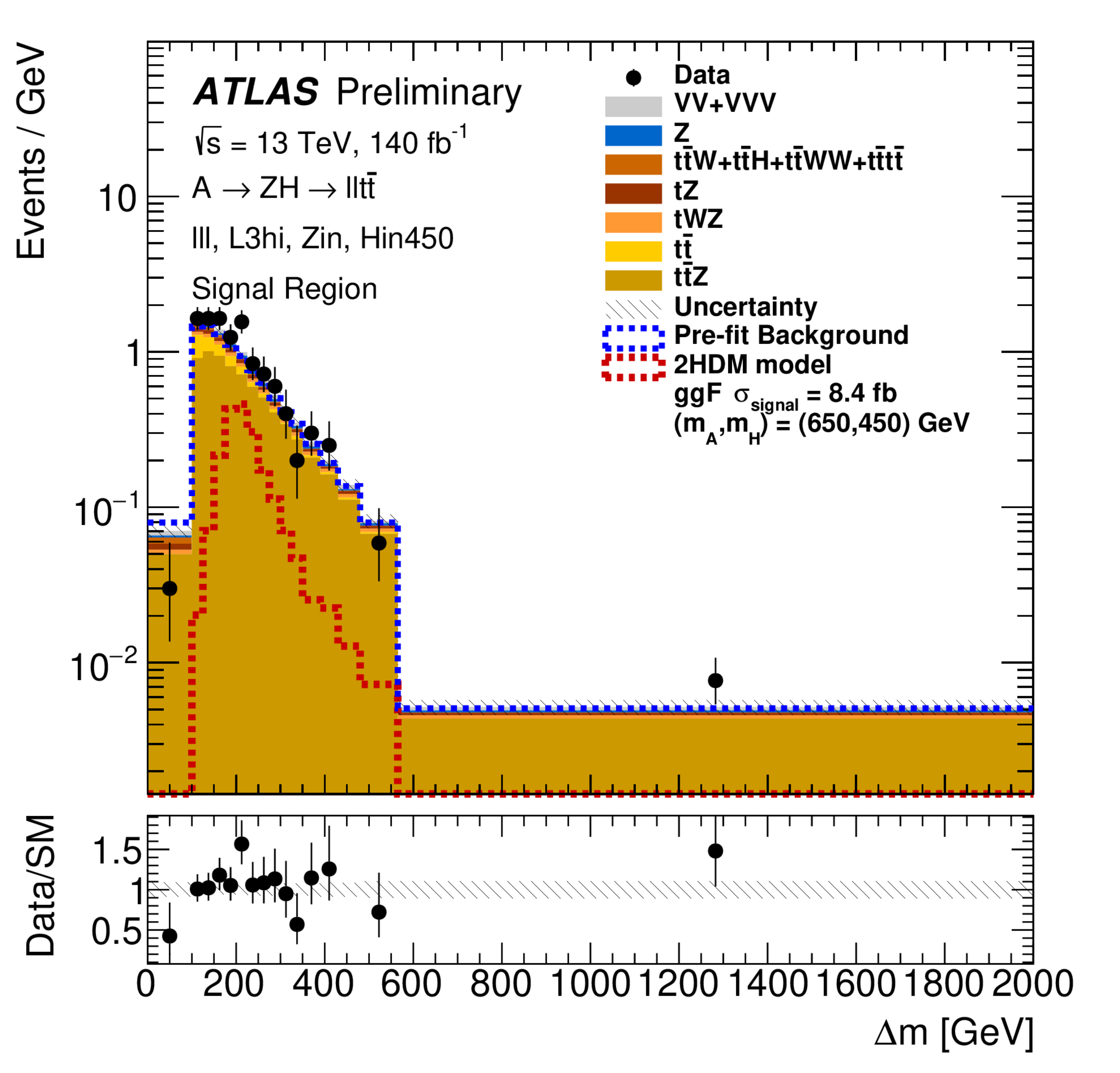


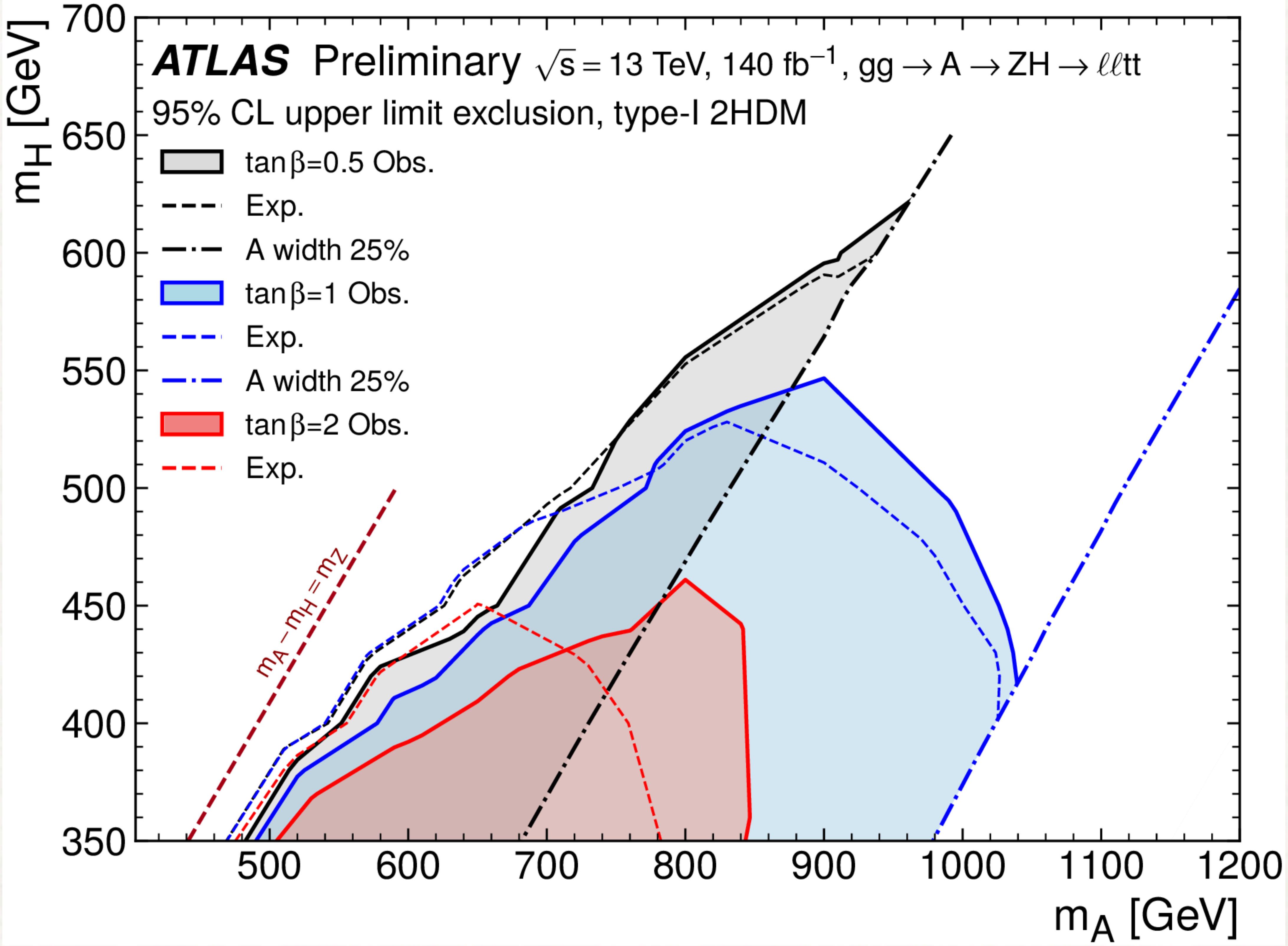




llt analysis - results

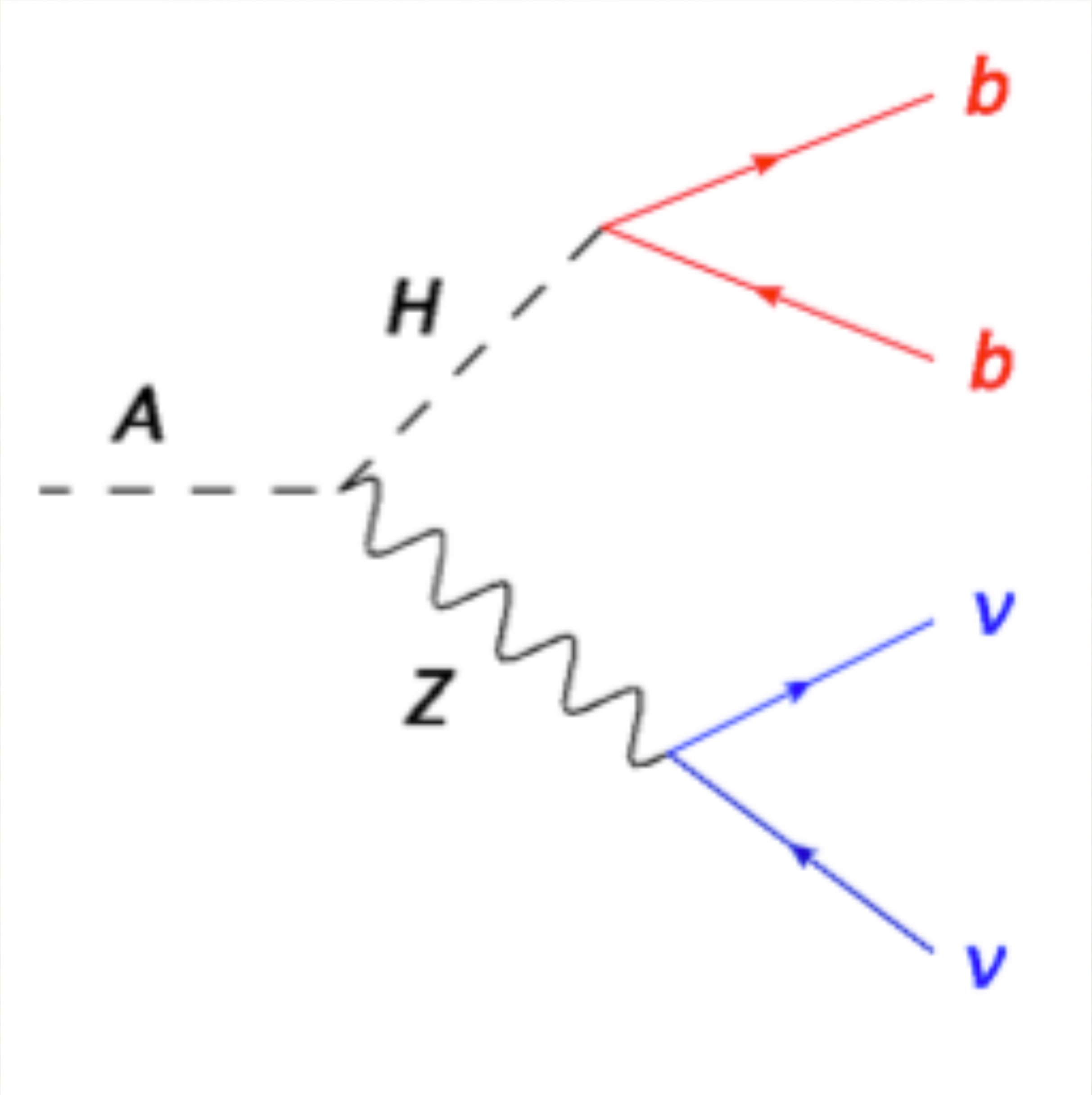
- $\Delta m = m(t\bar{t}Z) - m(t\bar{t})$ used in SR - expect bump if signal present
- No significant deviations from SM
- Highest deviation from SM prediction for $(m_A, m_H) = (650{,}450)$ GeV (2.85/2.35σ local/global)
- Exclusion limits provided for all 2HDM types





The ννbb final state

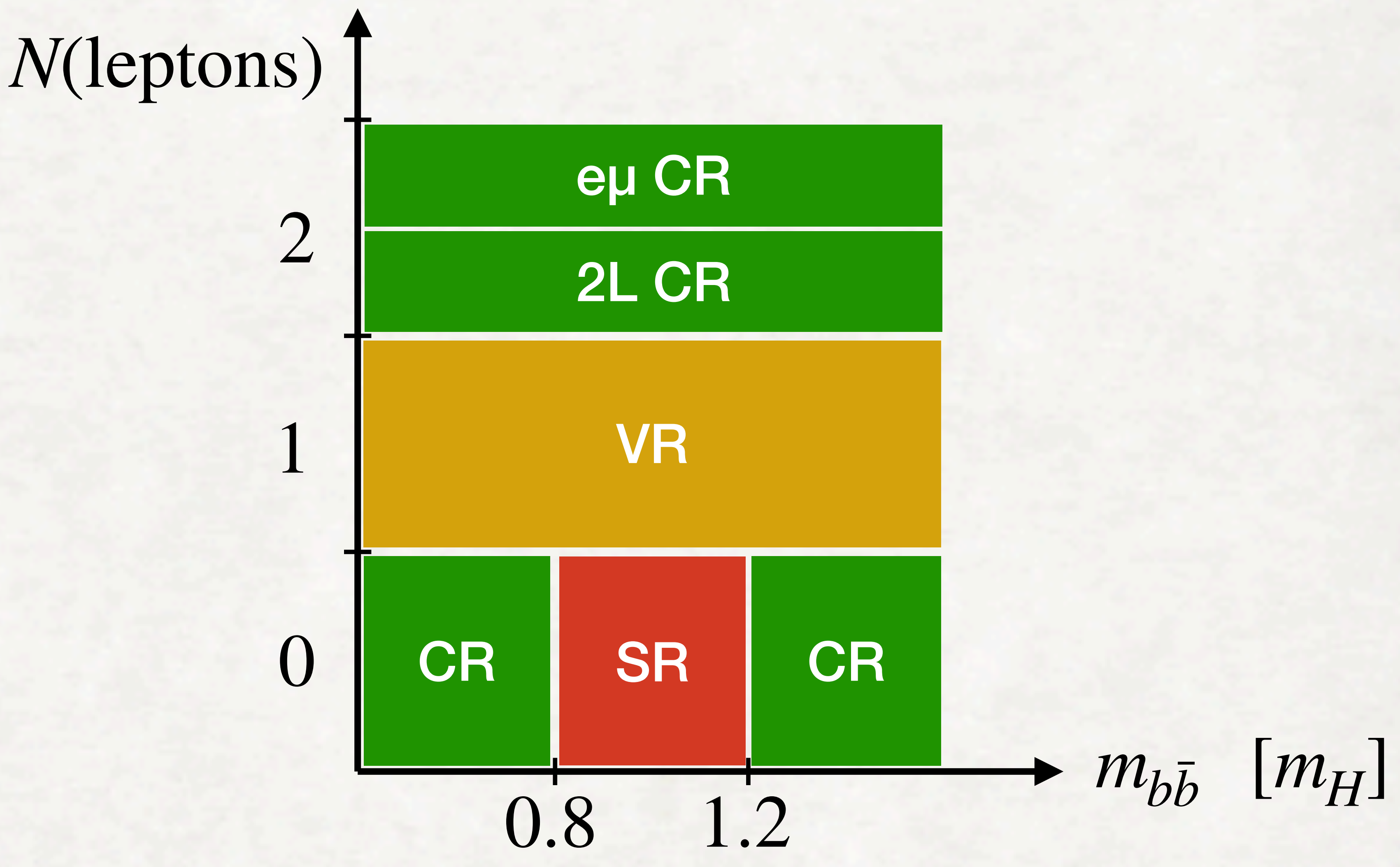
- 2 b-jets (ggF) or 3 b-jets (bbA), large E_T^{miss}
- Less complicated however significantly larger background than $\ell\ell t\bar{t}$
- Sophisticated cuts inspired by SM Higgsstrahlung and DM searches to suppress multi-jet and $t\bar{t}$ backgrounds
    - H-candidate: 2 highest p_T b-jets
    - can only reconstruct transverse mass of A-candidate

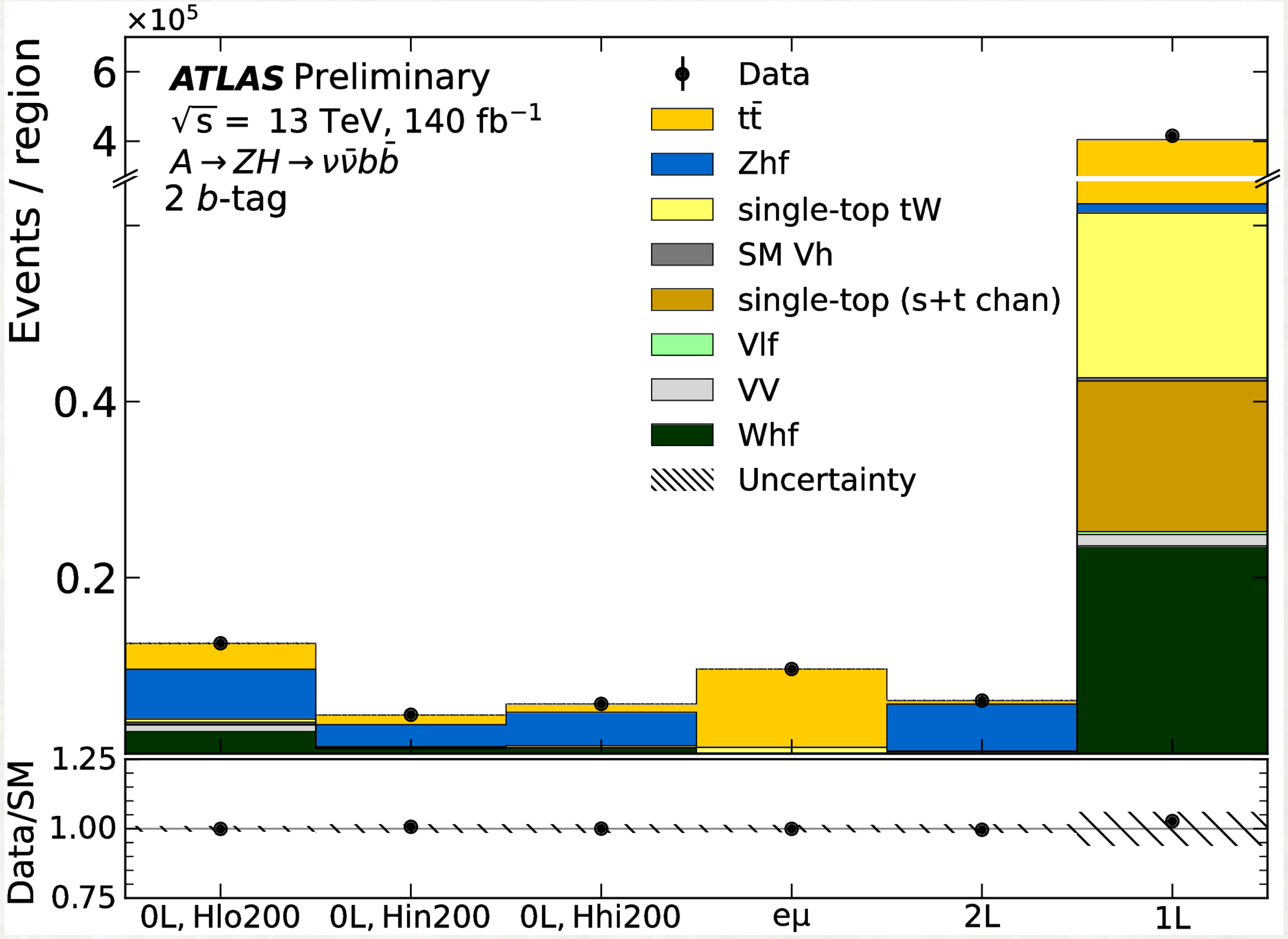


➡ ***2D bump search: fit $m_T(A)$ in bins of $m(b\bar{b})$***

Signal and control regions

- Major backgrounds:
  - **Z+hf** : can construct very pure control region by requiring exactly 2 same-flavour leptons
  - $t\bar{t}$: use eµ region
- few-bin fit in control regions
- Sliding $m(H)$ window used to define SR
  - multi-bin fit in SR

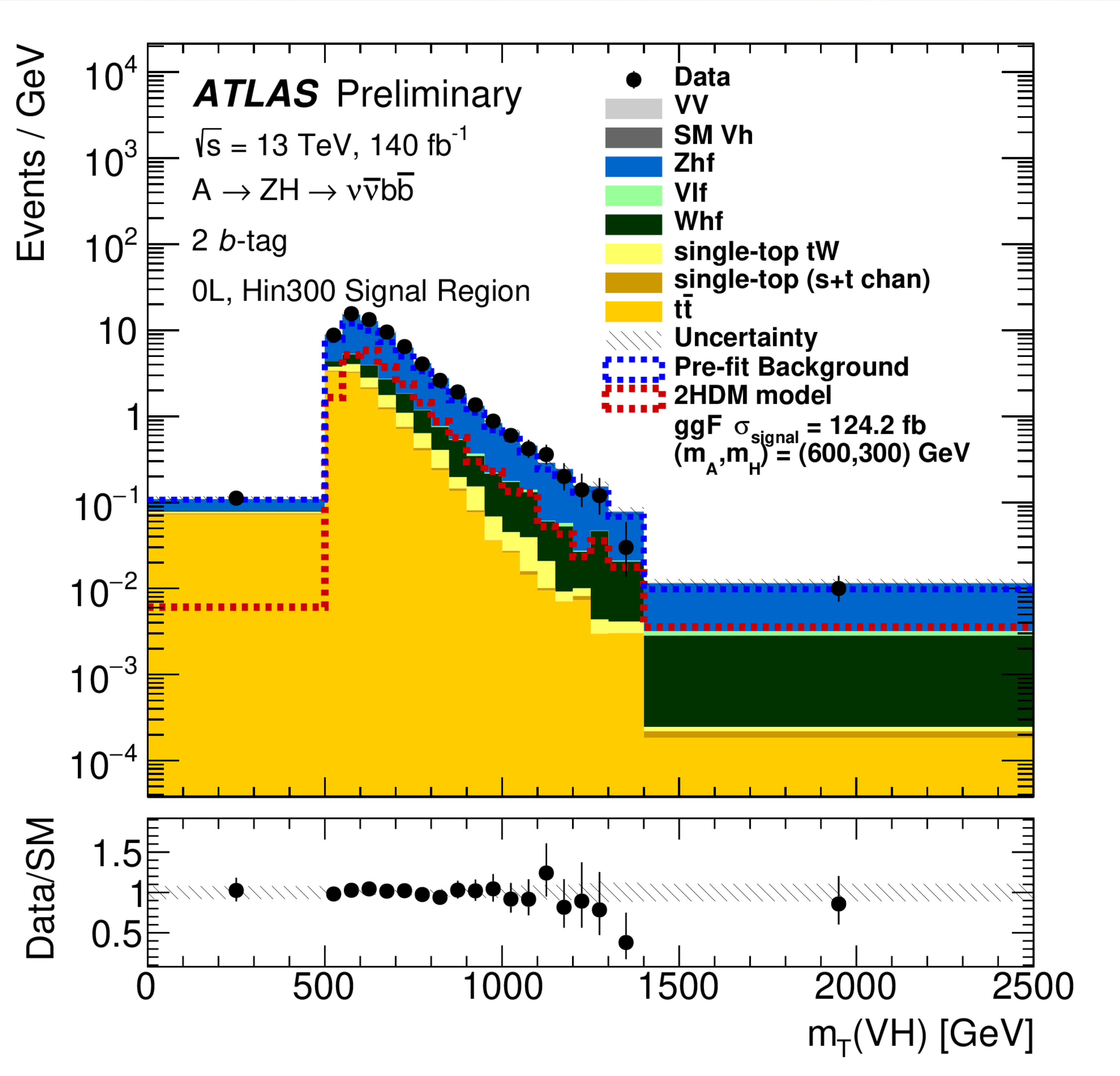


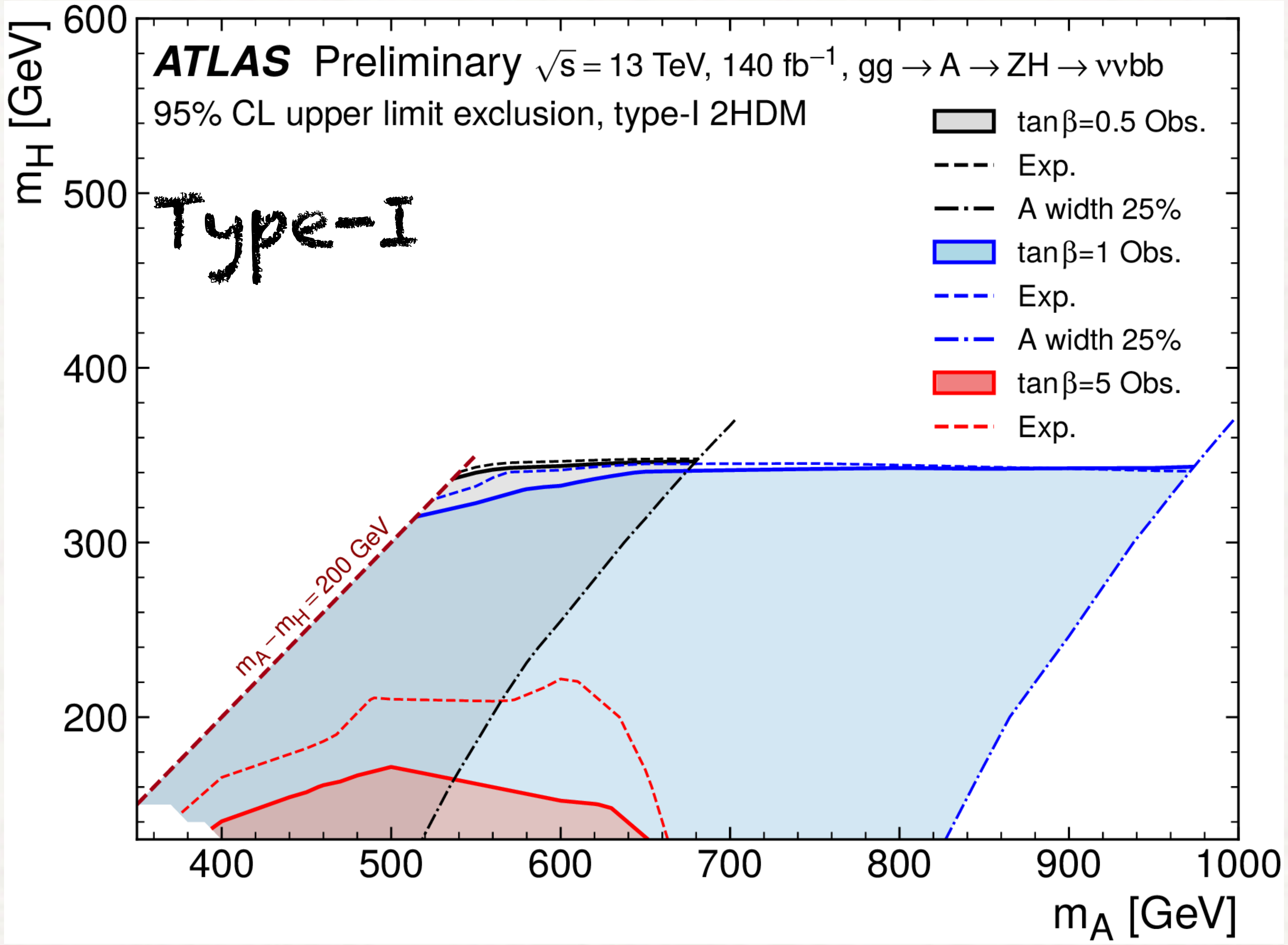


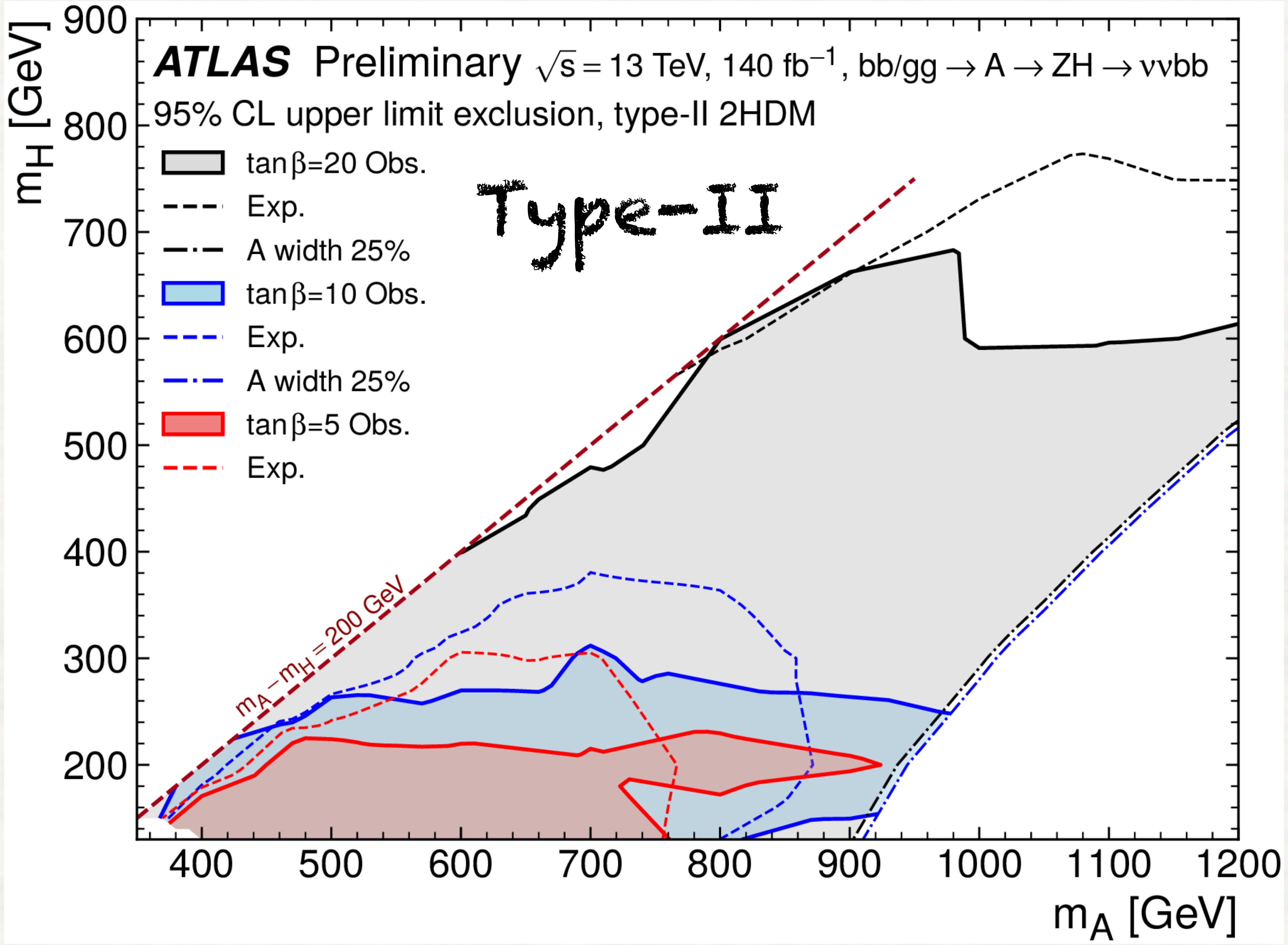
CR SR CR CR CR VR

vvbb analysis - results

- No significant deviations from SM
- Dedicated region with ≥ 3 b-jets allows to set very strong limits at high $\tan\beta$ (Type-II)

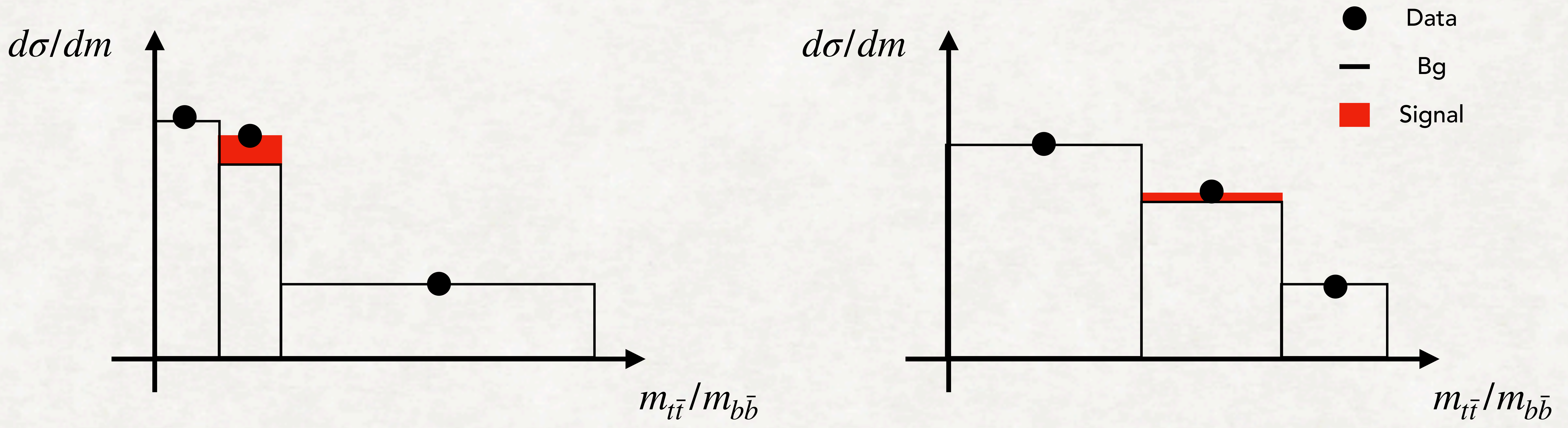






Model independent limits

- What if you have another model that predicts $t\bar{t}$+leptons or $b\bar{b} + E_T^{\text{miss}}$?
- Inject signal in one bin and perform multiple fits scanning the $m(t\bar{t})/m(b\bar{b})$ spectrum
- What is the maximum signal that the data can accommodate in a given $m(t\bar{t})/m(b\bar{b})$ bin

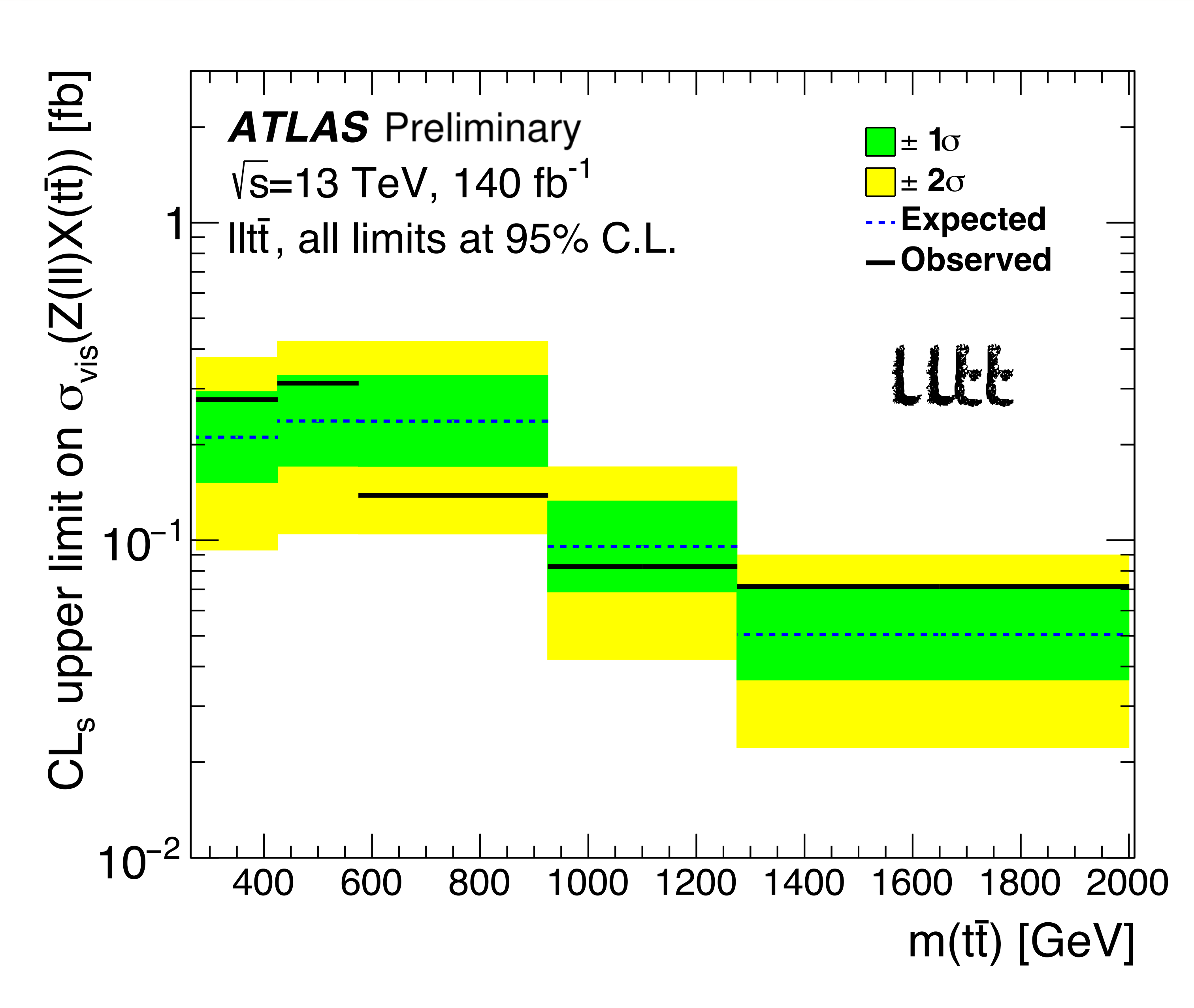


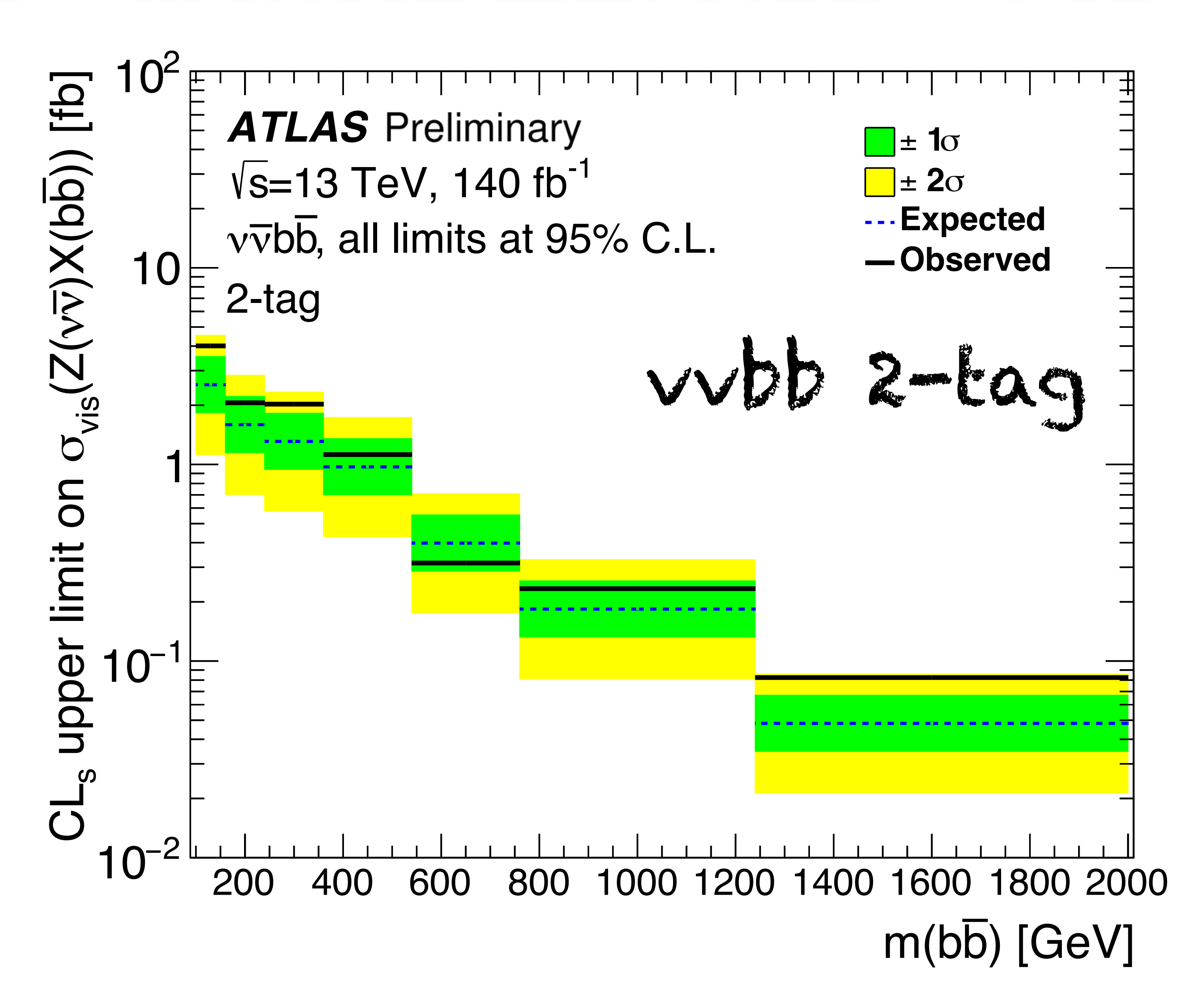
✓ **Reduced model dependence** - assumptions:

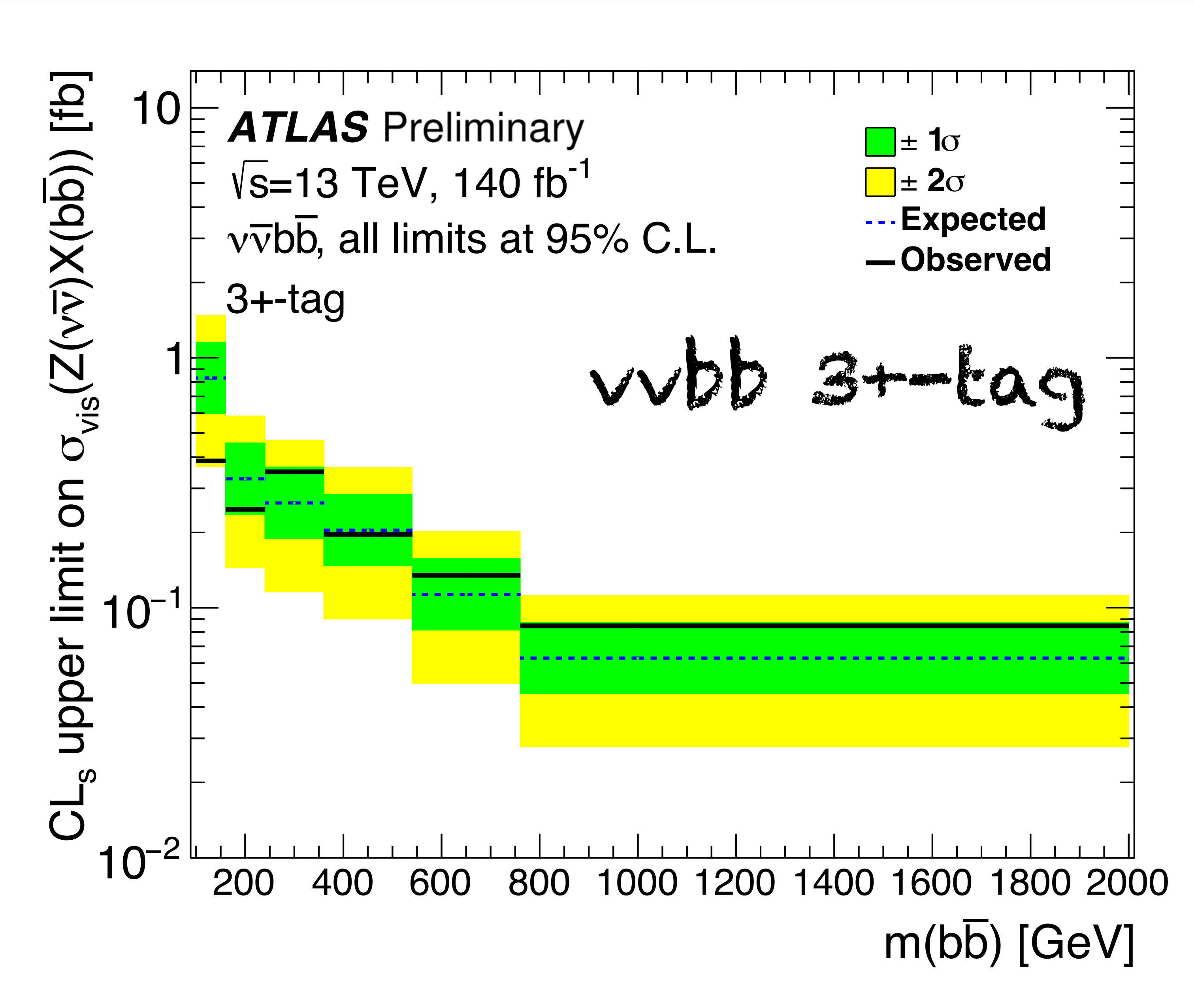
- final state is the same (3 leptons, 2 b-jets ($\ell\ell t\bar{t}$) / 0 leptons + E_T^{miss} ($\nu\bar{\nu}b\bar{b}$))
- $t\bar{t}/b\bar{b}$ pair produced by narrow resonance (however not necessarily in a cascade decay like $A \rightarrow ZH$)

Model independent limits

- We provide $\sigma^{\text{vis}}_{\text{limit}}$ = maximum cross-section allowed by data in each $m(t\bar{t}/b\bar{b})$ bin **at reco level**
- To be compared with: $\sigma^{\text{vis}}_{\text{theory}} \equiv \sigma_{\text{theory}} \times \text{BR} \times (\mathscr{A} \cdot \epsilon)$







- Allows for straightforward re-intrepretation provided that theorists can calculate reco-level acceptance*efficiency effects (we also provide the numbers for the 2HDM benchmark for comparison)

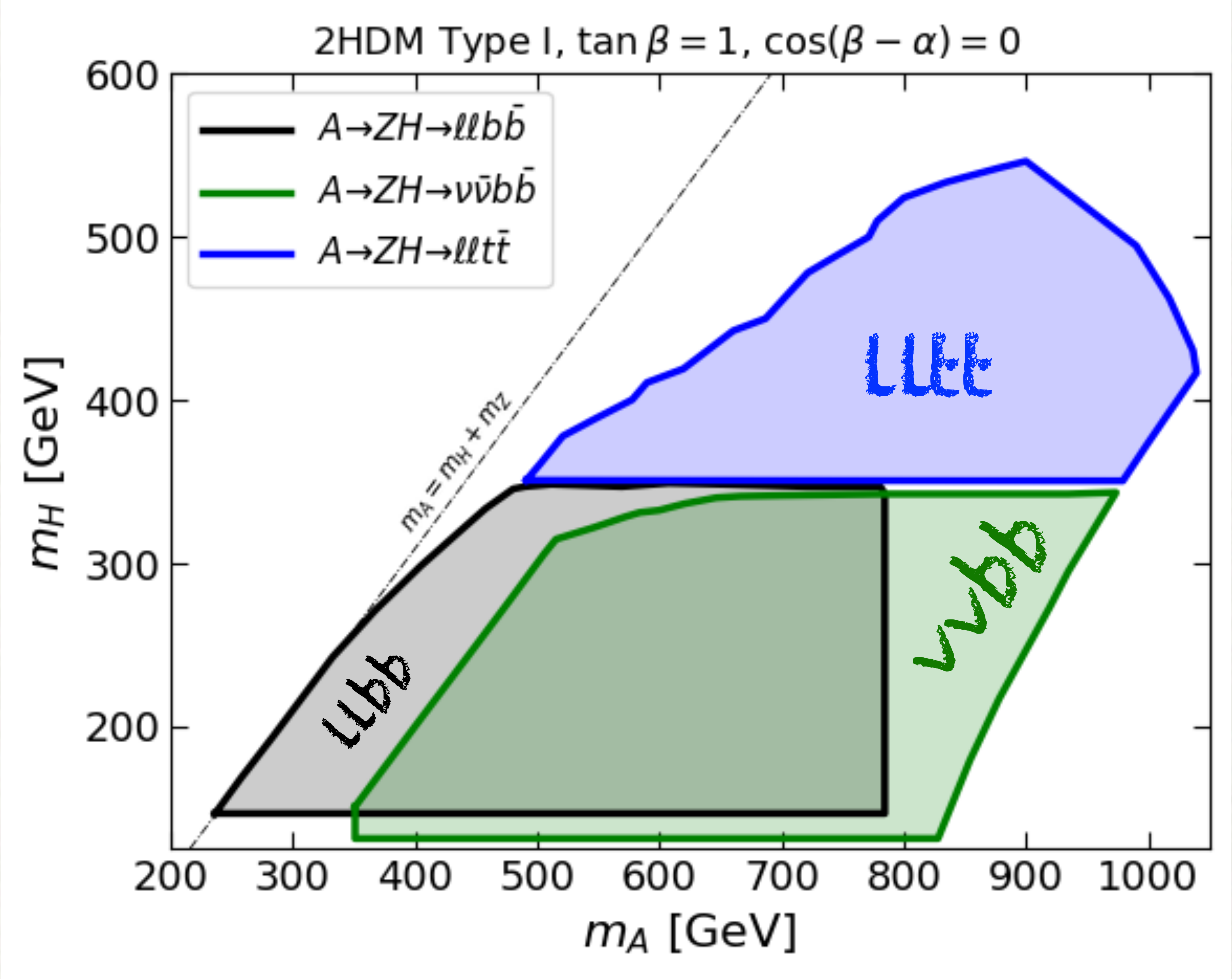
Conclusions

- New searches for $A \to ZH$ **extend the probed phase space to higher $m(A)$ & $m(H)$**

- $\ell\ell t\bar{t}$
  - first search for resonantly produced $t\bar{t}Z$
  - $m_H > 350$ GeV region in alignment limit

- $\nu\bar{\nu}b\bar{b}$
  - first search for $b\bar{b} + E_T^{\text{miss}}$ with $m(b\bar{b}) \gtrsim 200$ GeV
  - complements previous $\ell\ell b\bar{b}$ searches probing higher m_A

- Limits on visible cross-section provided for re-interpretations covering up to $m(b\bar{b}/t\bar{t}) = 2$ TeV



own compilation of results from ATLAS-CONF-2023-034 & EPJC 81 (2021) 396

Topical workshop: "Roadmap of Dark Matter models for LHC Run 3"

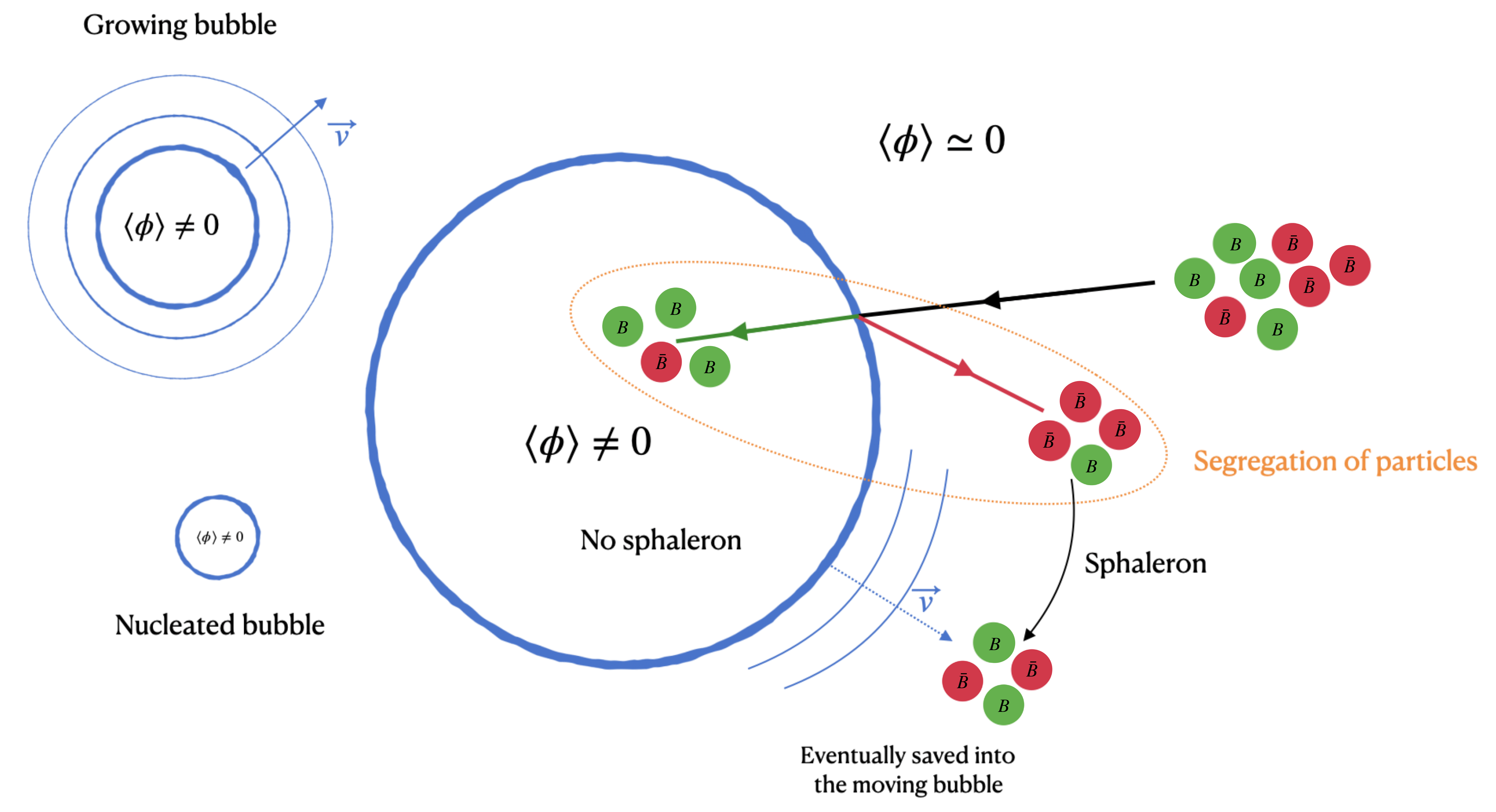
Spring 2024 @ CERN - organised by the LHC DM Working Group

Topics include:
- New models and unexplored signatures
- Invisible Higgs decays
- Simplified models (s-channel, t-channel)
- Extended scalar/gauge sectors

If you are interested: register & submit contribution: https://indico.cern.ch/event/1303940/

Backup

EW baryogenesis in 2HDM

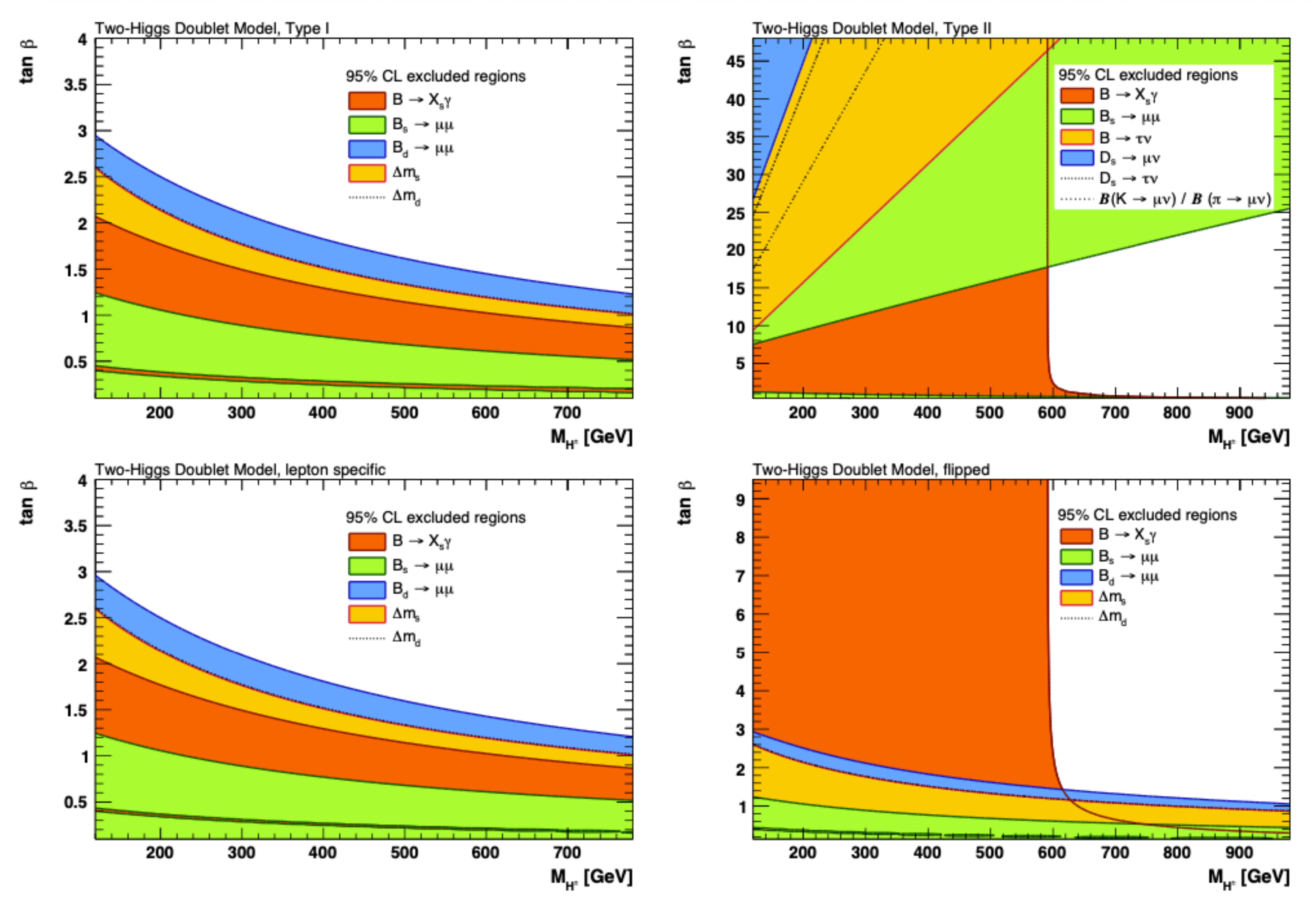


Adapted from R. Gannouji, Galaxies 2022, 10(6), 116

2HDM couplings

Coupling modifier	Type I	Type II
$\xi(h,u)$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$
$\xi(h,d)$, $\xi(h,l)$		$s_{\beta-\alpha}-c_{\beta-\alpha}t_\beta$
$\xi(H,u)$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$
$\xi(H,d)$, $\xi(H,l)$		$c_{\beta-\alpha}+s_{\beta-\alpha}t_\beta$
$\xi(A,u)$	$1/t_\beta$	$1/t_\beta$
$\xi(A,d)$, $\xi(A,l)$		t_β
$\xi(h,VV)$	$s_{\beta-\alpha}$	
$\xi(H,VV)$	$c_{\beta-\alpha}$	
$\xi(A,VV)$	0	

2HDM constraints



lltt event selection

Cut	Regions				
	ss (CR)	L3hi_Zout (VR)	Hlo / Hhi (CR)	Hin (SR)	L3lo_Zin (VR)
N leptons	3				
$p_{\mathrm{T}}\ (\ell_1)$	> 27 GeV				
N jets	≥ 4				
N b-jets	2				
$\lvert\eta^{\mathrm{ZH-r.fr.}}_{H\mathrm{-cand}}\rvert$	$< 2.2 + 0.0004 \cdot m_H^{\mathrm{cand}} - 0.0011 \cdot m_A^{\mathrm{cand}}$				
$p_{\mathrm{T}}\ (\ell_3)$	> 13 GeV				> 7 GeV & < 13 GeV
Lepton flavour	$ee\mu/\mu\mu e$	$eee/ee\mu/\mu\mu e/\mu\mu\mu$			
OSSF lepton pairs	0	≥ 1			
$\lvert m_Z^{\mathrm{cand}} - m_Z\rvert$	< 20 GeV	> 10 GeV & < 20 GeV	< 10 GeV		
$\lvert m_H^{\mathrm{cand}} - m_H^{\mathrm{hypo}}\rvert$ $m_H^{\mathrm{hypo}} < 500$ GeV	-		$> 0.32 \cdot m_H^{\mathrm{hypo}}$	$< 0.32 \cdot m_H^{\mathrm{hypo}}$	-
$\lvert m_H^{\mathrm{cand}} - m_H^{\mathrm{hypo}}\rvert$ $m_H^{\mathrm{hypo}} > 500$ GeV			$> 0.24 \cdot m_H^{\mathrm{hypo}}$	$< 0.24 \cdot m_H^{\mathrm{hypo}}$	

vvbb event selection

Cut	Regions				
	2L (CR)	eμ (CR)	1L (VR)	Hlo / Hhi (CR)	Hin (SR)
N jets	2-5				
N b-jets	> 2				
m_H^{cand}	> 50 GeV				
N hadronically decaying τ-leptons	0				
$p_{\text{T}}(V)$	> 150 GeV				
$\min_i \Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, \vec{p}_i^{\text{jet}})$	$> \pi/10$				
$\Delta R(b_1, b_2)$	< 3.3 (2 b-jets) < 3.5 (≥ 3 b-jets)				
N leptons	2		1	0	
Lepton flavour	$ee/\mu\mu$	$e\mu$	e/μ	-	
$p_{\text{T}}(\ell_1)$	> 27 GeV			-	
$\lvert m_Z^{\text{cand}} - m_Z \rvert$	< 10 GeV	-			
$\mathcal{S}_{\text{MET}}$	< 5	-	> 3	> 10	
$m_{\text{top}}^{\text{near}}$	-			> 180 GeV	
$m_{\text{top}}^{\text{far}}$	-			> 200 GeV	
$\lvert m_H^{\text{cand}} - m_H^{\text{hypo}} \rvert$	-			$> 0.2 \cdot m_H^{\text{hypo}}$	$< 0.2 \cdot m_H^{\text{hypo}}$