2HDM type I
$H_2 \rightarrow W^+H^-$

- A forgotten channel?
- Or just too difficult?

Bill Murray &
Rachel Ashby-Pickering,
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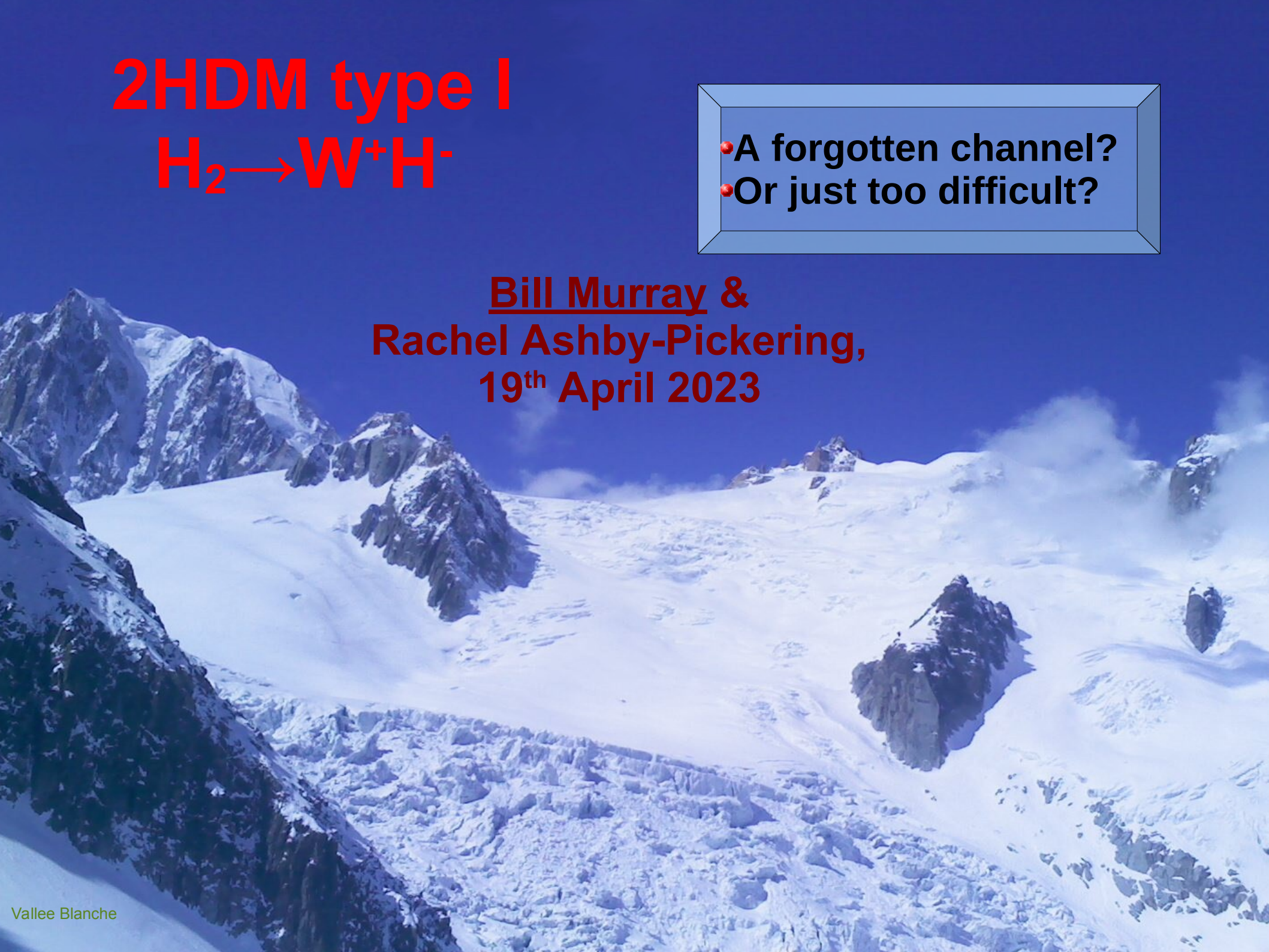
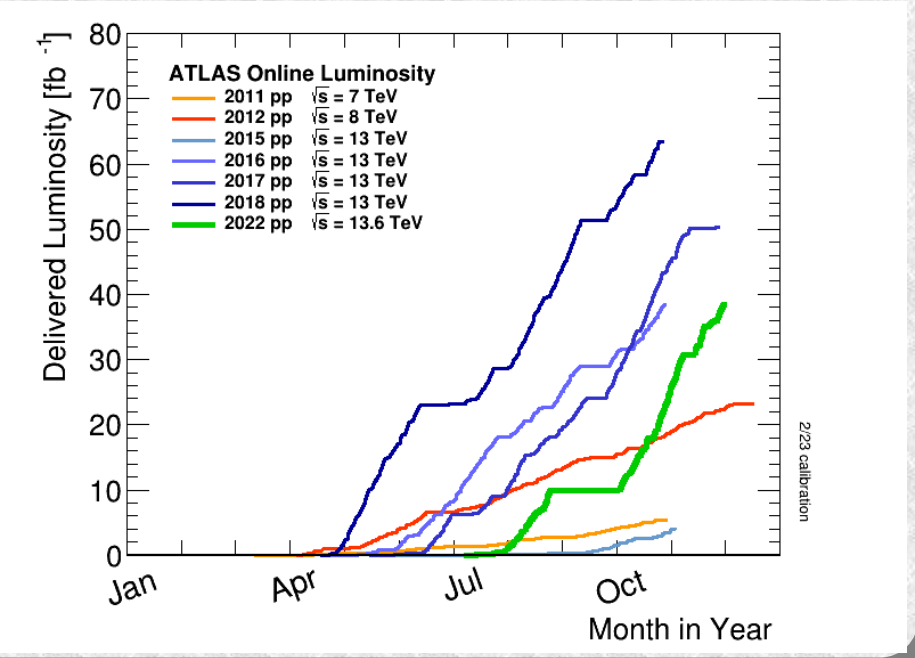


Extended Higgs sectors

- The Higgs boson is an amazing discovery
  - A fundamental scalar has never been seen
  - It seems to confirm the VeV, filling the Universe
- But it comes with mathematical instabilities
  - Extended Higgs sectors might address these
  - And can solve other issues
- They are weakly coupled
  - 180fb^{-1} of LHC data 💰 💰
- Every reason to explore
- Two Higgs doublet models are a good benchmark



Two Higgs doublet model

- A second Higgs doublet leads to 5 physical scalars
- Mixing in a generic 2HDM gives FCNCs
  - Fixed if each fermion couples to one doublet Glashow-Weinberg
  - Frequently four types are defined via Z_2 symmetry
    - Though there are other ways to avoid G-W

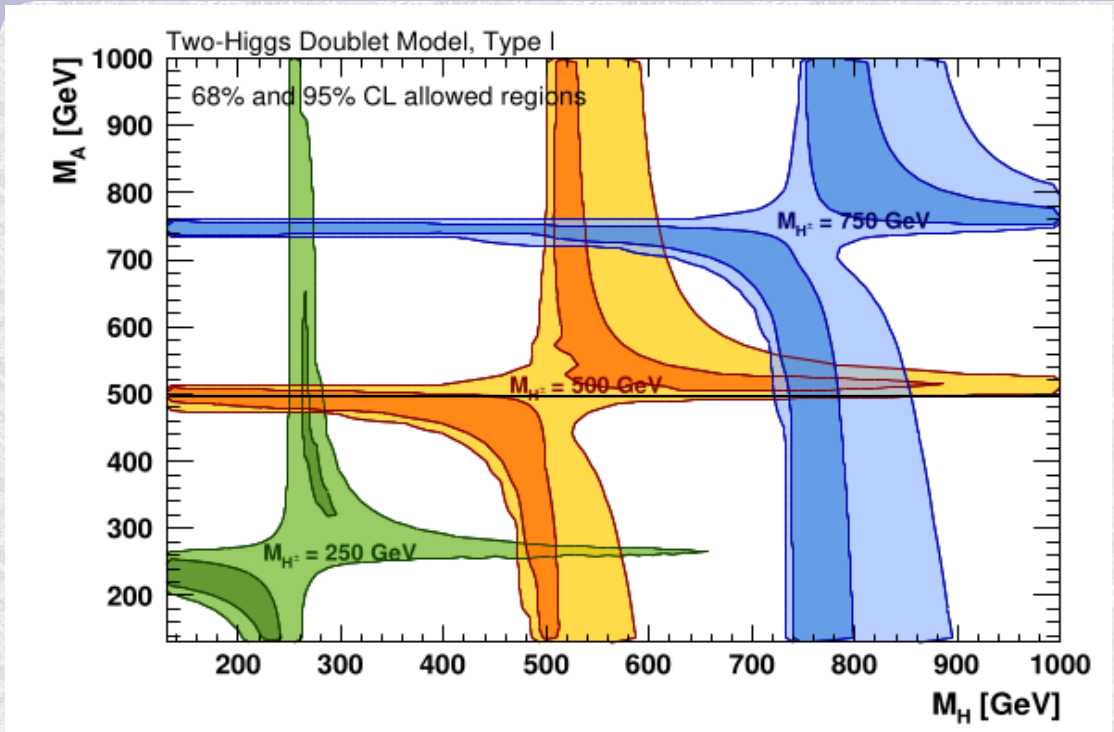
	Type I	Type II	Type III / Y / Flipped	Type IV / X / Lepton-specifc
ρ^D	$K^D \cot\beta$	$-K^D \tan\beta$	$-K^D \tan\beta$	$K^D \cot\beta$
ρ^U	$K^U \cot\beta$	$K^U \cot\beta$	$K^U \cot\beta$	$K^U \cot\beta$
ρ^L	$K^L \cot\beta$	$-K^L \tan\beta$	$K^L \cot\beta$	$-K^L \tan\beta$

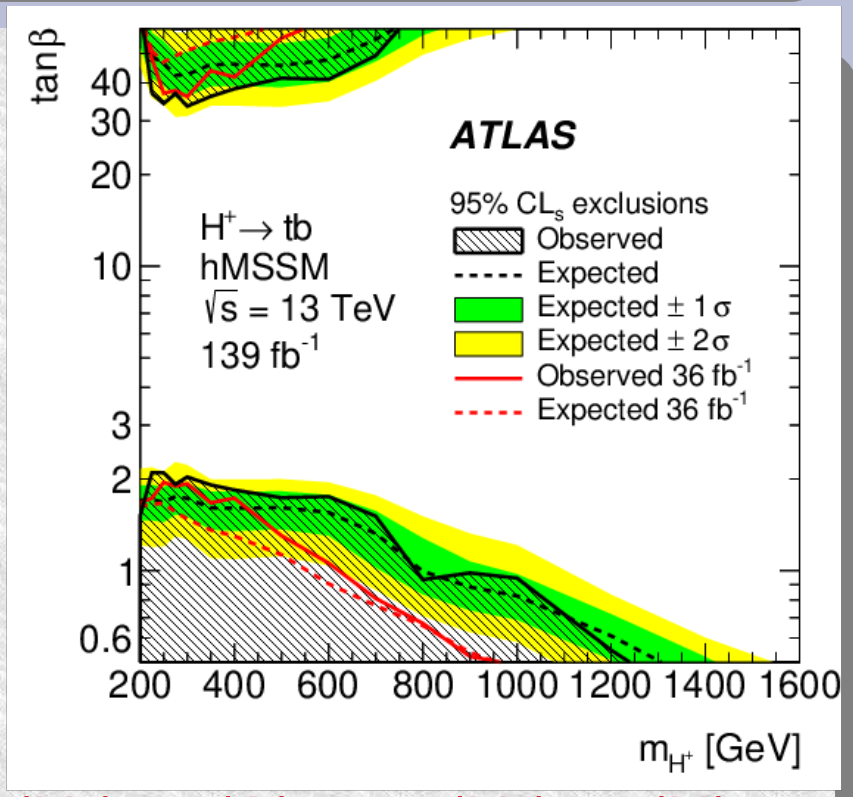
- Bur we know:
  - Properties of H(125) changed by mixing
    - Aligned models forbid doublet mixing, avoid this
  - $b \rightarrow s\gamma$ excludes $m(H^+) < 590$ GeV in types II/IV
  - g-2 favours low $m(H^+)$ and high $\tan\beta$ in all models.
  - EW fit limits mass-differences in 2nd doublet

So why Type I?

- Type I has been less explored than type II
- Two papers attracted our attention:
  - Gildener-Weinberg Higgs warning: non-standard notation
    - Eichten & Lane 2022
    - Naturally aligned model from 1976
    - Type I model with linkage $m(H)^4+m(A)^4+2m(H^+)^4=540^4$
      - Modified in this paper at two-loop level
    - Proposed $H\rightarrow W^+H^-$ search mode (et al.)
  - Electroweak baryogenesis in aligned 2HDM
    - Enomoto, Kanemura & Mura 2022
    - CP-violating Type I models giving matter asymmetry
    - Two benchmark points proposed:
      - $m(H)=267$, $m(H^+)= 381$GeV
      - $m(H)=397$, $m(H^+)= 302$GeV – has $H\rightarrow W^+H^-$
- So our focus is m_A, m_{H+} and m_H all >125 and <700

Allowed regions: gfitter 2018

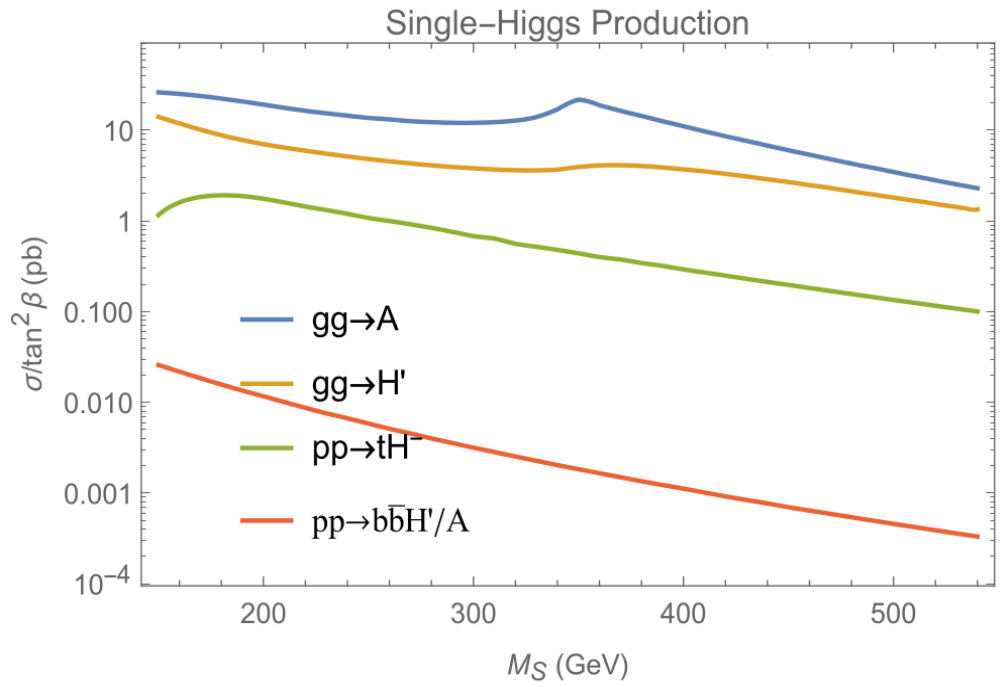


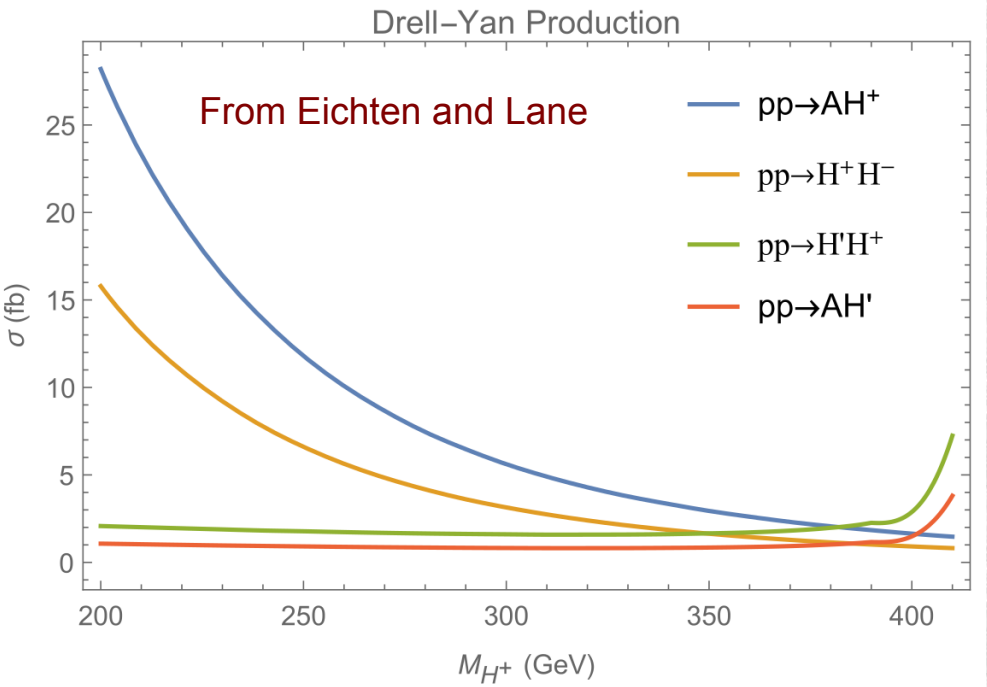


- EW fit, g-2 and B data constrain either $m(H^+) \sim m(A)$ or $m(H^+) \sim m(H)$
  - m(H+)=m(A) is imposed in papers mentioned last page
  - Actually A slightly heavier than H^+ preferred if H is heaviest
    - Some tens of GeV allowed on this.

Tan β < 1 – 2 are excluded by published H^+ searches at these masses: applies to type I too.

Higgs cross-sections

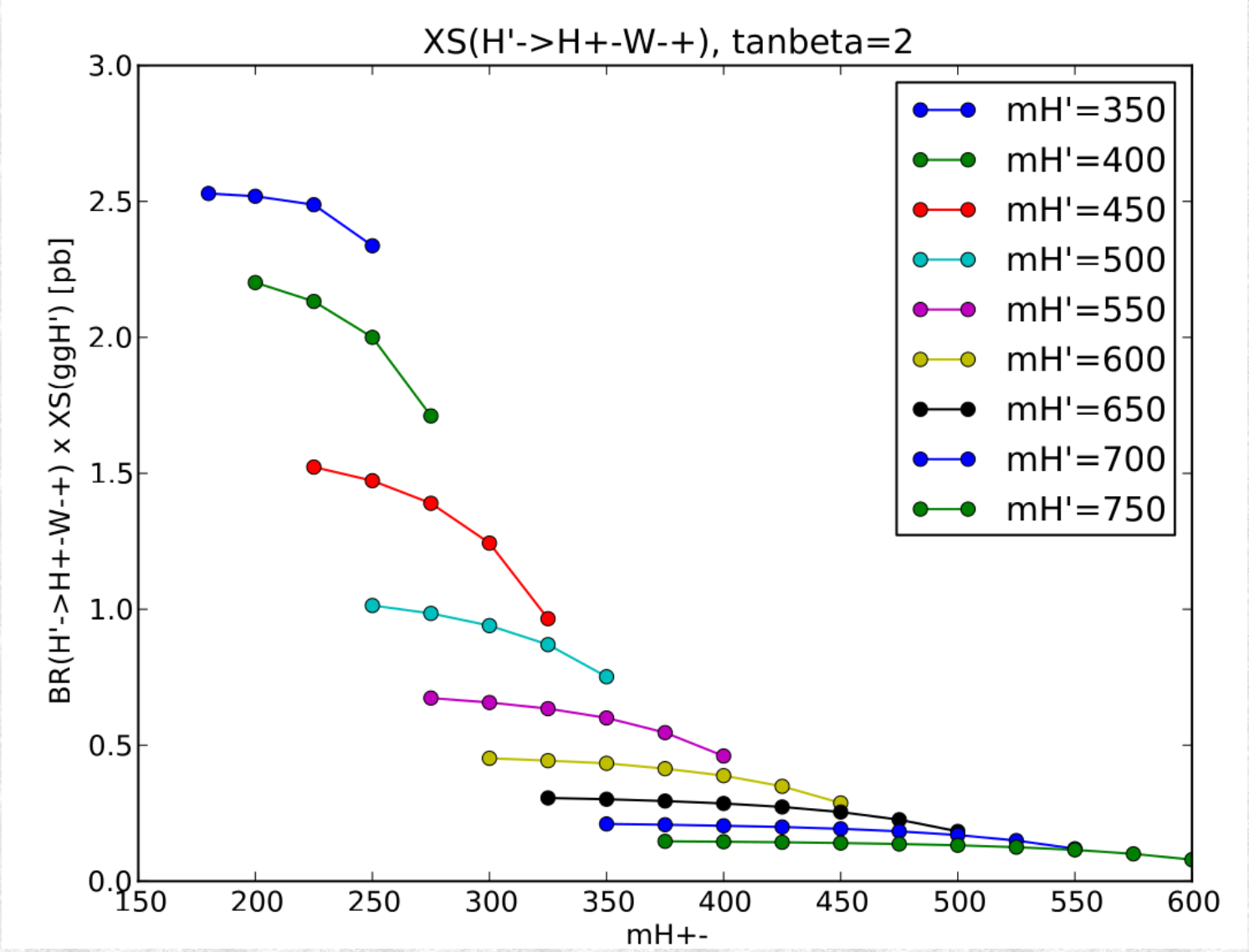




- Cross-sections for heavy scalar O(few)pb
  - But scaled down by $\tan\beta^2$, at least 4 in this range
  - 100K H possible
  - H, A cross-section ten times single H^+
  - b associated is not useful in type I 2HDM
- Drell-Yan pair production if O(few)fb, so much rarer – ignored

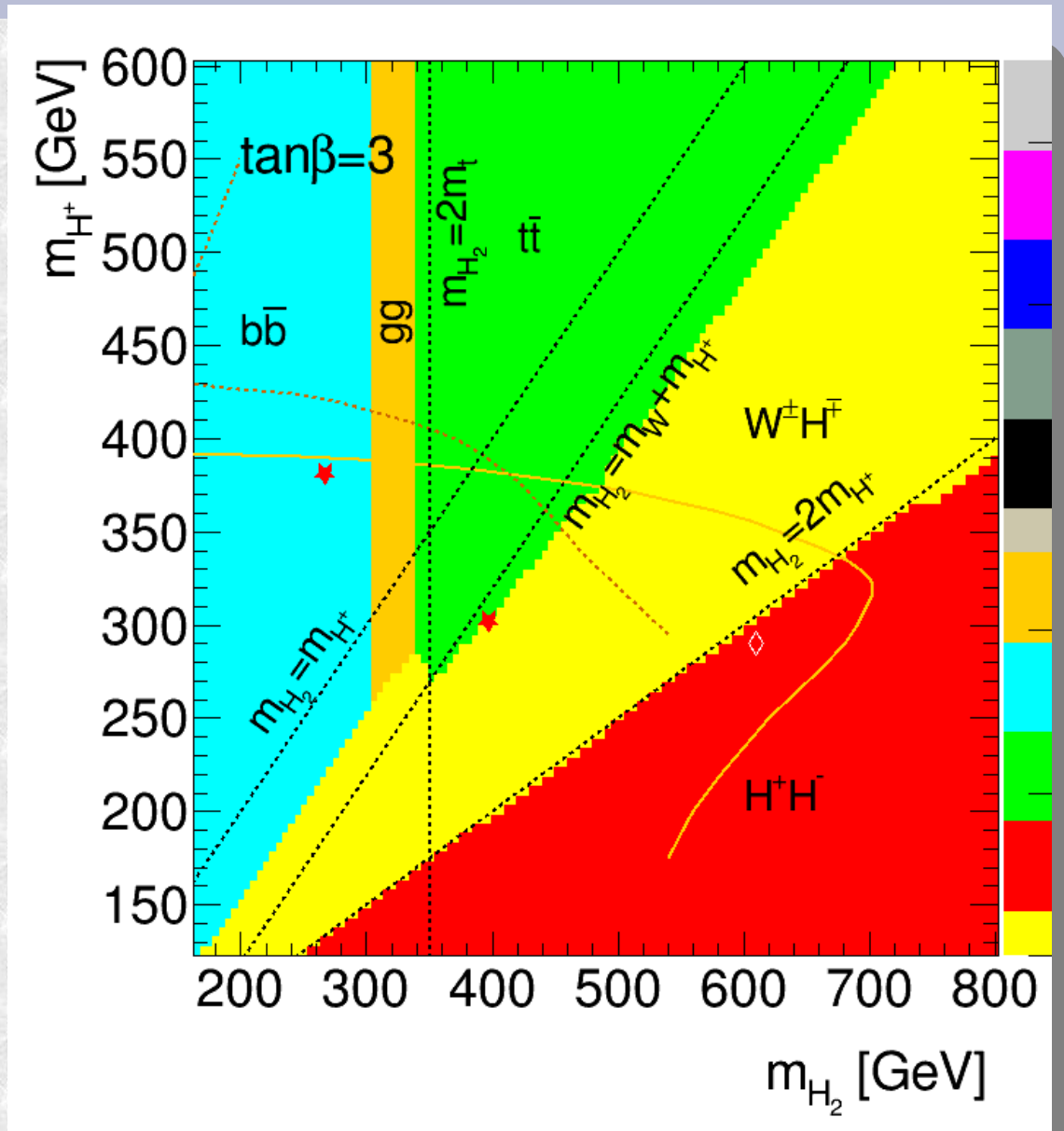
Cross-section: Sushi+2HDMC

- We repeat with SUSHI @ NNLO QCD, NLO EW
- Independent calculation
- Confirms rates from previous plot
- Possibly could have K-factor from SM H calculation?



Largest H_2 decay mode

- Imposing $m_A=m_{H+}$ plus:
  - $\sin(\beta-\alpha)=1$ - aligned
  - $\lambda_6=\lambda_7=0$ – CP conserving
  - $M_{12}^2=m_A^2\tan\beta/(1+\tan\beta^2)$
  - Varying $\tan\beta$, here 3
- We see bb, gg, tt, W^+H^-, H^+H^-.
  - ZA and AA secondary
  - About 50% of W^+H^-, H^+H^-
- Red dots EWSB benchmarks
- Red/Orange lines G-W Higgs (two methods)
- Br $H_2 \rightarrow H^+W^-$ dominates when kinematically allowed and $H_2 \rightarrow H^+H^-$ is not
- If $m(H_2) < m(H^+)$ A & H_2 flip roles – so top left corner can also be tested.

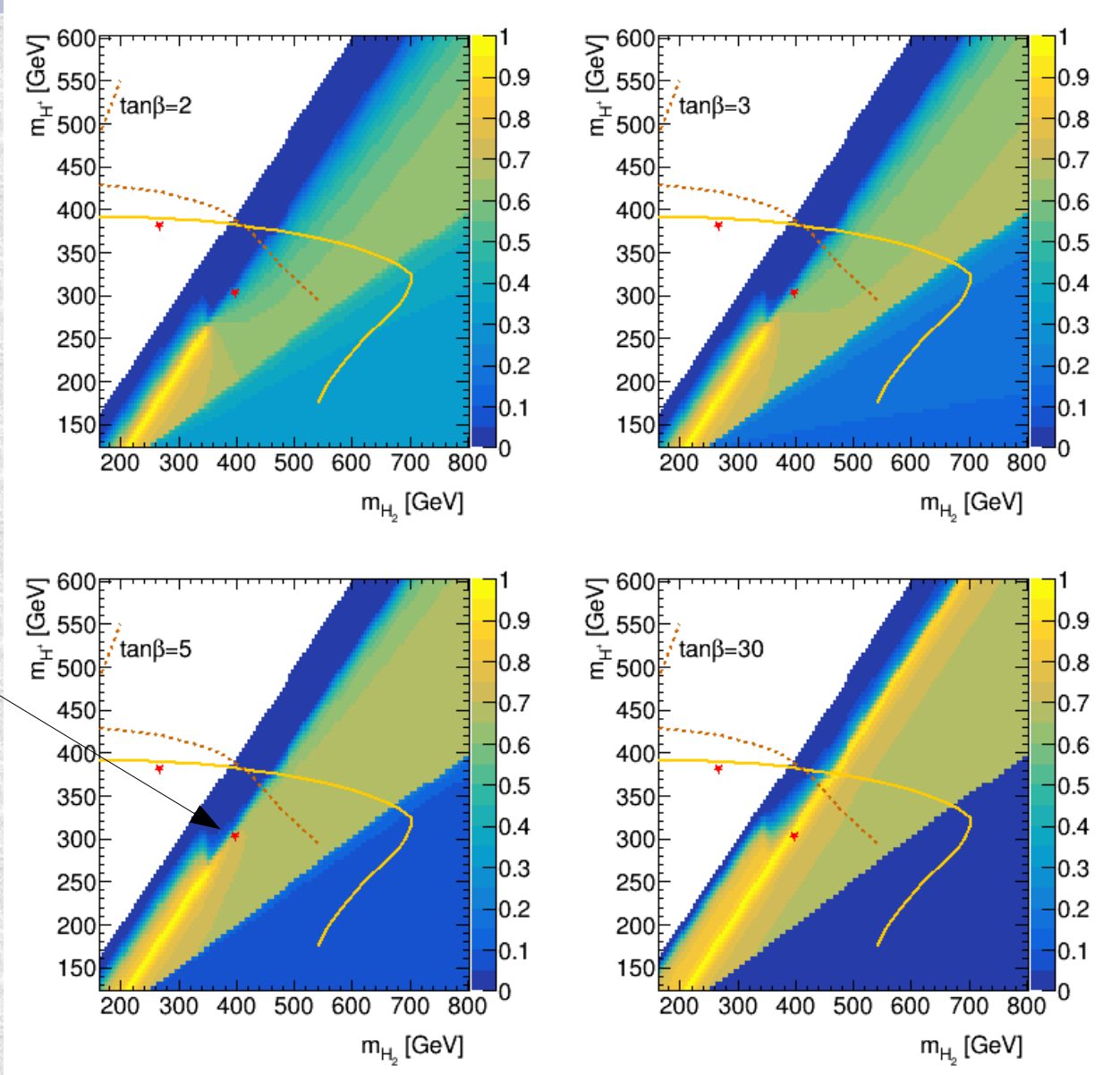


Practicality: $H \rightarrow W^+H^-$

- $H \rightarrow W^+H^- \rightarrow W^+b\bar{t}$ so experimental signature is $pp \rightarrow W^+b\bar{t}+cc$
  - Looks rather like $t\bar{t}$ – or SM Wtb
  - But resonant peaks for H, H^+
    - Is that enough to reduce the top background?
  - Use semileptonic for trigger
- Alternative mode: $H \rightarrow ZA \rightarrow Zt\bar{t}$ / $Zb\bar{b}$
  - Is already being studied
  - Br is half that to W^+H^- if Q^2 of decay similar
    - I.e. $m_H - (m_Z+m_A) \approx m_H-(m_W+m_{H+})$
  - Probably a much cleaner mode, owing to the Z
  - But some scenarios suppress $H \rightarrow ZA$ Br e.g. if $m_A > m_{H+}$
- Why not just look for H^+ directly?
  - Recall cross-section is 10x less
  - And does not have resonant H peak
  - It does gives rise to $t\bar{b}tb$ so lower background

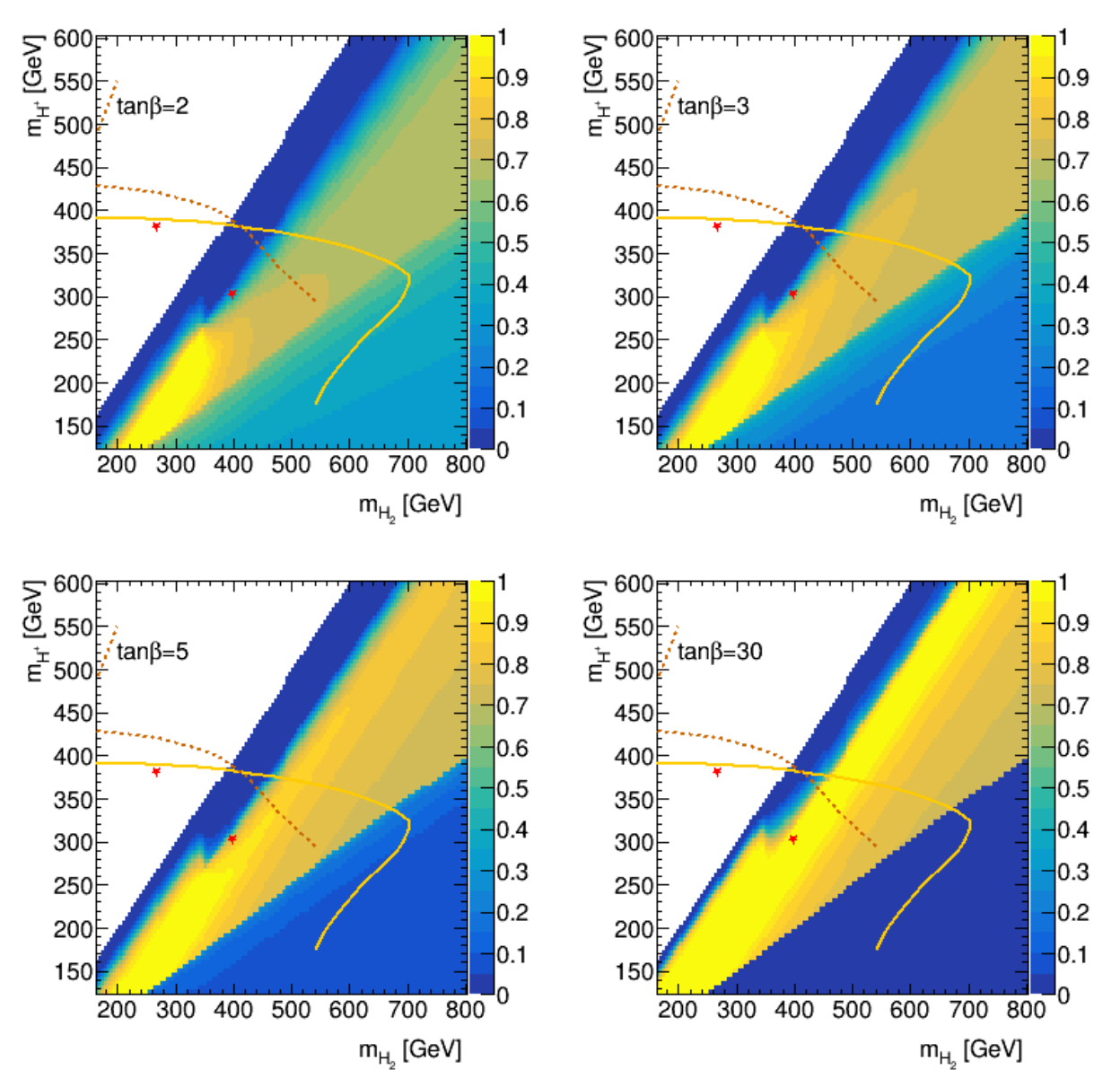
Details of $H_2 \rightarrow W^+H^-$ BR

- W^-H^+ decay Brs
- Fraction > 50% for parts of parameter space
- EWSB benchmark (tanβ=5.6) sits on sweet spot!
- $H_2 \rightarrow ZA$ is normally 50% of $H_2 \rightarrow W^+H^-$ bar kinematic effect from $m_Z > m_W$
- Near WH^+ threshold $H_2 \rightarrow t\bar{t}$ competes
  - tan β dependent
  - And only above 350 GeV



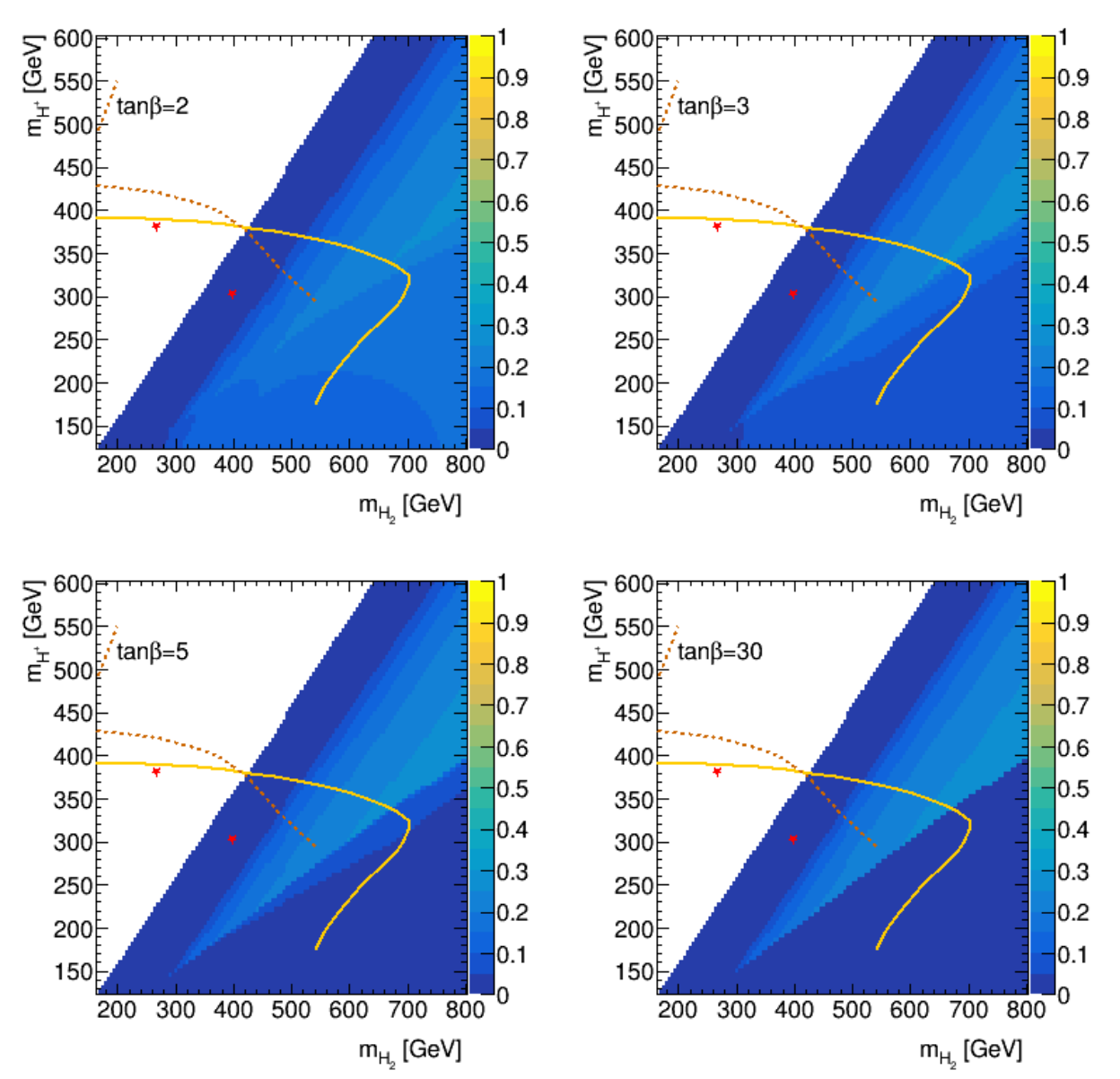
Br to W^+H^- with m_A increased

- W^-H^+ decay BRs
- Imposing $m_A=m_{H+}+40$
  - Other parameters as before
- This was suggested by the gfitter results
- The theorists agree imposing equality was for convenience.
- Effect is to suppress ZA

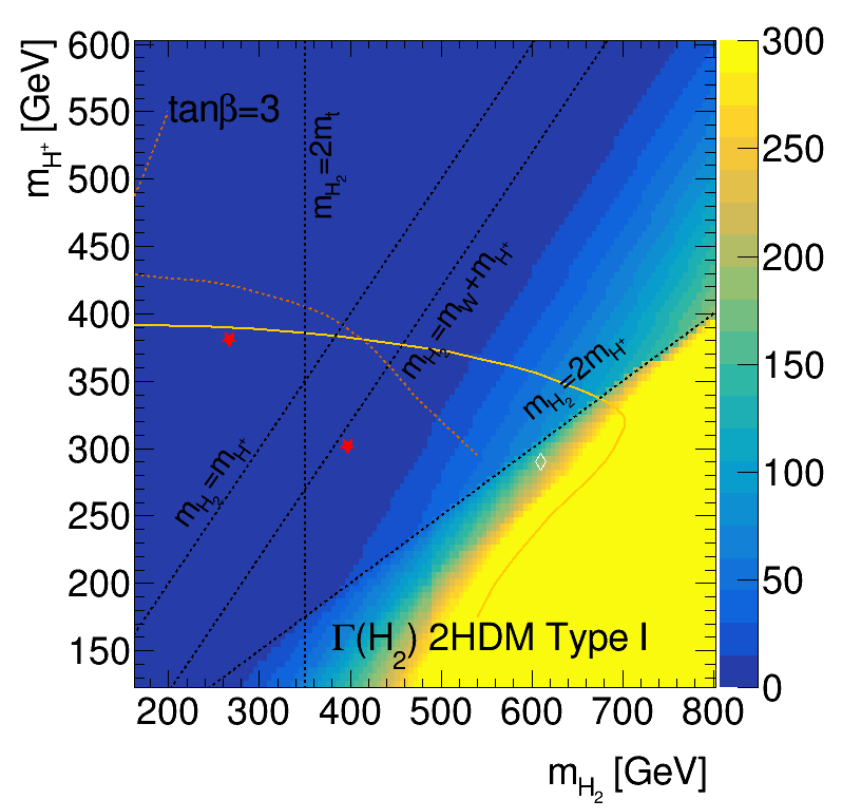


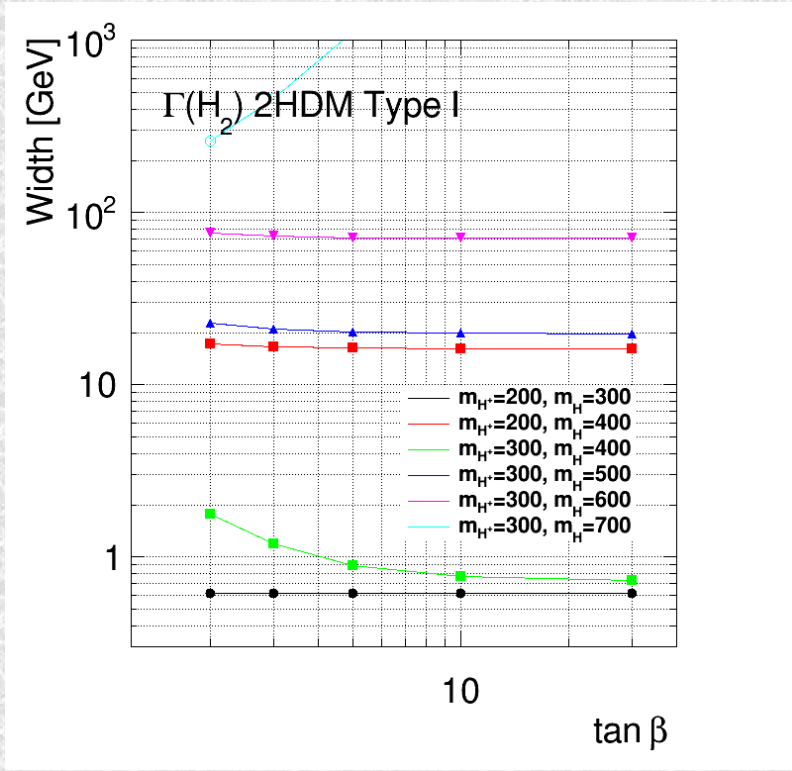
H BR to ZA with 2HDMC

- Imposing $m_A = m_{H^+} + 40$
- The ZA → llbb channel is already studied
  - Presumably easier than tbW
  - EW Z background << top!
- But near the diagonal it is suppressed
  - e.g. for the EWSB benchmark it is <0.1%



Width of H_2 (with $m_A=m_{H^+}+40$)

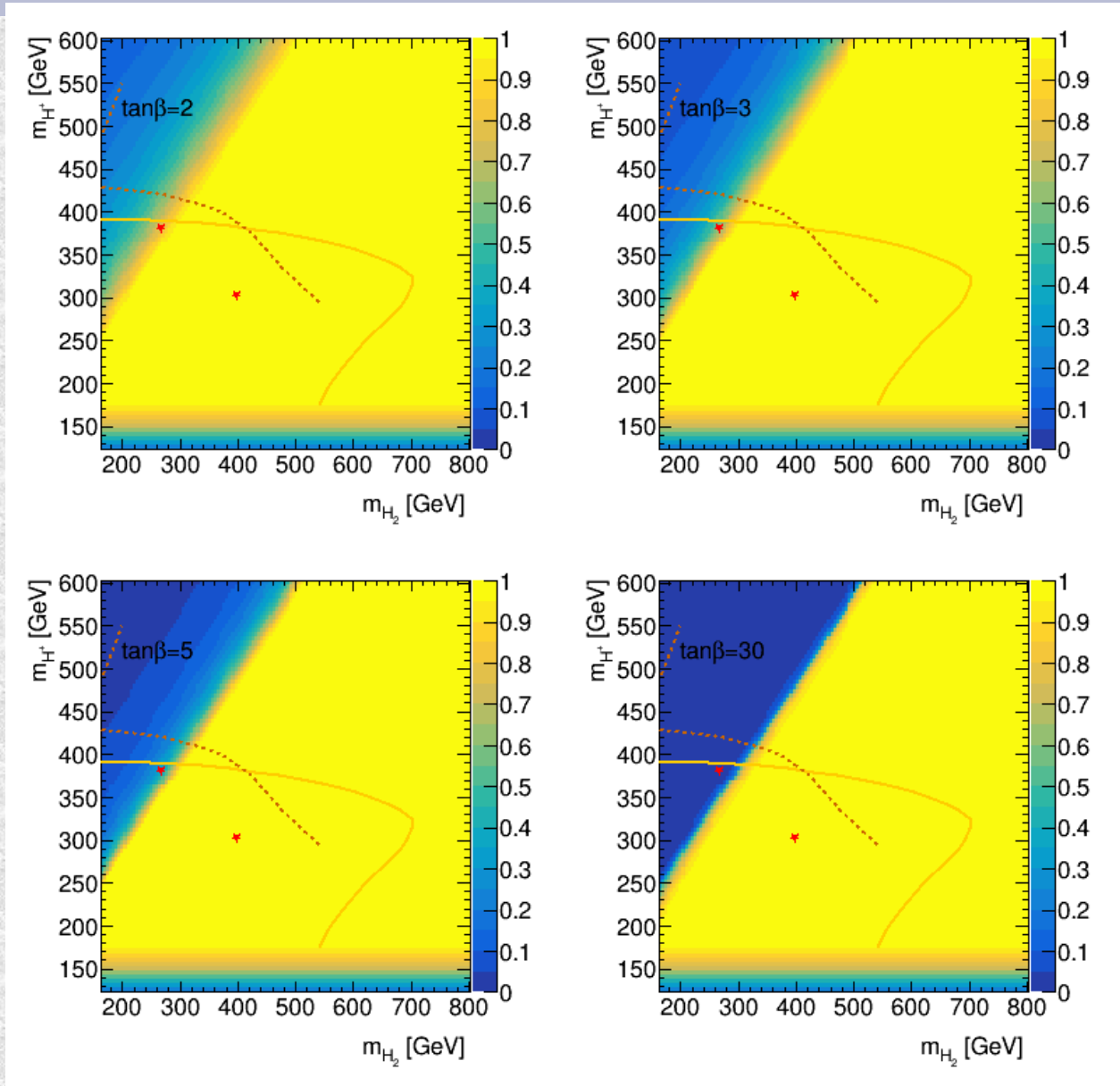




- Near kinematic limit, where Br to ZA is small, so is the width
  - e.g. EWSB benchmark has $\Gamma(H_2)$~0.6 GeV
- But grows »100 GeV when AA / H^+H^- decays are allowed.
- Nb: H^+ always narrow:
  - 1% in worst case, tanβ=2 and m(H^+) 500 GeV

H^+ decays

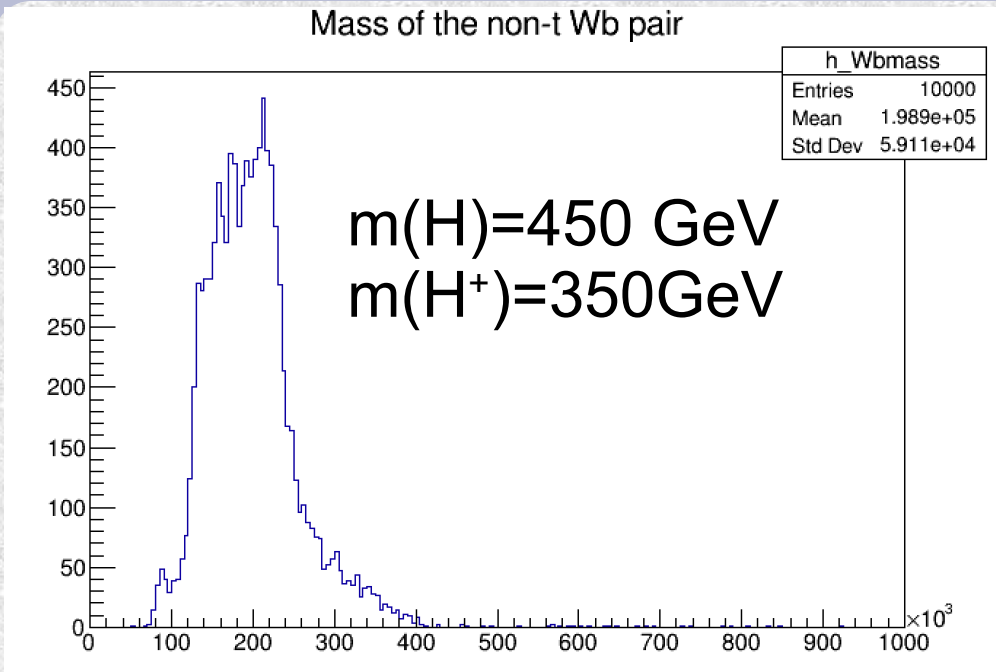
- Br of H^+ to tb plotted
- In interesting region this always dominates

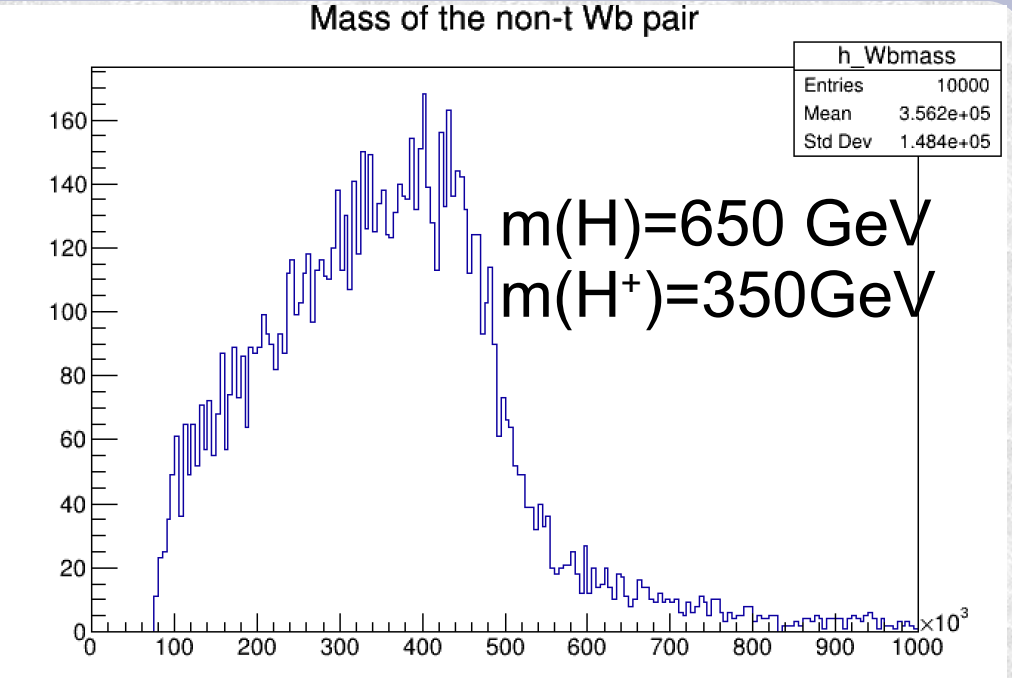


Proposed search recap

- Start from O(pb) cross-sections,
  - Br($A \rightarrow H^+W^- \rightarrow tbW$)+cc ~50% for a large area of space
  - But $t\bar{t}$ cross-section is O(1000) pb
    - And well known to be poorly modeled
- Optimistically:
  - Presumably only top-related backgrounds important
  - The H_2 and H^+ mass peaks must reduce the background
    - With semileptonic events and m_W constraint can reconstruct both mass peaks
  - Sidebands of those peaks can constrain $t\bar{t}$ modelling
  - Idea: use MVA for other kinematics but fit the mass peaks
- Pessimistically:
  - The Wb system mass is awfully close to m_t
  - m(H_2) O(400-500 GeV) is close to peak in m(tt)
- Statistically it looks possible...but poor s/b

Exploring the kinematics

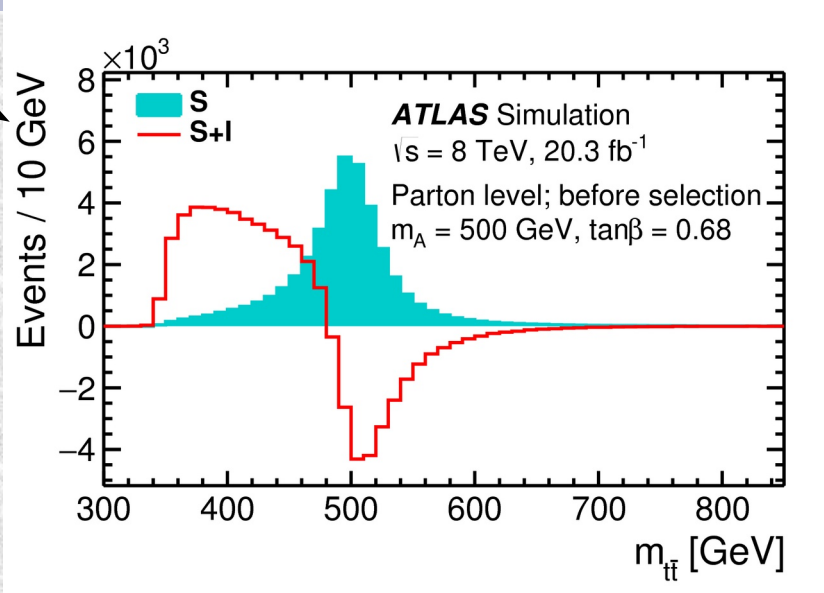


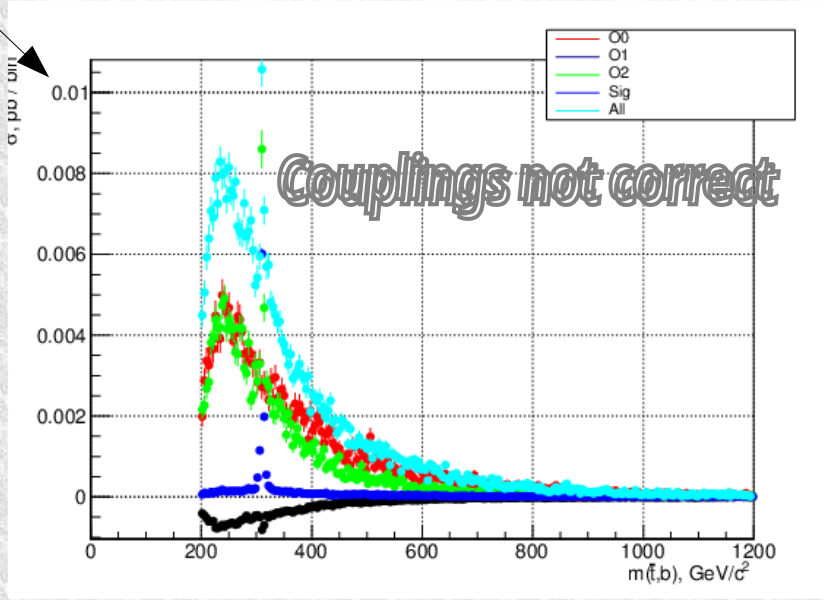


- One feature to reduce top: the mass of the non-top W-b system
  - Power will vary dramatically across the plane

Interference

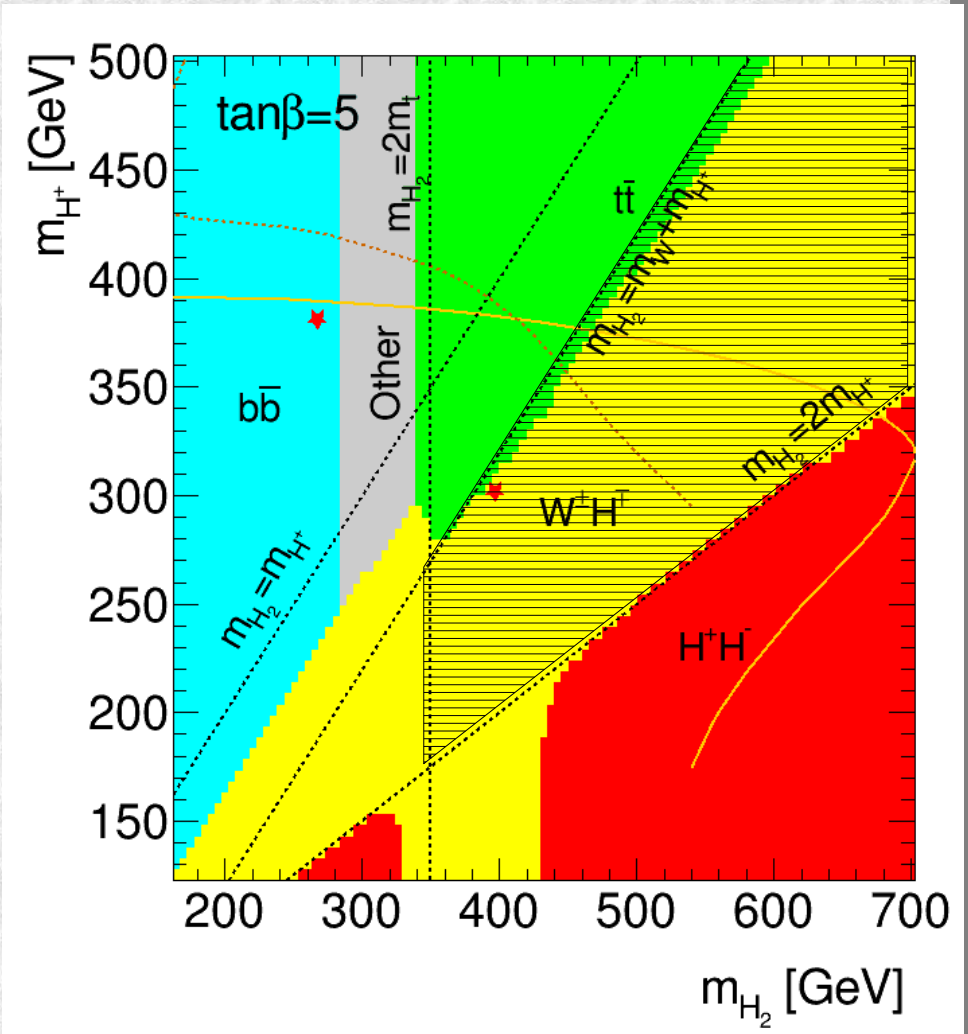
- Interference is important in $A \rightarrow t\bar{t}$
  - Though it is less so for $H \rightarrow t\bar{t}$
- Work in progress on $H^+ \rightarrow tb$ (right) seems to show interference has small impact on peak
- Does it matter for $H \rightarrow WH^+$?
  - We have failed to find code running $gg \rightarrow tbW$ with QCD tree, H loop and interference
  - But the narrow H^+ peak improves s/b factor more than 10
    - So situation better than $H \rightarrow t\bar{t}$
  - We propose to ignore interference
- Comments?





Concluding remarks

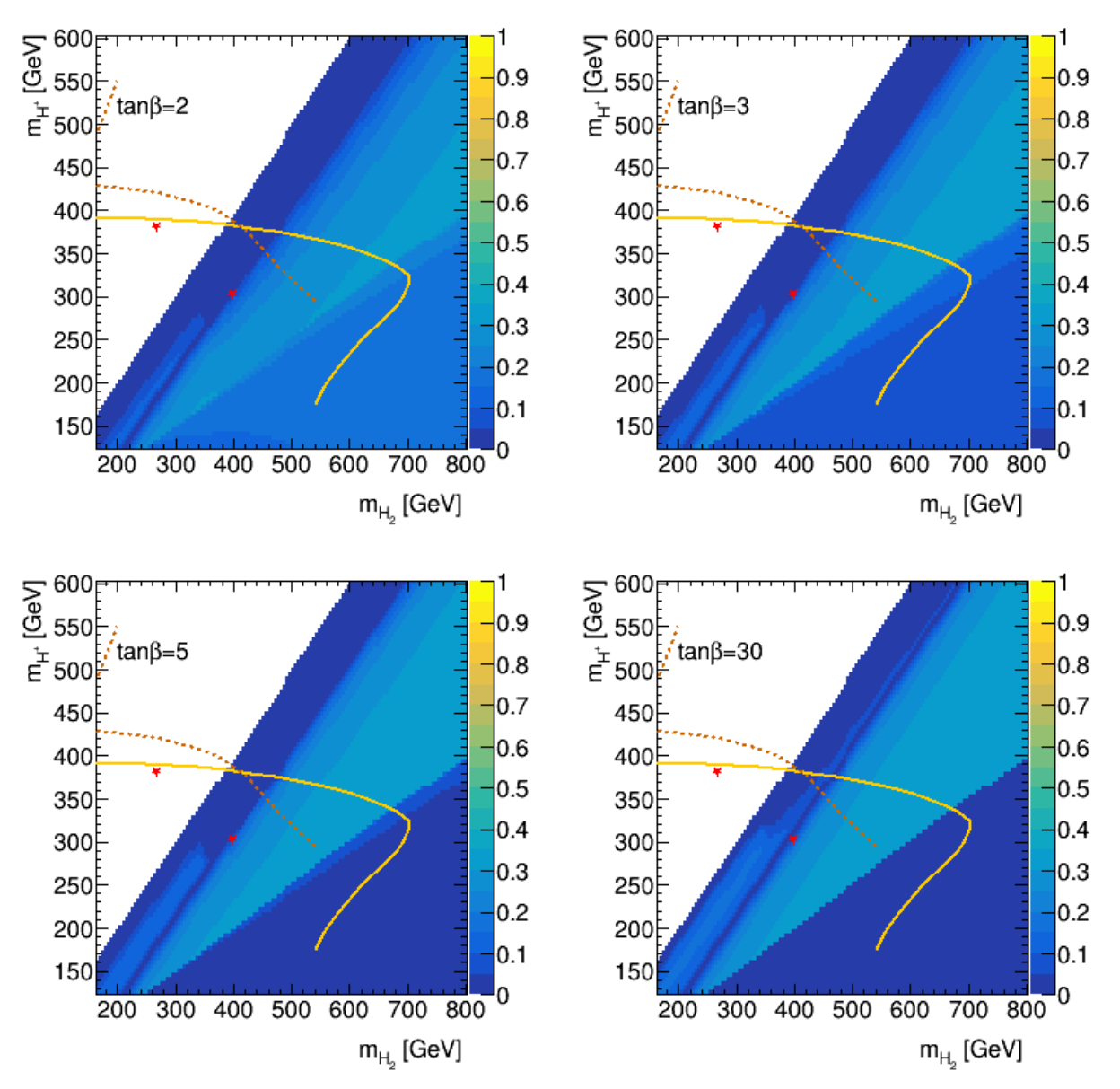
- The $H \rightarrow W^{+}H^{-}$ decay has never been searched for
- But the top background is 1000 times any possible signal
  - And known to be hard to model
- For some unexcluded space it is the dominant H decay mode
  - So any limit is new information
- That space happens to include theoretically interesting models
- Interference is a bit of an unknown
- Any comments or suggestions welcome



Backup

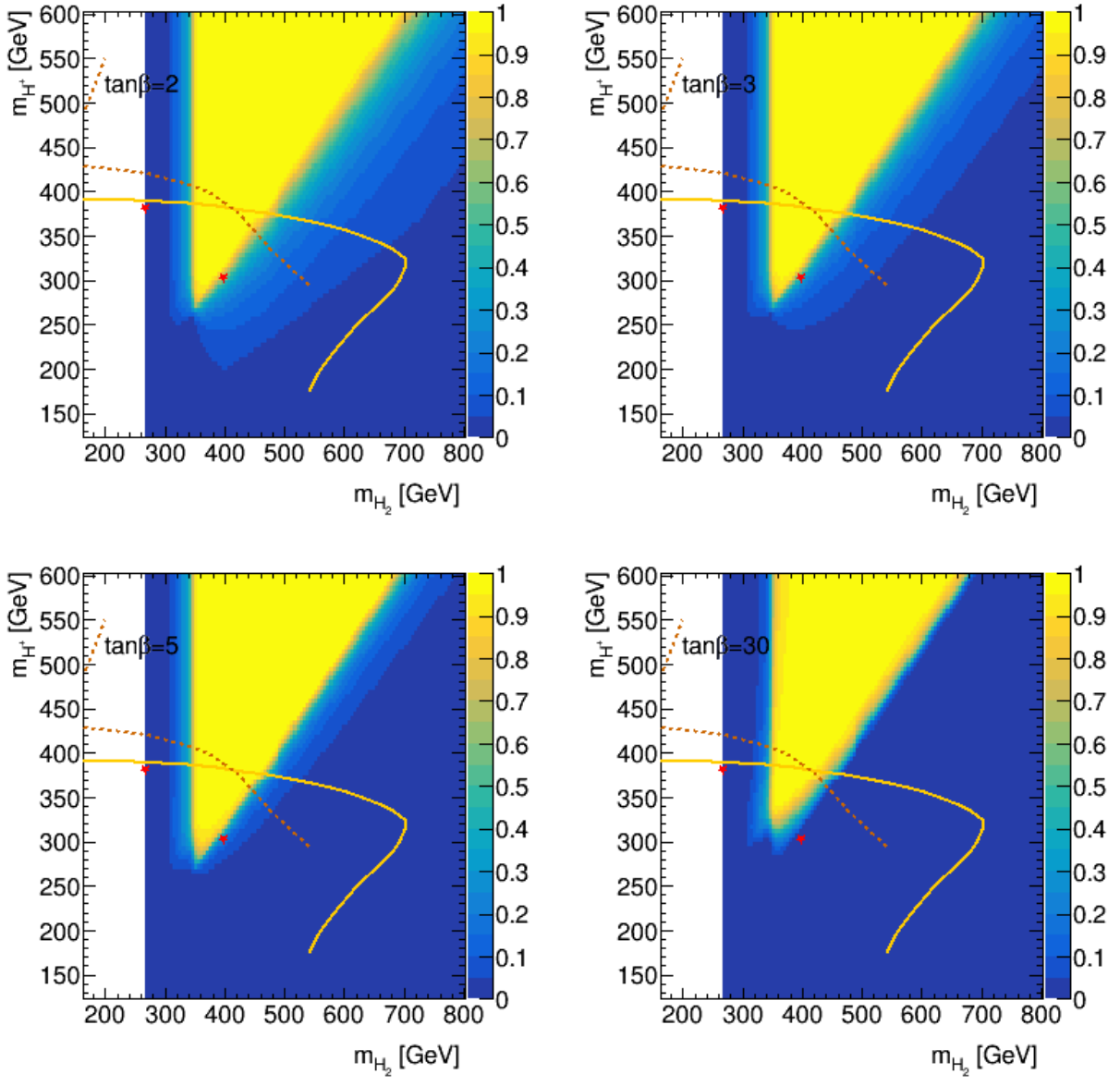
Examine H BR with 2HDMC

- ZA mode
- Imposing $m_A = m_{H+}$
- The ZA mode has llbb channel already studied,
  - Presumably easier than tbW
- But near the diagonal it is suppressed
  - e.g. for the EWSB benchmark



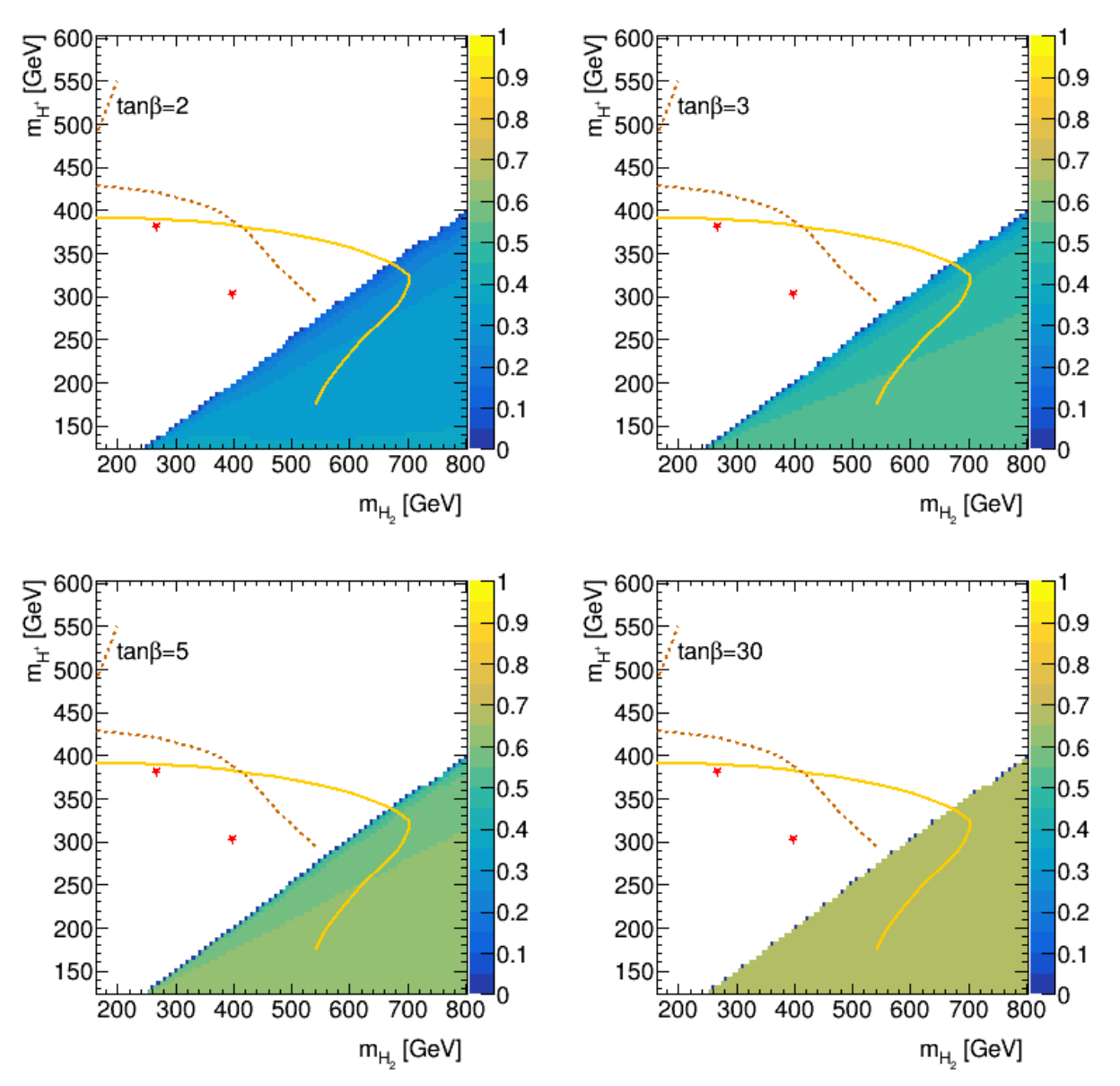
Examine H BR with 2HDMC

- $t\bar{t}$ mode
- Imposing $m_A = m_{H^+}$
- $H_2 \rightarrow tt$ is already much studied



Examine H BR with 2HDMC

- H^+H^- mode
- Imposing $m_A=m_{H+}$
- This then has $H^+ \rightarrow t\bar{b}$
- So $t\bar{b}t\bar{b}$ final state
  - Messy, but interesting



Examine widths with 2HDMC

- Γ H^+ plotted
- Imposing $m_A=m_{H+}+40$
- Plus:
  - $\sin(\beta-\alpha)=1$
  - $\lambda_6=\lambda_7=0$
  - $m_{12}^2=m_A^2\tan\beta/(1+\tan\beta^2)$
  - Varying tanβ
- Red dots EWSB benchmarks
- Orange line G-W Higgs
- Always narrow for tanβ>1