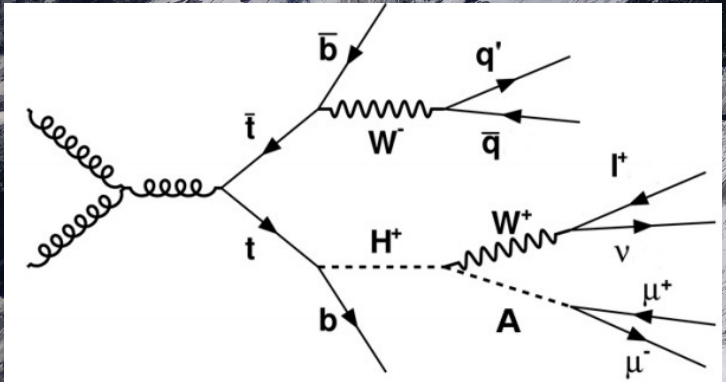
NeXT Southampton

- $H^+ \rightarrow WA \rightarrow \mu\mu$ in 2HDM

Bill Murray, 10th Nov 2021



2HDMs

- Many reasons to introduce a second Higgs doublet
  - ~~EW Baryogenesis~~
  - g-2
  - Diffuse gamma ray excess
- Produce 4 more scalars H^+H^-,H,A
- But risk of flavour changing neutral currents
  - Avoided if all same-charge fermions get mass from only 1 doublet
  - 4 classes of couplings normally considered:

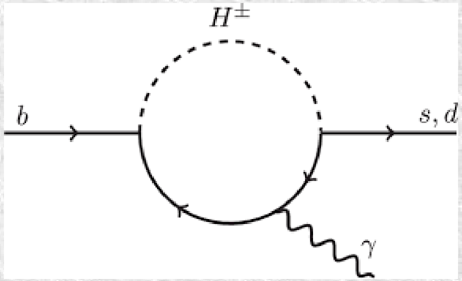
SUSY

Model	Type I	Type II	Lepton-specific	Flipped
Φ_1	–	d, ℓ	ℓ	d
Φ_2	u, d, ℓ	u	u, d	u, ℓ

  - We only looked at I and II

2HDMs

- In general 4 masses free m_A, m_{H+}, m_H, m_h
- Also tanβ and α – mixing of fields and scalars
  - Plus m_{12}^2, λ_6 and λ_7 but a Z_2 symmetry is often invoked
    - Forces them to 0, but can be softly broken
- Type II: Much studied as it includes SUSY
  - but $b \rightarrow s\gamma$ rate bounds m_{H+}> ~750 GeV
    - Can be cancelled with SUSY loops
    - But then $H^+ \rightarrow WA$ hard to get
- Type I: All fermion couplings 1/tanβ
    - m_{H+}> 80 GeV from $b \rightarrow s\gamma$
    - Much more freedom!



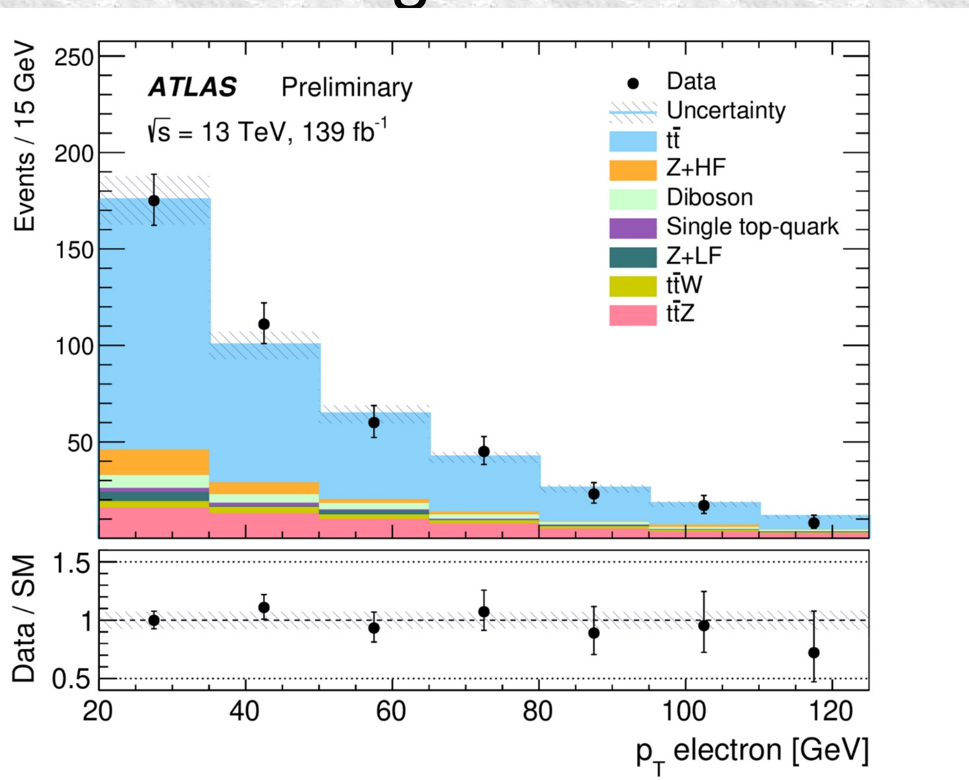
ATLAS CONF 2021-047

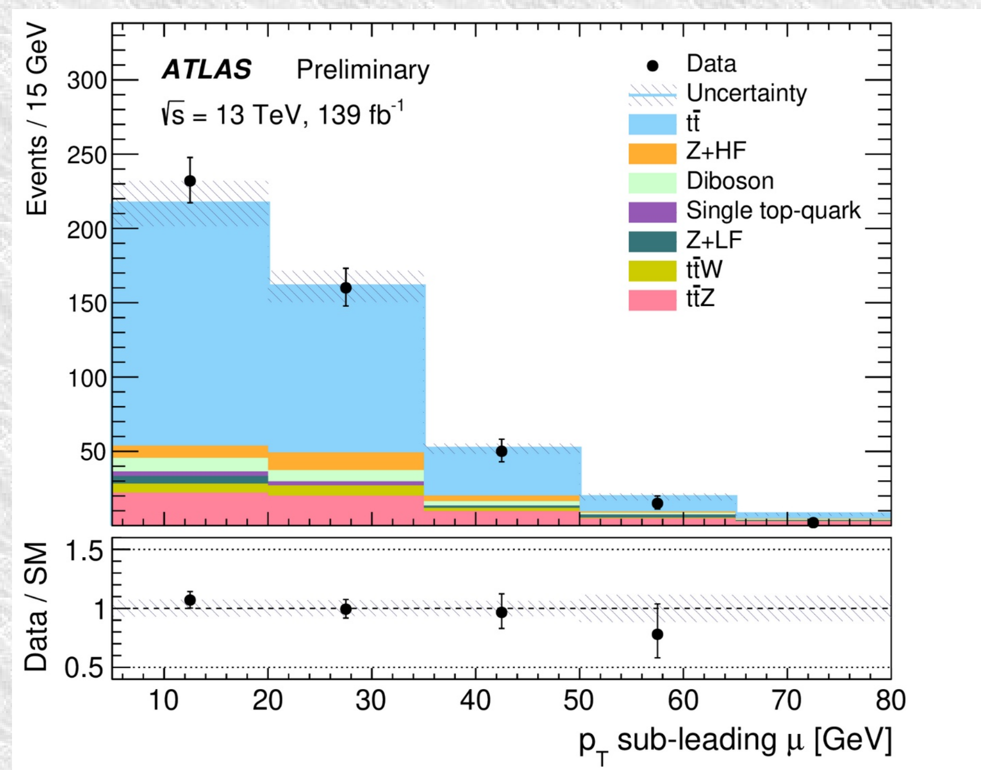
- Moretti et al proposed $H^+ \rightarrow$ WA in Type I
  - Using tt production, $t \rightarrow H^+ b$
  - And A decay to bb or ττ
- CMS published this in $A \rightarrow \mu\mu$ with $36 fb^{-1}$
- ATLAS followed CMS strategy with $139 fb^{-1}$

	Event selection	
Trigger	single muon	di-muon
Muons	$p_T^{\text{leading}} > 27$ GeV, $p_T^{\text{subleading}} > 5$ GeV	$p_T^{\text{leading}} > 15$ GeV, $p_T^{\text{subleading}} > 15$ GeV
	exactly 2, opposite sign $12 < m_{\mu\mu}$ [GeV] < 77 $p_T(\mu^{SS})/p_T(\mu^{OS}) > 0.2$	
Electrons	exactly 1, $p_T > 20$ GeV	
Jets	≥ 3, $p_T > 20$ GeV ≥ 1 b-tagged jet	

Sample composition

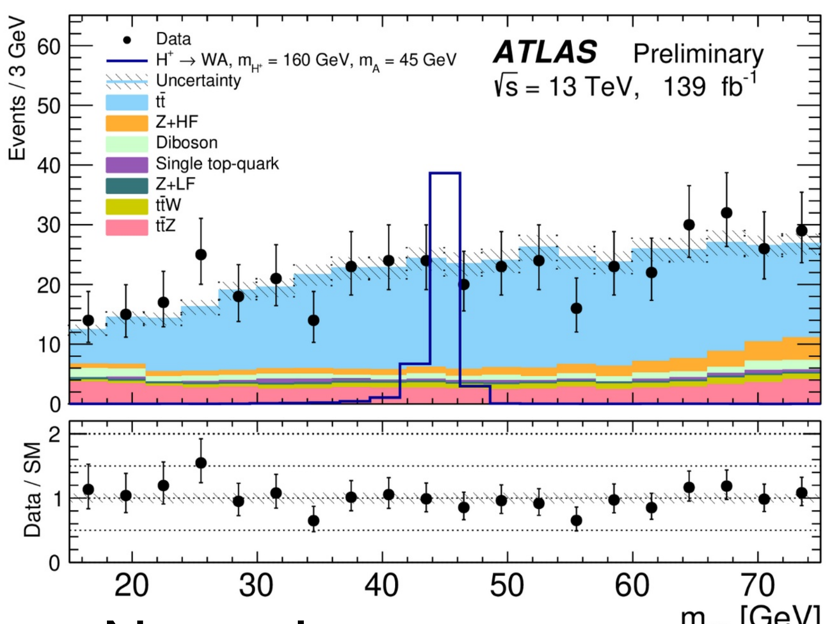
- No explicit H+ reconstruction
- Biggest background is tt with a fake lepton
  - Muon p_T cut lower, so fake is often that
  - Despite cut on same-sign muon pT
- Final background well modeled:





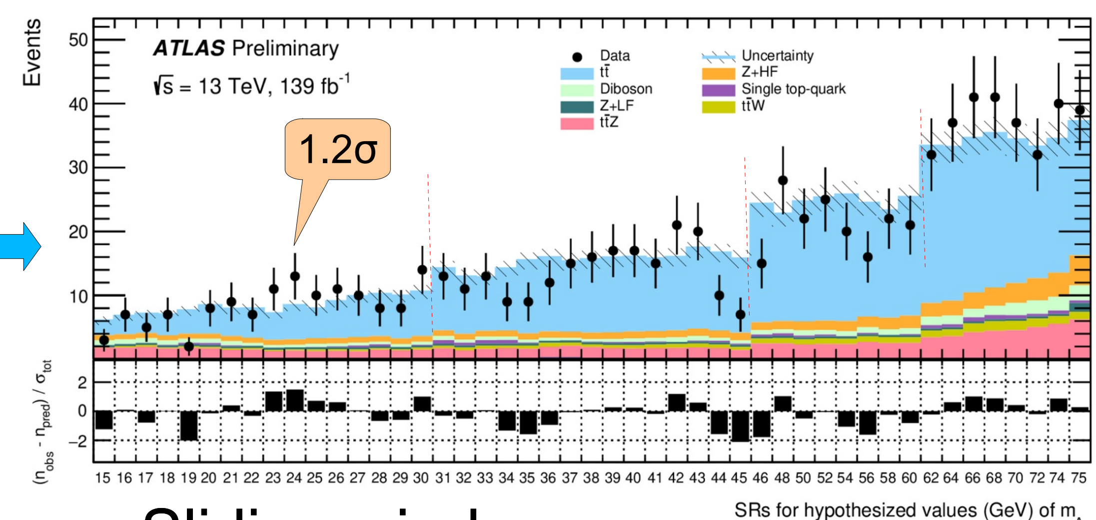
Analysis method

- Sliding window across 15-75 GeV
  - Width increases from 1.5 GeV to 4GeV
  - Count events and look for excess
- Background predicted from MC
  - But tt, ttZ and Z+HF scaled to match control regions



Normal mass

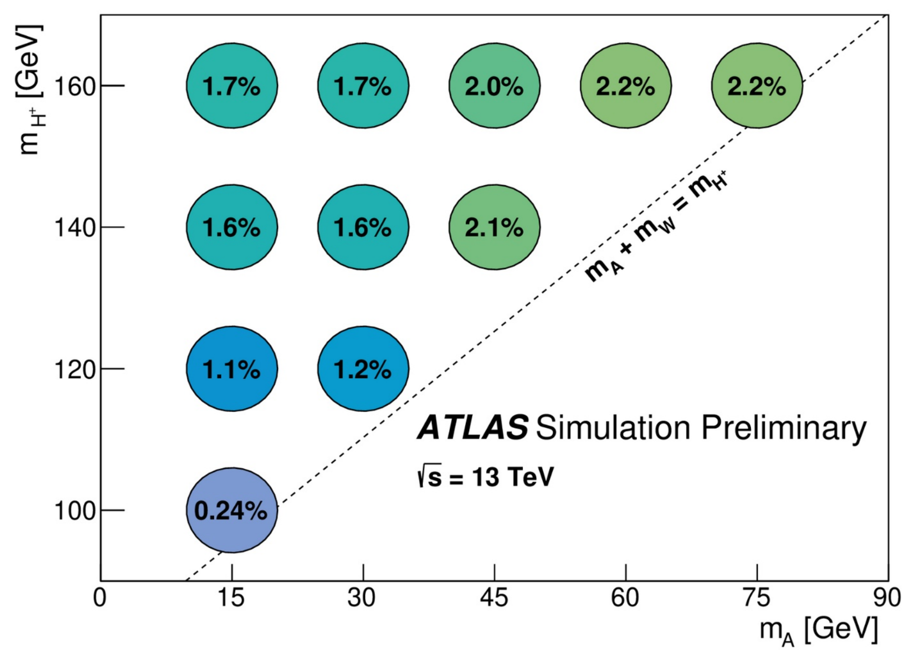
ttZ scaled up

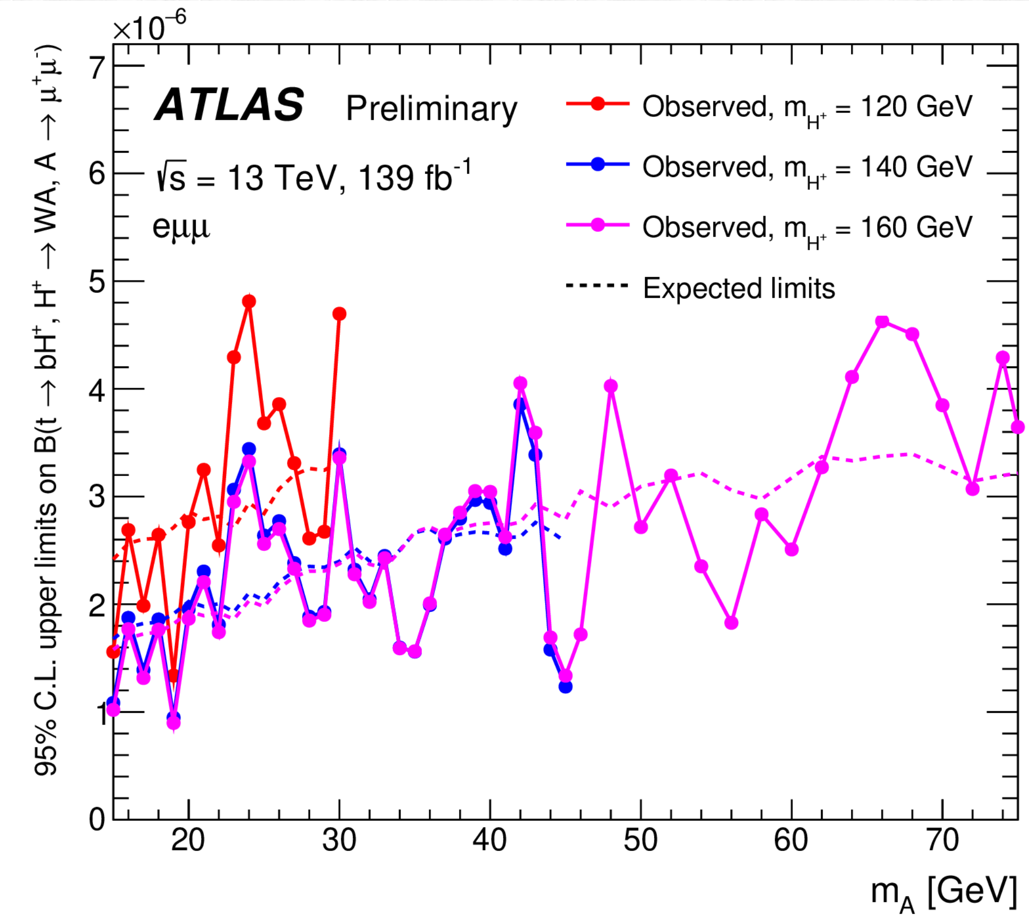


Sliding window

Limits set

- Grid in $m(H^+, m_A)$ sampled
- m_A is stepped through in 1GeV steps 15-75
- But H+ only enters via efficiency
  - See correlated limits
  - Poor eff at low m_{H+}



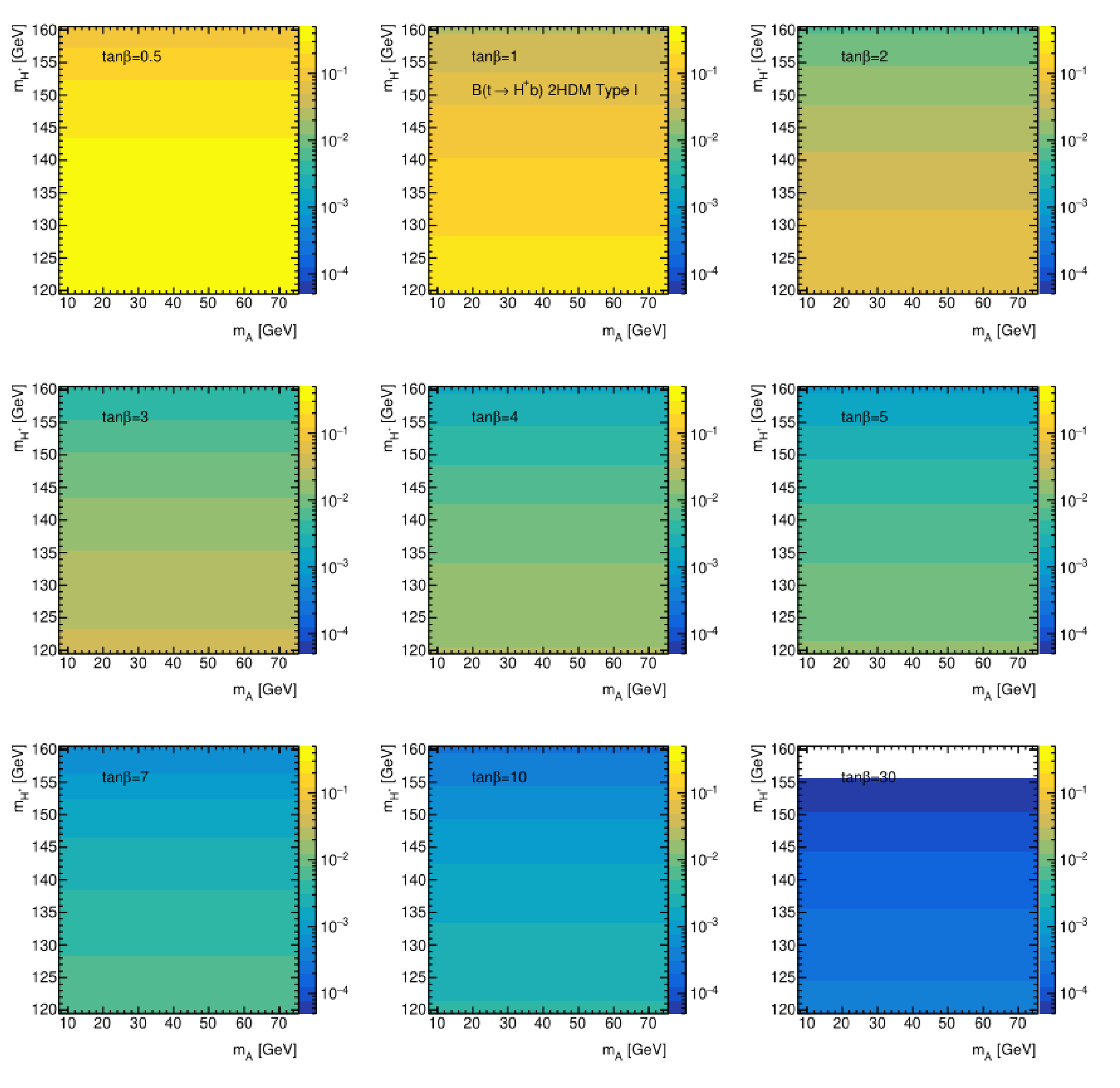


2HDMC

- Analysis set limits on Br $t \to H^+$, $H^+ \to WA$, $A \to \mu\mu$
- Also interpreted via 2HDMC
  - Its easy! Download, make and run – that's it
  - It predicts these 3 BRs and many other things
  - But needs: m_A, m_{H+}, m_H, m_h, $\tan\beta$, α, m_{12}^2, λ_6 and λ_7
- Found arXiv:1312.5571 (Interim recommendations for the evaluation of Higgs production cross sections and branching ratios at the LHC in the Two-Higgs-Doublet Model)
  - defines 3 scenarios, fixing all parameters
  - Extend them making 3D scan over m_{H+}, m_A and $\tan\beta$
    - Found α has no impact on Brs in question
      - Provided $h \to AA$ is removed.
    - m_H neither if decays to it are kinematically forbidden
    - and m_{12}^2 only affects 4th decimal place
- So can scan using only m_{H+}, m_A!

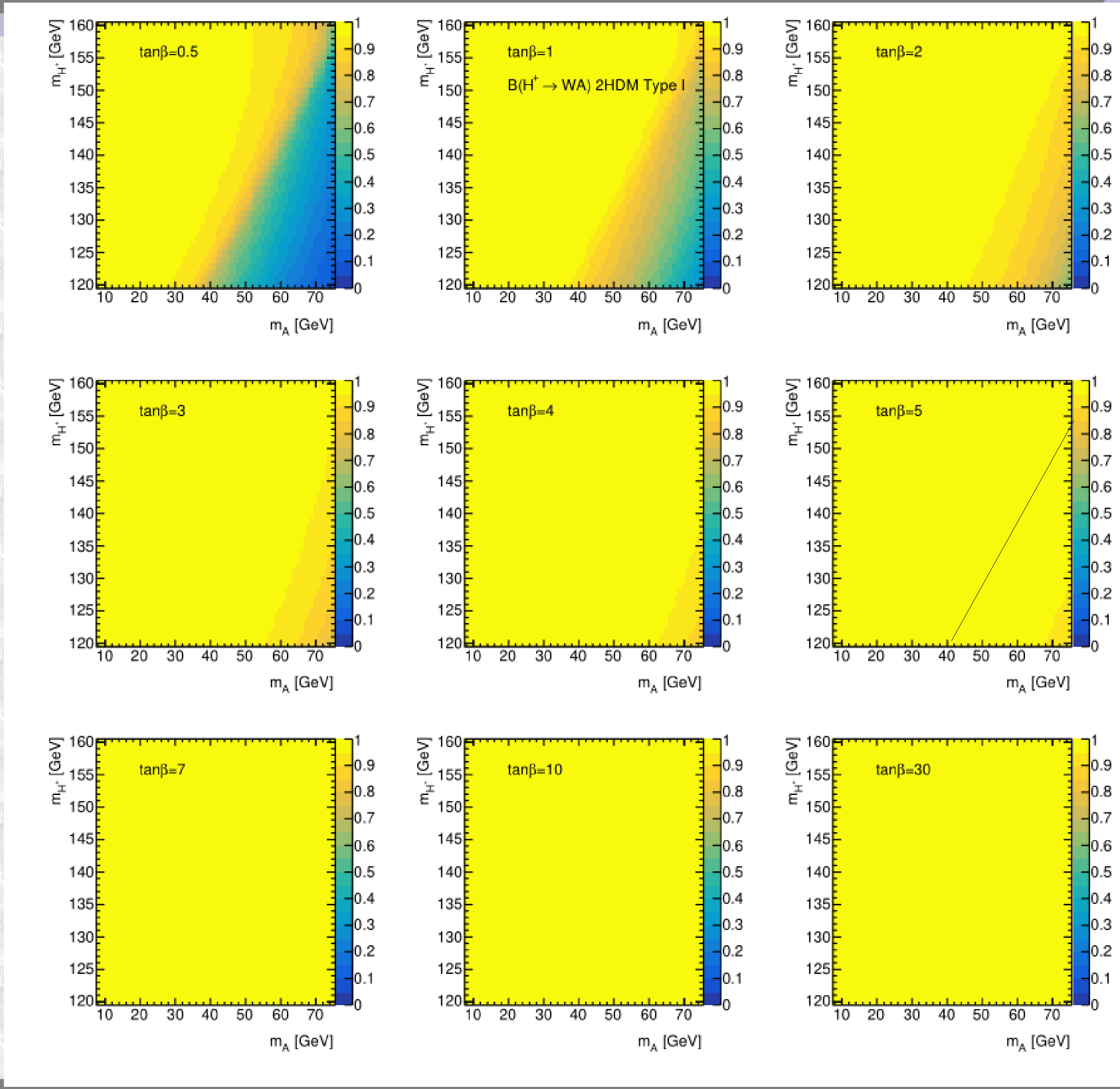
2HDMC scan Br t→ H^+b

- Type I
- Br Decreases with tan β
- Also with m_{H+}
- Independent of m_A
- In Type II would start to rise again at high tan β



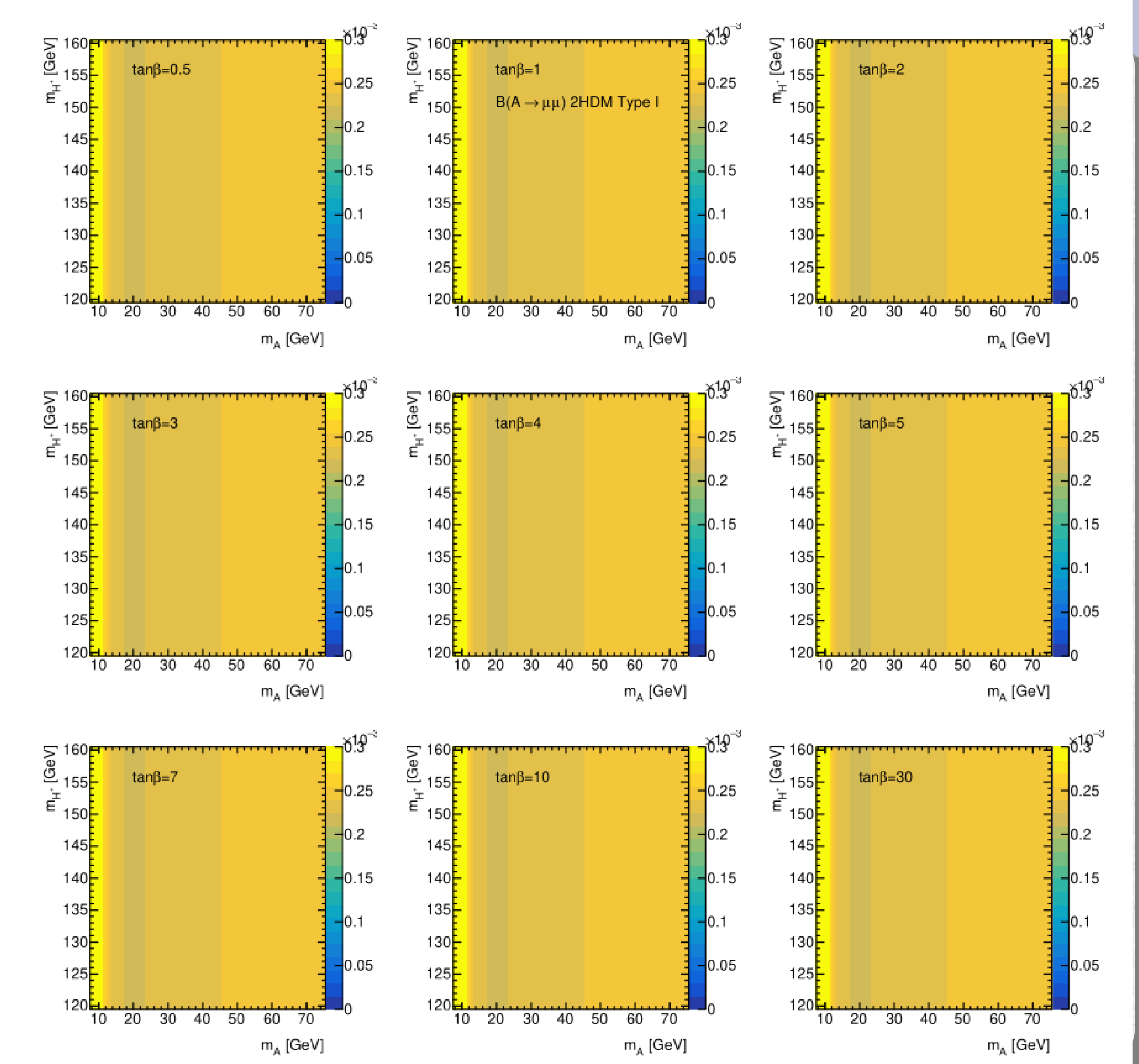
2HDMC scan Br $H^+ \rightarrow WA$

- If kinematically allowed it dominates!
- Even if W must be off-shell it still dominates at large tanβ
  - Though analysis sticks to on-shell
- This would not be true in type II



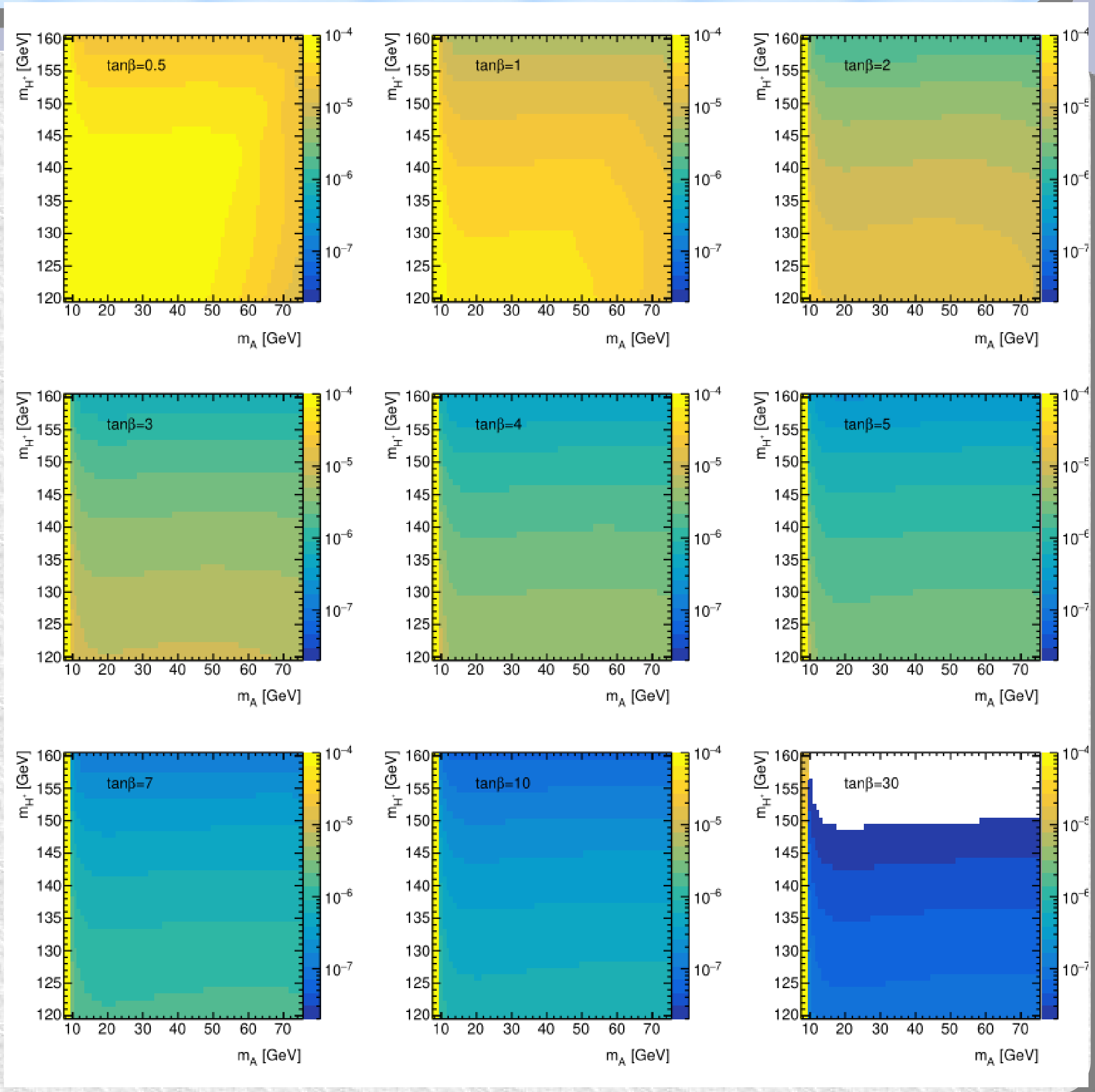
2HDMC scan Br A→ μμ

- 2.5×10^{-3} for most param space
- Rises when A→bb kinematically forbidden
  - But we do not test there
- There is a little more variation in type II

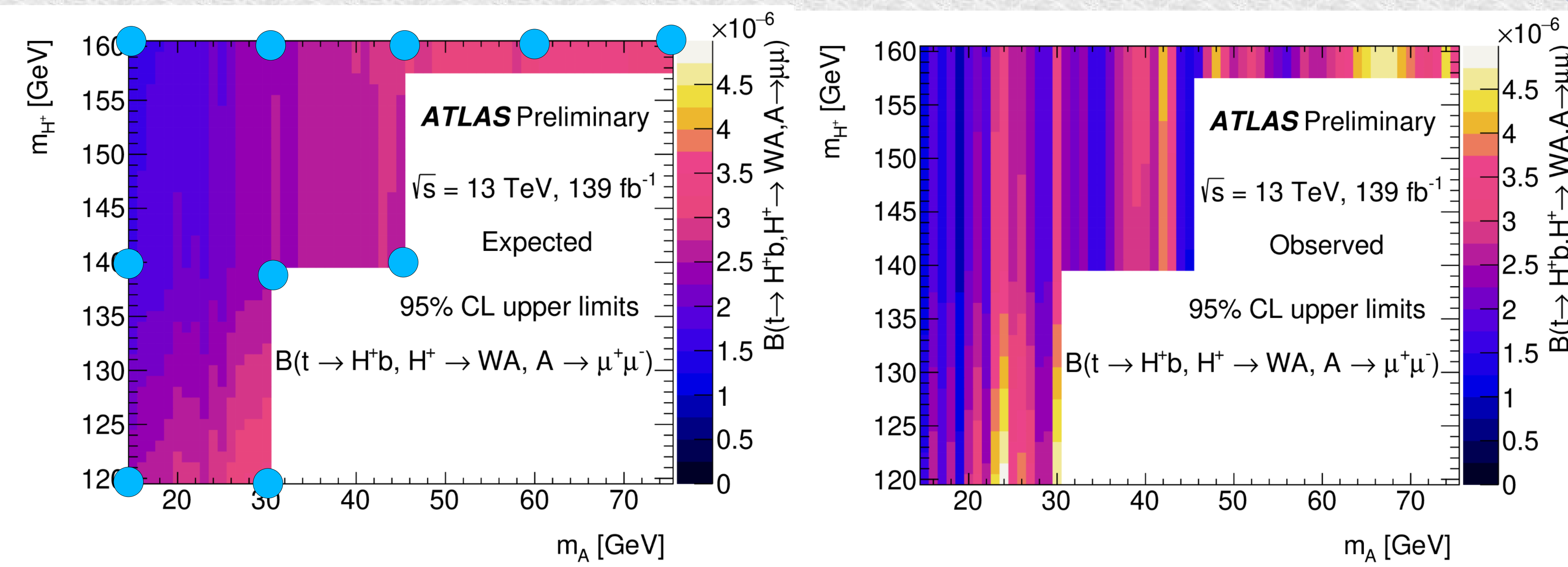


2HDMC product of BRs

- What actually matters for the search
- Br always decreases with tanβ
- Use this 3D map to read off a tanβ lower limit from a Br limit at m_A,m_{H+}
  - Interpolate for better precision

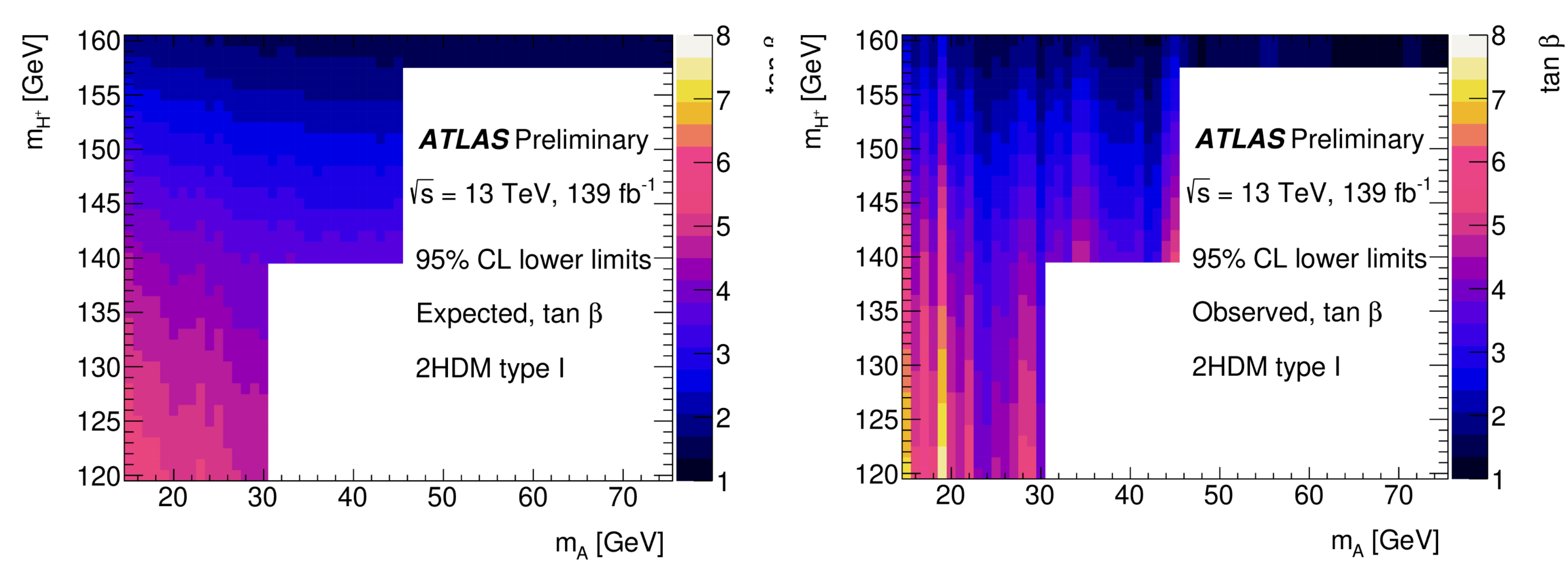


The Br limits in the CONF



- Only using interpolations of simulated points
- Expected results (fairly) smooth
- Observed wiggle with m_A as the data wiggles

The tanβ limits in the CONF



- Give limits on type I tan β in this parameter area
  - Range from 1.1 to 7
  - Right in the region of interest..great!
- Type II limits would always be tighter
  - but less interesting

Conclusions & Next steps

- CONF note give 2HDM limits.
  - Should we do a paper?
- If so possible additions?
  - Add μμμ channel
    - double statistics (nearly..some confusion loss)
  - Move to a functional form fit
    - I estimate bigger gain than the three muon addition
  - Add electron trigger
    - Would benefit especially low m_{H+}, to some extent low m_A
  - Increase upper mass range towards 125
    - There is the CMS (γγ)/LEP(bb) 96 GeV bump..
    - A lot of ttZ background though..could compare $Z \rightarrow ee/\mu\mu$
  - Decrease lower range: currently 15GeV, add 4-8GeV
    - Here absence of b decays increases BR a lot..
  - Include off shell $H+ \rightarrow WA$?
    - Type I BRs remain high far off shell

Regions		CRZ	CR$t\bar{t}$	CR$t\bar{t}Z$	VR	SRInclusive
Observed events		803	190	635	529	465
Fitted background events	Total	803 ±28	190 ±14	635 ±25	541 ±43	470 ±37
	$t\bar{t}$	136 ±21	170 ±14	97 ±19	388 ±46	320 ±39
	Z+HF	491 ±49	0.72 ± 0.16	43 ± 8	18 ± 6	29 ± 6
	Z+LF	84 ±29	0.41 ± 0.14	12 ± 4	2.82 ± 0.98	13 ± 4
	$t\bar{t}Z$	52 ±14	6.40 ± 1.64	327 ±83	76 ±19	64 ±16
	Diboson	34 ±17	0.58 ± 0.29	147 ±73	32 ±16	22 ±11
	W+jets	0.01 ± 0.01	0.40 ± 0.39	0 ± 0	0.08 ± 0.07	0.49 ± 0.48
	Single top	4.13 ± 0.29	4.38 ± 0.23	2.39 ± 0.12	9.00 ± 0.46	6.17 ± 0.33
	$t\bar{t}W$	1.06 ± 0.15	7.43 ± 0.97	6.42 ± 0.83	14 ± 2	16 ± 2
Pre-Fit background events	Total	762 ±93	181 ± 9	505 ±76	497 ±31	433 ±23
	$t\bar{t}$	131 ±15	163 ± 9	93 ±14	373 ±22	308 ±18
	Z+ HF	475 ±79	0.69 ± 0.08	42 ± 6	18 ± 7	28 ± 3
	Z+ LF	84 ±30	0.41 ± 0.14	12 ± 4	2.82 ± 0.99	13 ± 4
	$t\bar{t}Z$	32 ± 2	3.97 ± 0.12	202 ± 3	47 ± 1	40 ± 1
	Diboson	34 ±17	0.58 ± 0.29	147 ±74	32 ±16	23 ±11
	W+jets	0.01 ± 0.01	0.40 ± 0.40	0 ± 0	0.08 ± 0.07	0.49 ± 0.49
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