

Exotic Heavy Higgs Decays at the LHC

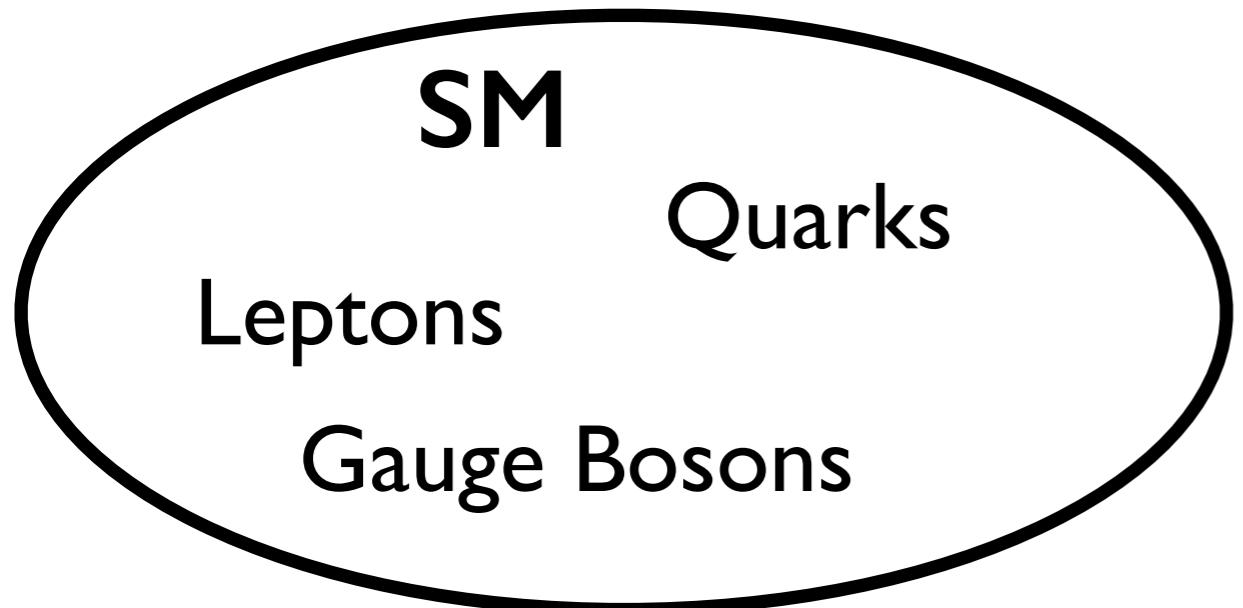
work with Baradhwaj Coleppa, Shufang Su, Jose No, Adarsh Pyarelal
arXiv: 1404.1992, 1408.4119, 1504.06624, 1504.06624, 1512.xxxx

Felix Kling

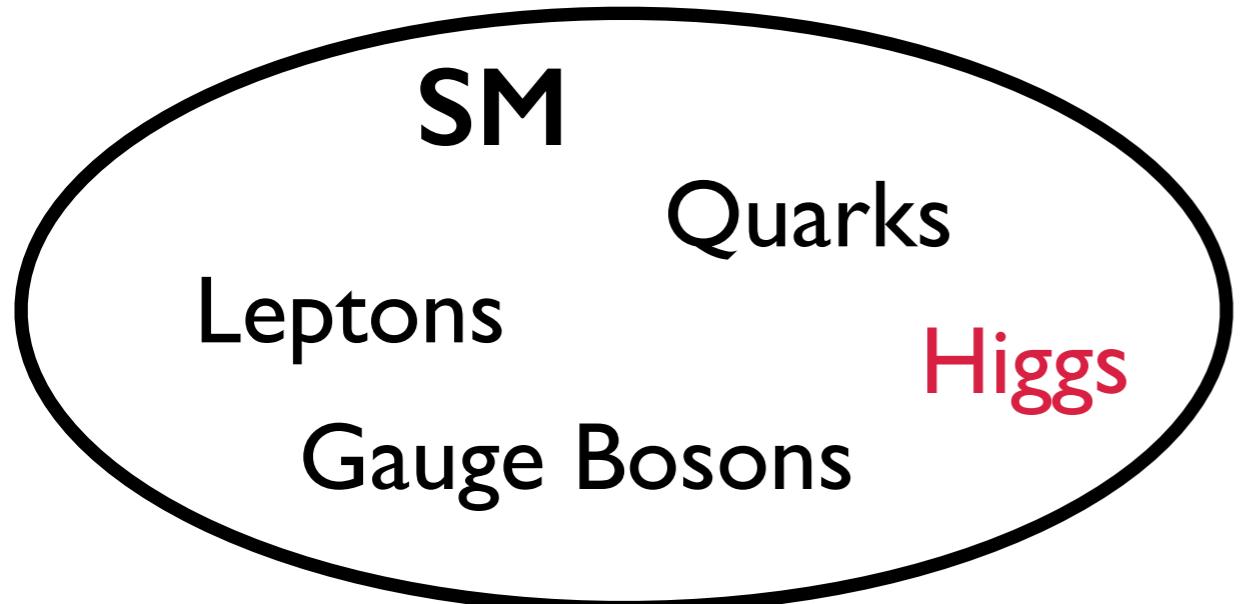


PITT PACC Workshop: Higgs and Beyond

Introduction

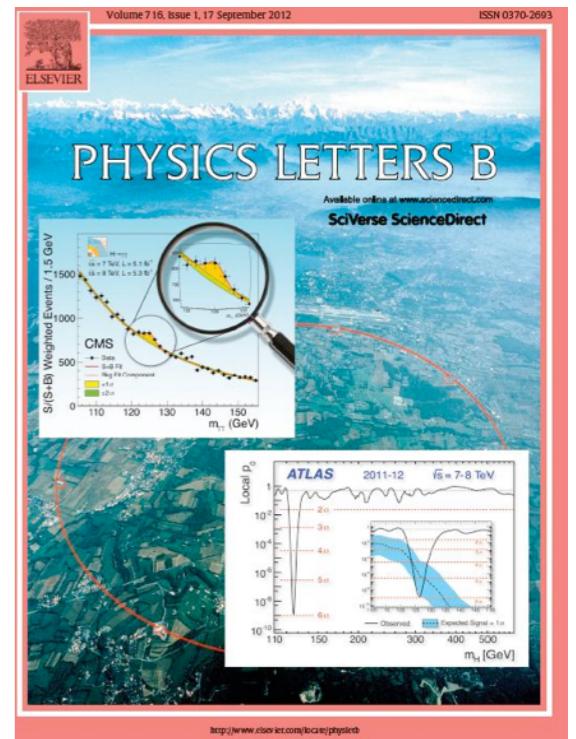


Introduction

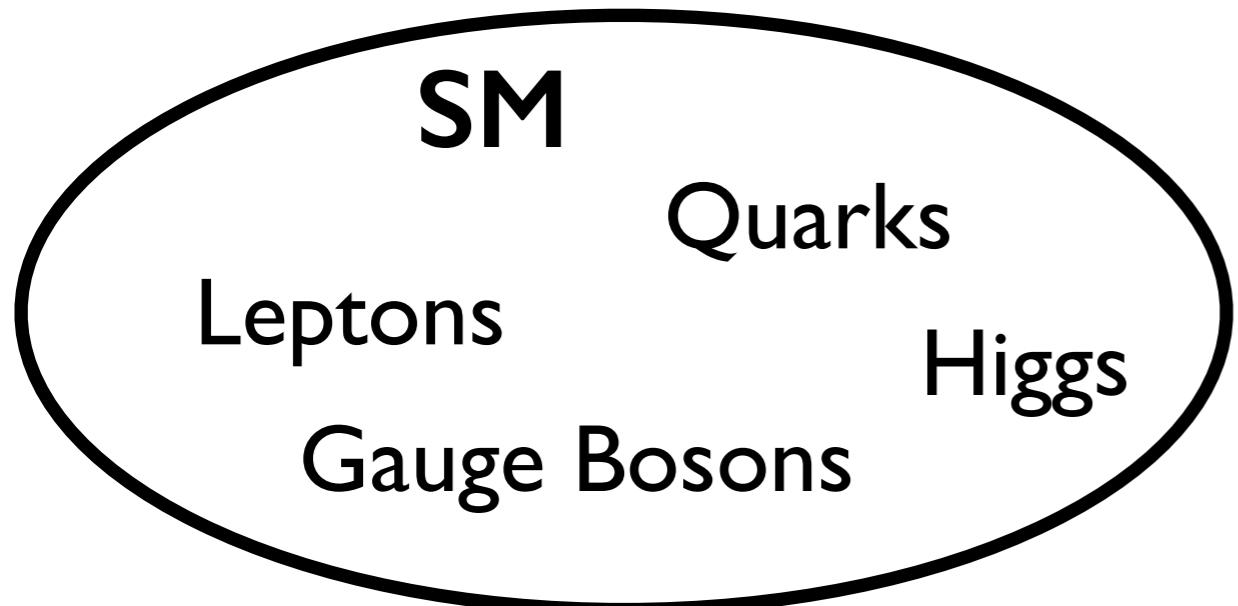


Discovery of the Higgs boson
in July 2012

Standard Model is complete

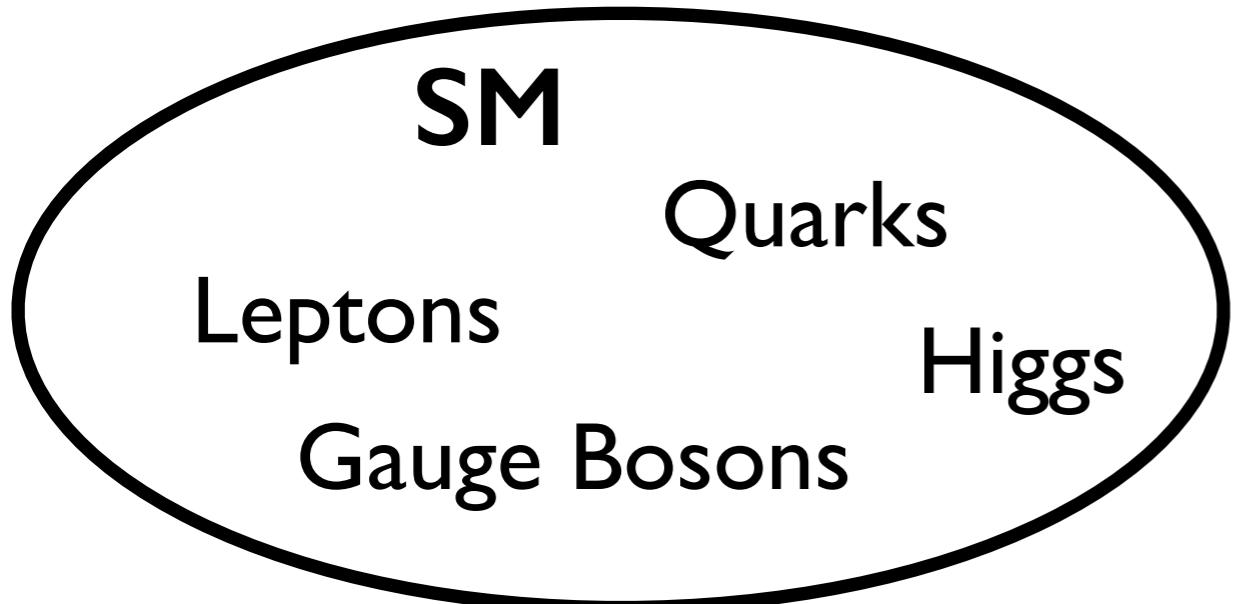


Introduction



Did we solve all problems?
Do we have a complete description of nature?
Can we stop doing High Energy Physics?

Introduction



Did we solve all problems?
Do we have a complete description of nature?
Can we stop doing High Energy Physics?

NO!

There are still open questions!

Introduction

New Physics Model

SM
Quarks
Leptons
Higgs
Gauge Bosons

Introduction

New Physics Model

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Gauge Bosons

Dark Matter Sector

Dark Matter



Introduction

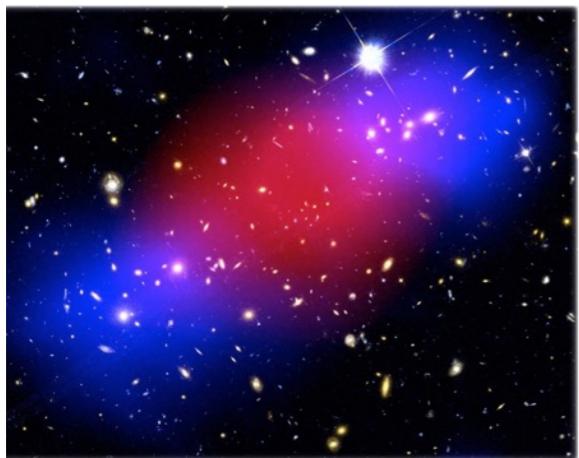
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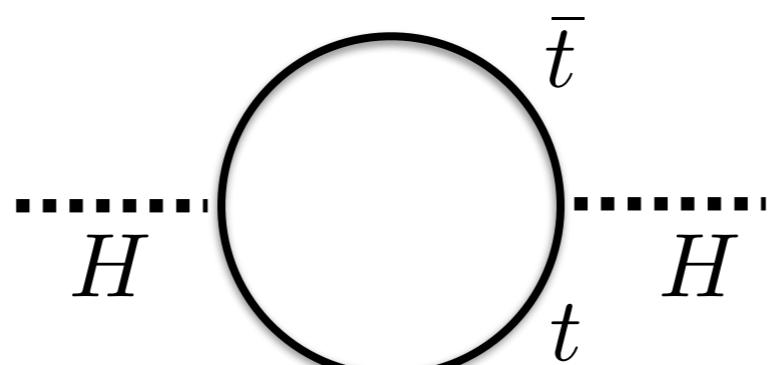
Dark Matter Sector

Top Partners

Dark Matter



Naturalness



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New Physics Model

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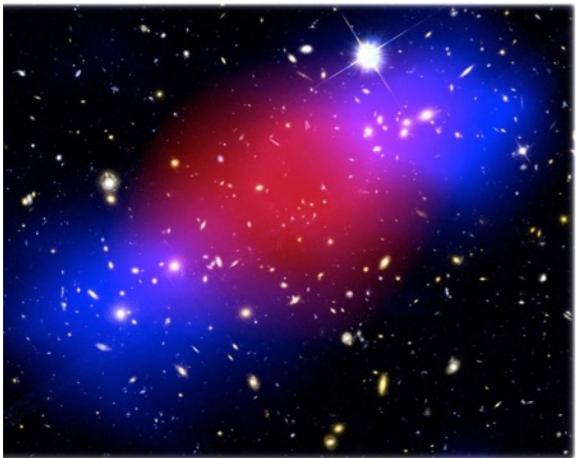
Higgs

Dark Matter Sector

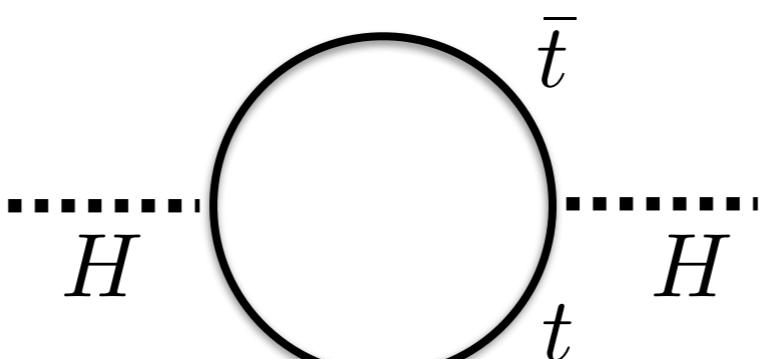
Top Partners

Extended Higgs Sector

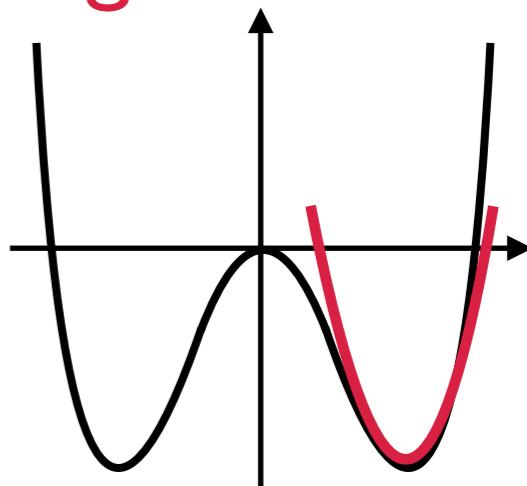
Dark Matter



Naturalness



Origin of EWSB



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Top Partners

Extended Higgs Sector

How can we describe the extended Higgs sector?

How can we find these additional Higgs?

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2HDM
Extended
Higgs Sector

Dark Matter
Sector

Top Partners

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Two Higgs Doublet Model

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Top Partners

How can we describe the
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Two Higgs Doublet Model

Exotic Higgs searches

How can describe the extended Higgs sector?

Two Higgs Doublets:

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + i\varphi_i)/\sqrt{2} \end{pmatrix}$$

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8 degrees of freedom

- 3 Goldstone Bosons
 - 5 Higgs Bosons
- h, H, A, H⁺, H⁻*

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Higgs Potential

$$\begin{aligned} V(\Phi) = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\ & + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ & + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda_5 \left\{ (\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right\} \end{aligned}$$

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Physical Mass Basis

m_h, m_H, m_A, m_{H⁺}

Higgs Masses

v, tan β

VEV

cos(β - α)

m₁₂²

g_{HVV}

Free

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Free

Type II 2HDM: Defined by Coupling to Fermions

- up-like quarks couple to Φ_1
- down-like quarks and leptons couple to Φ_2

Same in MSSM

How can we find additional Higgs?

Discovery of extra Higgs is direct evidence for BSM new physics

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Conventional Channels

Neutral Higgs:

$$A/H \rightarrow WW, ZZ, bb, \tau\tau, \gamma\gamma$$

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Results already available

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$$\begin{aligned} H &\rightarrow hh, AA \\ A/H &\rightarrow hZ, HZ/AZ \\ A/H &\rightarrow WH^\pm \\ H &\rightarrow H^+H^- \end{aligned}$$

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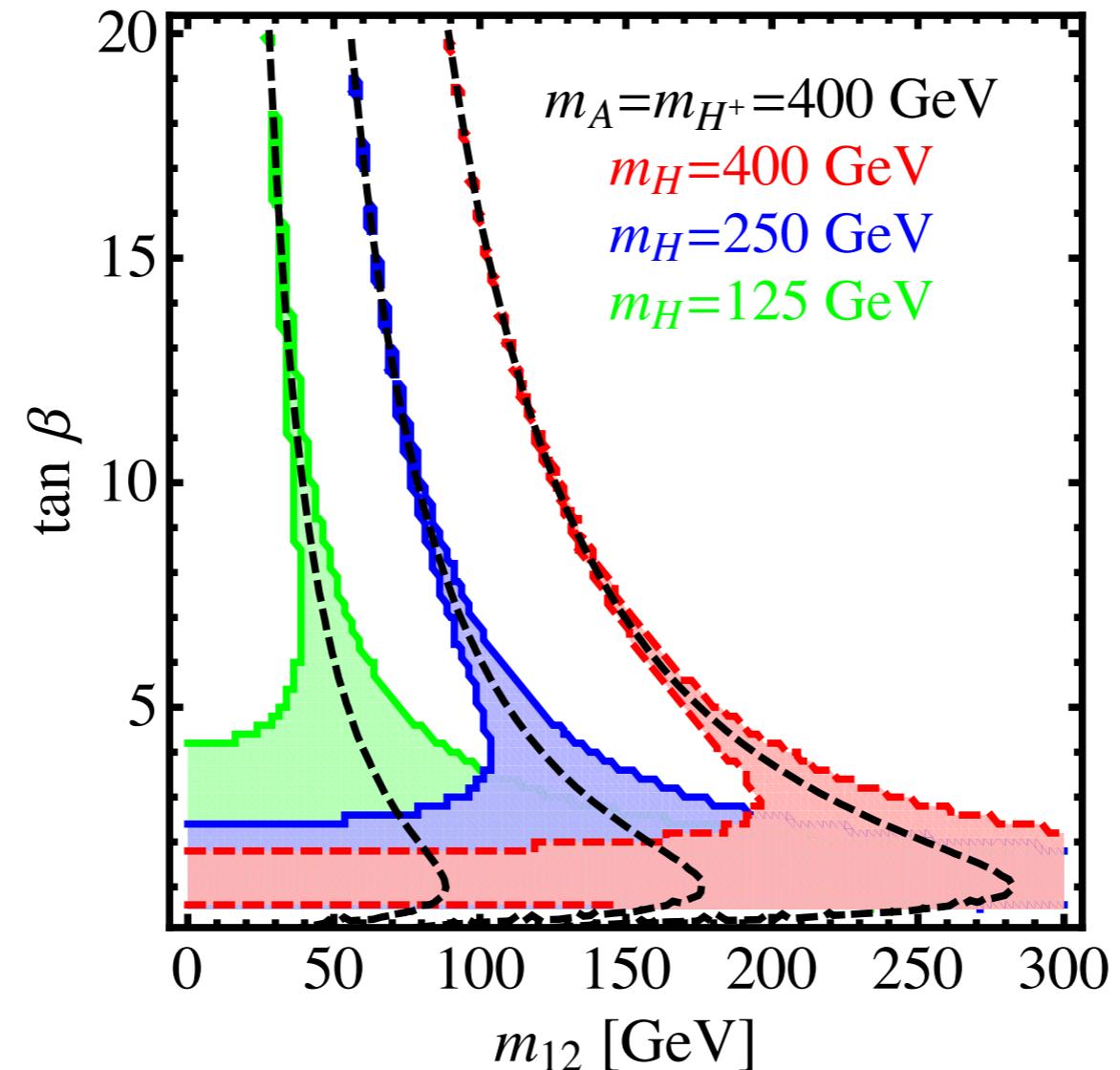
New!

Theoretical and Experimental Constraints (in the alignment limit)

Unitarity:

- high $\tan \beta$: $\lambda_1 < 8\pi \rightarrow m_{12}^2 = m_H^2 s_\beta c_\beta$
 $\rightarrow g_{Hhh} = g_{HAA} = g_{HH^+ H^-} = 0$
- low $\tan \beta$: arbitrary m_{12}^2 but $m_{H,A,H^+} < \mathcal{O}(TeV)$

~~$H \rightarrow hh, AA$~~
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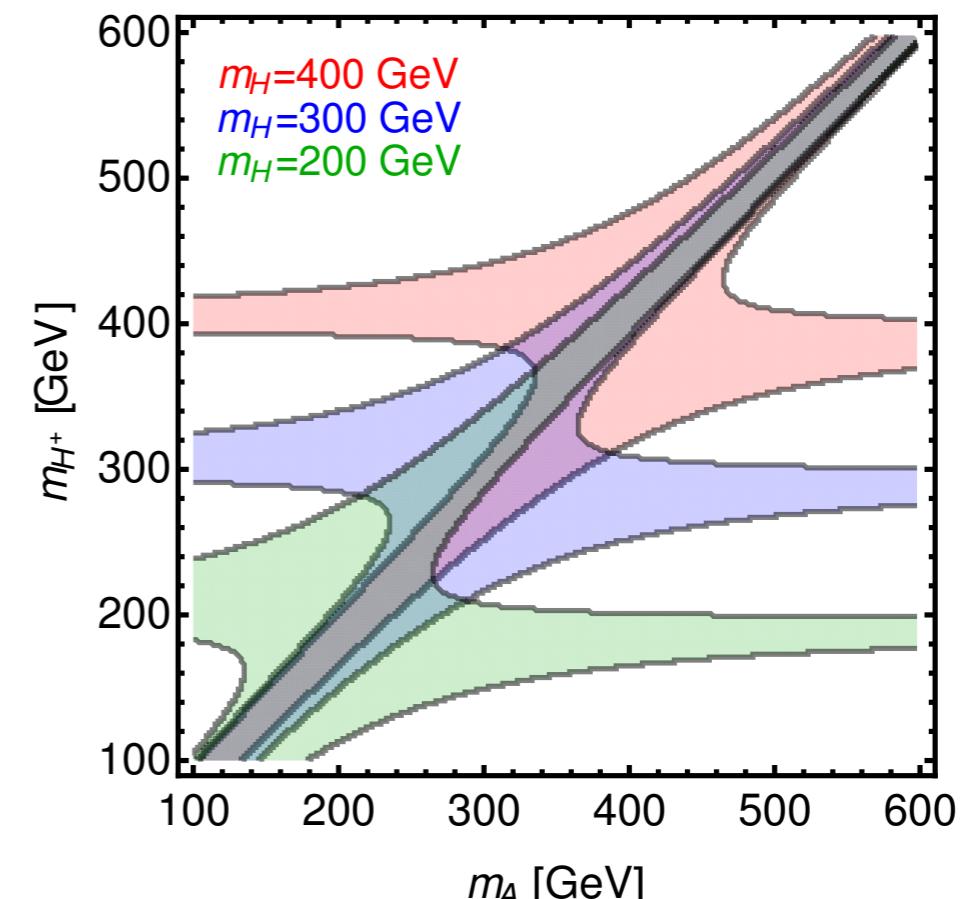
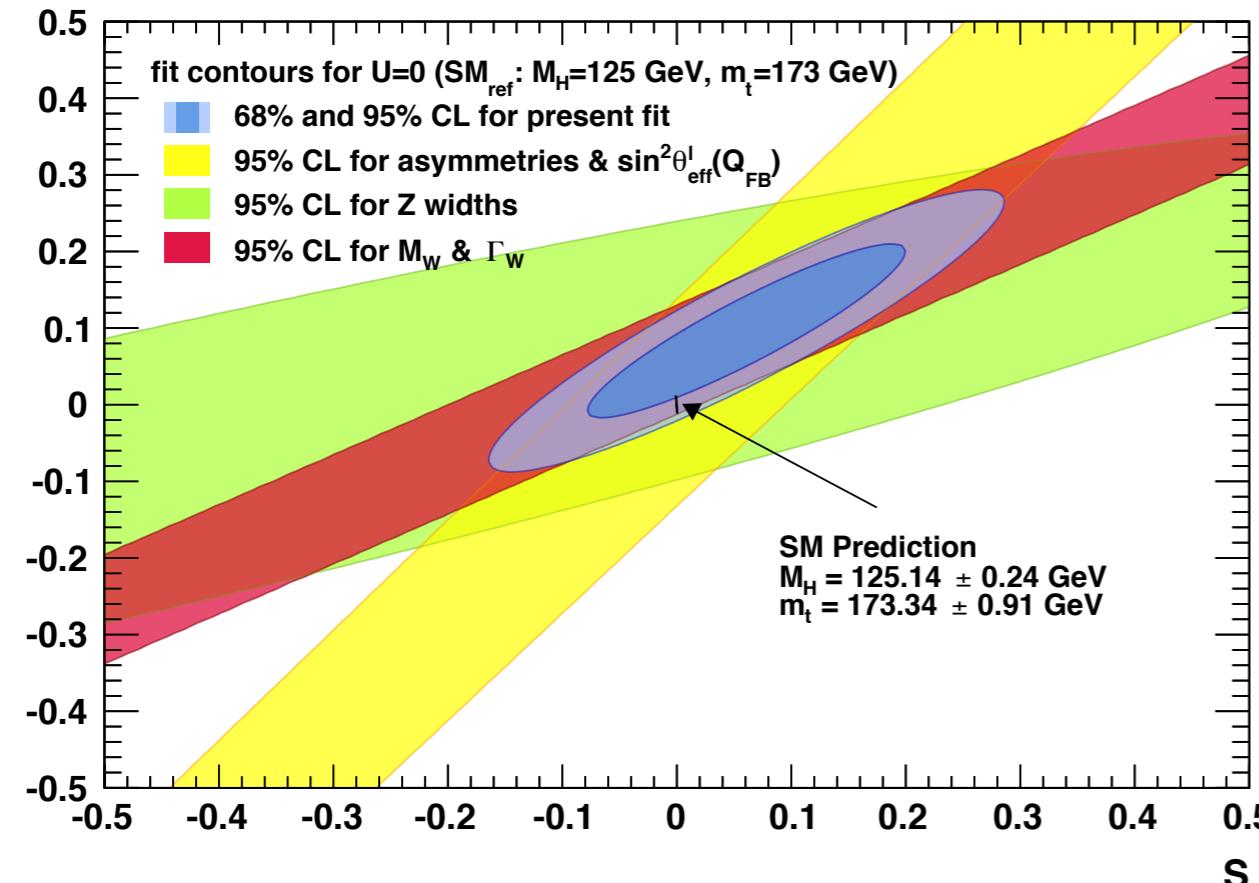
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Vacuum Stability:

- **high** $\tan \beta$: $m_H < m_A, m_{H^+}$

~~$H \rightarrow AZ, H^+ W$~~

Theoretical and Experimental Constraints



Electroweak Precision Measurements:
- S,T Parameter: $m_{H^+} \approx m_H$ or m_A

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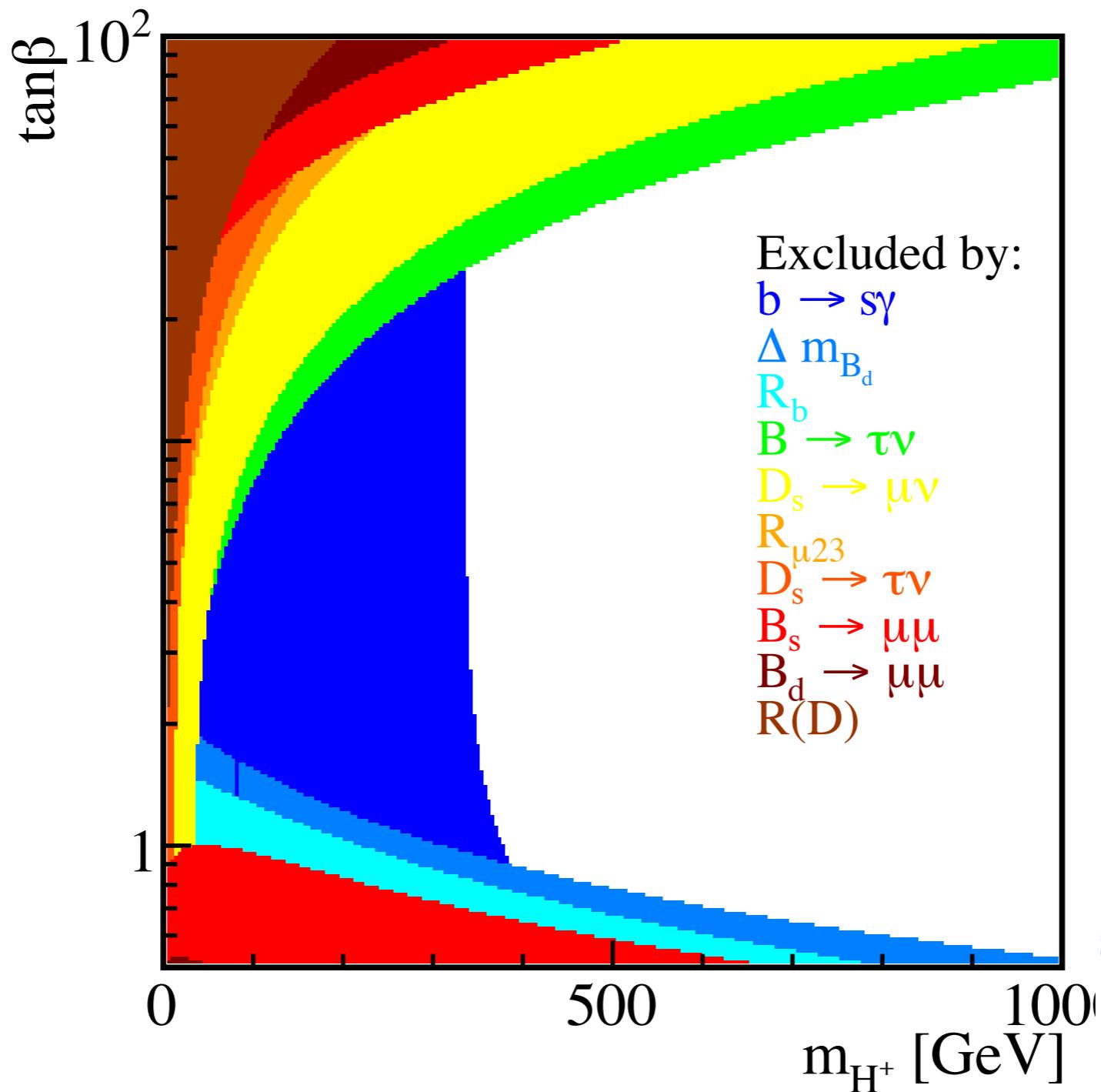
- S,T Parameter: $m_{H^+} \approx m_H$ or m_A

Higgs Searches:

- LHC: $A/H \rightarrow \tau\tau, H^+ \rightarrow \tau\nu$
 $t \rightarrow H^+ b$
- LEP: $e^+ e^- \rightarrow AH$

bounds $\tan \beta$ from above
 $m_{H^+} > m_{top}$
 $m_A + m_H < 200$ GeV

Theoretical and Experimental Constraints



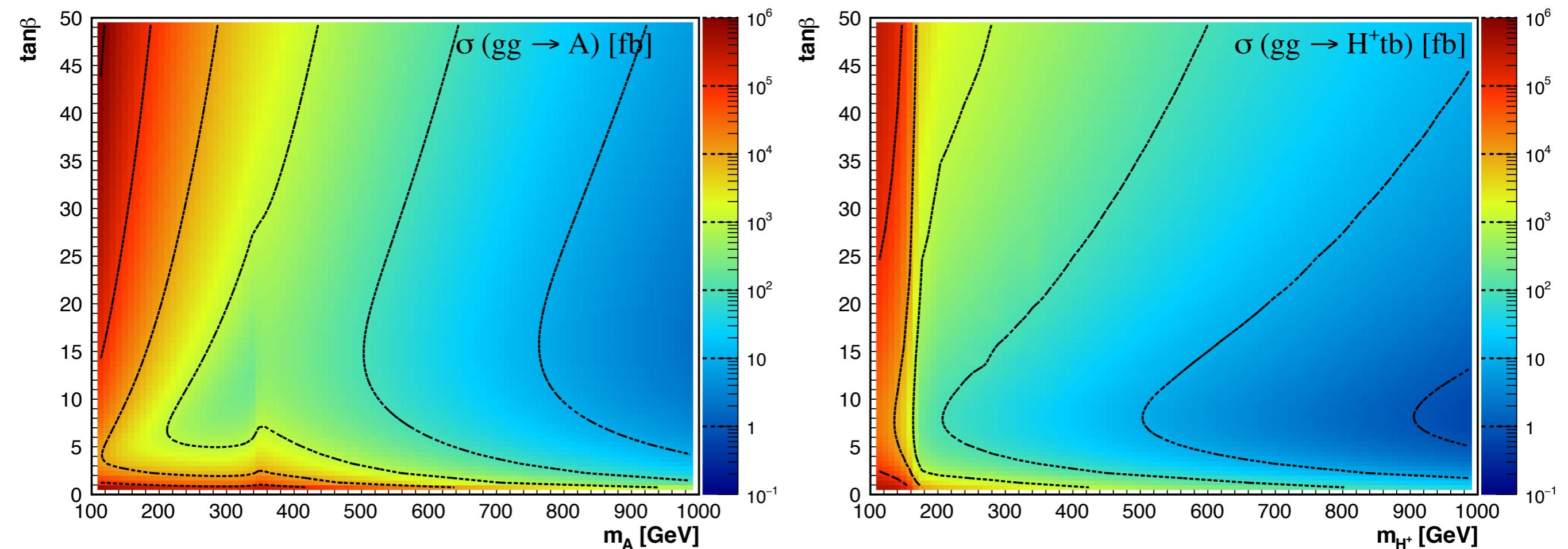
(Flavour):

- $b \rightarrow s\gamma$: $m_{H^+} > 350$ GeV

Heavy Higgs Production

Neutral Higgs:

- main production channel: $ggF, bbH/bbA$
- enhancement at low/high $\tan\beta$: $g_{Att} \sim \cot\beta, g_{Abb} \sim \tan\beta$
- no VBF/HV production: $g_{AVV} = 0, g_{HVV} = \cos(\beta - \alpha) \approx 0$



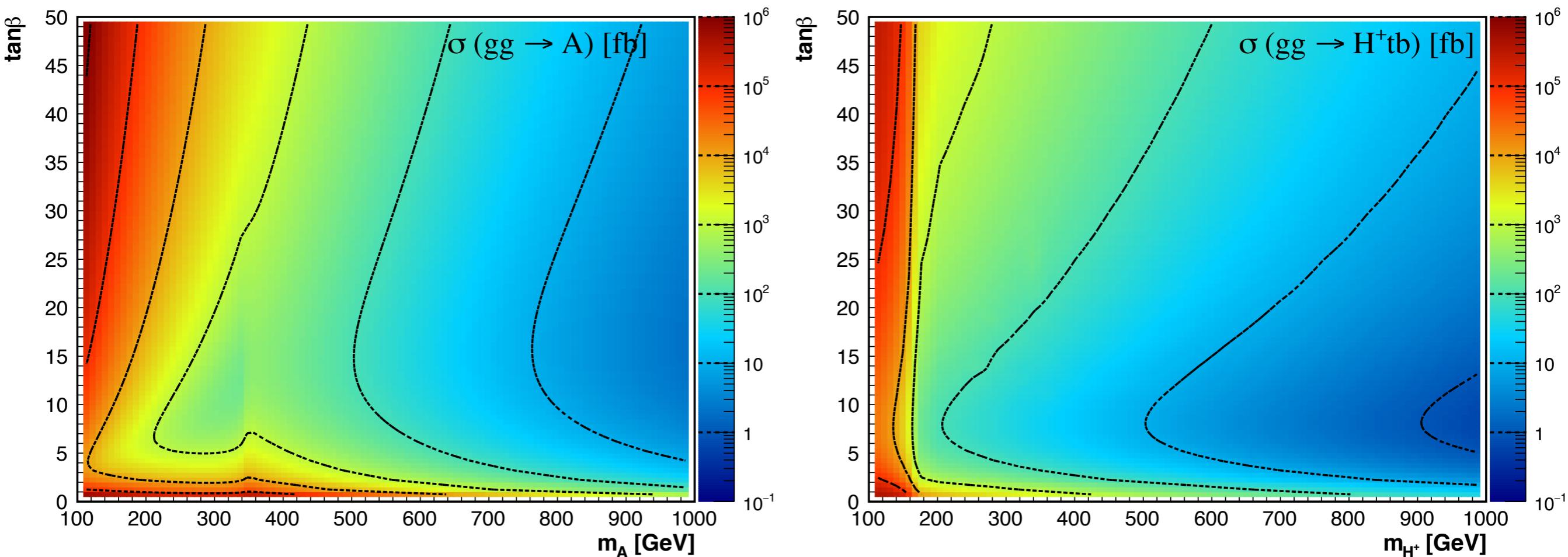
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Heavy Higgs Production

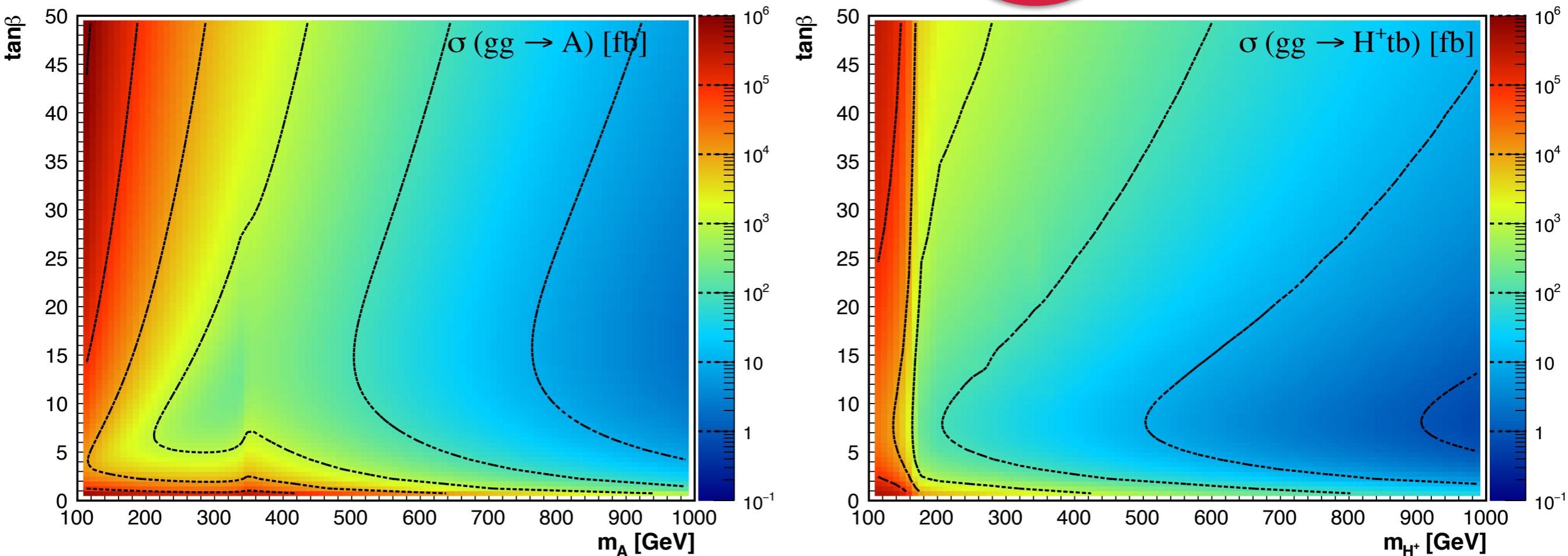
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Charged Higgs:

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small



Benchmark Scenarios

$m_H < m_A = m_{H^+}$
 $A \rightarrow HZ$
 $H^+ \rightarrow HW$

$m_A < m_H = m_{H^+}$
 $H \rightarrow AZ, AA$
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~~$m_{H^+} < m_H = m_A$~~
 ~~$H \rightarrow H^+W, H^+H^-$~~
 ~~$A \rightarrow H^+W$~~

always possible

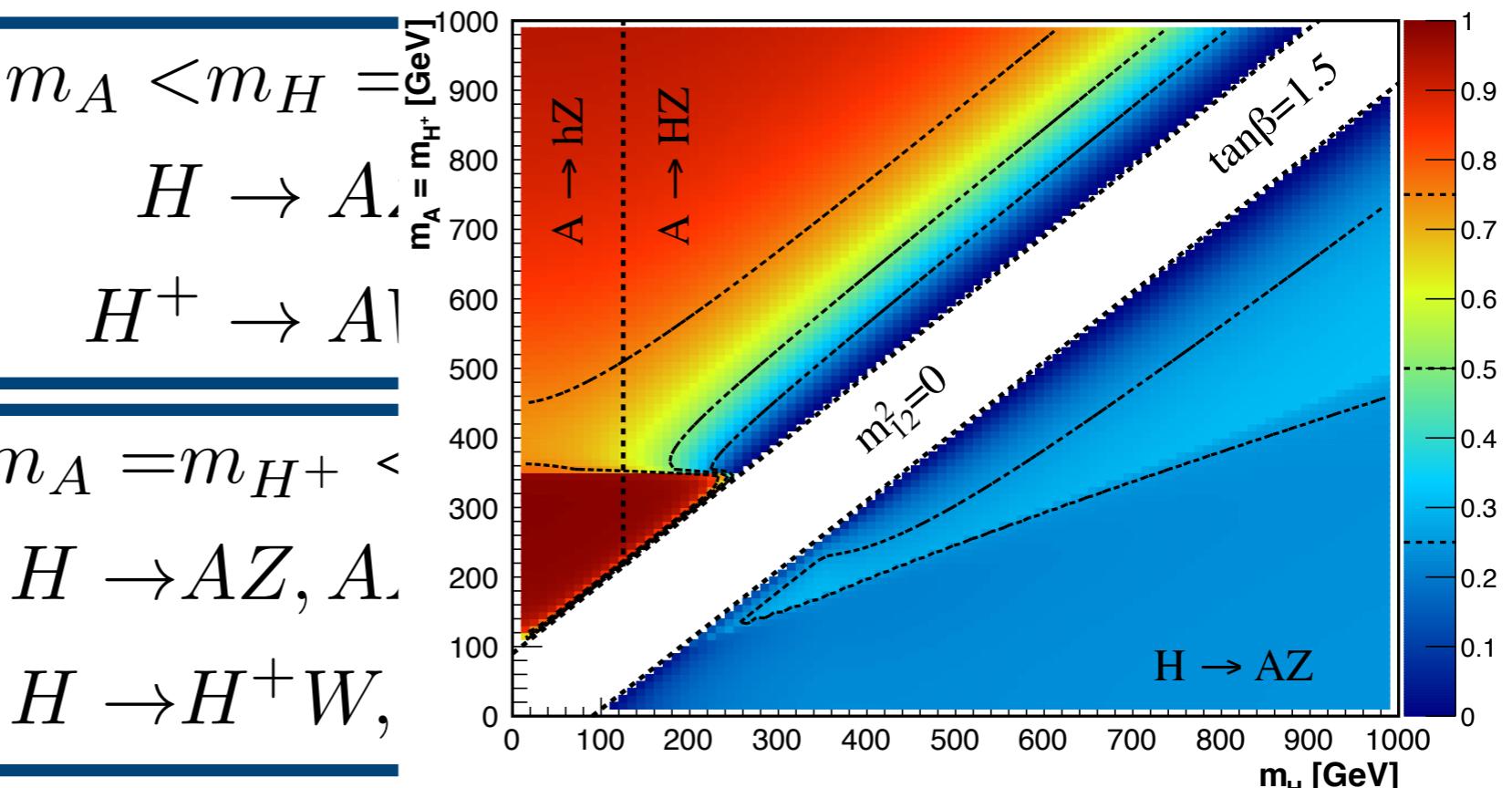
only at low $\tan \beta$

not allowed by S,T

Benchmark Scenarios

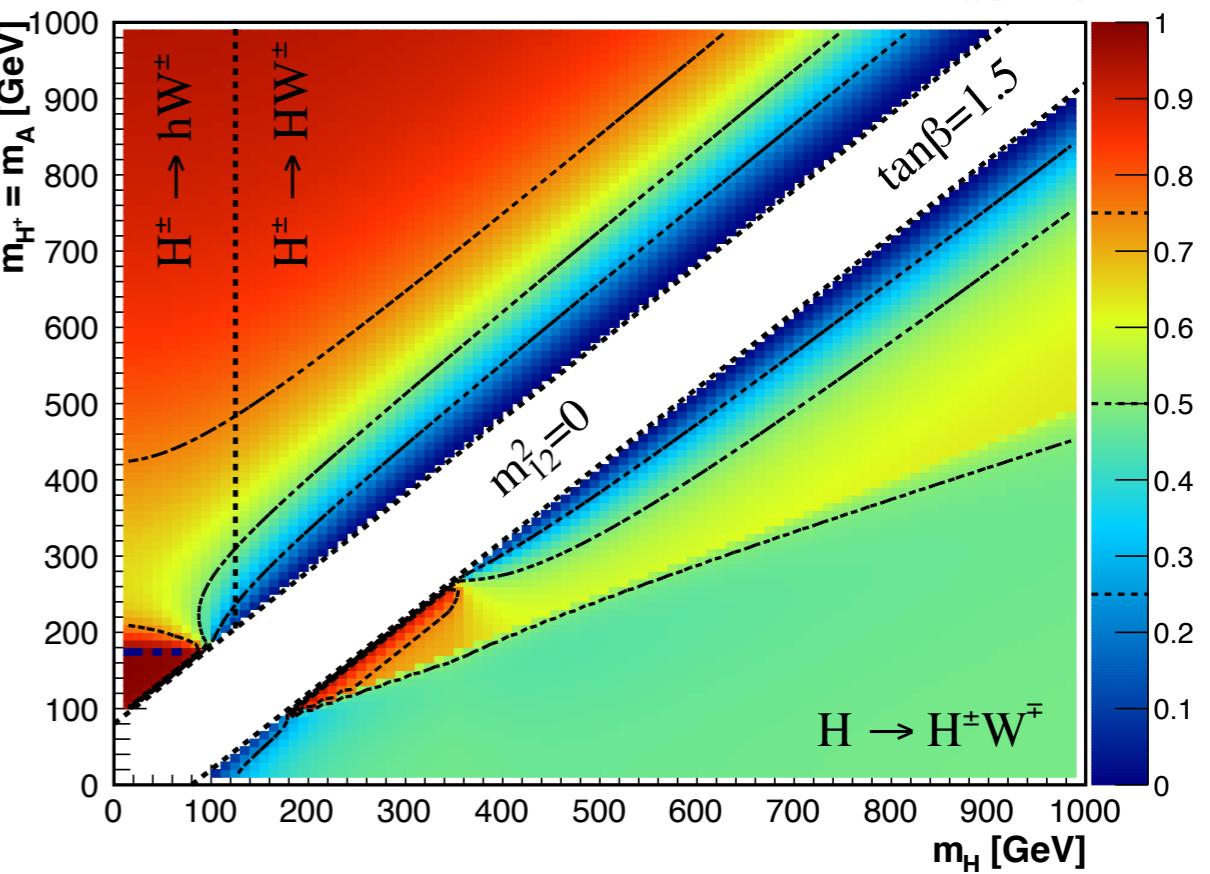
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 $A \rightarrow HZ$
 $H^+ \rightarrow HW$

$m_H = m_{H^+} < m_A$
 $A \rightarrow HZ$
 $A \rightarrow H^+W$



- always possible**
- large exotic BR($H \rightarrow H'V$)
 - small exotic BR($H \rightarrow H'H'$)

only at low



Benchmark Scenarios

$$m_H < m_A = m_{H^+}$$

✓ $A \rightarrow HZ$

$$H^+ \rightarrow HW$$

$$m_A < m_H = m_{H^+}$$

(✓) $H \rightarrow AZ, AA$

$$H^+ \rightarrow AW$$

$$m_H = m_{H^+} < m_A$$

$$A \rightarrow HZ$$

$$A \rightarrow H^+W$$

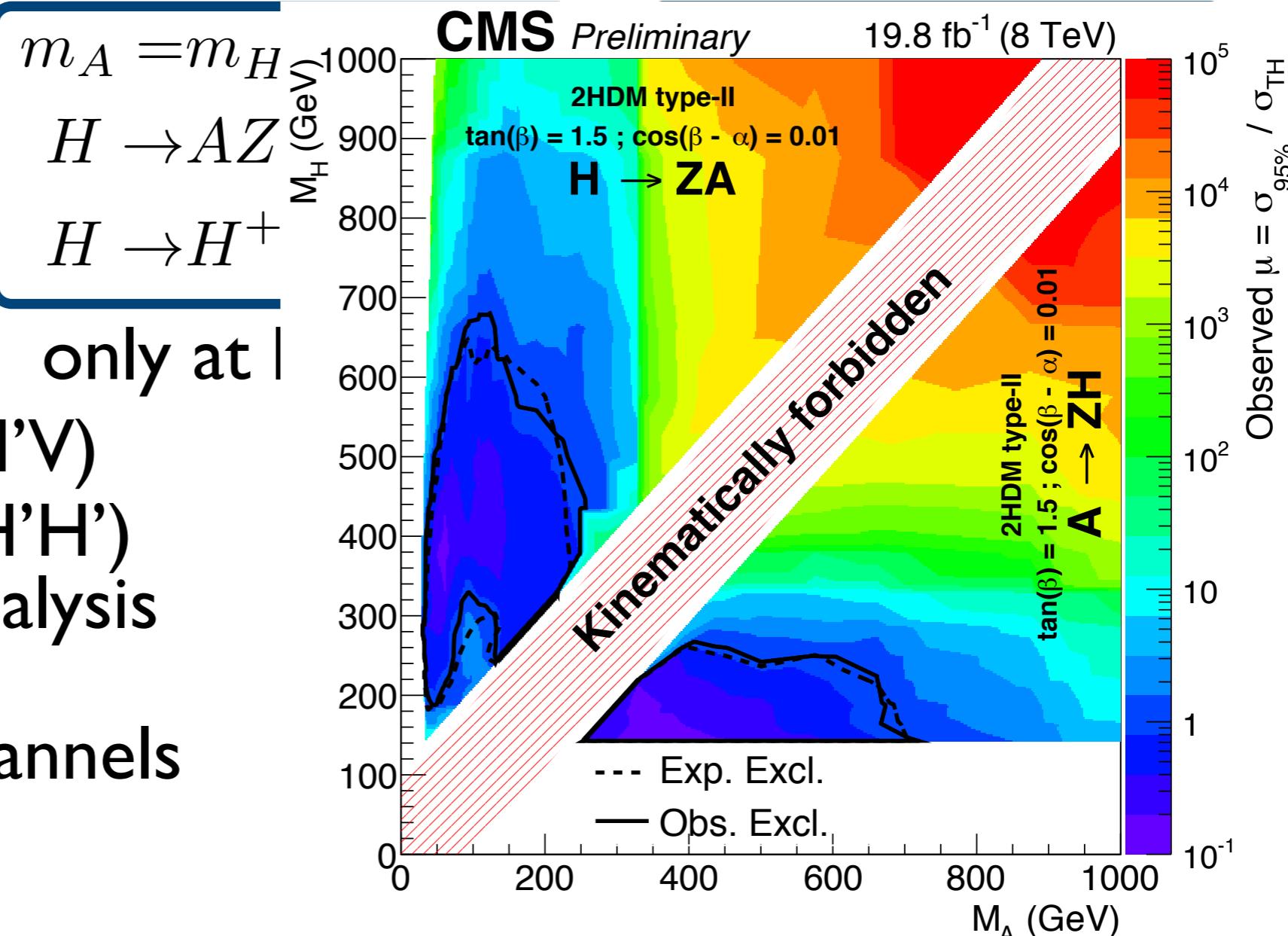
always possible

- large exotic BR($H \rightarrow H'V$)
- small exotic BR($H \rightarrow H'H'$)
- first experimental analysis available

available

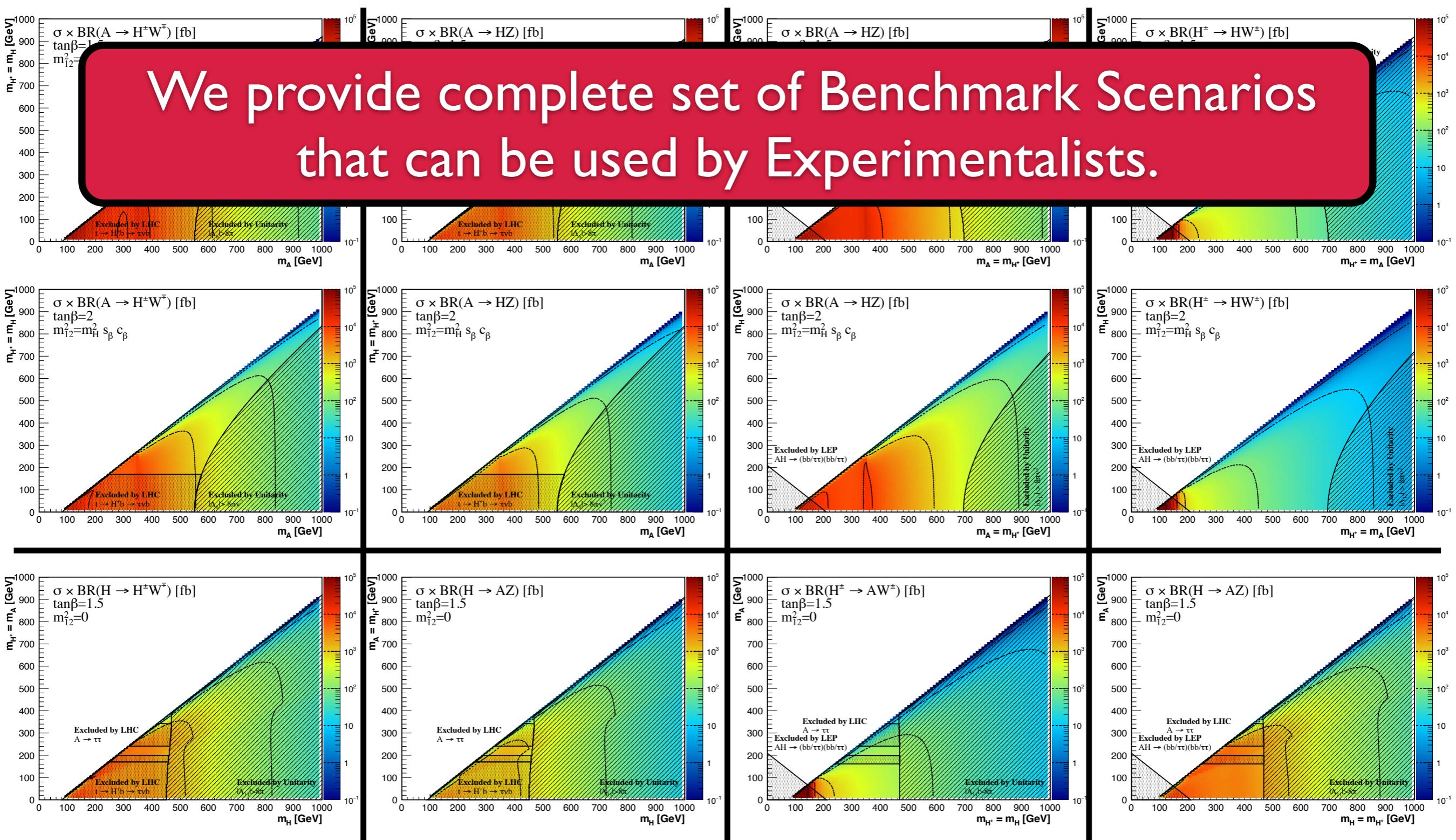
- more unexplored channels need to be analyzed

~~$$m_H = m_A < m_{H^+}$$~~
~~$$H^+ \rightarrow HW$$~~
~~$$H^+ \rightarrow AW$$~~



Benchmark Scenarios

We provide complete set of Benchmark Scenarios
that can be used by Experimentalists.

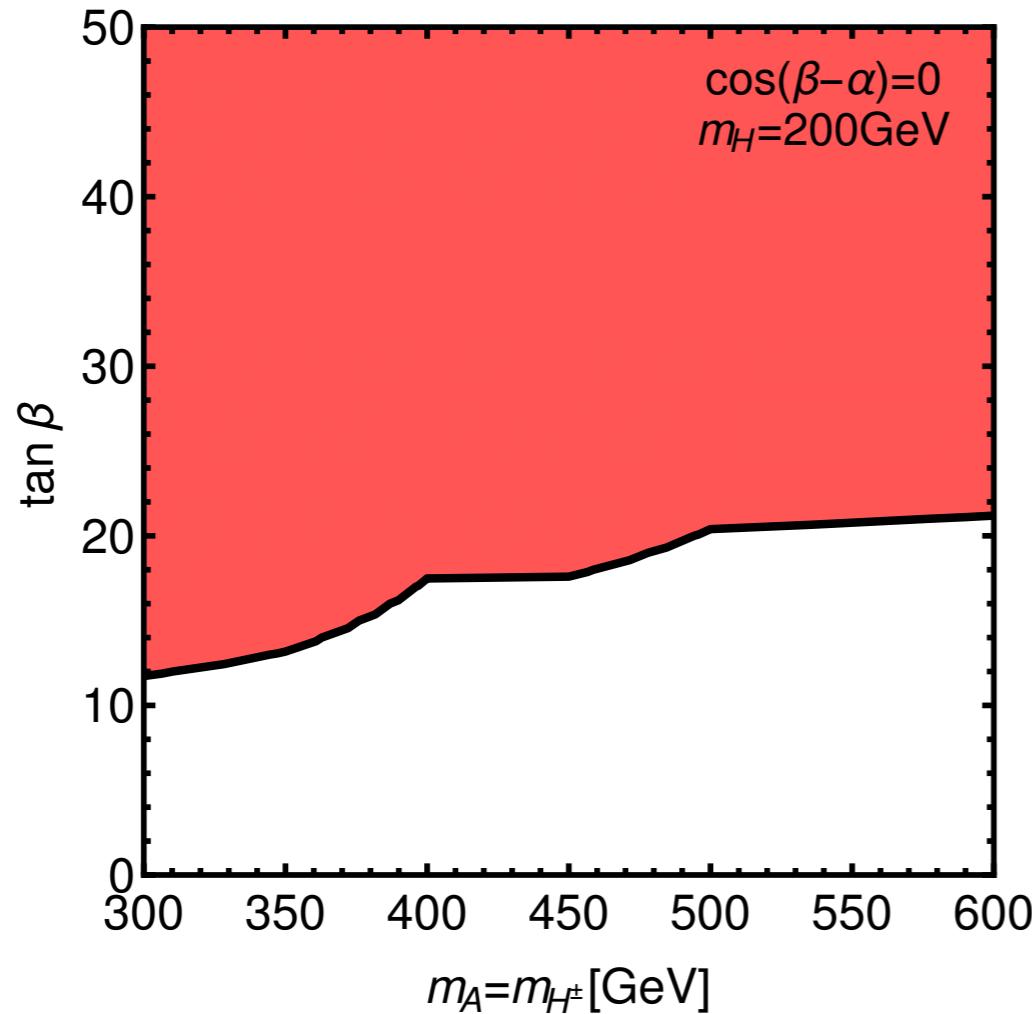


Collider Reach

Limits:

- strongest constraints from $H/A \rightarrow \tau\tau$

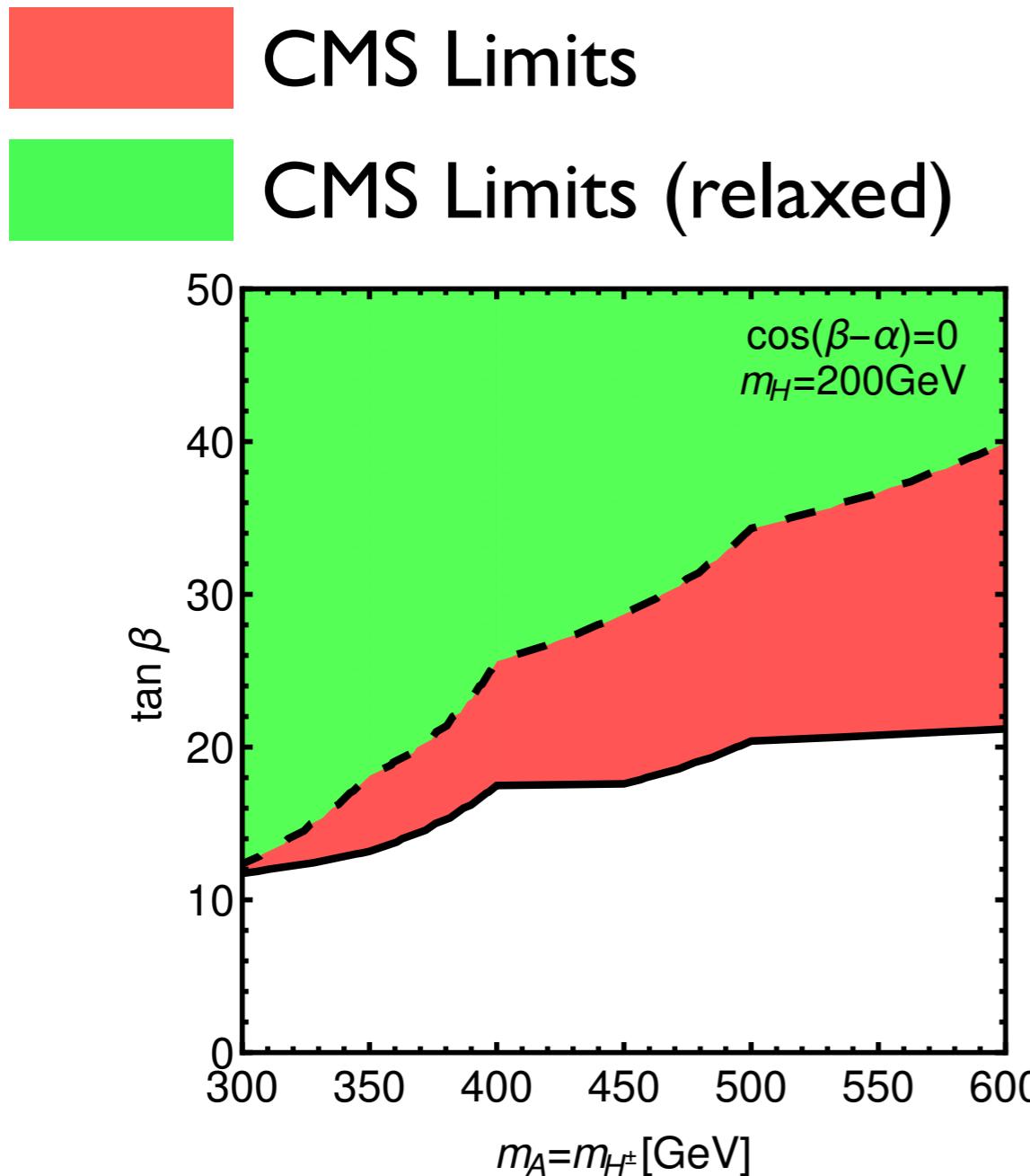
CMS Limits



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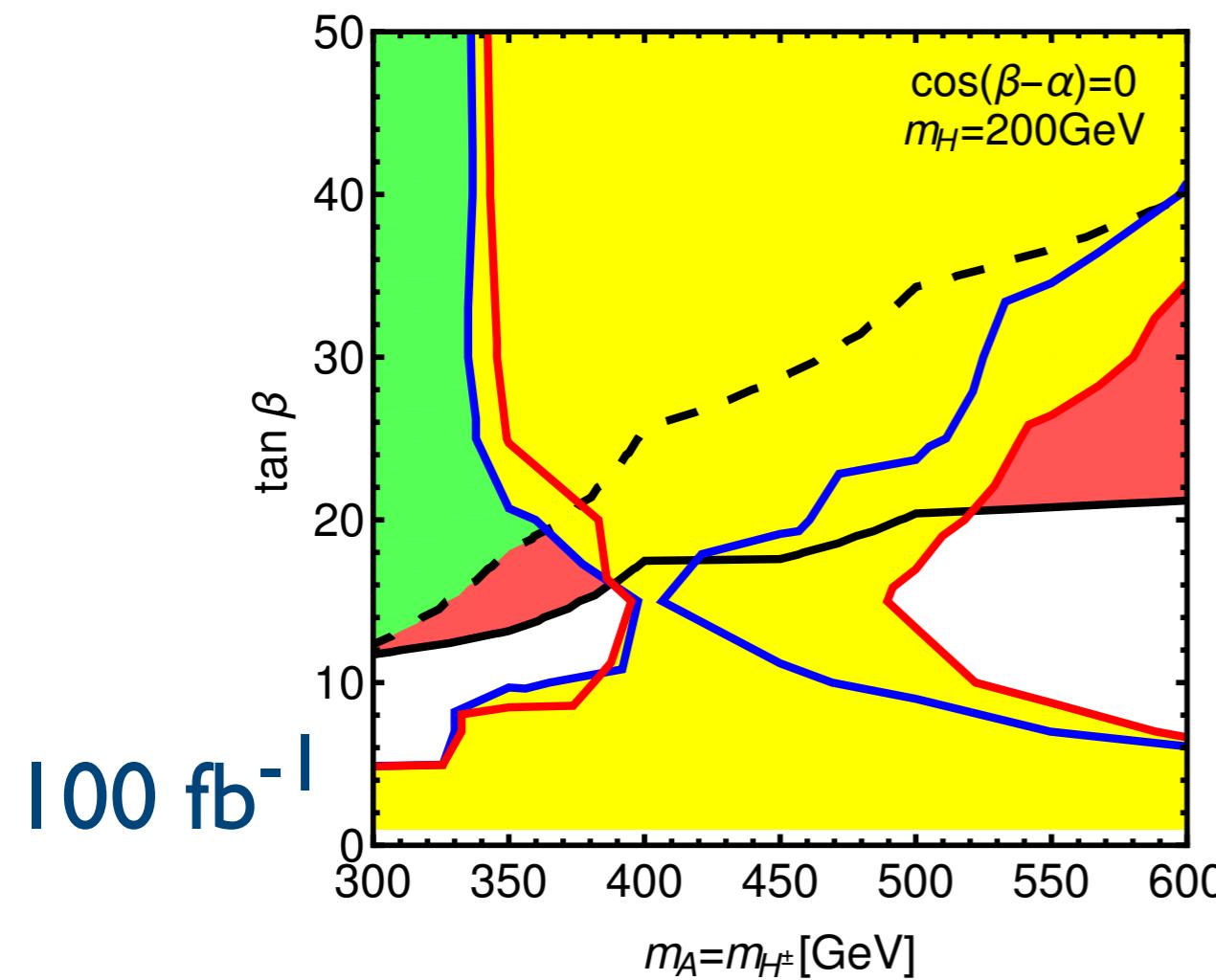
CMS Limits



$A \rightarrow HZ$ 95%CL Exclusion



CMS Limits (relaxed)

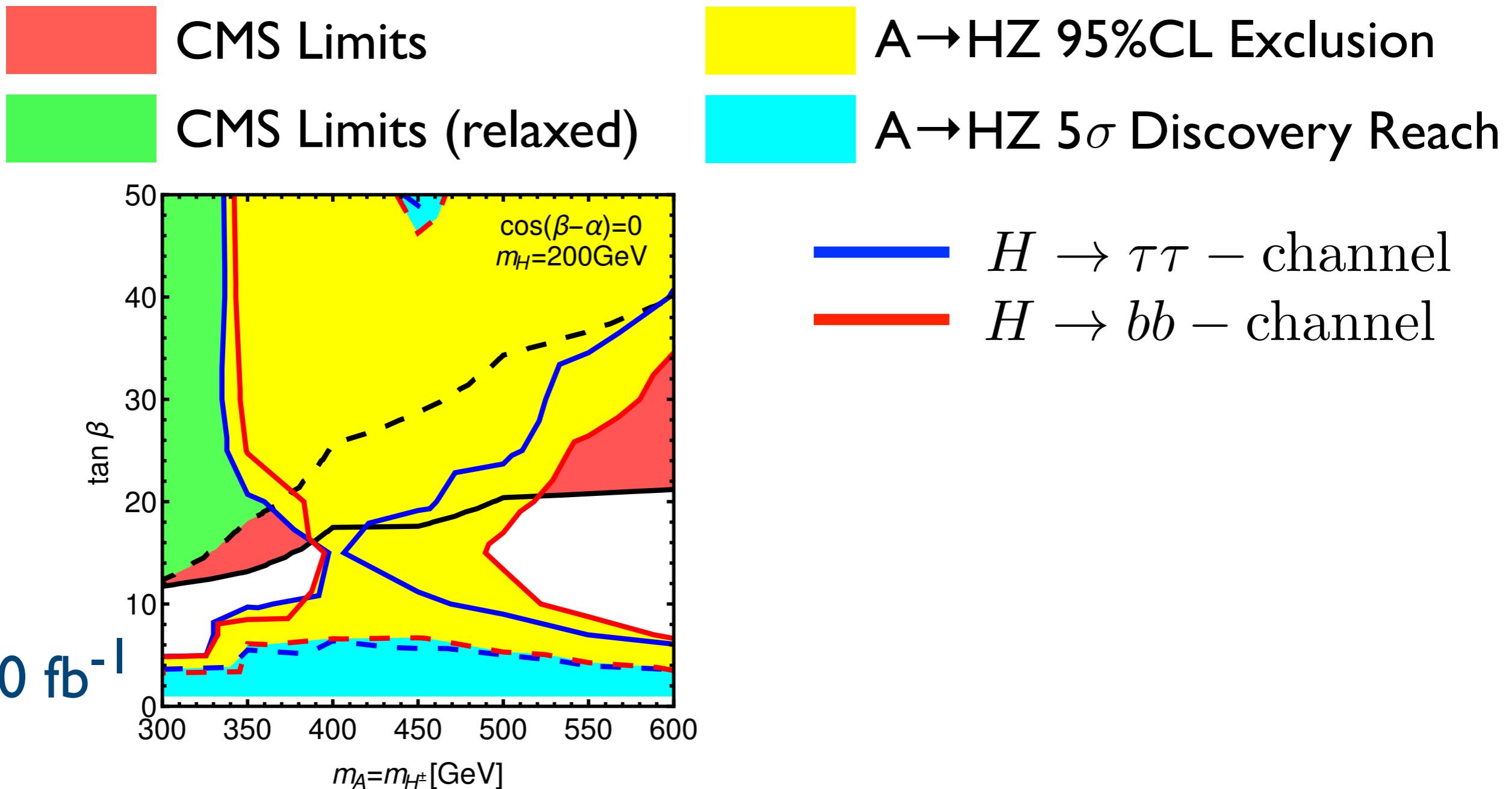


- --- $H \rightarrow \tau\tau$ – channel
- — $H \rightarrow bb$ – channel

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Collider Reach

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1

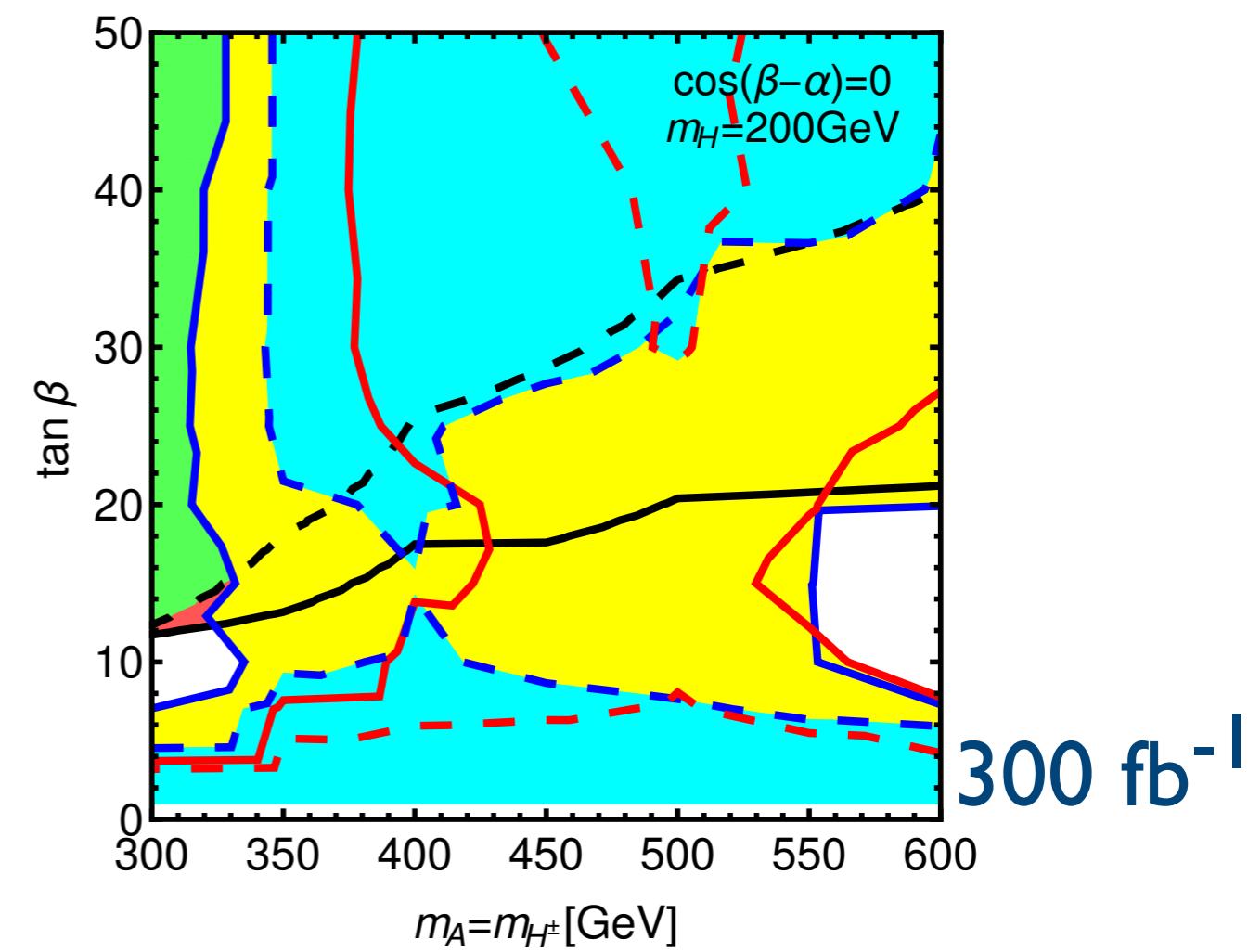
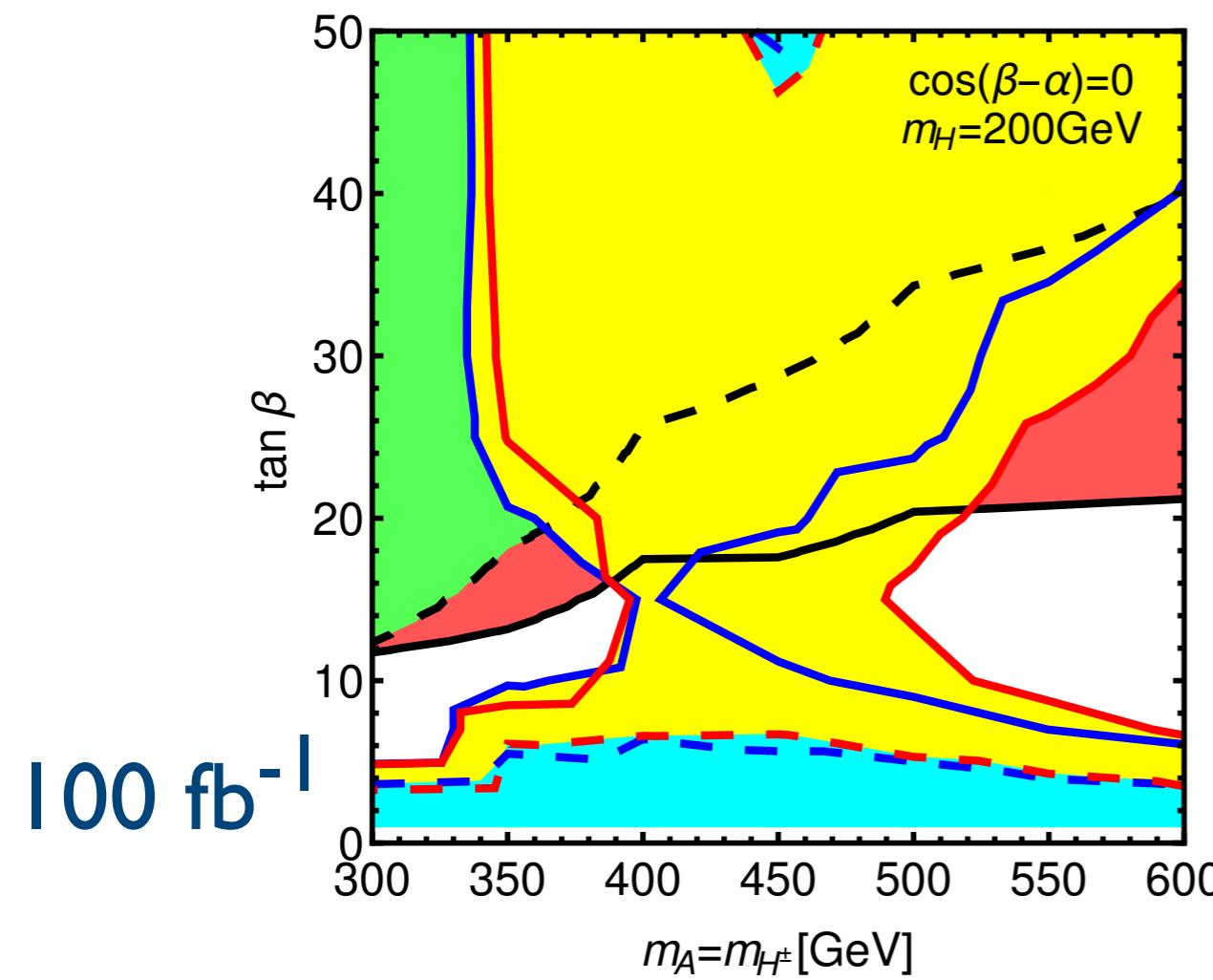
CMS Limits

2

CMS Limits (relaxed)

A \rightarrow HZ 95%CL Exclusion

A \rightarrow HZ 5 σ Discovery Reach



Collider Reach

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CMS Limits



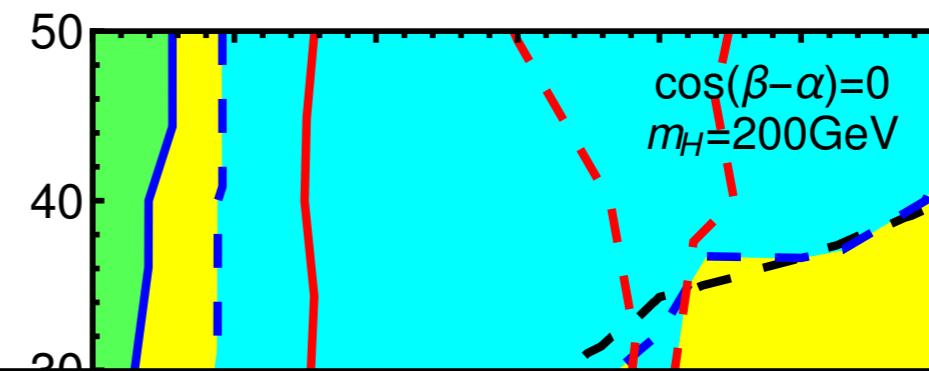
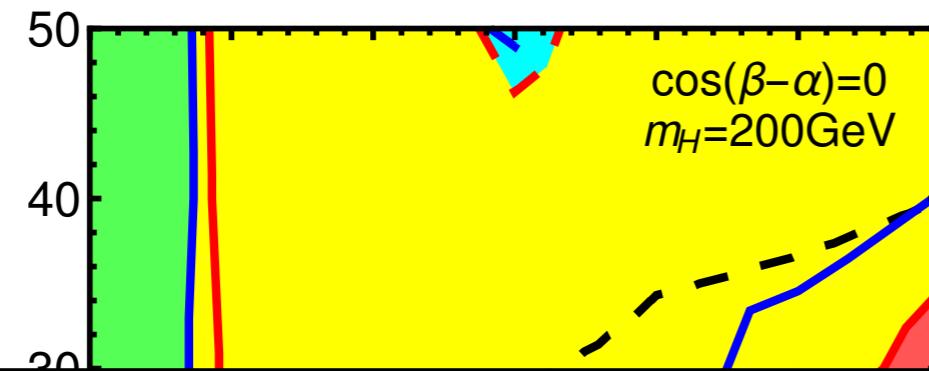
CMS Limits (relaxed)



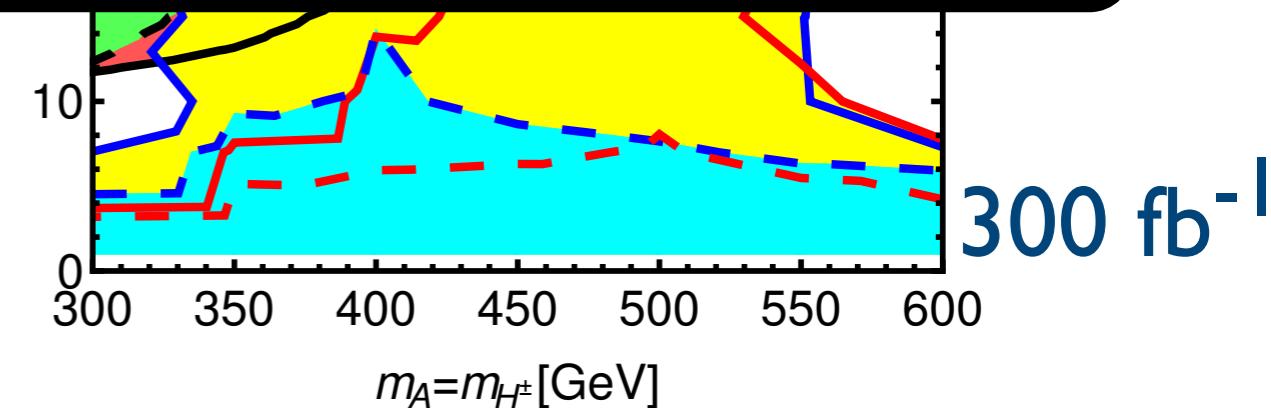
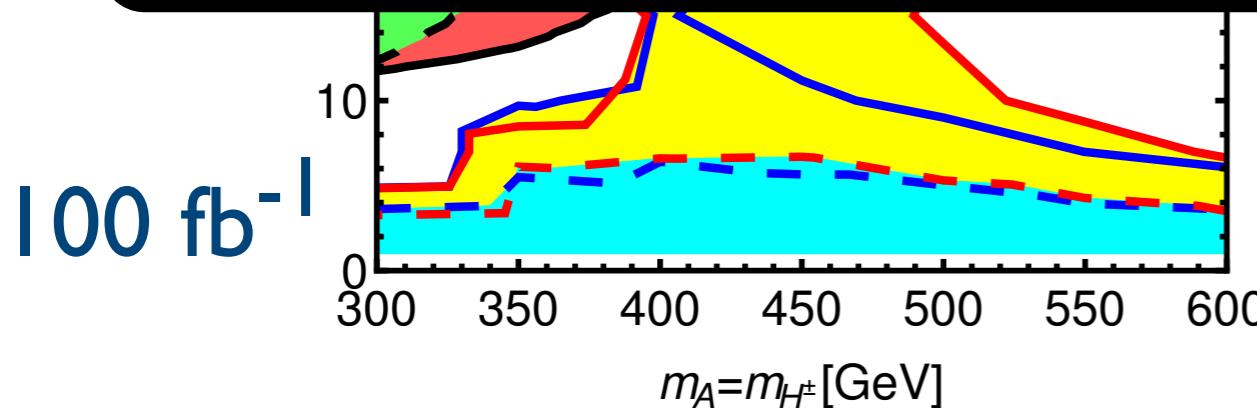
$A \rightarrow HZ$ 95%CL Exclusion



$A \rightarrow HZ$ 5σ Discovery Reach



exotic decays/conventional decays are complementary

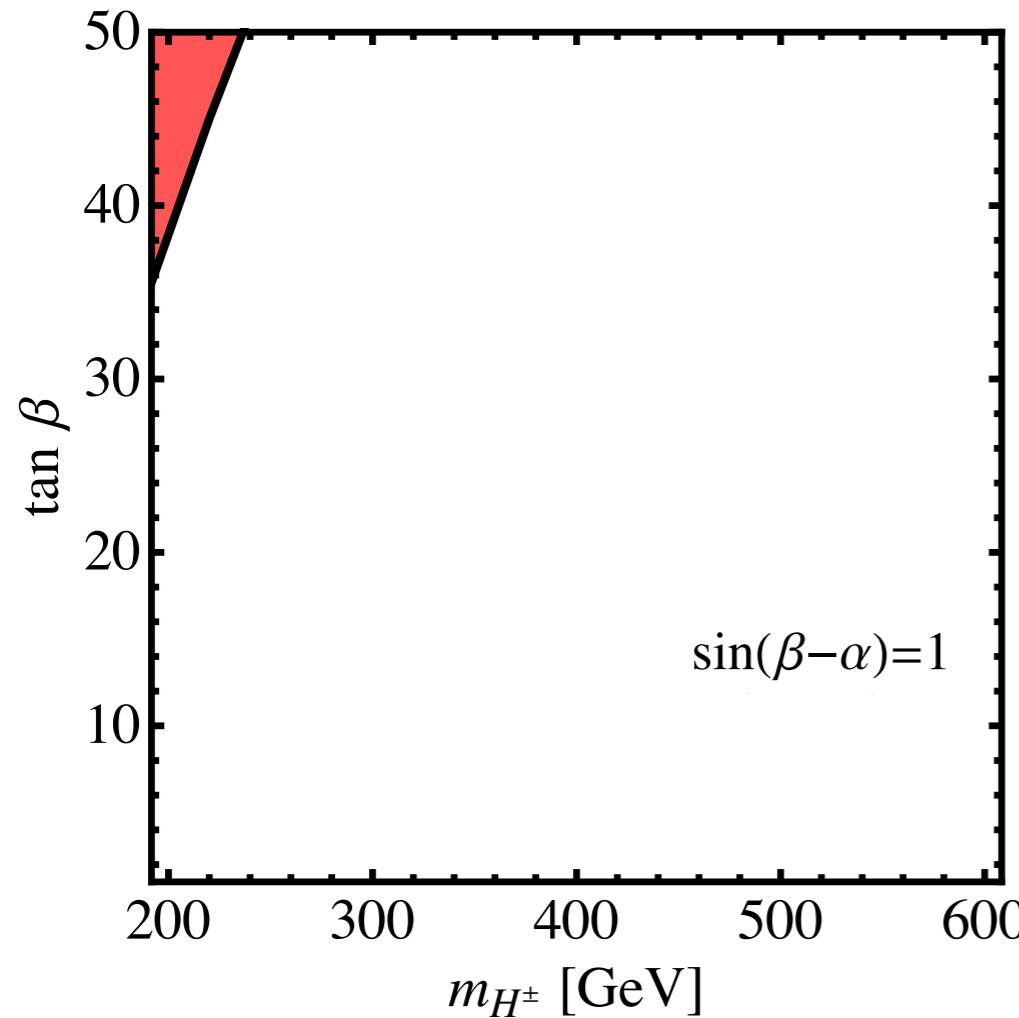


Charged Higgs at LHC

Limits:

- strongest constraints from $H^\pm \rightarrow \tau\nu$ (still weak)

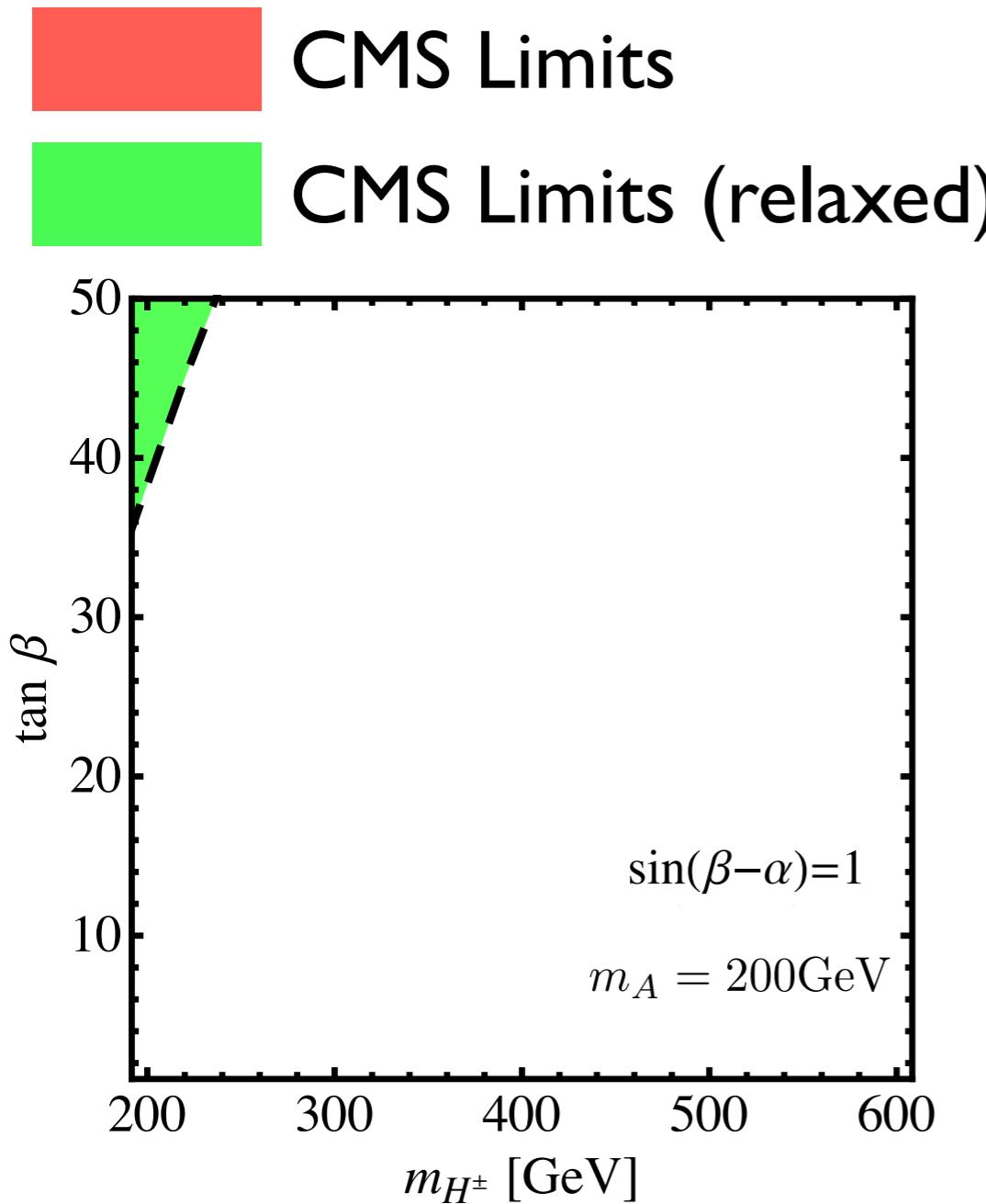
CMS Limits



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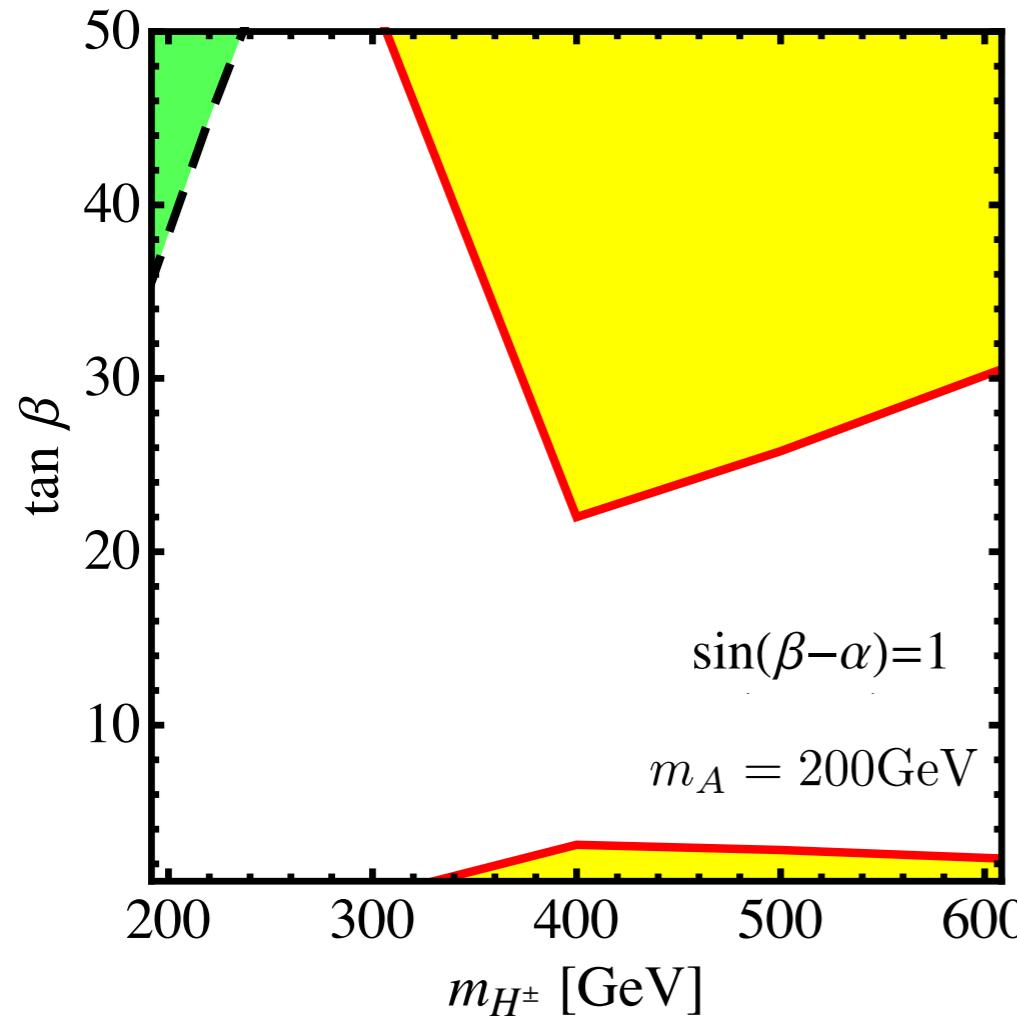
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$H^+ \rightarrow A W$ 95%CL Exclusion



CMS Limits (relaxed)



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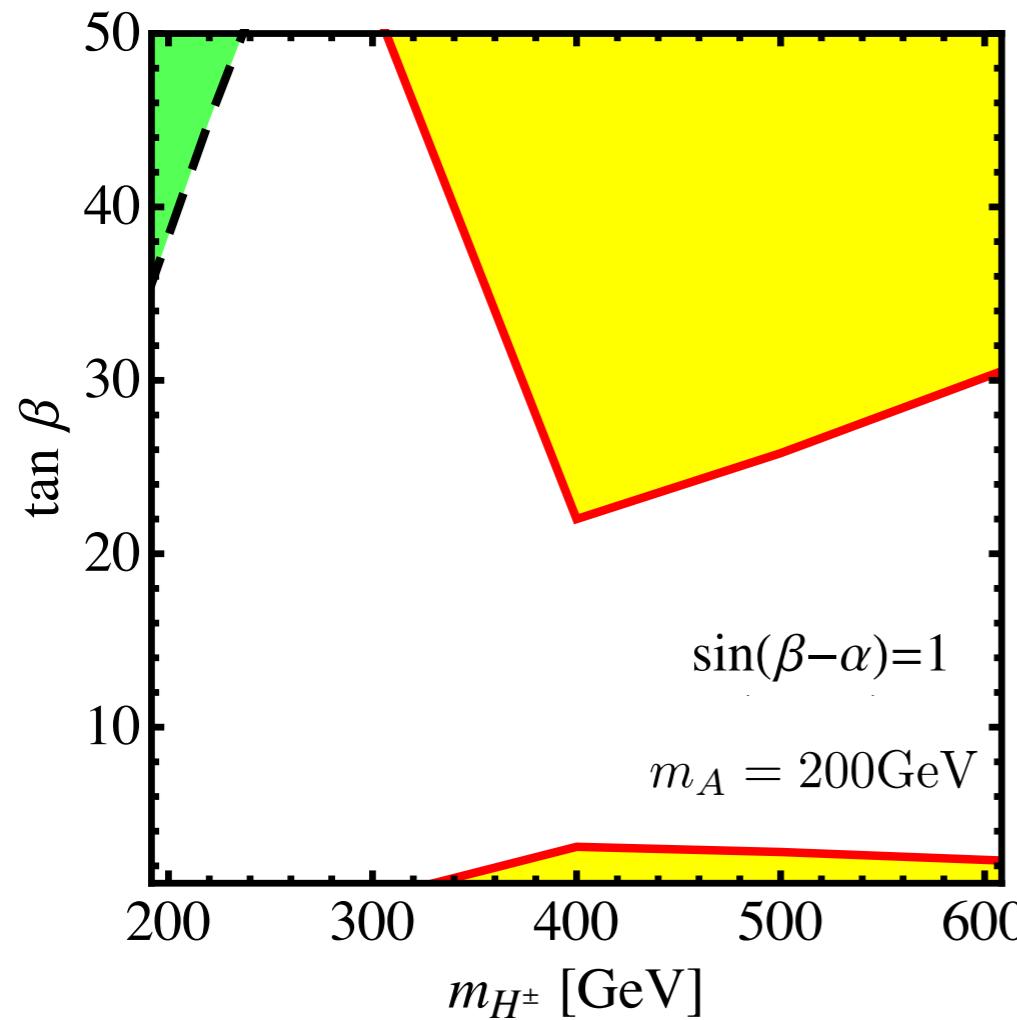
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at 1000 fb^{-1}



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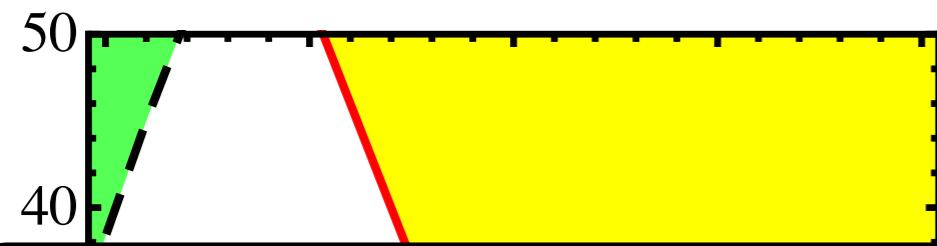


$H^+ \rightarrow A W$ 95%CL Exclusion
at 1000 fb^{-1}

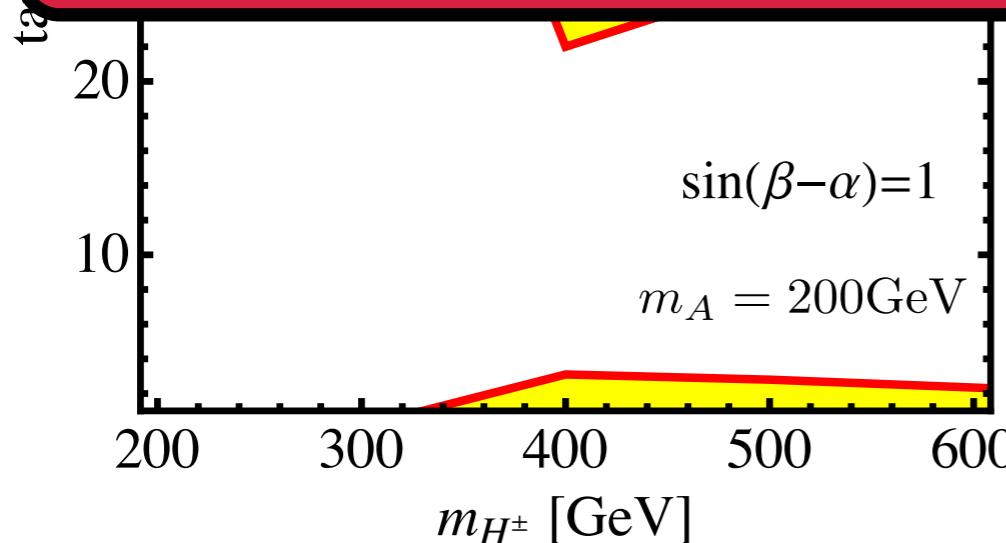


CMS Limits (relaxed)

no discovery reach



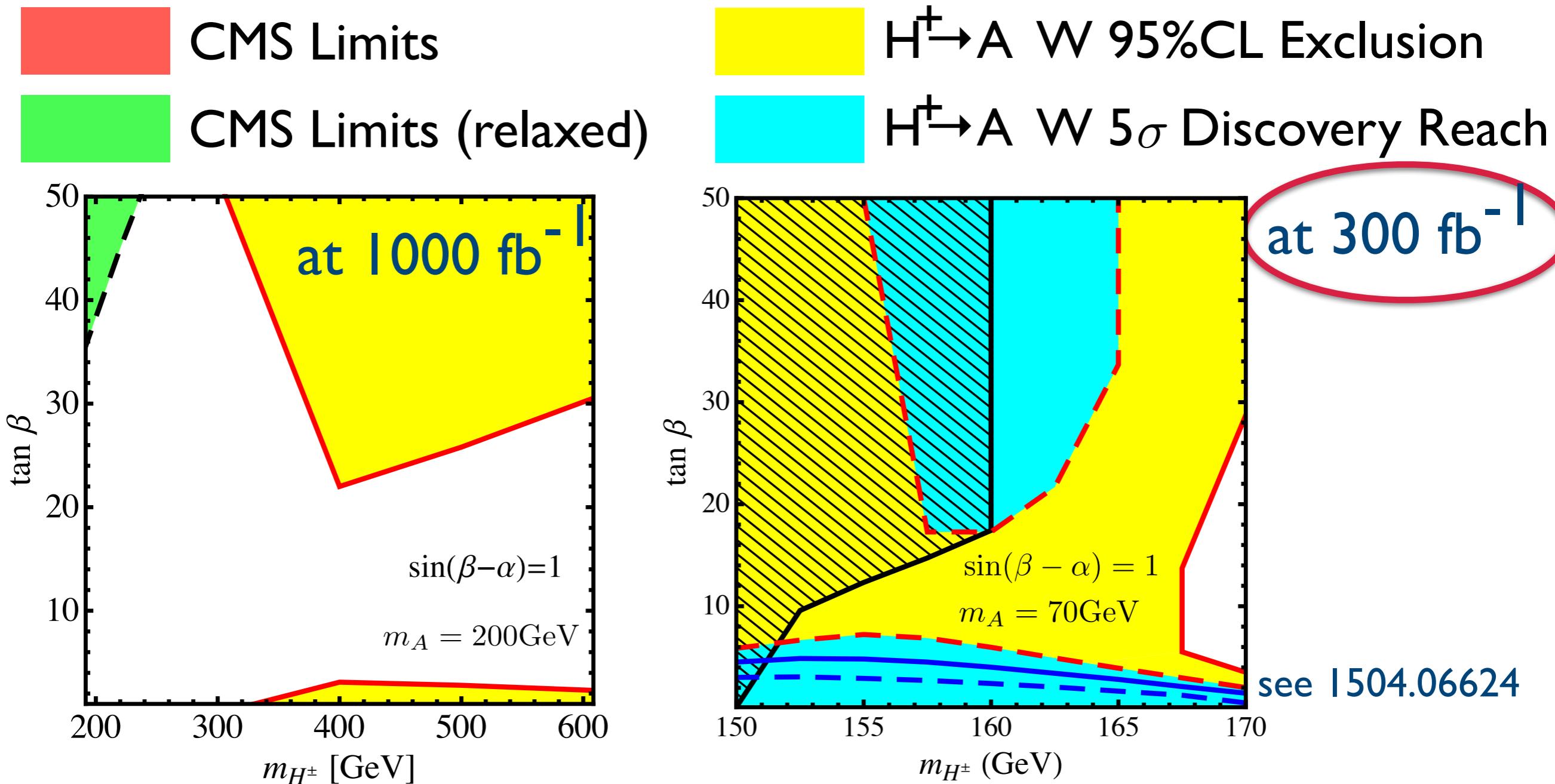
Heavy Charged Higgs is difficult to detect at LHC



Charged Higgs at LHC

Limits:

- strongest constraints from $H^\pm \rightarrow \tau\nu$ (still weak)
- exotic decays barely affect current limits



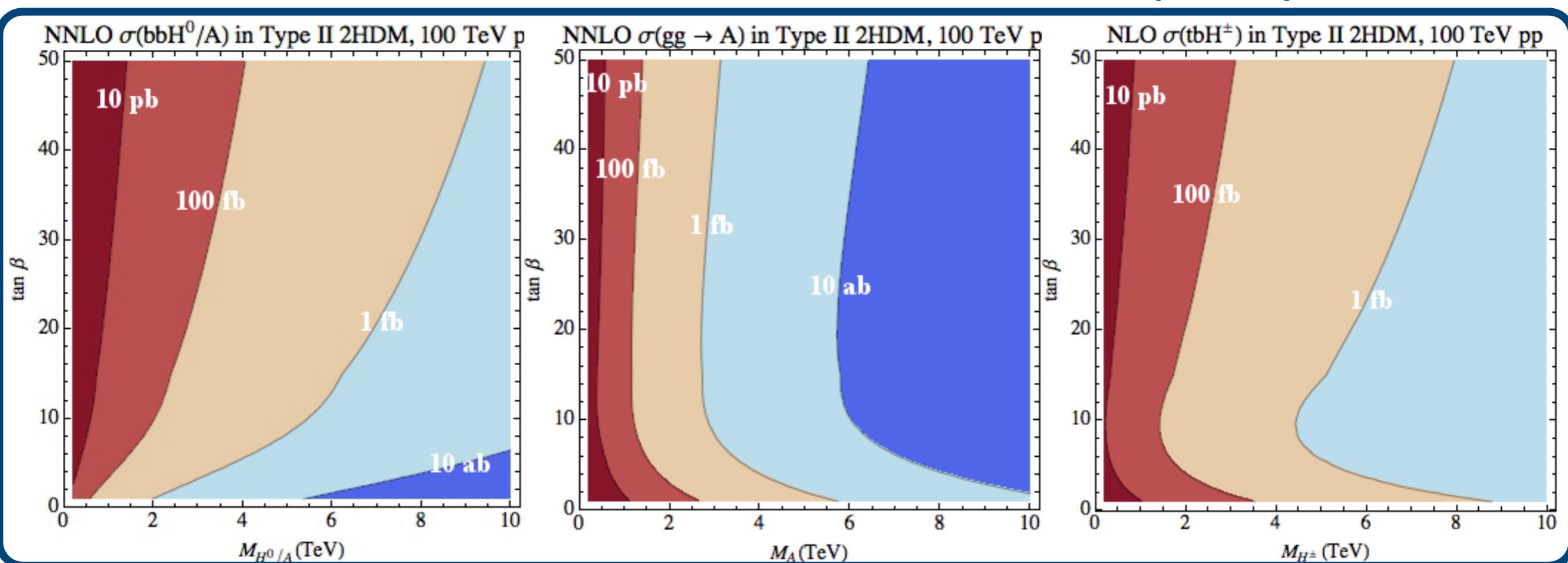
Future Hadron Collider: 100TeV

Production rate increases:

- neutral Higgs: $gg \rightarrow H/A$ and $gg \rightarrow bbH/bbA$ (30-50 x)
- charged Higgs: $gg \rightarrow tbH^+$ (90x)
- sizable cross section up to few TeV

Large discovery potential for exotic decays

plots by Ahmed Ismail



Conclusion

Physics beyond Standard model

- most models contain enlarged Higgs sector

Exotic decays

- 5 types of exotic decays
- constrained choice of mass hierarchy
- reduce reach of conventional channels
- can dominate conventional decays

Heavy Higgs Searches

- conventional/exotic channels
are complementary
- charged Higgs is difficult at LHC

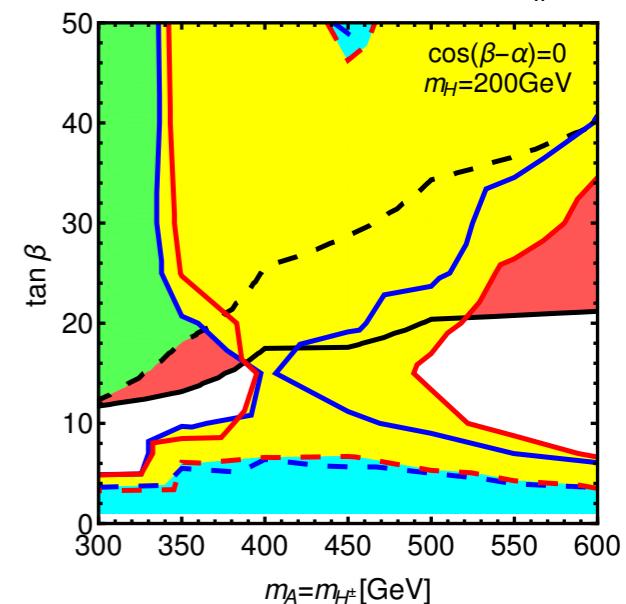
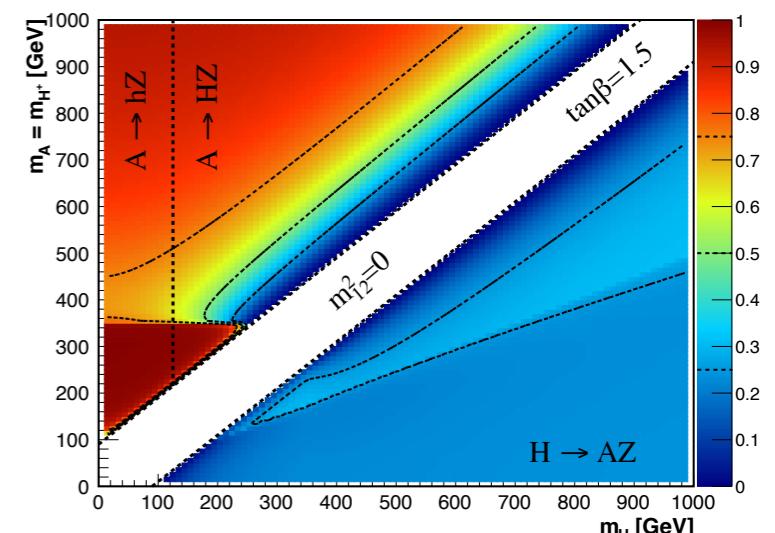
$H \rightarrow AZ$

$H \rightarrow AA$

$H \rightarrow H^+W$

$H \rightarrow H^+H^-$

$H^+ \rightarrow AW$



Benchmark Scenario

