LHC searches for the CP-odd Higgs by the jet substructure analysis

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Outline

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New Physics

After Higgs discovery at LHC

- Deviation from the Standard Model prediction for Higgs couplings

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- Deviation from the Standard Model prediction for Higgs couplings
- Extra scalar degrees of freedom in an extended electroweak symmetry breaking sector

New Physics in 2HDM

2HDM can accommodate

- Dark Matter
- CPV and Baryogenesis
- Flavor Physics

...

CPC 2HDM

$$
\begin{aligned}
V(\Phi_1\,\Phi_2) &= m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + H.c.) \\
&+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\
&+ \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + H.c.\right],
\end{aligned}
$$

$$
\Phi_i = \begin{pmatrix} \pi_i^+ \\ (v_i + h_i + i\pi_i^0)/\sqrt{2} \end{pmatrix}, \quad i = 1\,,2\,.
$$

CPC 2HDM

- Five Higgs bosons after EWSB CP-even h, H CP-odd A
  Charged $H^{\pm}$ h SM-like Higgs boson

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	2HDM-I	2HDM-II
ξ_A^u	$1/t_\beta$	$1/t_\beta$
ξ_A^d	$-1/t_\beta$	t_β
ξ_A^ℓ	$-1/t_\beta$	t_β

Table: The Yukawa couplings of the SM quarks and charged leptons to the CP-odd Higgs boson A in the 2HDM-I and 2HDM-II.

Fitting Higgs data

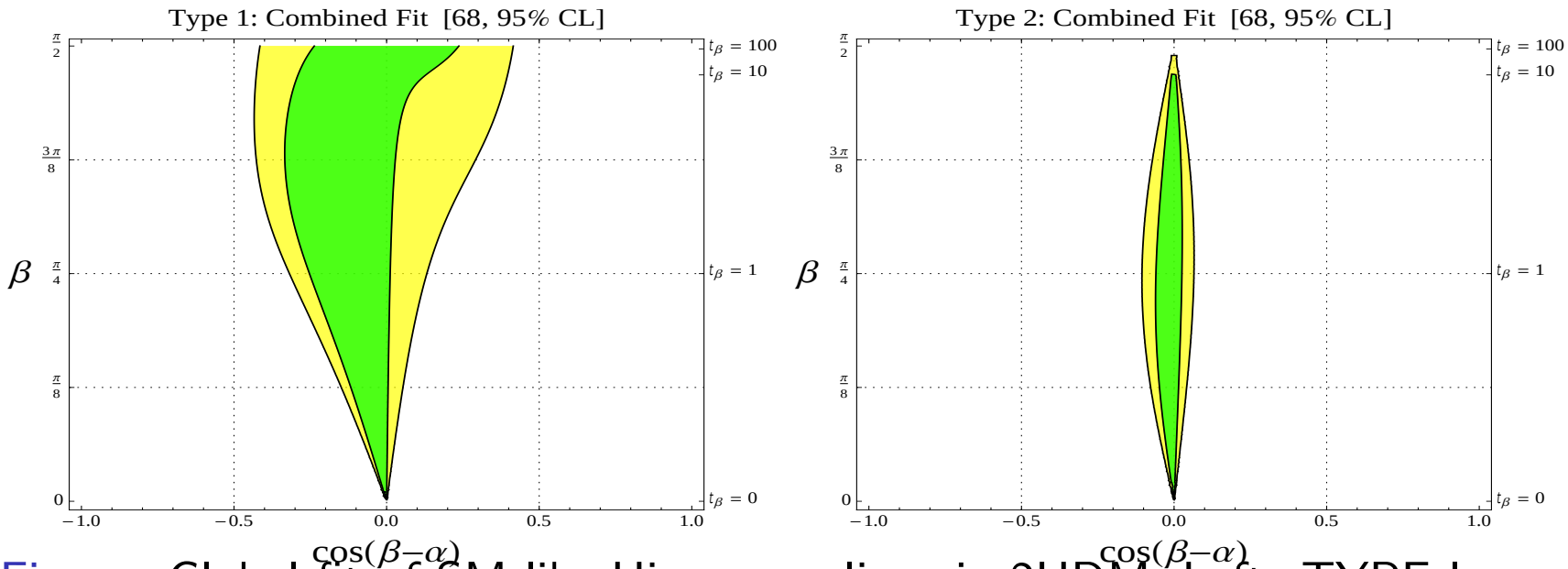

Figure: Global fit of SM-like Higgs couplings in 2HDM. Left: TYPE-I, Right: TYPE-II. From 1305.2424

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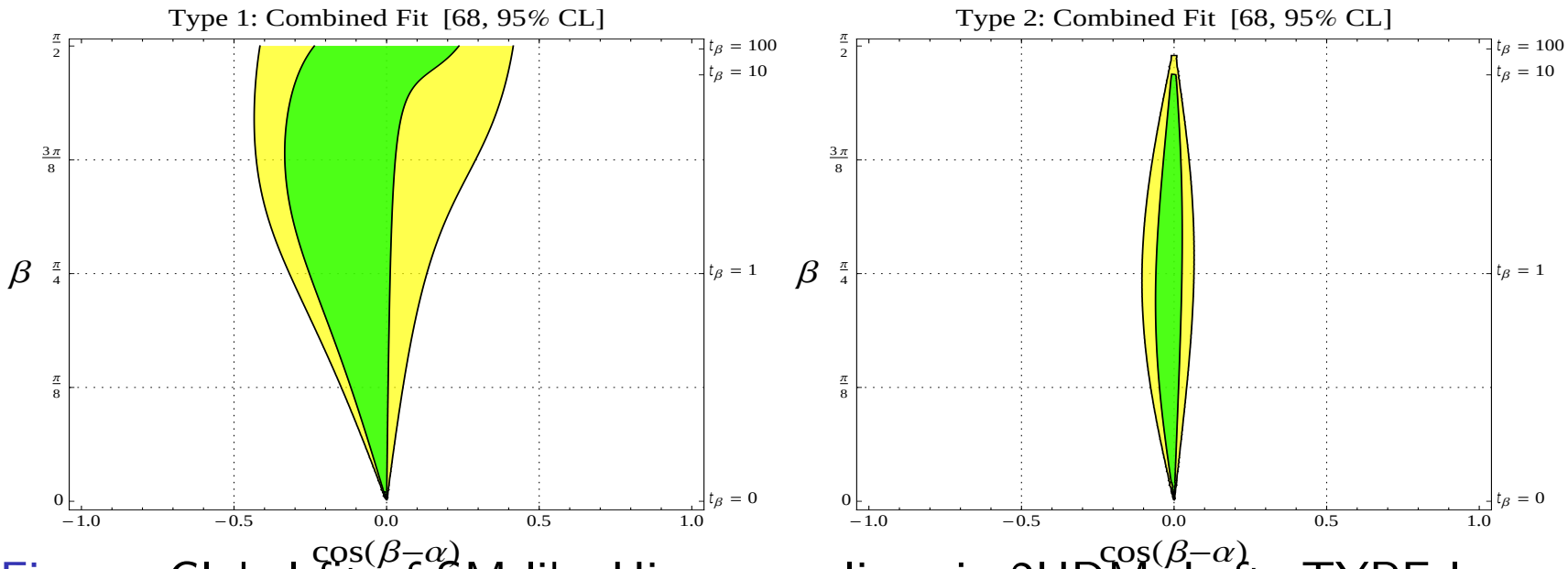

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$$h^{\mathrm{SM}} = \cos(\beta-\alpha)H + \sin(\beta-\alpha)h$$

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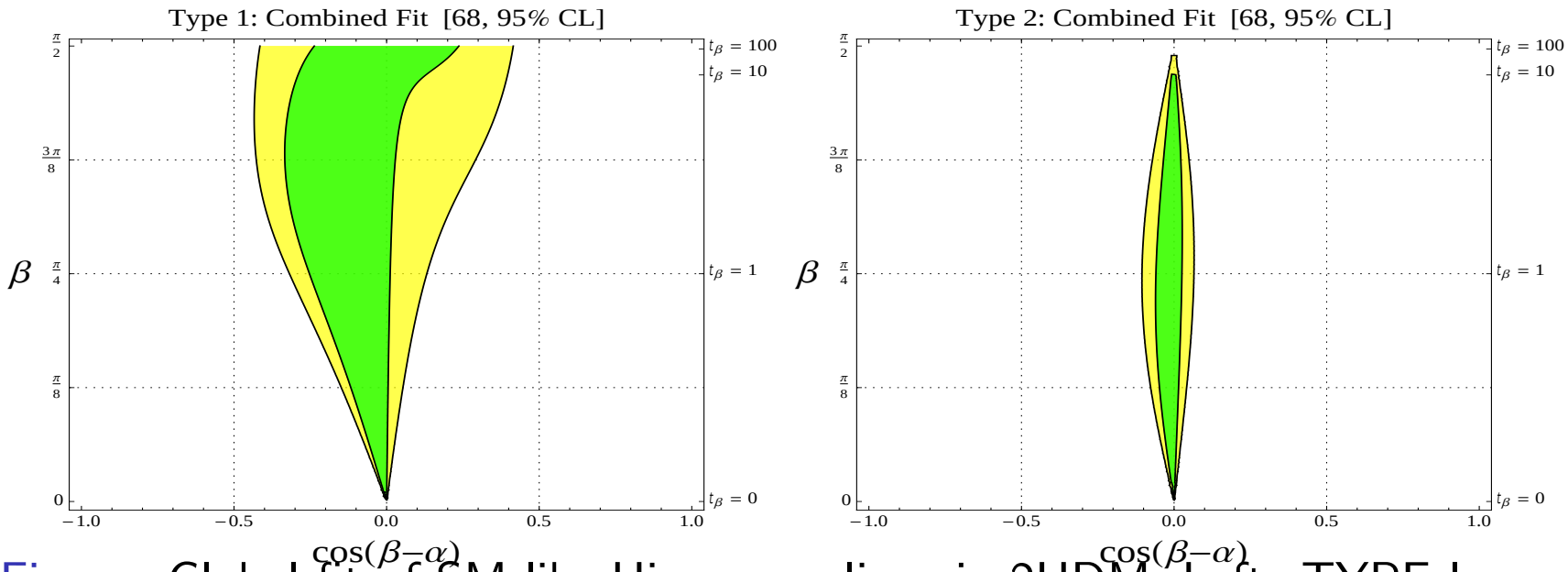

Figure: Global fit of SM-like Higgs couplings in 2HDM. Left: TYPE-I, Right: TYPE-II. From 1305.2424

$$h^{\mathrm{SM}} = \cos(\beta-\alpha)H + \sin(\beta-\alpha)h$$

$$2\mathrm{HDM}-\mathrm{I}: c_{\beta-\alpha} = 0.2\,, \quad 2\mathrm{HDM}-\mathrm{II}: c_{\beta-\alpha} = -0.02$$

Extra Scalar Search

- Charged Higgs boson $H^{\pm}$,
  CMS-HIG-14-020, ATLAS-CONF-2014-050

Extra Scalar Search

- Charged Higgs boson $H^{\pm}$,
  CMS-HIG-14-020, ATLAS-CONF-2014-050
- Neutral CP-odd Higgs boson A
  $A \to \bar{b}b$ CMS-HIG-12-033
  $A \to \bar{\tau}\tau$ 1409.6064, CMS-HIG-11-029

Outline

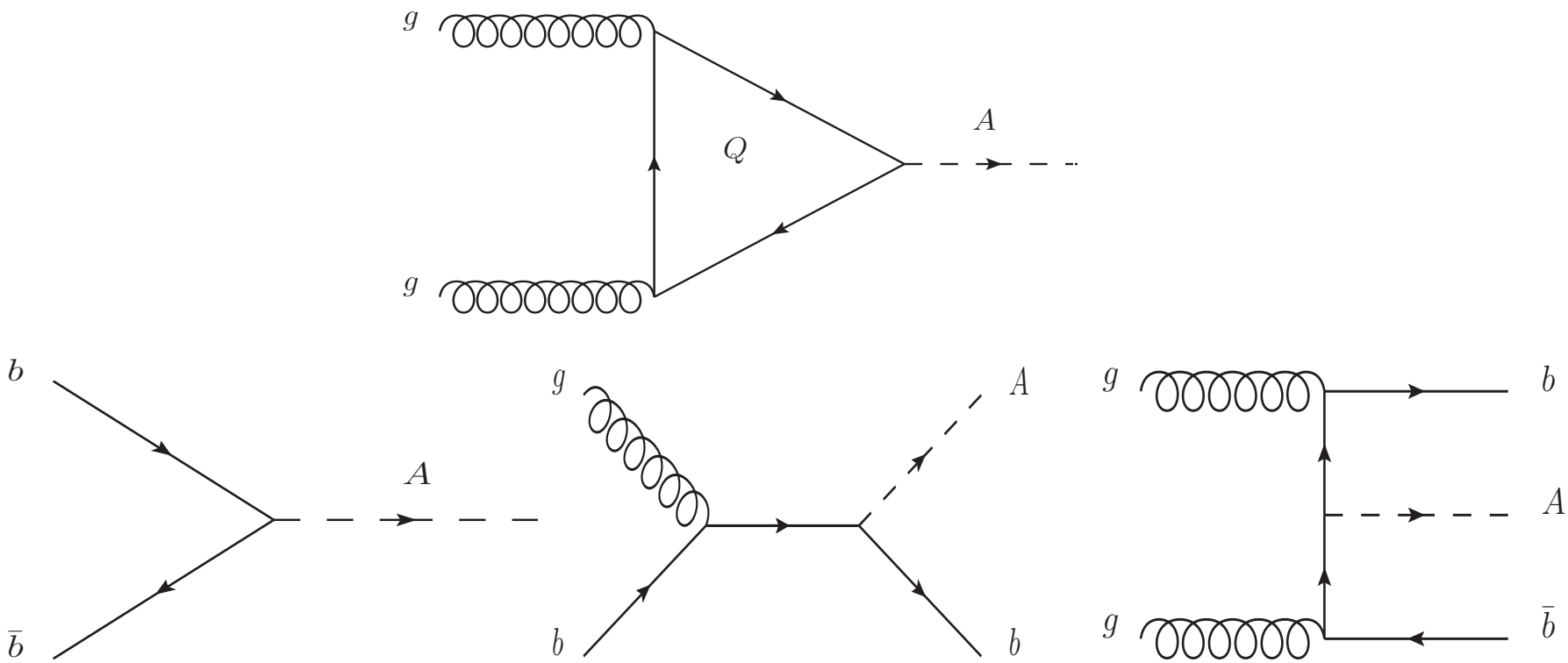

Figure: The Feynman diagrams for the production channels of the CP-odd Higgs boson A.

Production at 14 TeV LHC

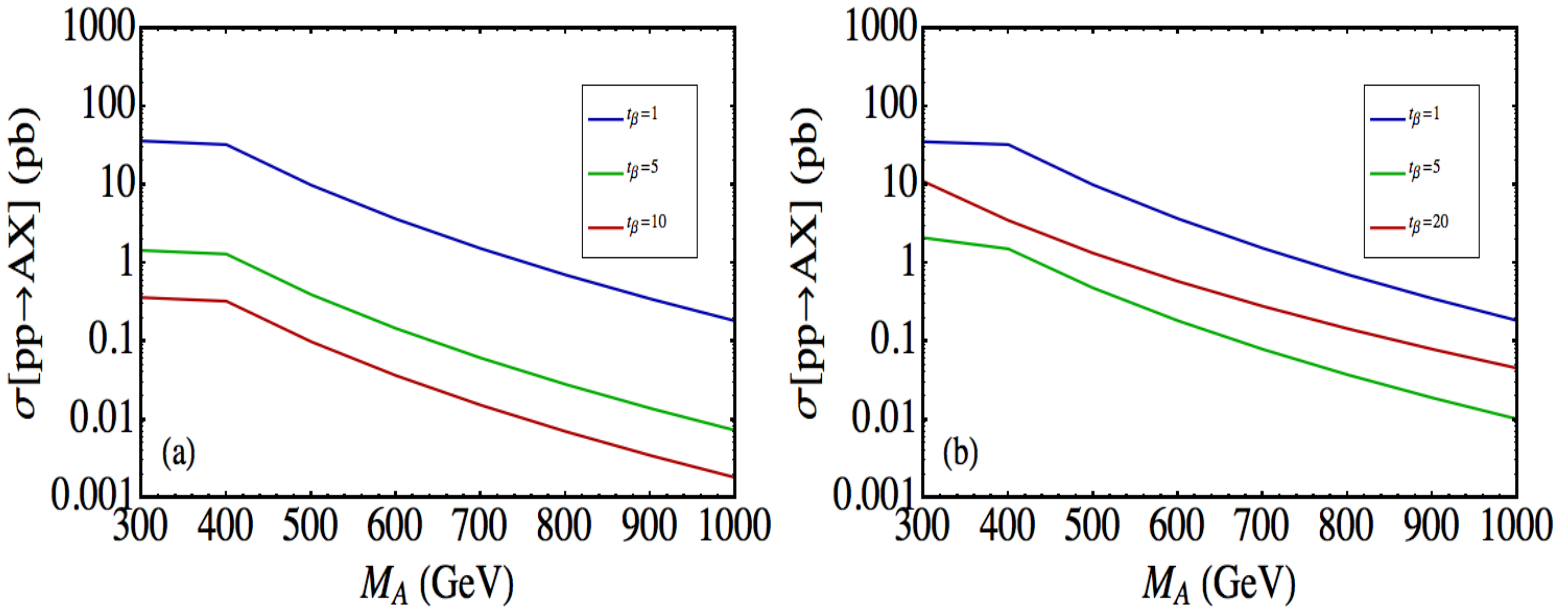

Figure: The inclusive production cross section $\sigma[pp \to AX]$ for $M_A \in (300GeV, 1TeV)$ at the LHC 14 TeV runs. Left: 2HDM-I; Right: 2HDM-II.

$$\begin{aligned}
\Gamma[A \to \bar{f} f] &= \frac{N_{c,f} m_f^2 M_A}{8\pi v^2} (\xi_A^f)^2 \sqrt{1 - \frac{4m_f^2}{M_A^2}}\,, \\
\Gamma[A \to hZ] &= \frac{g^2 c_{\beta-\alpha}^2}{64\pi M_A c_W^2} \lambda^{1/2}\left(1, \frac{m_Z^2}{M_A^2}, \frac{M_h^2}{M_A^2}\right) \\
&\times \left[m_Z^2 - 2(M_A^2 + M_h^2) + \frac{(M_A^2 - M_h^2)^2}{m_Z^2}\right],
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\end{aligned}$$

$$\Gamma[A \to hZ]_{\rm deg} = \Gamma[A \to hZ] + \Gamma[A \to HZ]$$

Decay Branch Ratio

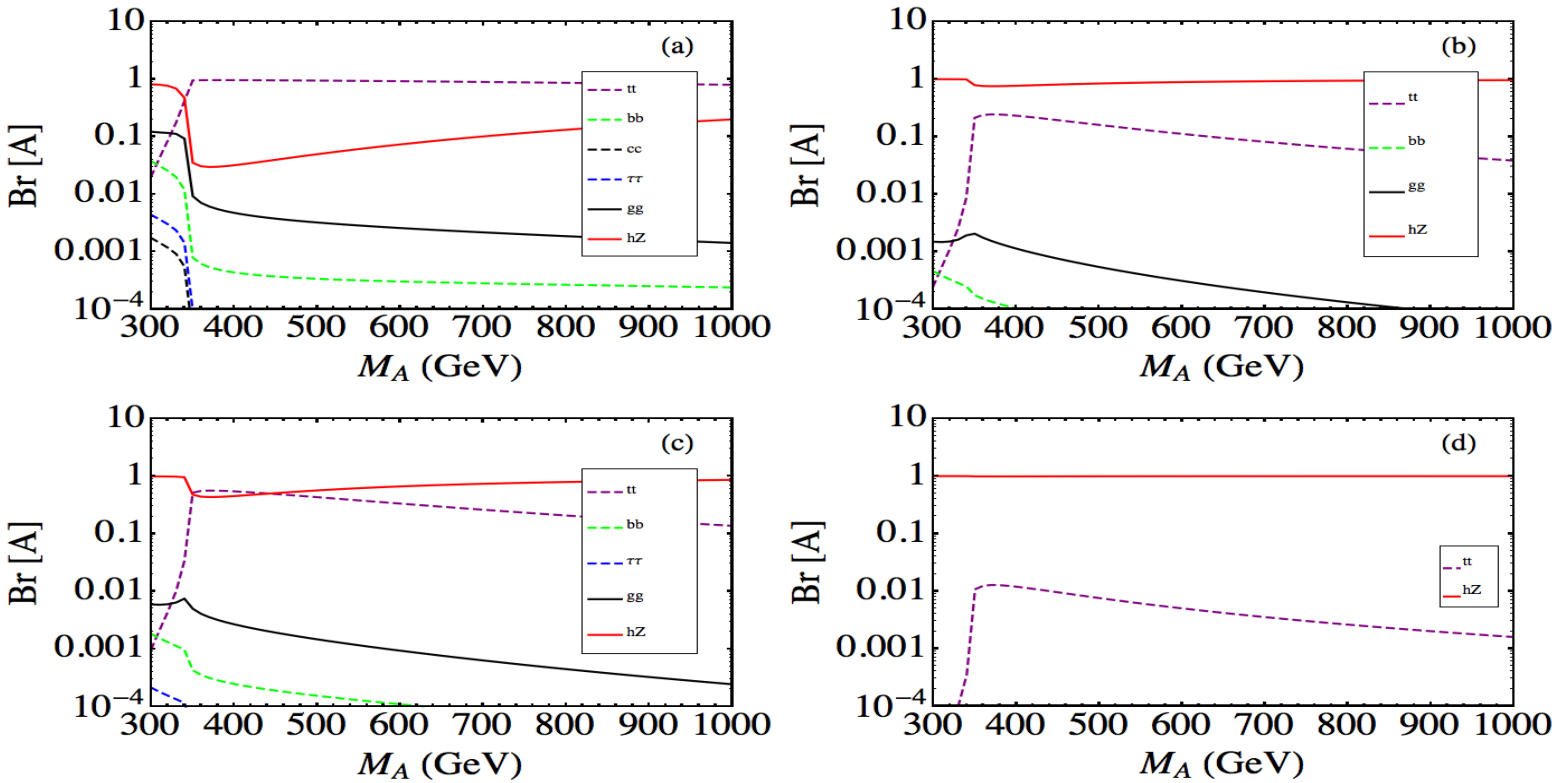

Figure: The decay branching ratios of the CP-odd Higgs boson $\mathrm{BR}[A]$ for the 2HDM-I case. Upper: $M_h = 125$GeV, Lower: $M_h = M_H = 125$ GeV; Left: $t_\beta = 1$, Right: $t_\beta = 10$.

Decay Branch Ratio

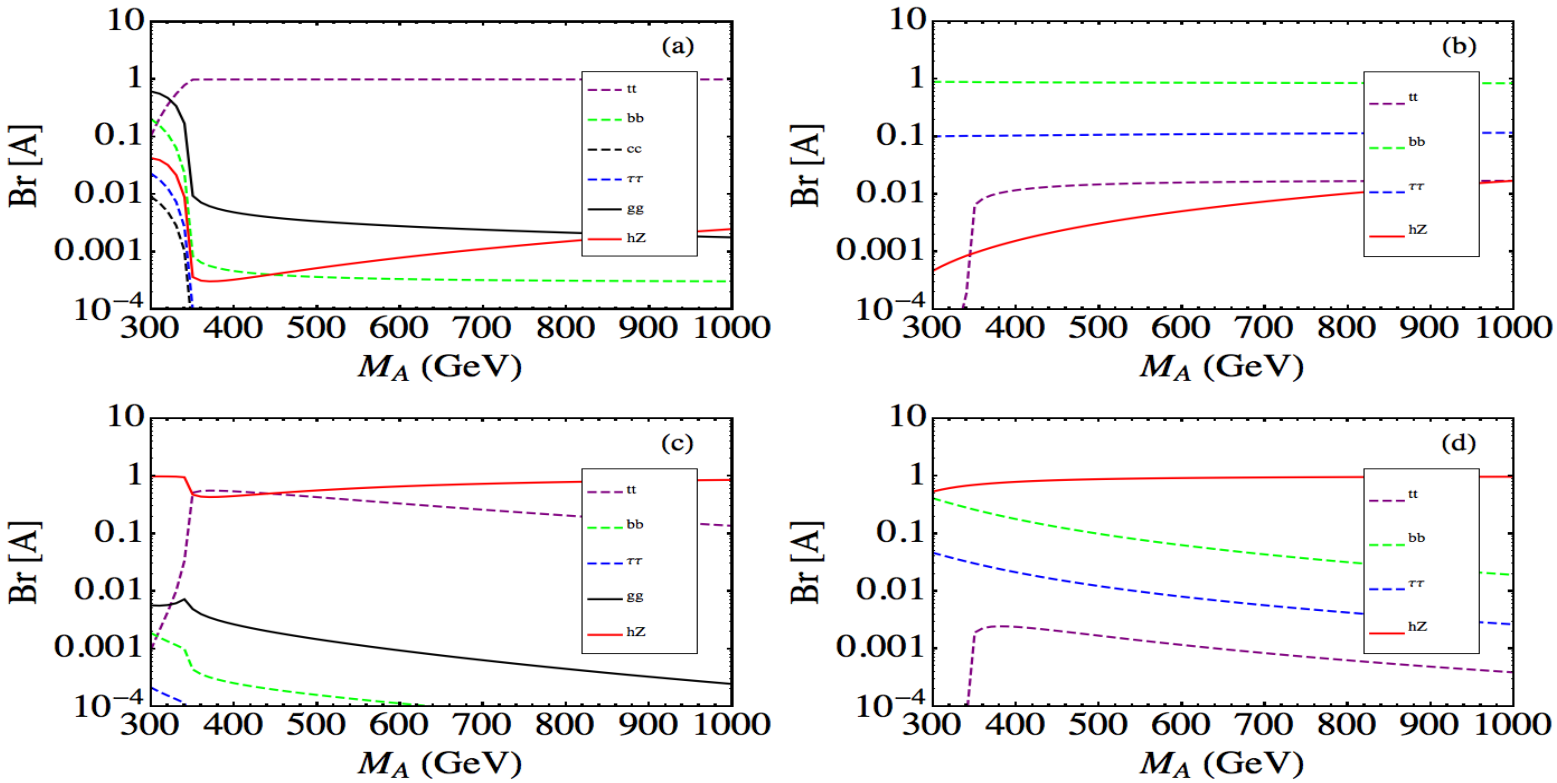

Figure: The decay branching ratios of the CP-odd Higgs boson $\mathrm{BR}[A]$ for the 2HDM-II case. Upper: $M_h = 125$GeV, Lower: $M_h = M_H = 125$ GeV; Left: $t_\beta = 1$, Right: $t_\beta = 10$.

pp→AX→hZ

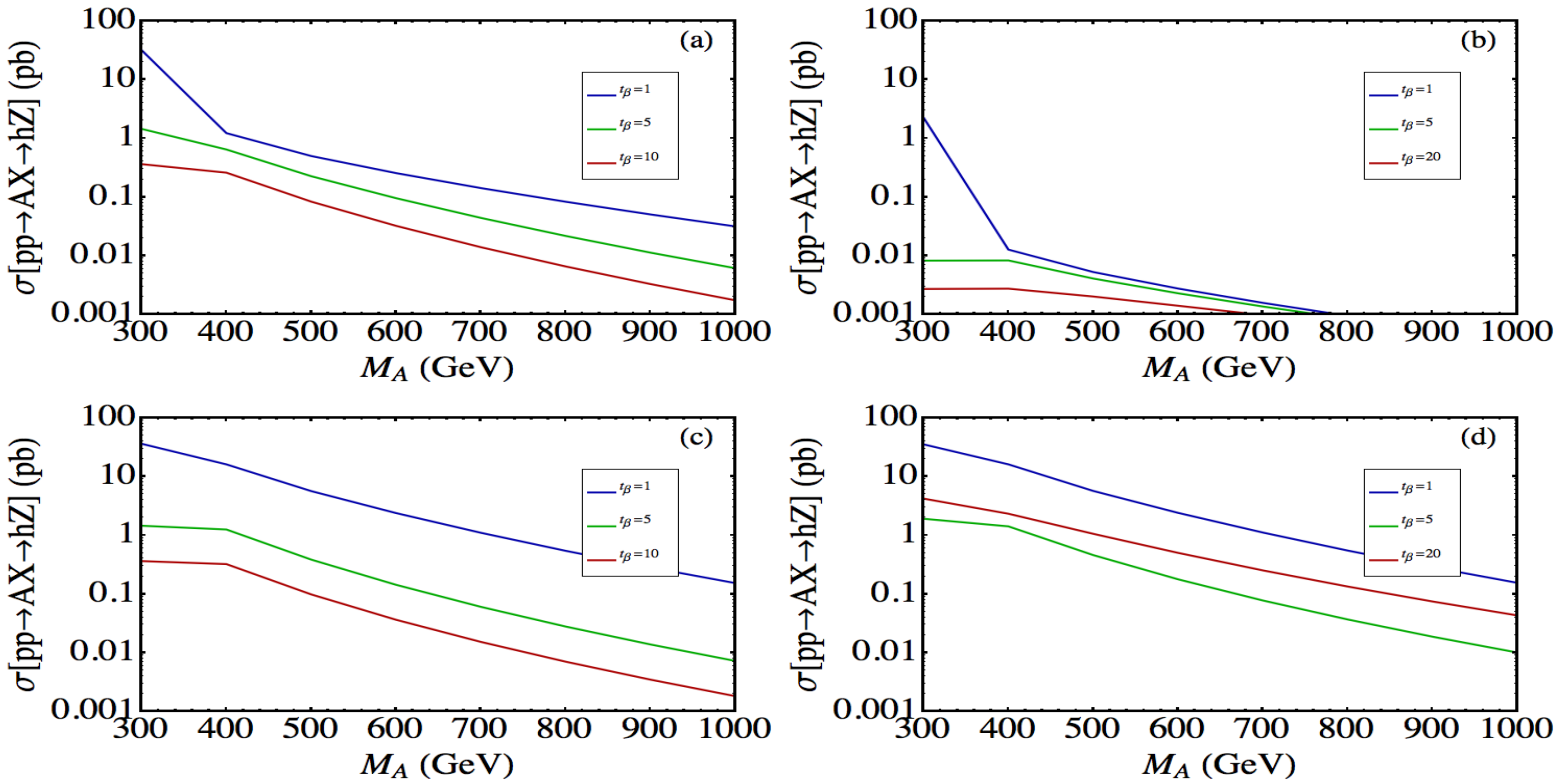

Figure: The $\sigma[pp \to AX] \times \mathrm{BR}[A \to hZ]$ for $M_A \in (300\ \mathrm{GeV}, 1\ \mathrm{TeV})$ at the LHC 14 TeV runs. Upper: $M_h = 125$ GeV (a) for 2HDM-I, (b) for 2HDM-II. Lower: $M_h = M_H = 125$ GeV (c) for 2HDM-I, (d) for 2HDM-II.

Outline

Background

Signal Channel $A \to h(\to \bar{b}b)Z(\to l^+l^-)$

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Background:

$$\sigma(pp \to \bar{t}t) \approx 855pb,$$
$$\sigma(pp \to b\bar{b}\ell^+\ell^-) \approx 82pb,$$
$$\sigma(pp \to ZZ \to \bar{b}b\ell^+\ell^-) \approx 180fb,$$
$$\sigma(pp \to h_{\rm SM}Z \to \bar{b}b\ell^+\ell^-) \approx 34fb.$$

Cuts

- Cut 1: Opposite-sign-same-flavor (OSSF) dileptons ($\ell^+\ell^-$)

$$|\eta_\ell| < 2.5\,, \quad p_T(\ell_1) \geq 20\text{GeV}, \quad p_T(\ell_2) \geq 10\text{GeV}$$

- Cut 2: Mass window of Z boson $|m_{\ell\ell} - m_Z| \leq 15\,\mathrm{GeV}$.
- Cut 3: At least one filtered fat jet is required, which should also contain two leading subjets that pass the b-tagging and satisfy $p_T > 20\,\mathrm{GeV}$ and $|\eta| < 2.5$.
- Cut 4: $M_h(\mathrm{tagged}) \in (100\text{GeV}, 150\text{GeV})$.

Cuts

- Cut 5: $p_{T,h}(\mathrm{tagged})_{\mathrm{cut}} \in (50GeV, 500GeV)$, for the most optimal cuts on $p_{T,h}(\mathrm{tagged})$ by counting the corresponding cut efficiencies of S/B.
- Cut 6: Mass window of the CP-odd Higgs boson A: $|M_{h,\ell^+\ell^-} - M_A| \leq 100\mathrm{GeV}$.

Cut Flow

Cuts	$A \to hZ$	$\bar{t}t$	$\bar{b}b\ell^+\ell^-$	ZZ	hZ	S/B	$S/\sqrt{B}$
fb	500	8.6×10^5	8.2×10^4	180	34	–	
Cut 1	10.76	1.0×10^4	4.3×10^4	98.94	0.81	1.3×10^{-4}	0.47
Cut 2	10.29	2061	3.9×10^4	93.49	0.78	1.6×10^{-4}	0.51
Cut 3	2.41	120.63	1,759	4.92	0.05	8.2×10^{-4}	0.56
Cut 4	1.38	13.12	100.54	1.12	0.03	7.7×10^{-3}	1.29
Cut 5	0.91	0.38	12.14	0.19	0.01	0.04	2.55
Cut 6	0.91	0.06	5.40	0.08	–	0.10	3.87

Table: The event cut efficiency for the $M_A = 600$ GeV case at the LHC 14 TeV running of the signal and background processes. We assume the nominal cross section for the signal process to be $\sigma[pp \to AX] \times \mathrm{BR}[A \to hZ] = 500$ fb. The $S/\sqrt{B}$ is evaluated for the $\int \mathcal{L} dt = 100$ fb^{-1} case.

Results

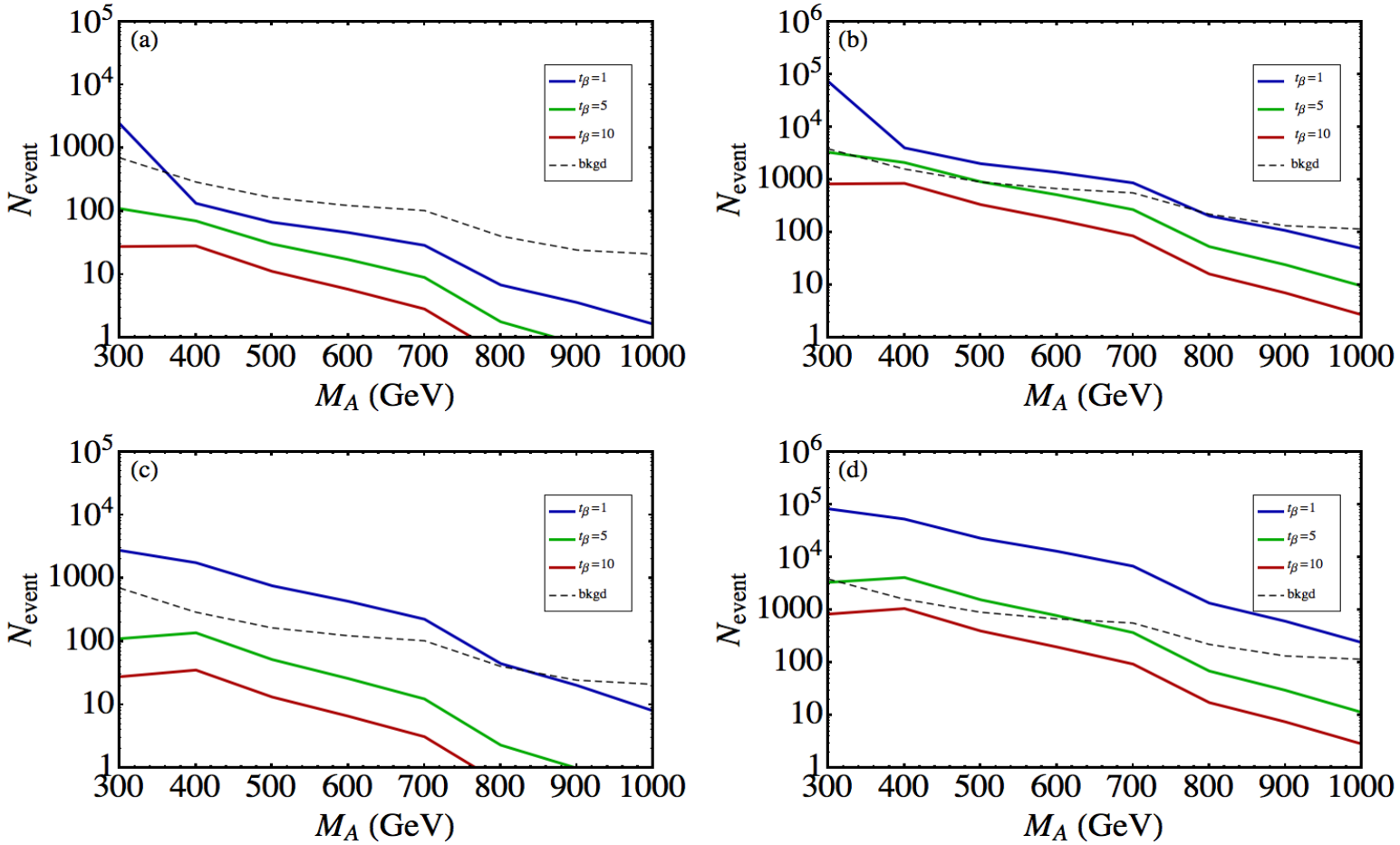
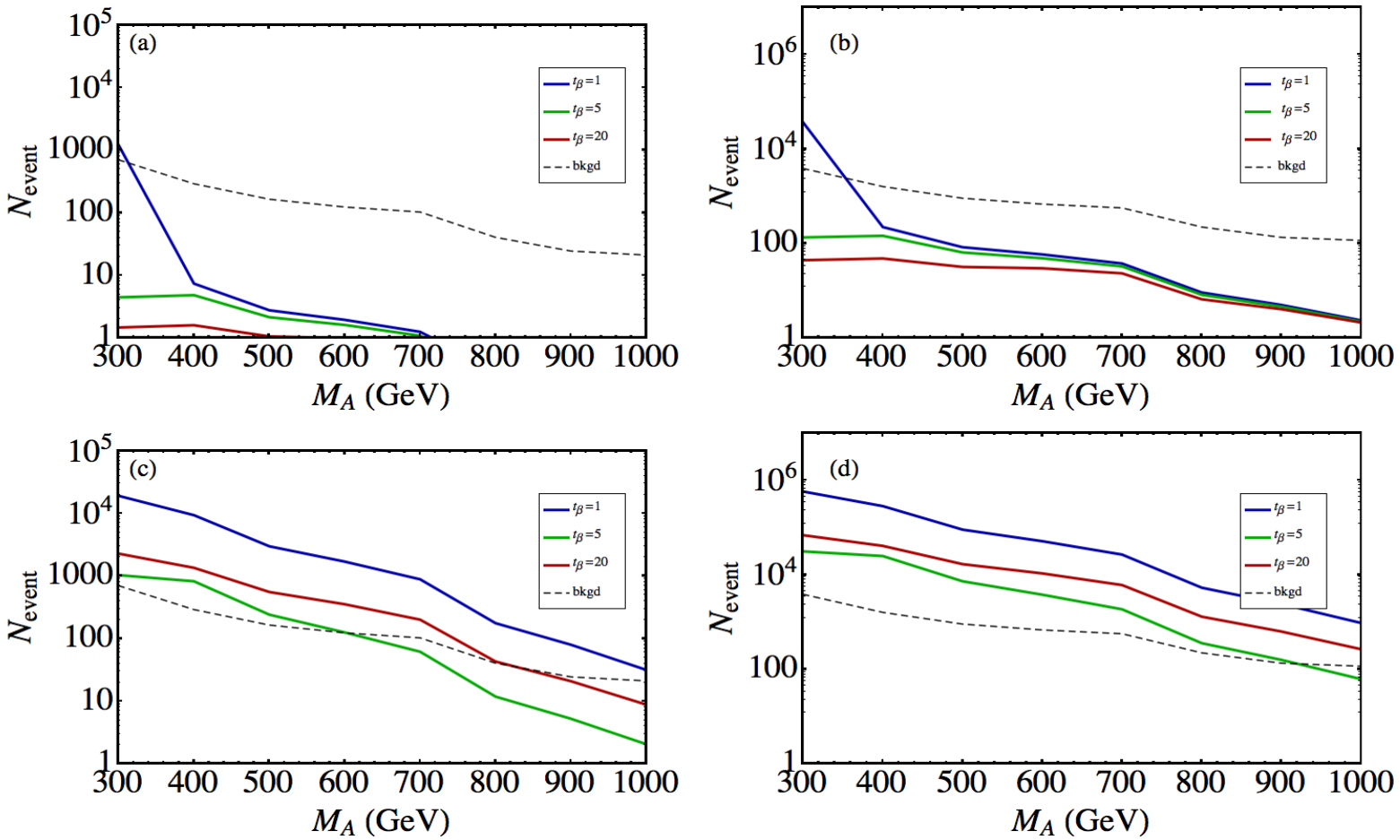


Figure: Black dashed curve is the the discovery limit of $\max\{5\sqrt{B}, 10\}$.

Results



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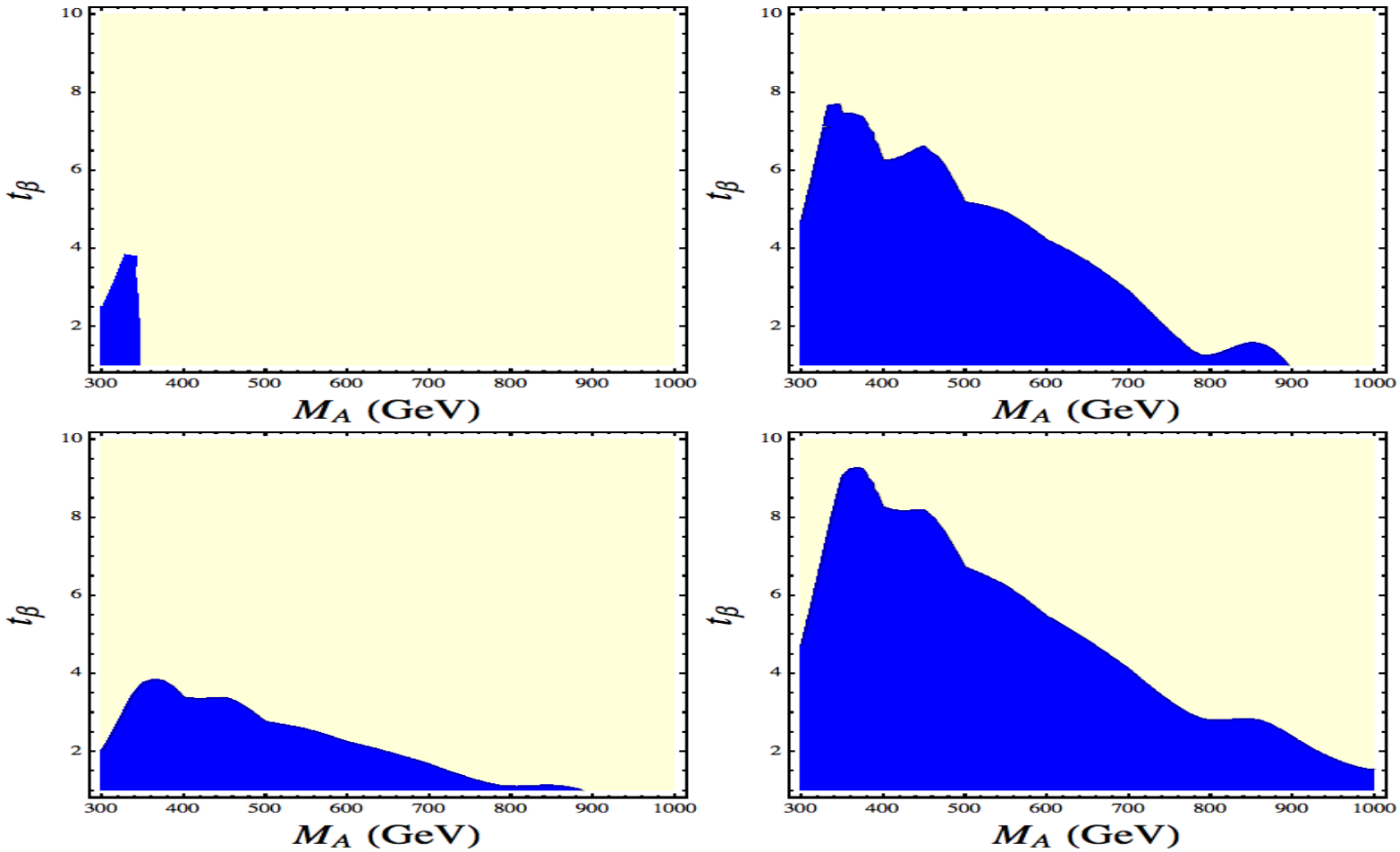
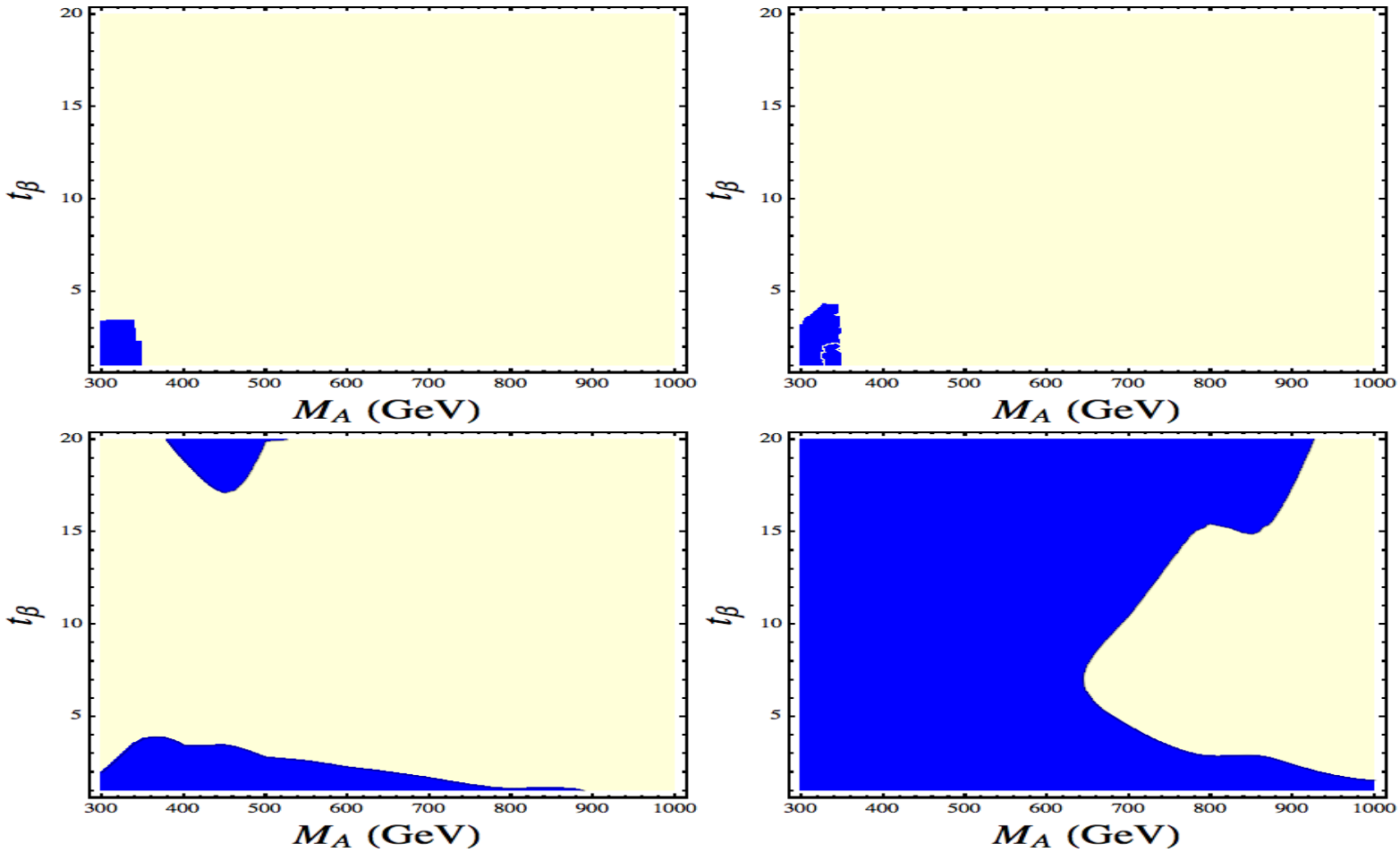


Figure: Parameter regions of $(M_A\,, t_\beta)$ in blue are within the reach for each case.



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Thanks!

Cut Optimization

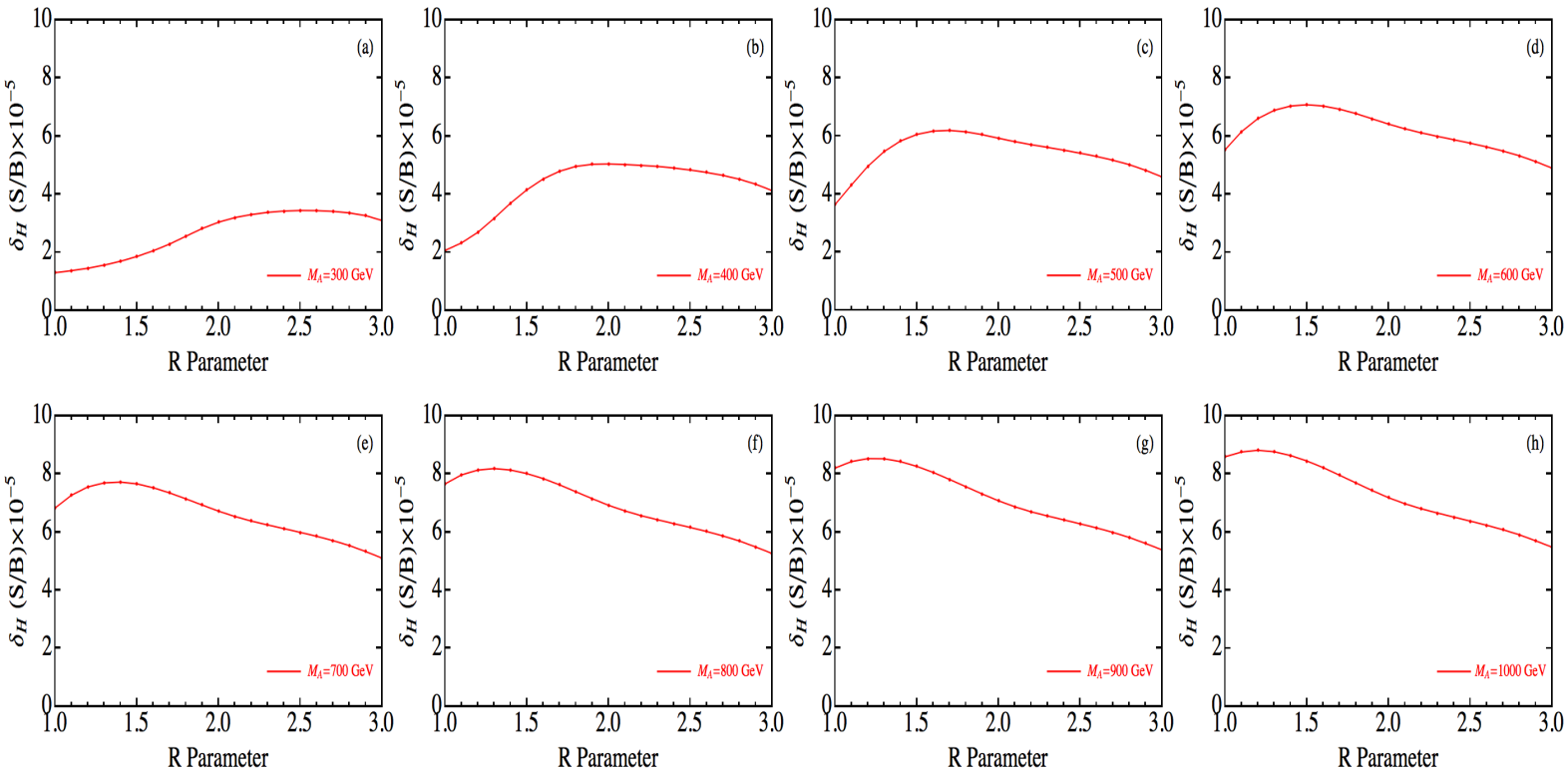

Figure: $\delta_H(S/B)$ with the varying jet cone sizes R in the C/A jet algorithm. For comparison, we take a common cross section of $\sigma[pp \to AX \to hZ] = 100$fb for all signal processes.

Cut Optimization

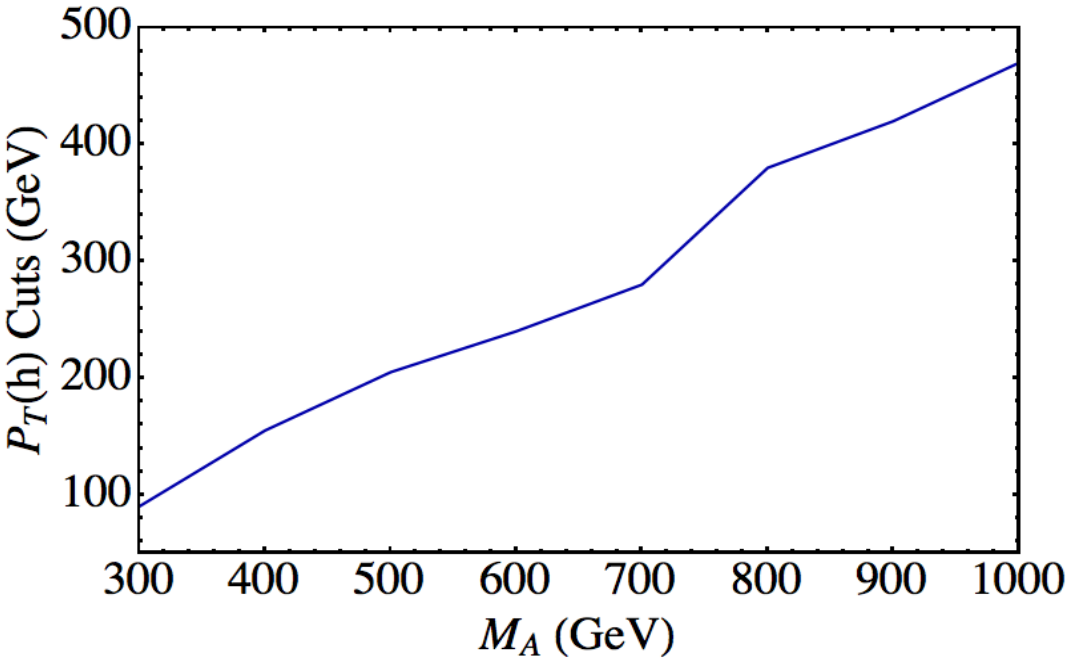

Figure: The most optimal cuts to the p_T of the tagged SM-like Higgs boson for different M_A inputs.