The Hunt for the Rest of the Higgs Bosons

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Base on arXiv:1504.04630[hep-ph] in collaboration with Nathaniel Craig, Francesco D'Eramo, Patrick Draper and Scott Thomas

Introduction

- Exotic scalar fields exist in a lot of new physics models.

  2HDM, Z', W', MSSM, NMSSM, Little Higgs model …

- The scalar which carries EW charge and gets non-zero vev must contribute to the EWSB and might contribute to the SM fermion masses.

- Higgs boson vs. Higgs bosons

- Searching for the rest of the Higgs sector at colliders!

Alignment Limit

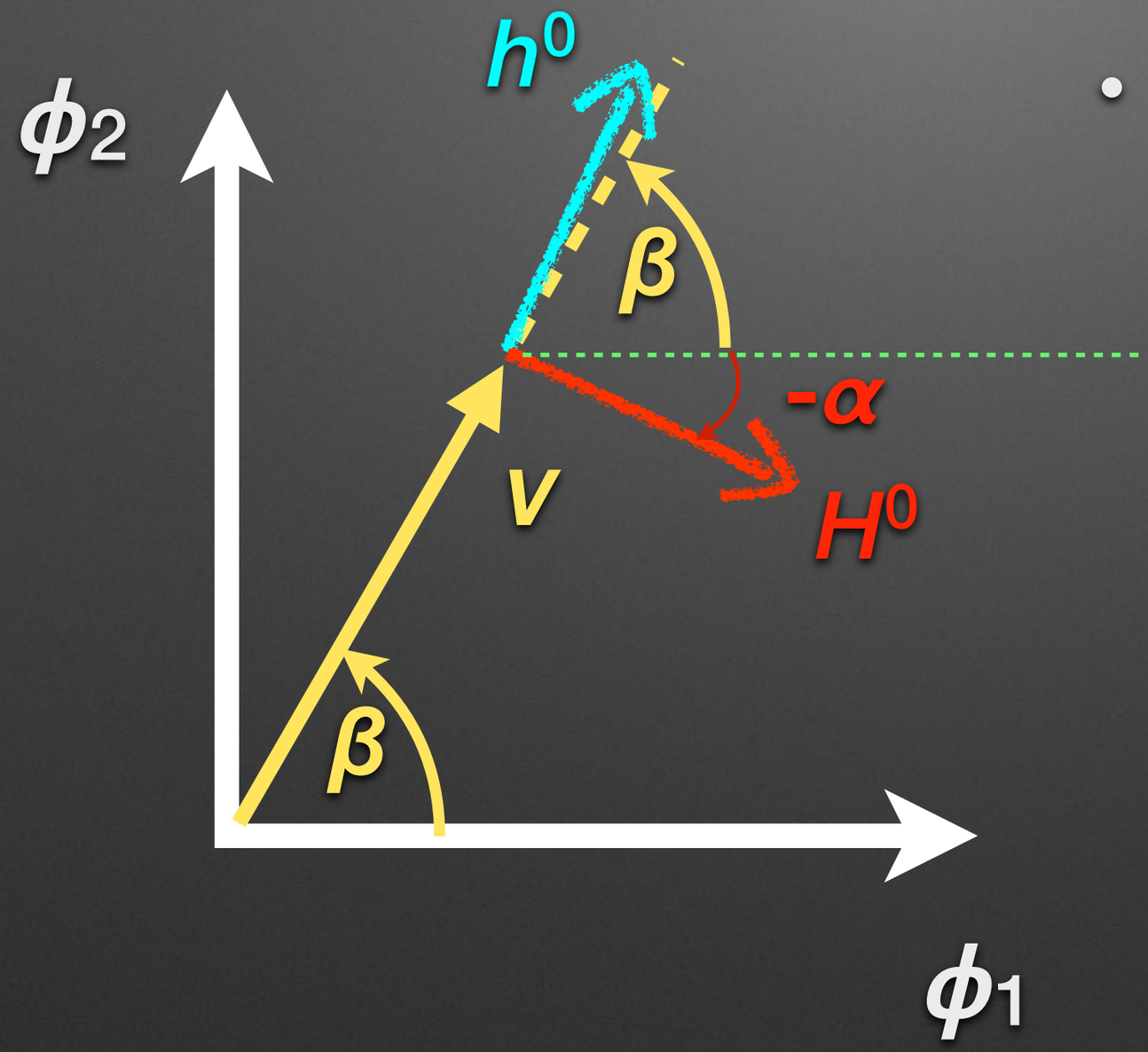
- A Higgs boson is discovered at the LHC.
- All of its properties are consistent with the SM Higgs boson within the uncertainties from both theory and experiment.

- A Great news for the SM!
- Not very great news for NP…
- Strong constraint to the rest Higgs bosons!

ATLAS Collaboration, PLB716(2012)1; CMS Collaboration, PLB716(2012)30;
ATLAS-CONF-2015-007; CMS-PAS-HIG-14-009

Alignment Limit

- Taking 2HDM as a simple exercise, it hints that the hWW, hZZ, htt vertices are SM-like.



- If the Higgs sector is N-HDM and one of the mass eigenstate is parallel to the vev, it will be the SM-like Higgs boson and other HVV interaction will be suppressed.

N. Craig and S. Thomas, JHEP1211(2012)083; N. Craig, J. Galloway, and S. Thomas, arXiv:1305.2424[hep-hp]; M. Carena, I. Low, N. R. Shah, C. E. Wagner, JHEP1404(2014)015; H. E. Haber, arXiv:1401.0152[hep-hp]

Direct and Indirect Limit

- FCNC ☛ Glashow-Weinberg theorem.
- Type I and Type II 2HDM.
- hVV is SM-like ⇔ HVV vanishes.
- Searching additional Higgs bosons with their interactions with SM fermions!

$y_{\rm 2HDM}/y_{\rm SM}$	Type 1	Type 2
hVV	$s_{\beta-\alpha}$	$s_{\beta-\alpha}$
hQu	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$
hQd	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$
hLe	$s_{\beta-\alpha}+c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha}-t_\beta c_{\beta-\alpha}$
HVV	$c_{\beta-\alpha}$	$c_{\beta-\alpha}$
HQu	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$
HQd	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$
HLe	$c_{\beta-\alpha}-s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha}+t_\beta s_{\beta-\alpha}$
AVV	0	0
AQu	$1/t_\beta$	$1/t_\beta$
AQd	$-1/t_\beta$	t_β
ALe	$-1/t_\beta$	t_β

S. L. Glashow and S. Weinberg, PRD15(1977)1958.

Direct and Indirect Limit

Channel	$\sqrt{s}$	$\hat{\mu}_a$	ϵ_a(GGH, VBF/VH, TTH)
$Vh \to b\bar{b}$ (0ℓ) [91]	7/8 TeV	$-0.35^{+0.55}_{-0.52}$	(0.0, 1.0, 0.0)
$Vh \to b\bar{b}$ (1ℓ) [91]	7/8 TeV	$1.17^{+0.66}_{-0.60}$	(0.0, 1.0, 0.0)
$Vh \to b\bar{b}$ (2ℓ) [91]	7/8 TeV	$0.94^{+0.88}_{-0.79}$	(0.0, 1.0, 0.0)
$tth \to b\bar{b}$ [92]	7/8 TeV	$1.7^{+1.4}_{-1.4}$	(0.0, 0.0, 1.0)
$h \to \tau\tau$ (jj) [93]	7/8 TeV	$3.6^{+2.0}_{-1.6}$	(0.60, 0.4, 0.0)
$h \to \tau\tau$ (ℓj) [93]	7/8 TeV	$0.9^{+1.0}_{-0.9}$	(0.65, 0.35, 0.0)
$h \to \tau\tau$ $(\ell\ell)$ [93]	7/8 TeV	$3.0^{+1.9}_{-1.7}$	(0.65, 0.35, 0.0)
$hjj \to \tau\tau$ (jj) [93]	7/8 TeV	$1.4^{+0.9}_{-0.7}$	(0.15, 0.85, 0.0)
$hjj \to \tau\tau$ (ℓj) [93]	7/8 TeV	$1.0^{+0.6}_{-0.5}$	(0.12, 0.88, 0.0)
$hjj \to \tau\tau$ $(\ell\ell)$ [93]	7/8 TeV	$1.8^{+1.1}_{-0.9}$	(0.10, 0.90, 0.0)
$h \to WW$ $(0j)$ [94]	7/8 TeV	$1.14^{+0.34}_{-0.30}$	(0.98, 0.02, 0.0)
$h \to WW$ $(1j)$ [94]	7/8 TeV	$0.96^{+0.45}_{-0.40}$	(0.87, 0.13, 0.0)
$h \to WW$ $(2j$ ggH) [94]	7/8 TeV	$1.20^{+0.91}_{-0.84}$	(0.75, 0.25, 0.0)
$h \to WW$ $(2j$ VBF) [94]	7/8 TeV	$1.20^{+0.45}_{-0.38}$	(0.13, 0.87, 0.0)
$h \to ZZ$ (ggH) [95]	7/8 TeV	$1.66^{+0.5}_{-0.4}$	(1.0, 0.0, 0.0)
$h \to ZZ$ (VBF+VH)[95]	7/8 TeV	$0.26^{+1.6}_{-0.9}$	(0.0, 1.0, 0.0)
$h \to \gamma\gamma$ (ggH) [96]	7/8 TeV	$1.32^{+0.38}_{-0.38}$	(1.0, 0.0, 0.0)
$h \to \gamma\gamma$ (VBF) [96]	7/8 TeV	$0.8^{+0.7}_{-0.7}$	(0.0, 1.0, 0.0)
$h \to \gamma\gamma$ (WH) [96]	7/8 TeV	$1.0^{+1.6}_{-1.6}$	(0.0, 1.0, 0.0)
$h \to \gamma\gamma$ (ZH) [96]	7/8 TeV	$0.1^{+3.7}_{-0.1}$	(0.0, 1.0, 0.0)
$h \to \gamma\gamma$ (ttH) [96]	7/8 TeV	$1.6^{+2.7}_{-1.8}$	(0.0, 0.0, 1.0)

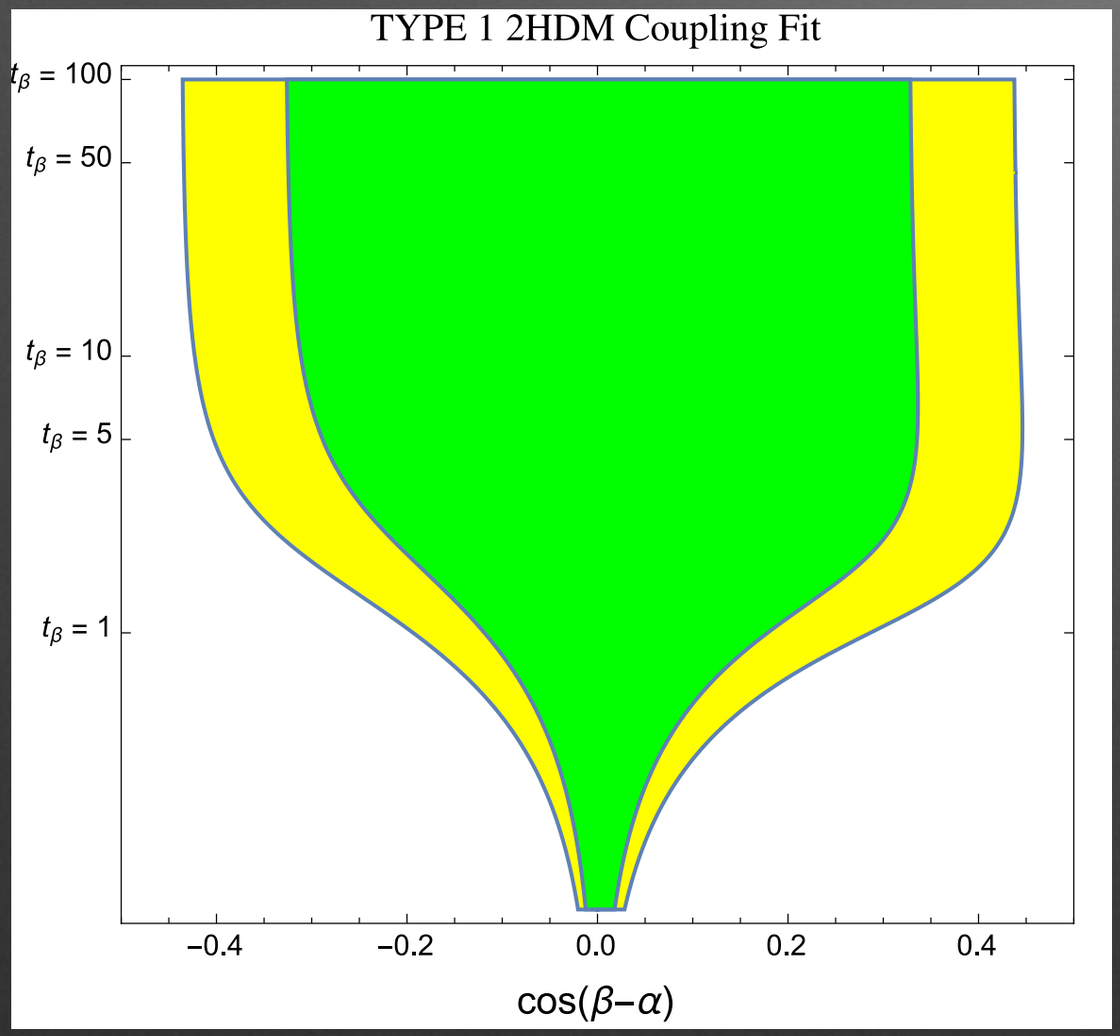
Direct and Indirect Limit

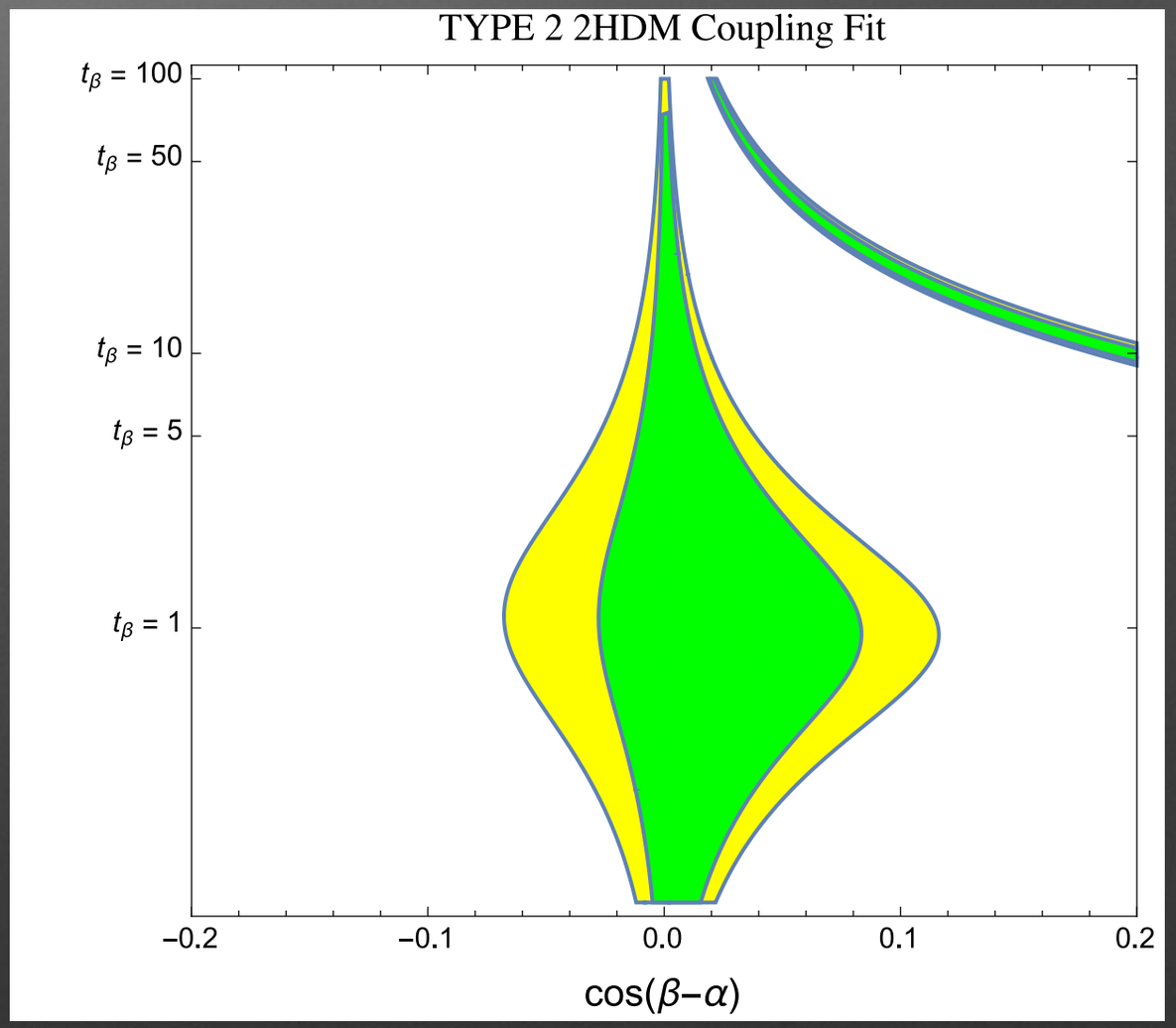
Channel	$\sqrt{s}$	$\hat{\mu}_a$	ϵ_a(GGH, VBF/VH, TTH)
$h \to bb$ [97]	7/8 TeV	$1.0^{+0.53}_{-0.50}$	(0.0, 1.0, 0.0)
$tth \to bb$ [98]	7/8 TeV	$0.67^{+1.35}_{-1.33}$	(0.0, 0.0, 1.0)
$h \to \tau\tau$ (0,1j) [97]	7/8 TeV	$0.84^{+0.42}_{-0.38}$	(0.87, 0.13, 0.0)
$hjj \to \tau\tau$ (2j) [97]	7/8 TeV	$0.95^{+0.43}_{-0.38}$	(.17, .83, 0.0)
$Vh \to \tau\tau$ [97]	7/8 TeV	$0.87^{+1.00}_{-0.88}$	(0.0, 1.0, 0.0)
$h \to WW$ (0,1j) [97]	7/8 TeV	$0.77^{+0.23}_{-0.21}$	(0.83, 0.17, 0.0)
$h \to WW$ (2j) [97]	7/8 TeV	$0.62^{+0.59}_{-0.48}$	(0.17, 0.83, 0.0)
$Vh \to WW$ [97]	7/8 TeV	$0.80^{+1.09}_{-0.93}$	(0.0, 1.00, 0.0)
$h \to ZZ$ [97]	7/8 TeV	$0.88^{+0.34}_{-0.27}$	(0.9, 0.1, 0.0)
$h \to ZZ$ (2j) [97]	7/8 TeV	$1.55^{+0.95}_{-0.66}$	(0.58, 0.42, 0.0)
$h \to \gamma\gamma$ (ggH) [99]	7/8 TeV	$1.12^{+0.37}_{-0.32}$	(1.0, 0.0, 0.0)
$h \to \gamma\gamma$ (VBF) [99]	7/8 TeV	$1.58^{+0.77}_{-0.68}$	(0.0, 1.0, 0.0)
$h \to \gamma\gamma$ (VH) [99]	7/8 TeV	$-0.16^{+1.16}_{-0.79}$	(0.0, 1.0, 0.0)
$h \to \gamma\gamma$ (ttH) [99]	7/8 TeV	$2.69^{+2.51}_{-1.81}$	(0.0, 0.0, 1.0)

ATLAS Collaboration, JHEP1501(2015)069, PRD90(2014)012015, PRD91(2015)012006, ATLAS-CONF-2014-011, ATLAS-CONF-2014-060, ATLAS-CONF-2014-061;
CMS Collaboration, EPJC71(2014)103076, arXiv:1412.8662[hep-ex], CMS-PAS-HIG-14-010.

Direct and Indirect Limit

- Constraint from the global-fit of the SM-like Higgs boson observables.





Direct and Indirect Limit

- Direct searching of the heavy scalars

Single Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^2)$	$gg \to H\,,\, A$
Single Heavy Higgs Associated Strong Production	$\mathcal{O}(g_s^4\lambda_f^2)$	$gg \to bbH\,,\, bbA\,,\, tbH^{\pm}\,,\, ttH\,,\, ttA$
Single Heavy Higgs Associated Weak Production	$\mathcal{O}(g_s^2 g_w^4\lambda_f^2)$	$gq \to bq'\,bH^{\pm}\,,\, bq\,tH\,,\, bq\,tA$
Double Heavy Higgs Weak Production	$\mathcal{O}(g_w^4)$	$q\bar{q} \to HA\,,\, HH^{\pm}\,,\, AH^{\pm}\,,\, H^+H^-$
Light + Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^4)$	$gg \to hH\,,\, hA$
Double Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^4)$	$gg \to HH\,,\, HA\,,\, AA\,,\, H^+H^-$

Direct and Indirect Limit

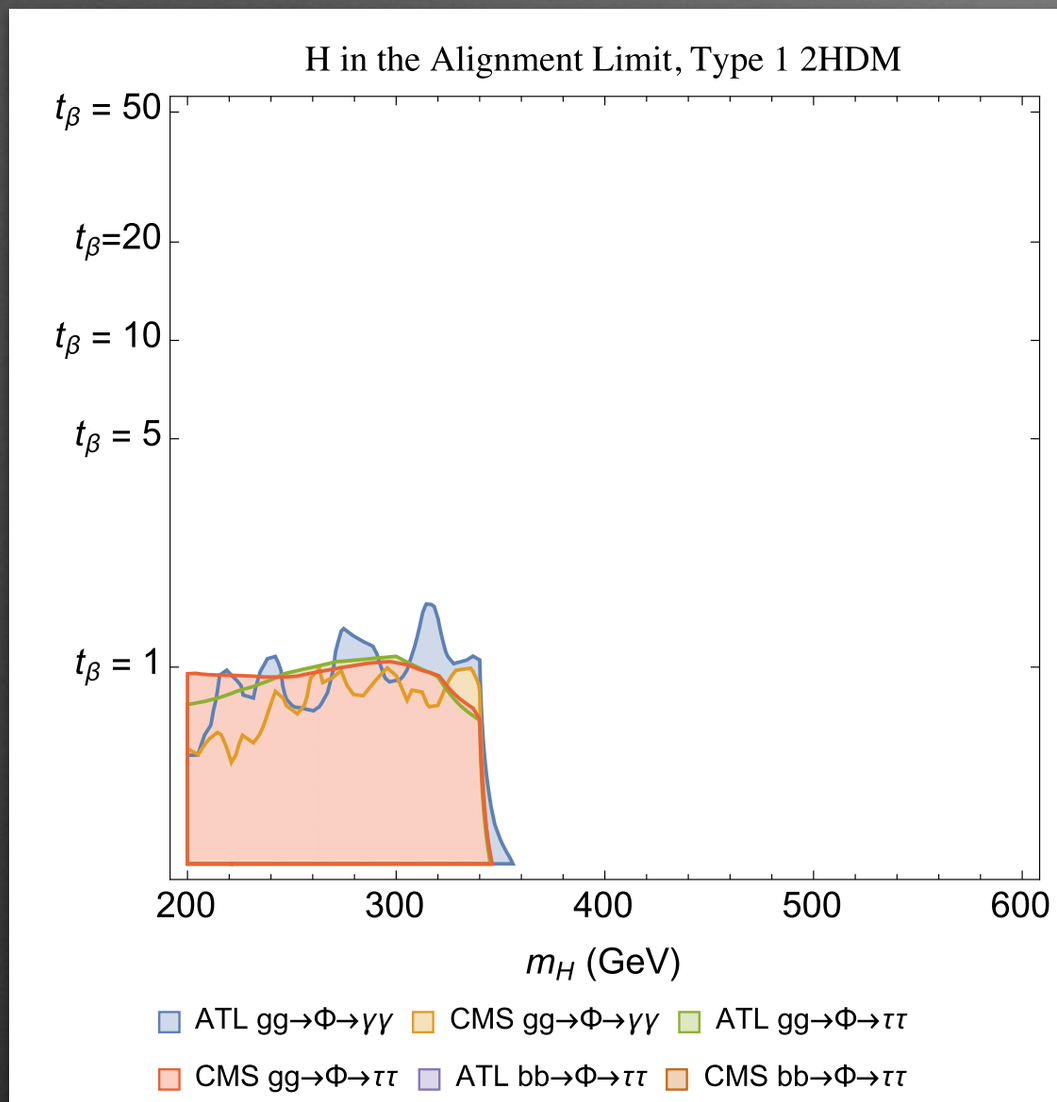
- Results from 7 and 8 TeV LHC

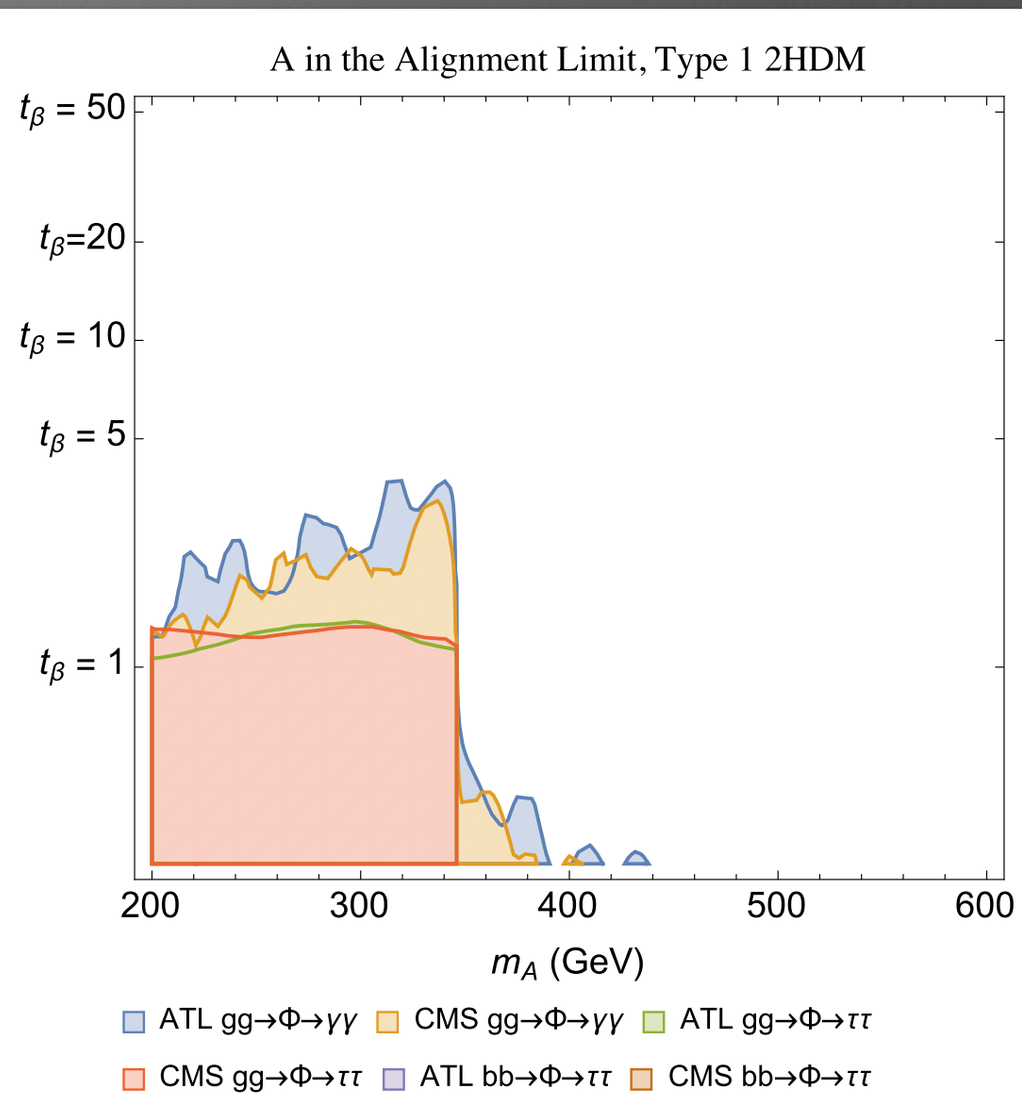
Channel	Collaboration	Reference
$gg \to \Phi \to \gamma\gamma$	ATLAS, 20.3 fb^{-1}	[51]
$gg \to \Phi \to \gamma\gamma$	CMS, 19.7 fb^{-1}	[52]
$gg \to \Phi \to \tau\tau$	ATLAS, 20.3 fb^{-1}	[8]
$b\bar{b} \to \Phi \to \tau\tau$	ATLAS, 20.3 fb^{-1}	[8]
$gg \to \Phi \to \tau\tau$	CMS, 19.7 fb^{-1}	[9]
$b\bar{b} \to \Phi \to \tau\tau$	CMS, 19.7 fb^{-1}	[9]
$gg \to A \to Zh \to \ell\ell + (b\bar{b}, \tau\tau)$	ATLAS, 20.3 fb^{-1}	[1]
$gg \to A \to Zh \to \ell\ell + b\bar{b}$	CMS, 19.7 fb^{-1}	[5]
$gg \to H \to hh \to b\bar{b} + \gamma\gamma$	ATLAS, 20 fb^{-1}	[53]
$gg \to H \to hh \to b\bar{b} + b\bar{b}$	CMS, 17.9 fb^{-1}	[54]
$gg \to H \to hh \to b\bar{b} + \gamma\gamma$	CMS, 19.7 fb^{-1}	[55]
$gg \to H \to ZZ \to 4\ell$	ATLAS, 20.7 fb^{-1}	[56]
$gg \to H \to ZZ$	CMS, 19.7 fb^{-1}	[6]
$gg \to H \to WW$	CMS, 19.7 fb^{-1}	[6]

ATLAS Collaboration, PLB744(2015)163, JHEP1411(2014)056, PRL113(2014)171801, PRL114(2015)081802, ATLAS-CONF-2013-012;
CMS Collaboration, JHEP1410(2014)160, arXiv:1503.04114[hep-ex], arXiv:1504.00936[hep-ex], CMS-PAS-HIG-13-032, CMS-PAS-HIG-14-006, CMS-PAS-HIG-14-011.

Direct and Indirect Limit

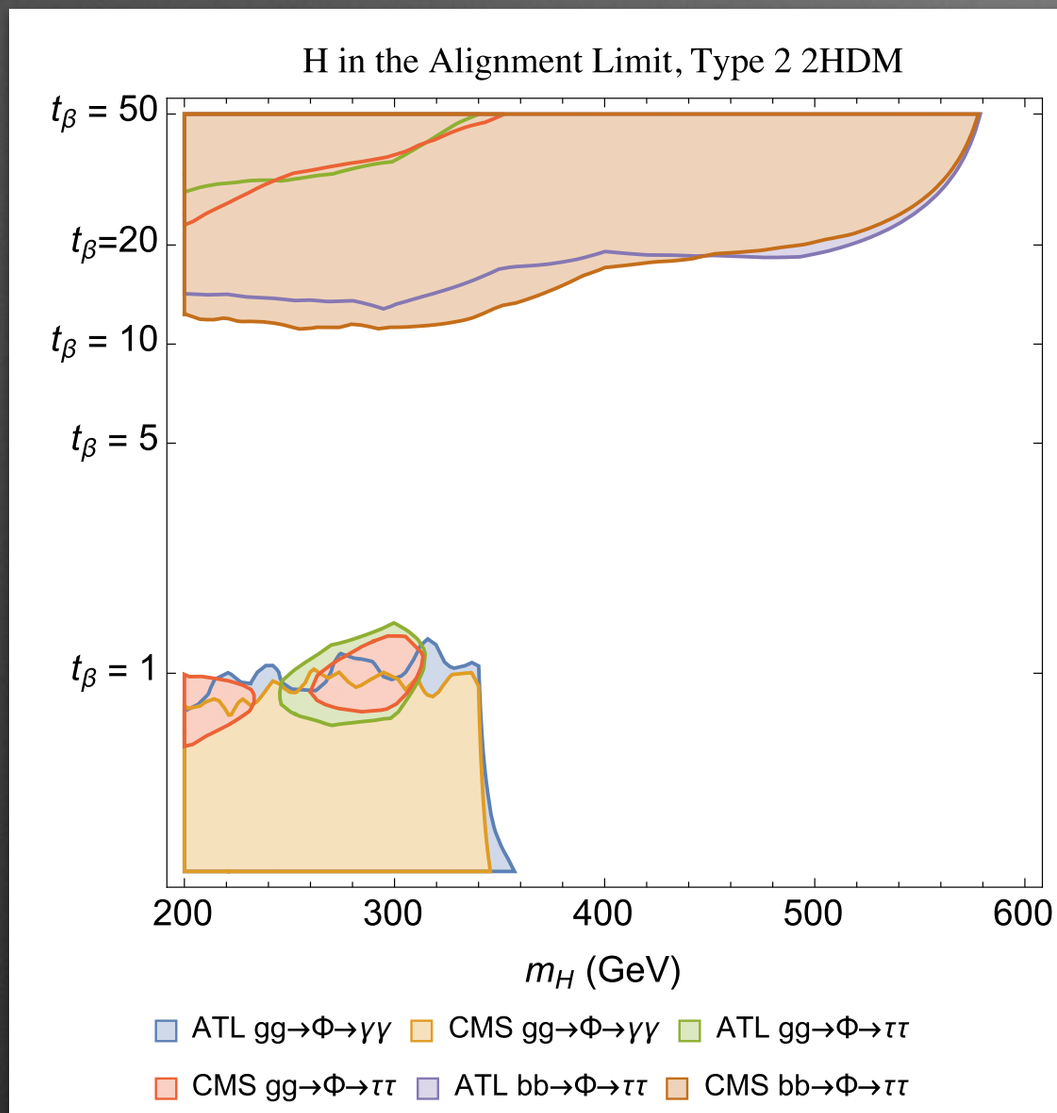
- Results from 7 and 8 TeV LHC (Type I 2HDM)

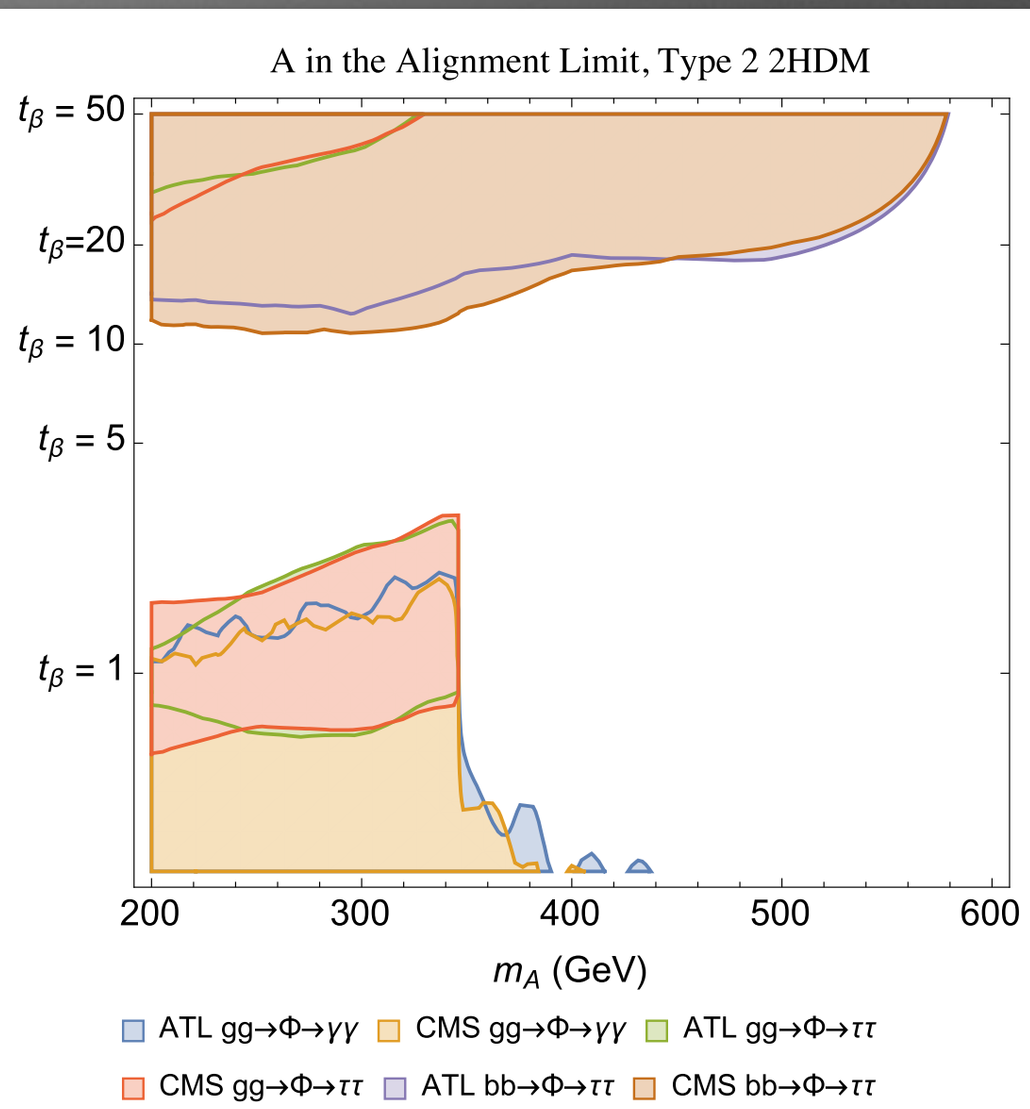




Direct and Indirect Limit

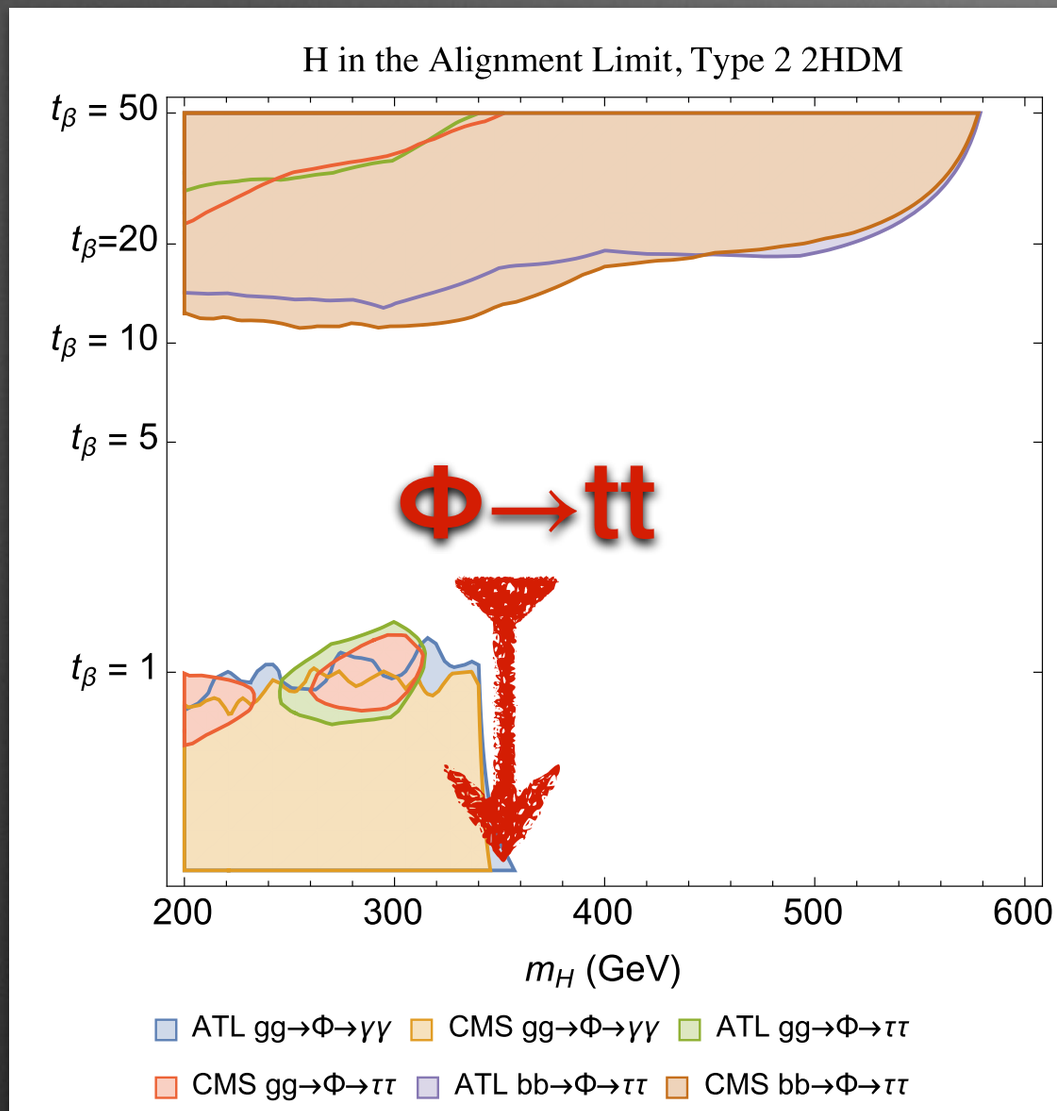
- Results from 7 and 8 TeV LHC (Type II 2HDM)

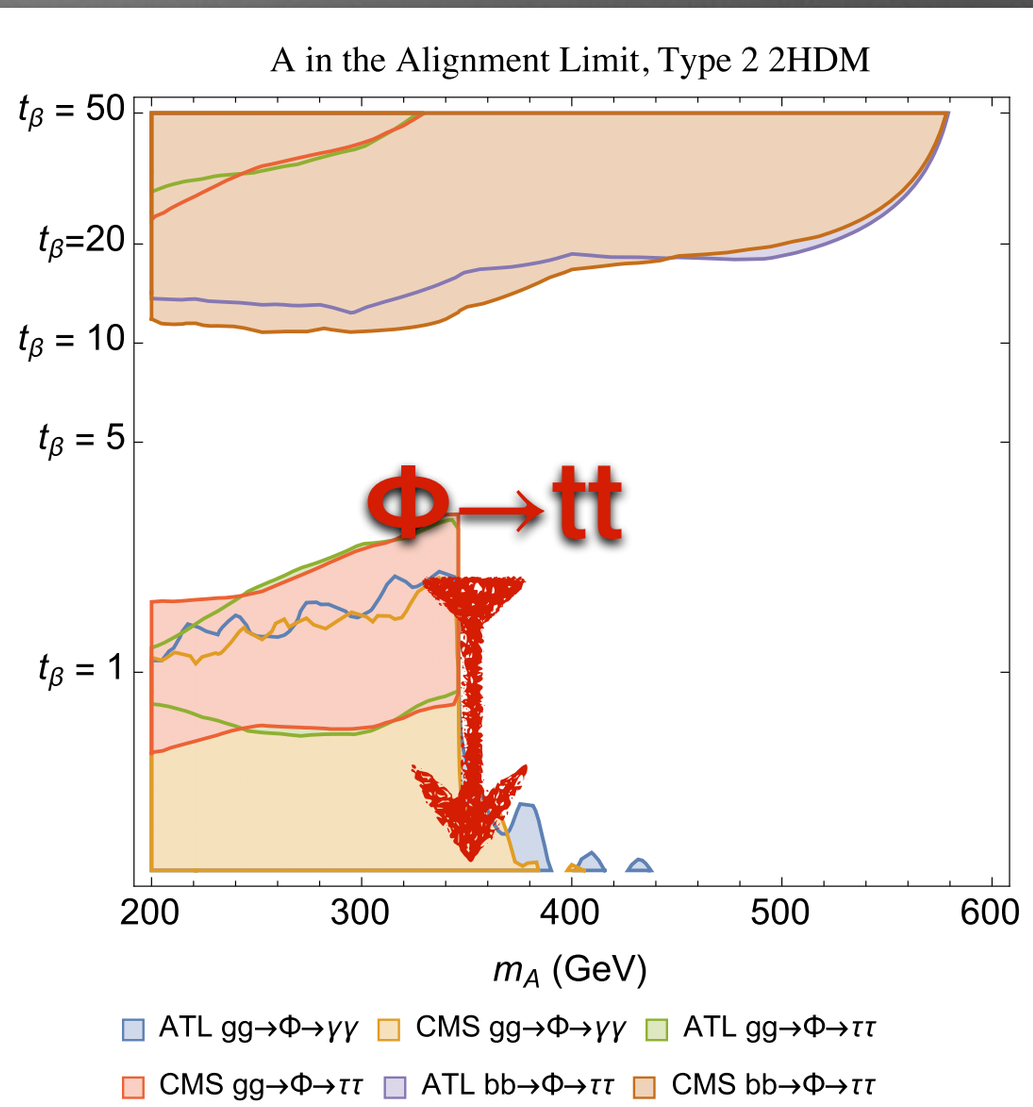




Direct and Indirect Limit

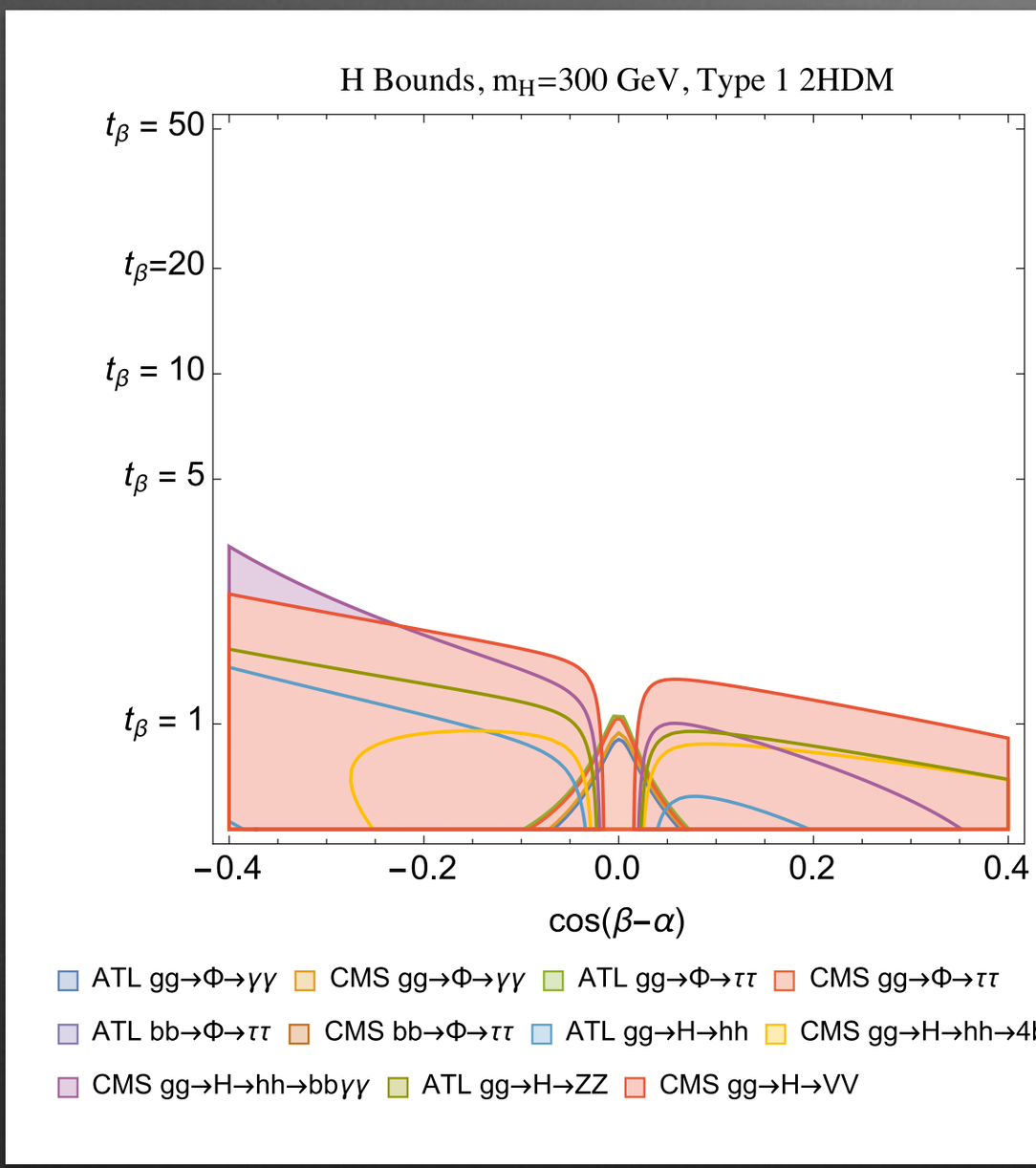
- Results from 7 and 8 TeV LHC (Type II 2HDM)

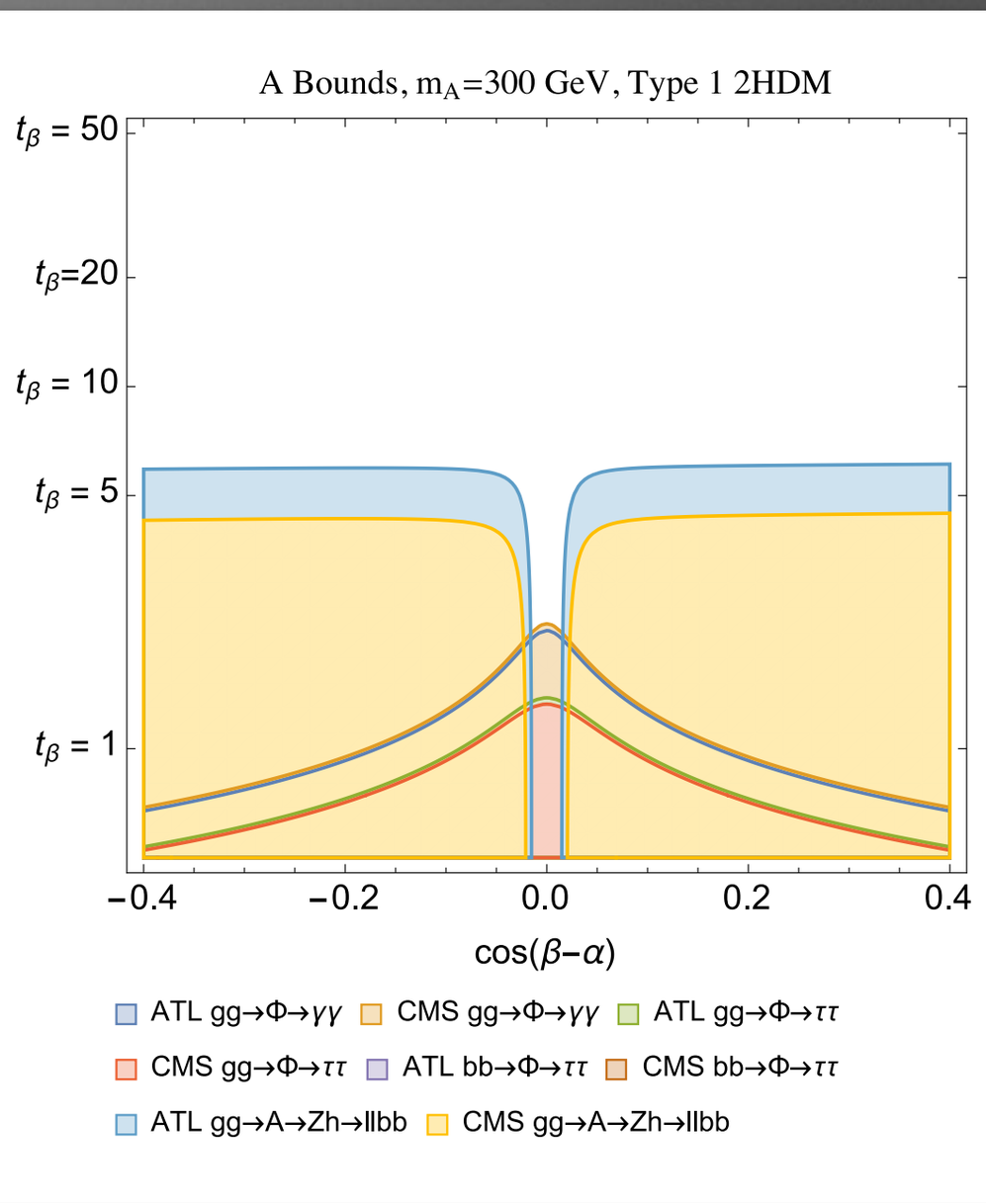




Direct and Indirect Limit

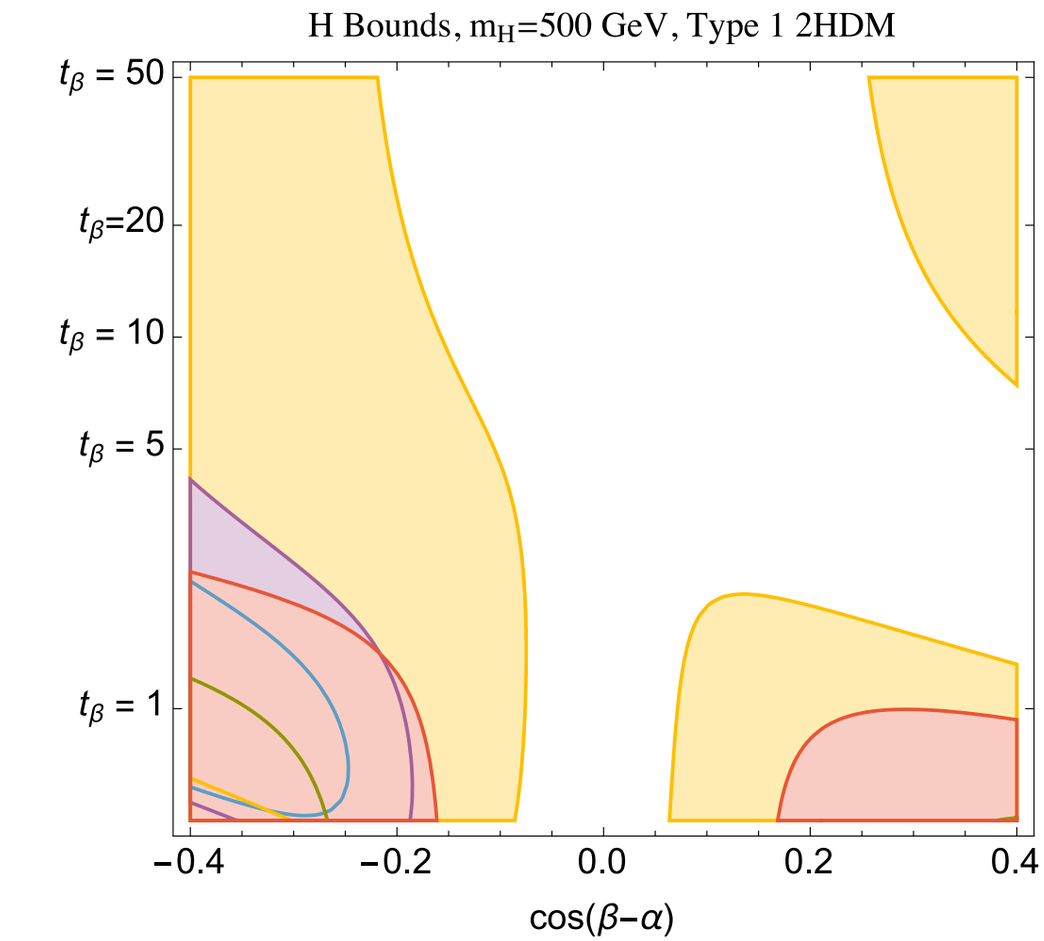
- Results from 7 and 8 TeV LHC (Type I 2HDM)

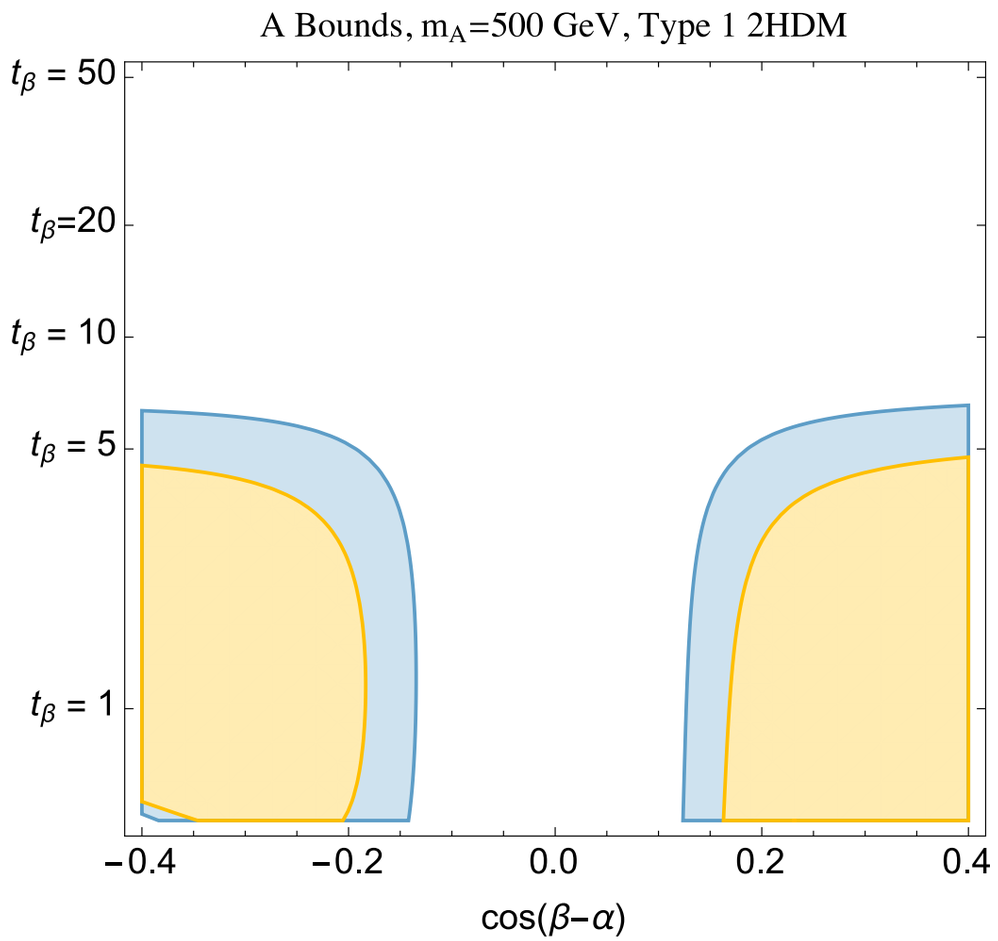




Direct and Indirect Limit

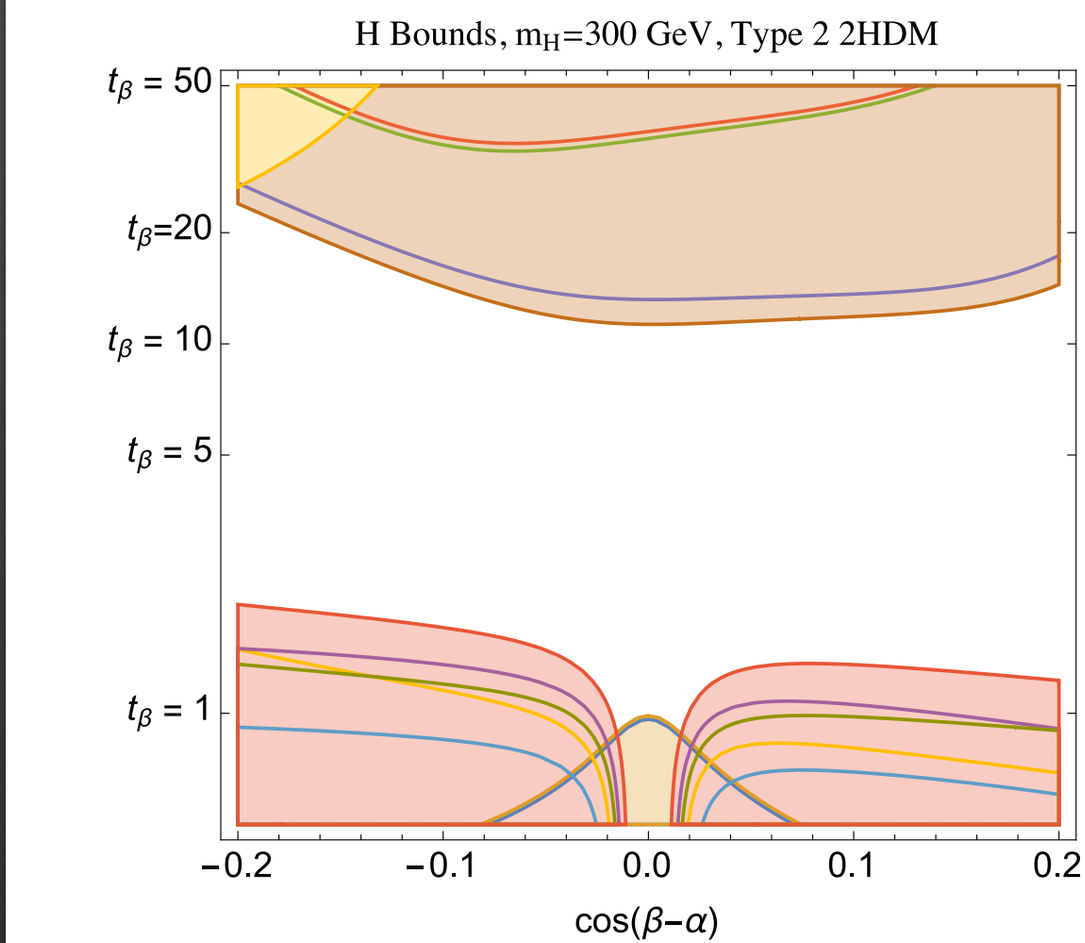
- Results from 7 and 8 TeV LHC (Type I 2HDM)

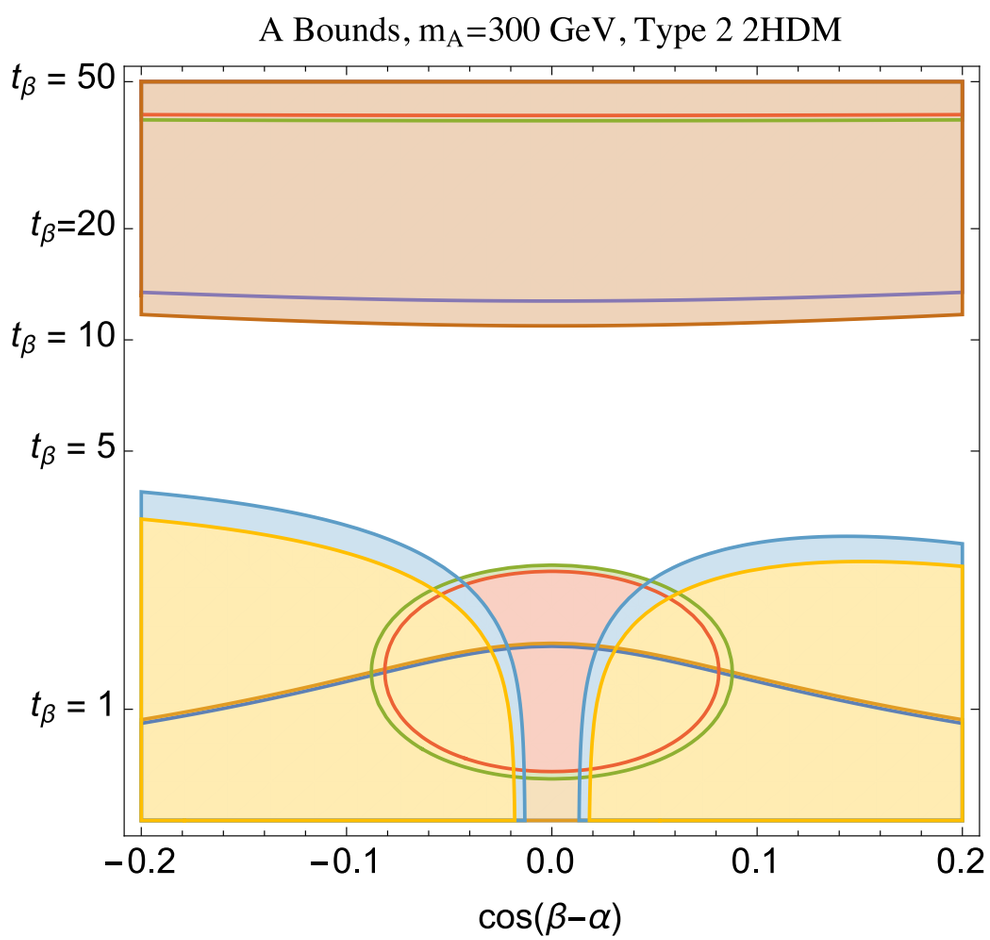




Direct and Indirect Limit

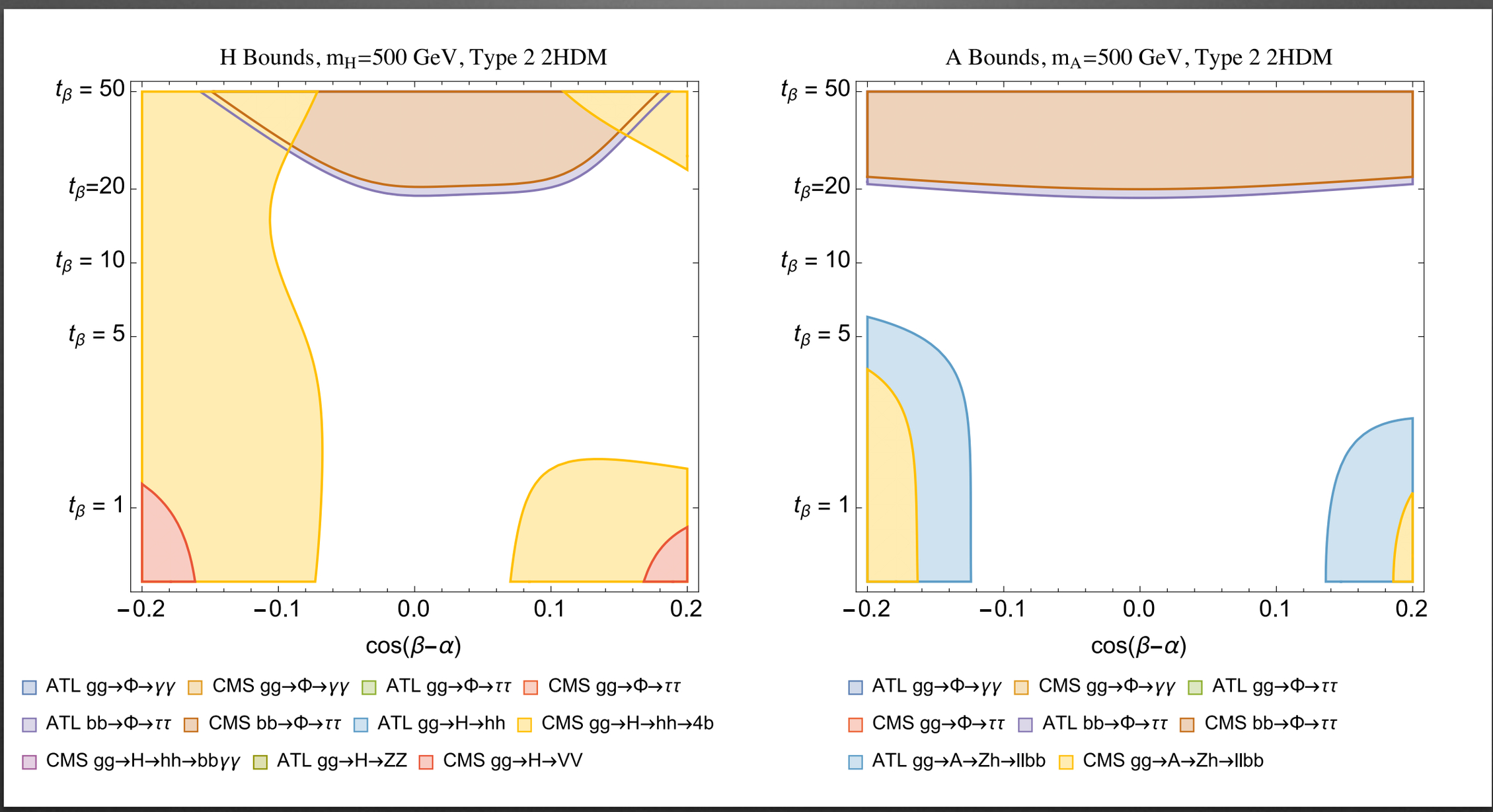
- Results from 7 and 8 TeV LHC (Type II 2HDM)





Direct and Indirect Limit

- Results from 7 and 8 TeV LHC (Type II 2HDM)

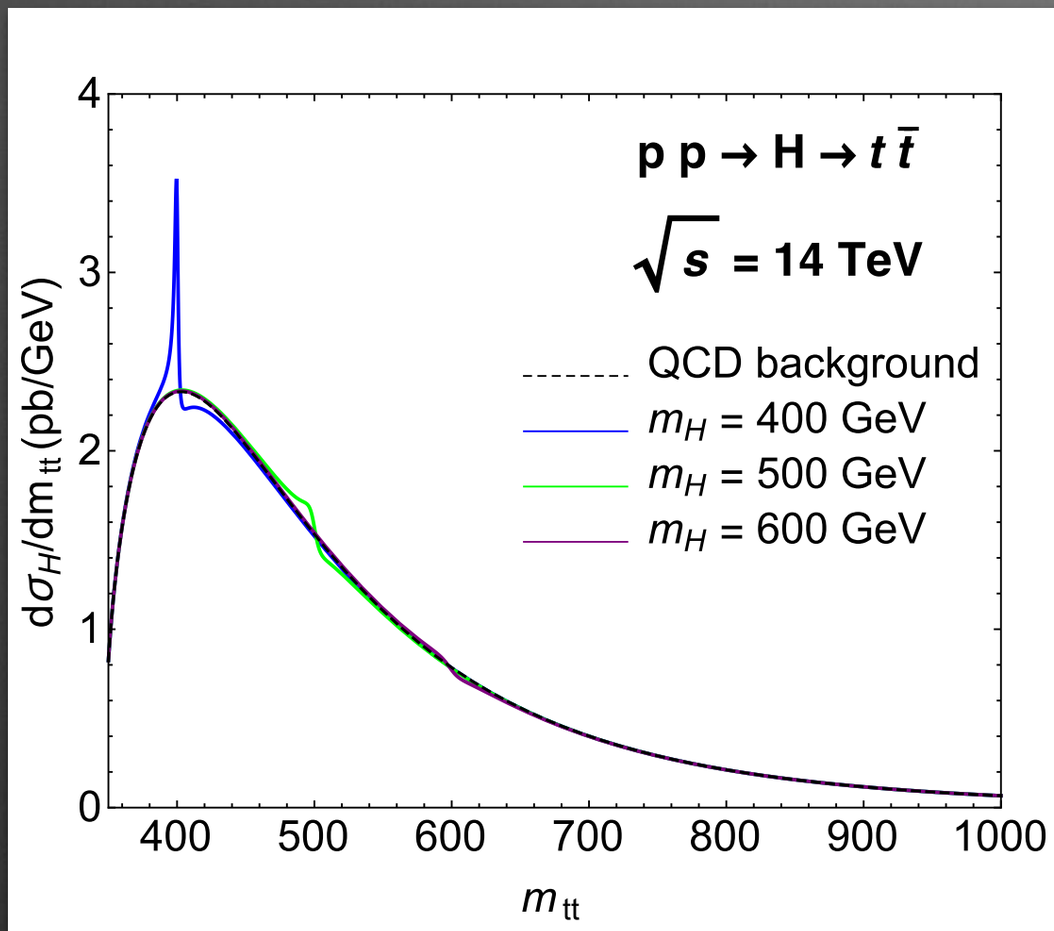


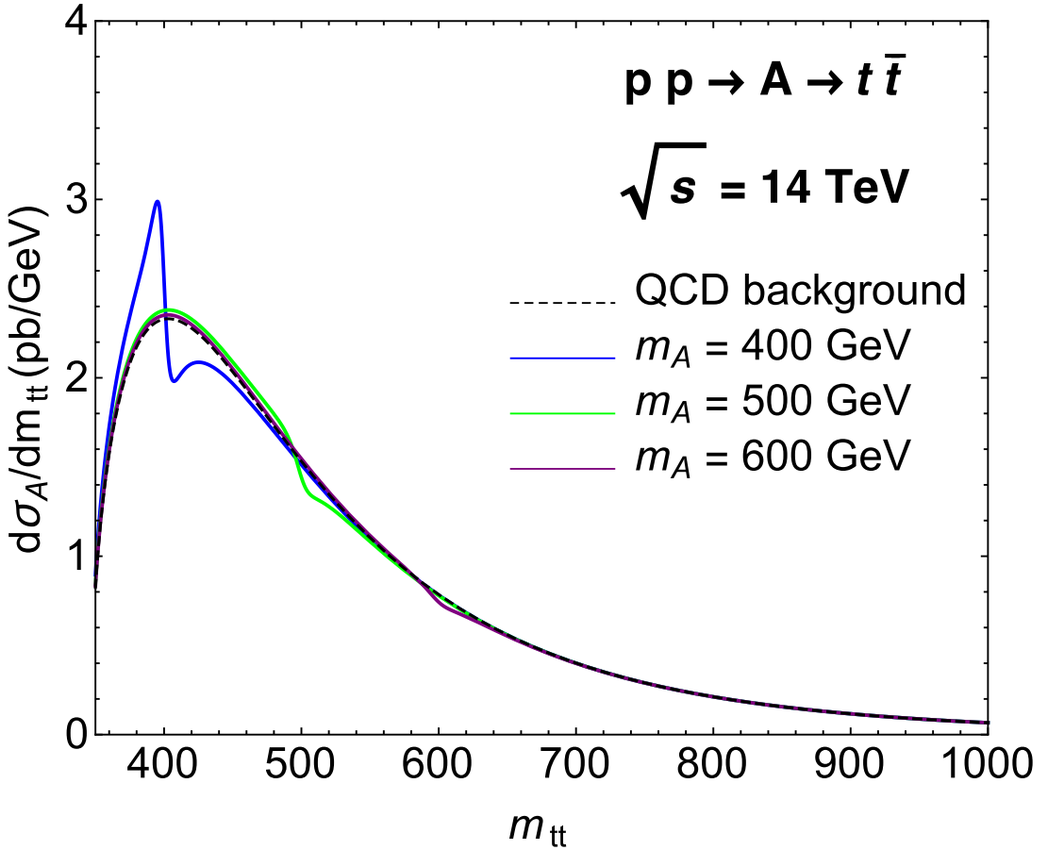
14 TeV LHC

- Direct searching of the heavy scalars
  - $pp \rightarrow H/A \rightarrow tt$
  - $pp \rightarrow bbH/bbA \rightarrow ttbb$
  - $pp \rightarrow ttH/ttA \rightarrow tttt$
  - $pp \rightarrow bbH/bbA \rightarrow bb$+missing E_T
  - $pp \rightarrow ttH/ttA \rightarrow tt$+missing E_T
  - $pp \rightarrow tbH^{\pm} \rightarrow tbtb$

$pp \to H/A \to tt$

- Huge SM background and significant interference effect!

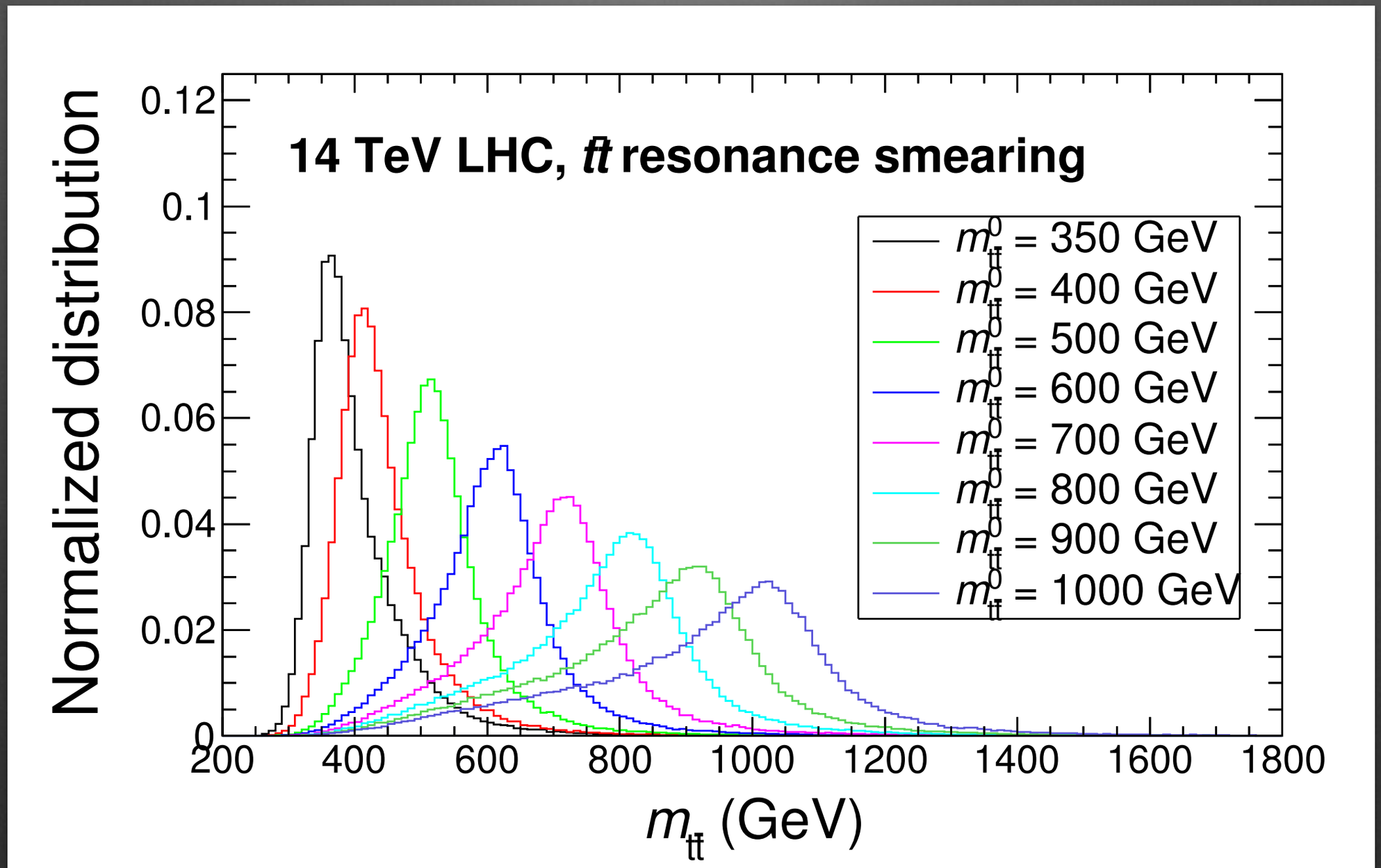




D. Dicus, A. Strange, and S. Willenbrock, PLB333(1994)126; R. Frederix and F. Maltoni, JHEP0901(2009)047, A. Djouadi, L.Maiani, A. Polosa, J. Quevillon, and V. Riquer, arXiv:1502.05653[hep-ph]

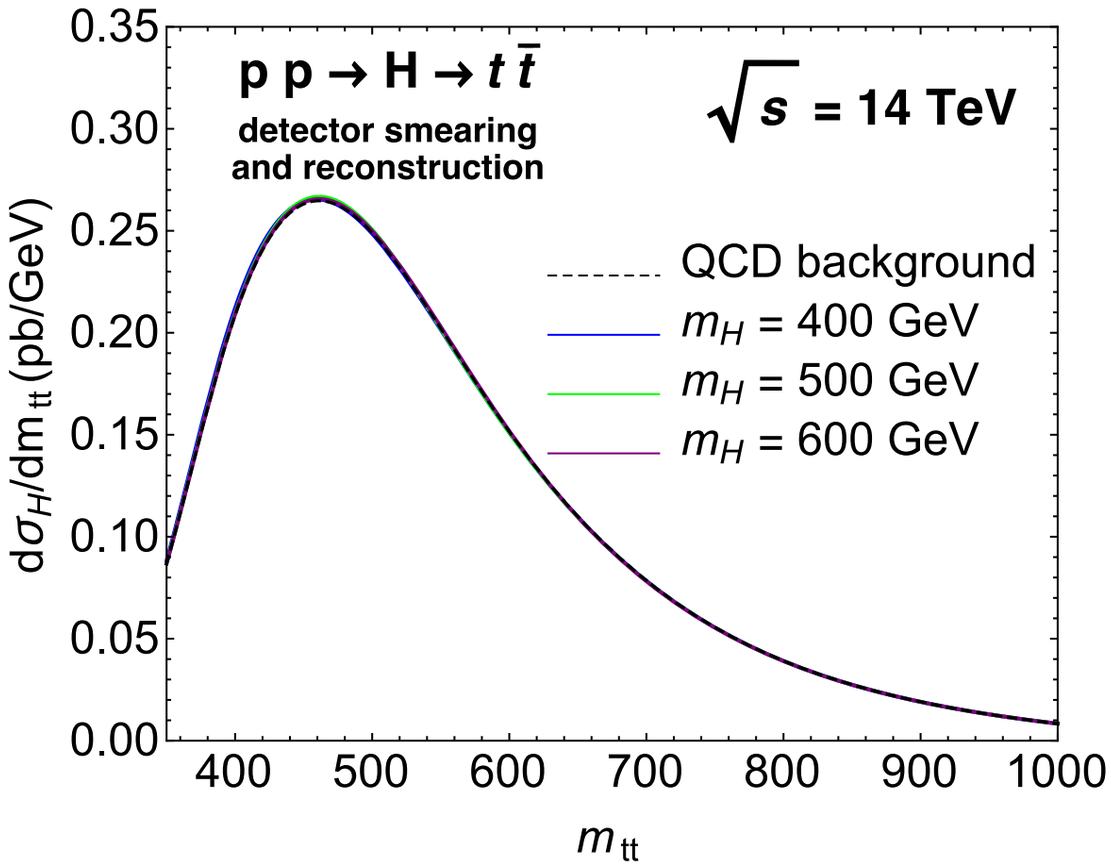
$pp \rightarrow H/A \rightarrow tt$

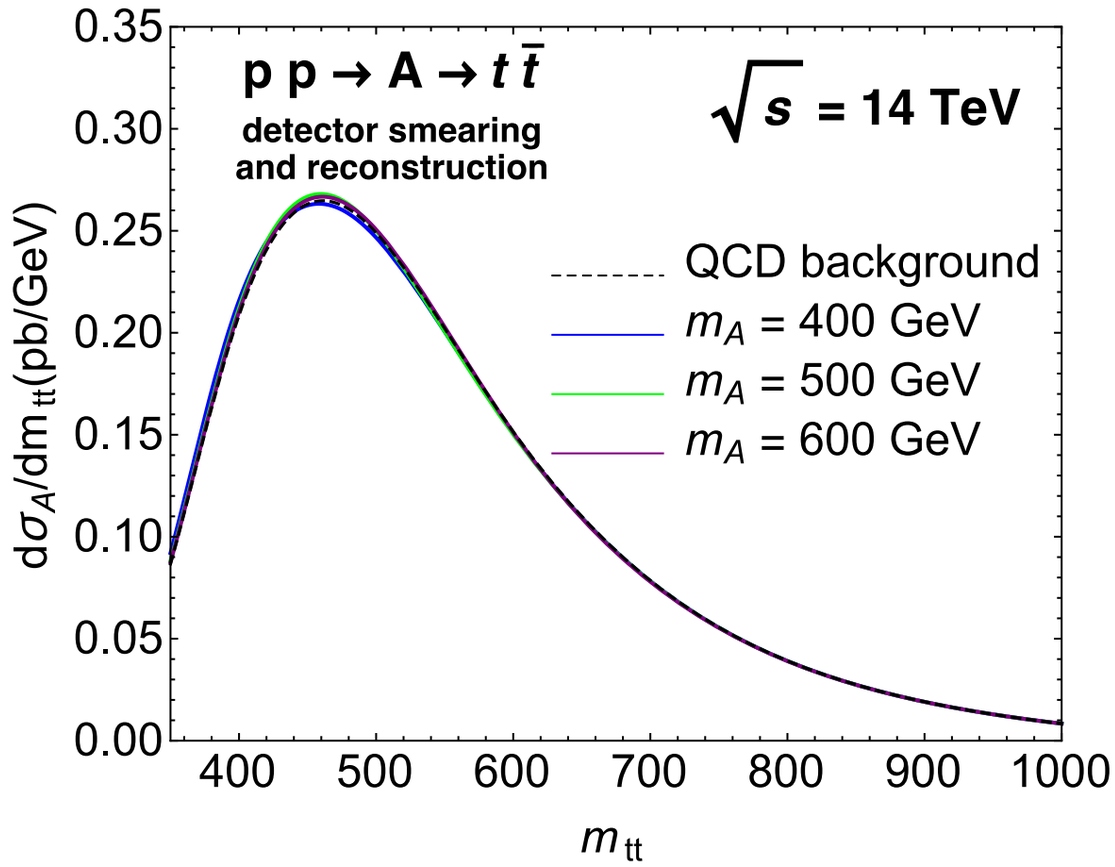
- Detector smearing effect from final state top quark reconstruction



$pp \to H/A \to tt$

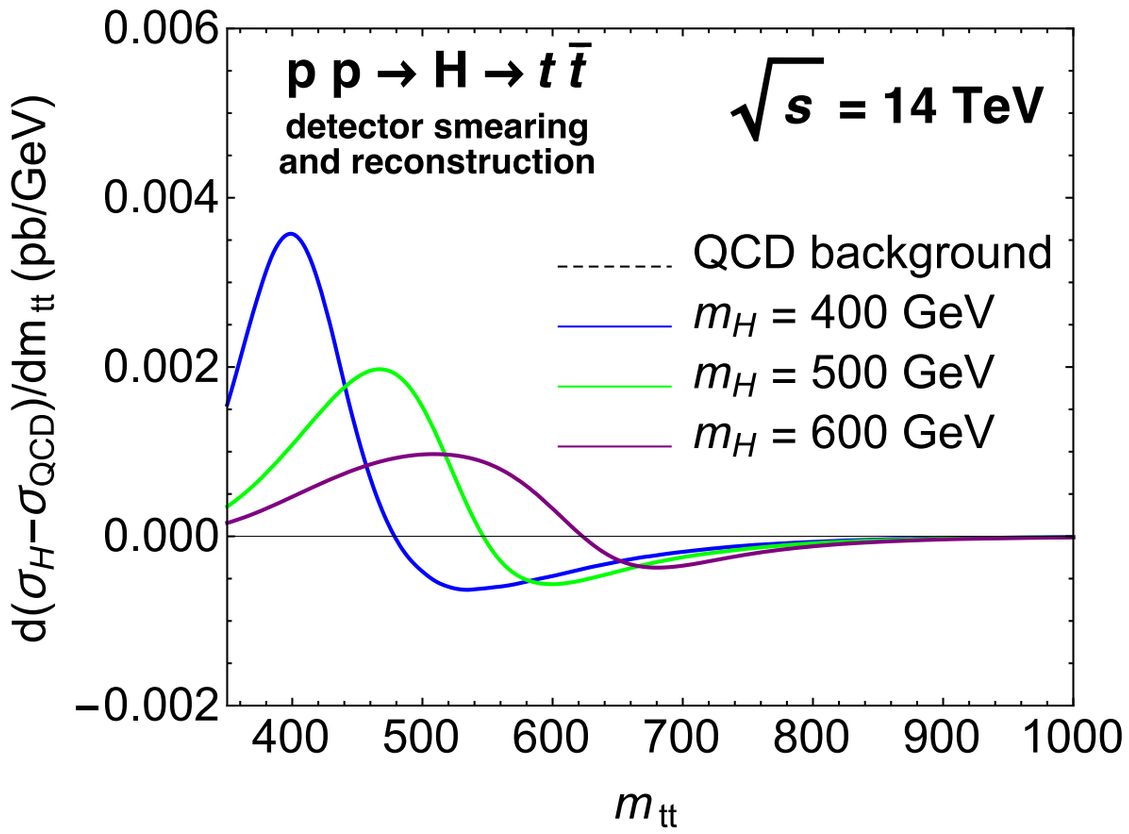
- Detector smearing effect from final state top quark reconstruction

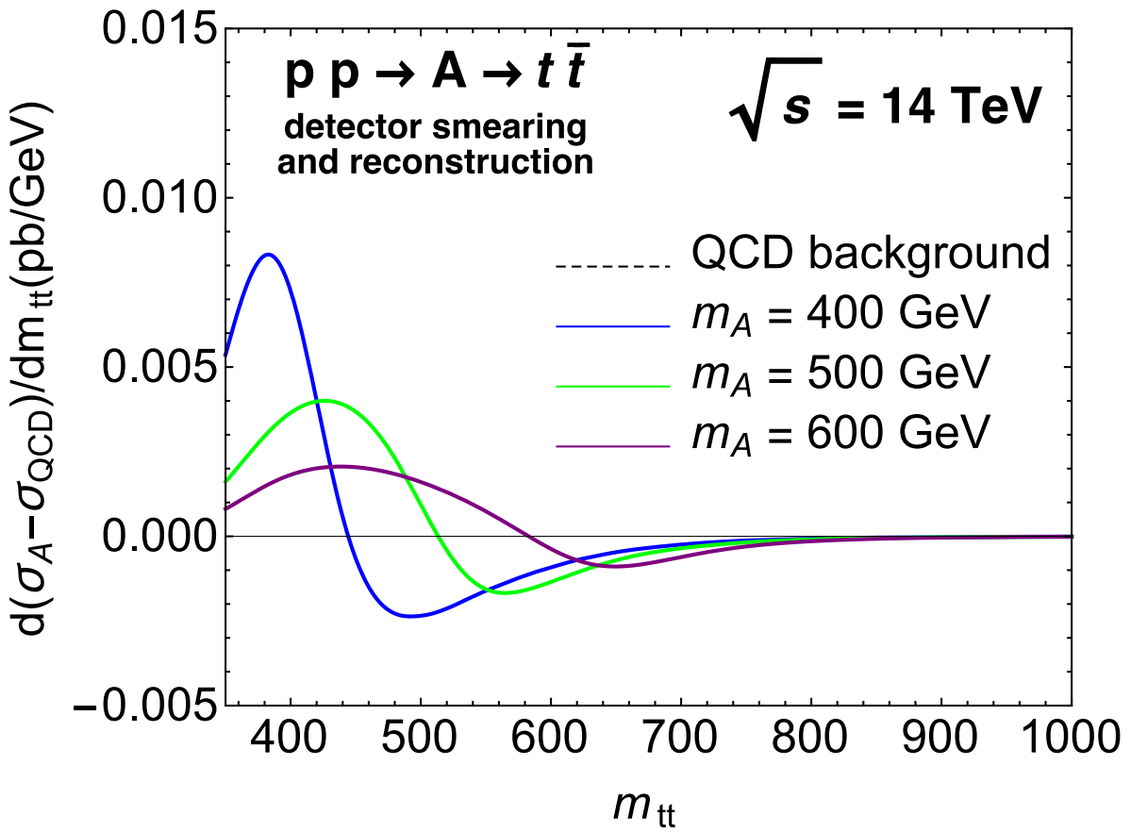




$pp \to H/A \to tt$

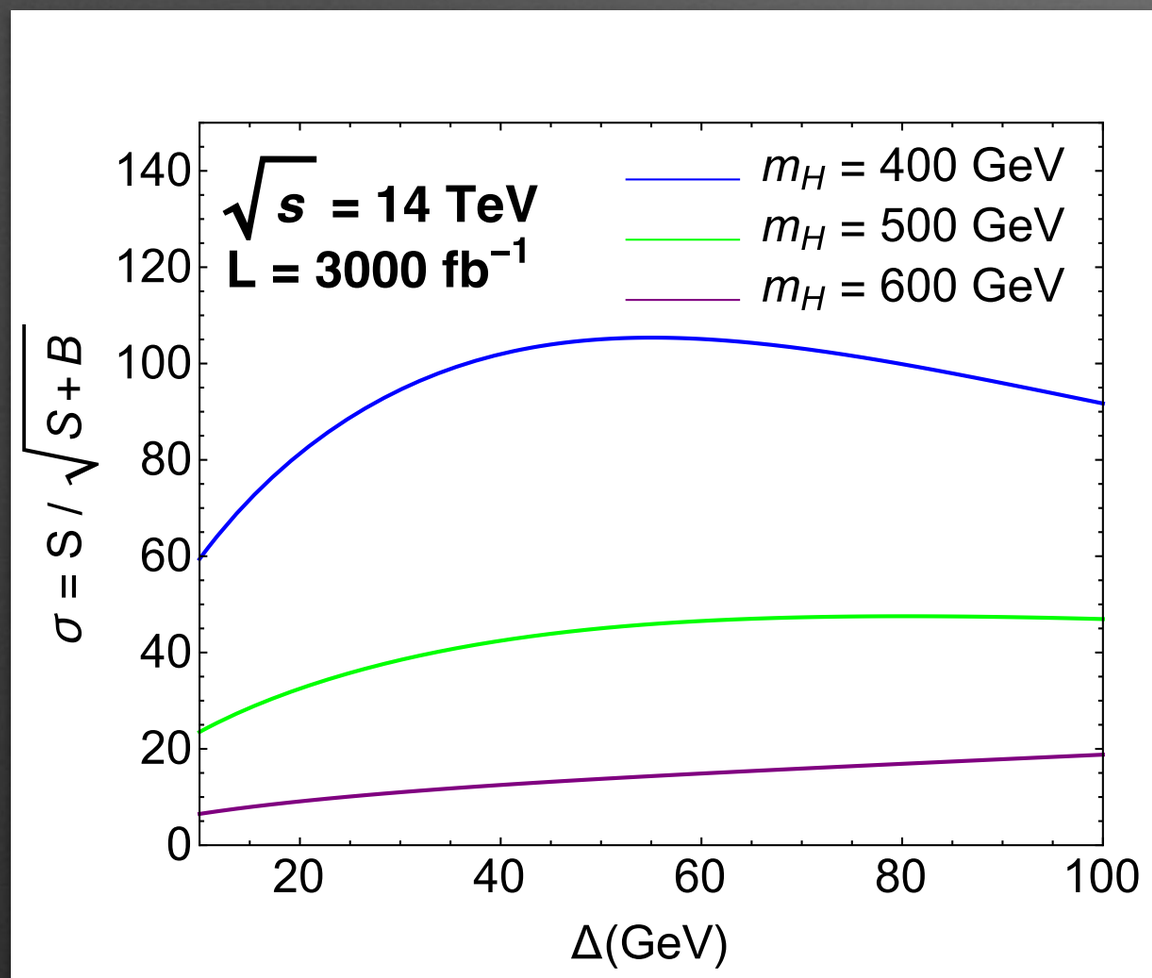
- Detector smearing effect from final state top quark reconstruction

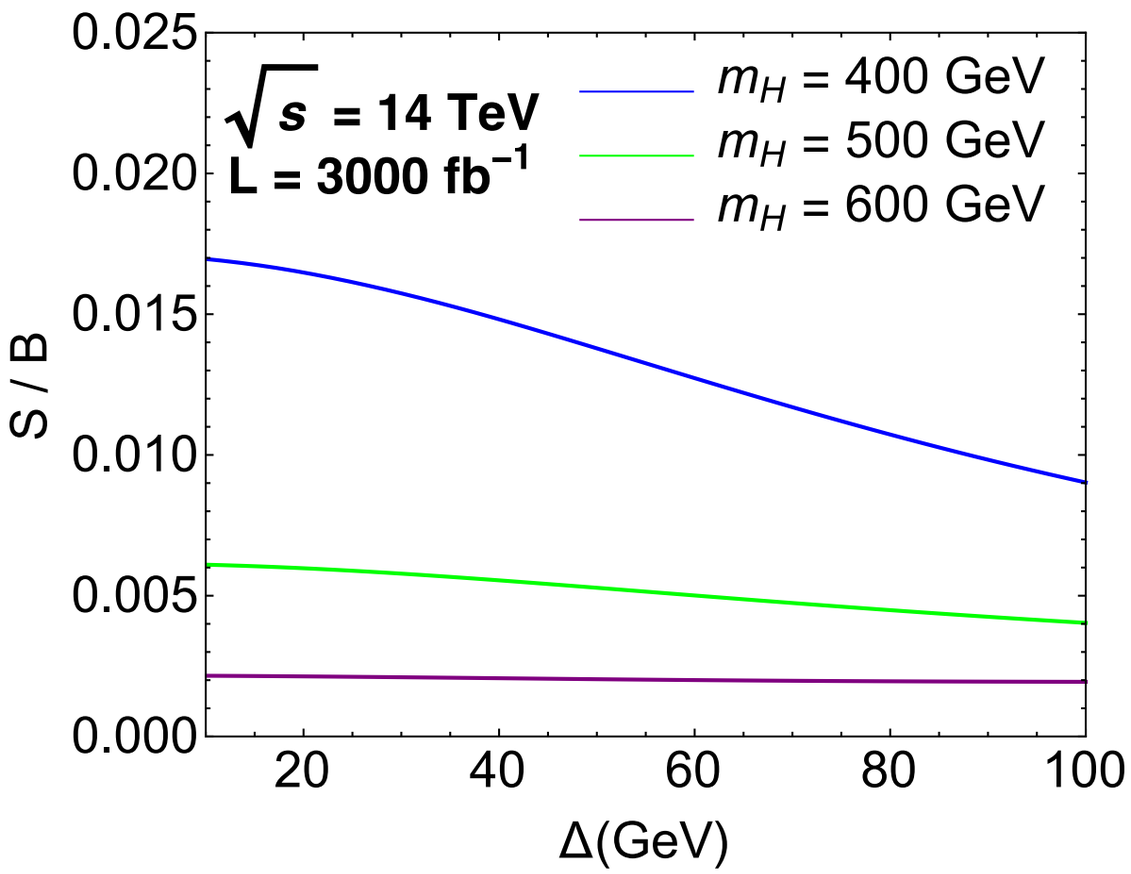




$pp \to H/A \to tt$

- Extremely difficult at 14 TeV LHC!
- bbH and ttH channels are needed!





NEW!! Sunghoon Jung, Jeonghyeon Song, and Yeo Woong Yoon, arXiv:1505.00291[hep-ph]

$pp \to tbH^{\pm} \to tbtb$

- Charge Higgs boson

$$\mathcal{L}_{\text{eff}} = y_{tb} H^{+} \bar{t} (P_L \sin\theta + P_R \cos\theta) b + \text{h.c.}$$

- In our simulation, the decay branching ratio to tb final state is assumed to be 100%

- The dominant SM bkgds are

  - $pp \to ttbb$
  - $pp \to ttbj$
  - $pp \to ttjj$

Also see K. A. Assamagan and N. Gollub, EPJC39S2(2005)25; J. Hajer, Y.-Y Li, T. Liu, and J. F. H. Shiu, arXiv: 1504.07617[hep-ph]

$pp \to tbH^{\pm} \to tbtb$

- Both signal and bkgds are generated at parton level using MadGraph5 with CTEQ6L1 pdf and 5-flavor scheme. The parton showering and hadronization of the parton level events are done using PYTHIA6.4.

- Detector simulation is done with Delphes 3.

- Jets are reconstructed using anti-k_T algorithm with R=0.5.

- Basic BTagging algorithm in Delphes is used. The b-tagging efficiency is tuned with Drell-Yan process to be

$$\epsilon_b = 70\%, \quad \epsilon(c \to b) = 25\%, \quad \epsilon(udsg \to b) = 2\%$$

CMS Collaboration, arXiv:1307.7135[hep-ex]

$pp \to tbH^{\pm} \to tbtb$

- Basic cuts:

  - one and only one charged lepton with

$$p_{\mathrm{T}}^{\ell} > 15\mathrm{GeV}, \quad |\eta^{\ell}| < 2.5, \quad I_{\mathrm{iso},\mu}(\Delta R = 0.3) < 0.1$$

  - missing transverse energy $\not{E}_{\mathrm{T}} > 30\mathrm{GeV}$

  - at least 6 jets with $p_{\mathrm{T}}^{j} > 20\mathrm{GeV}, \quad |\eta^{j}| < 4.5$

  - at least 4 of the 6 jets are tagged as b-jets with

$$p_{\mathrm{T}}^{b} > 40\mathrm{GeV}, \quad |\eta^{b}| < 2.5 \quad \text{and} \quad p_{\mathrm{T}}^{b_1} > 150\mathrm{GeV}$$

$pp \to tbH^{\pm} \to tbtb$

- Top quark reconstruction (semi-leptonic):

  - reconstructing hadronic decaying W with non-b jets

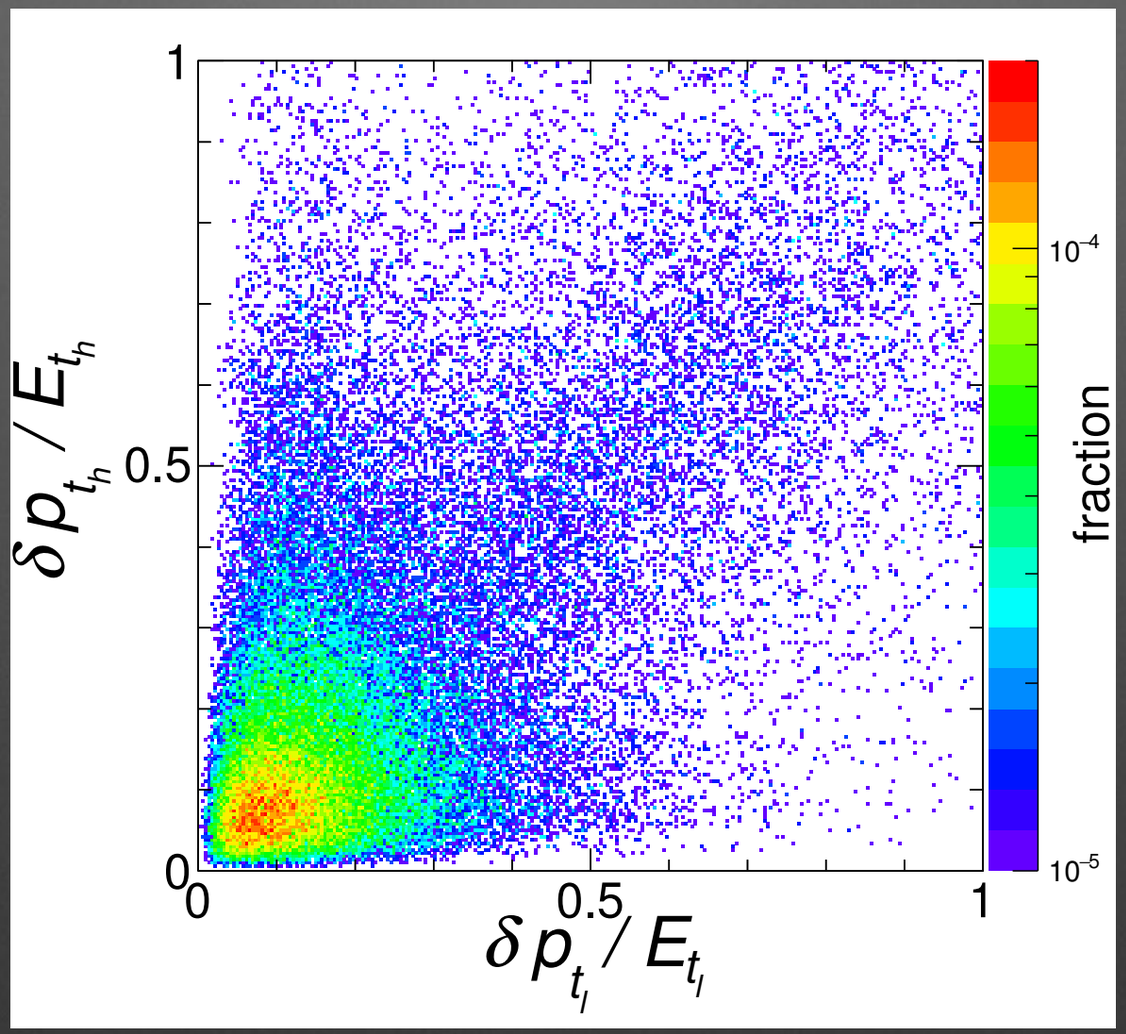
  - solving neutrino 4-momentum using mass-shell equation of the leptonic decaying W (If there are two solutions, keep both. If there is no real solution, we make a minimal modification of the missing transverse energy to get one.)

$$\chi^2 = \frac{(m_{W_h b_h} - m_t)^2}{\sigma_h^2} + \frac{(m_{W_\ell b_\ell} - m_t)^2}{\sigma_\ell^2}$$

  - σ_h=50GeV, σ_l=25GeV, requiring χ<5

$pp \to tbH^{\pm} \to tbtb$

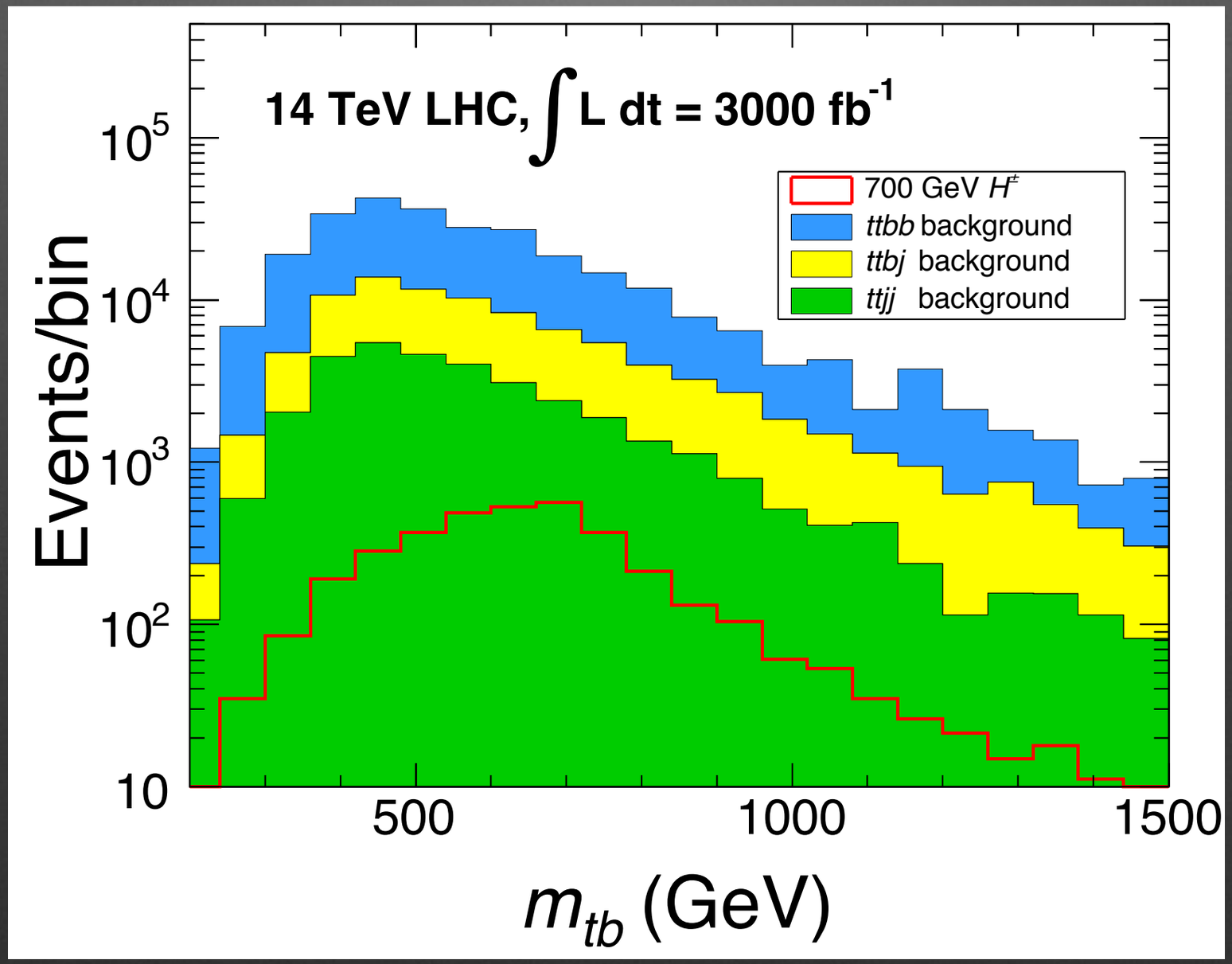
- Top quark reconstruction (semi-leptonic)



- Additional cuts: $\Delta R_{b_1 b_2} > 0.9$

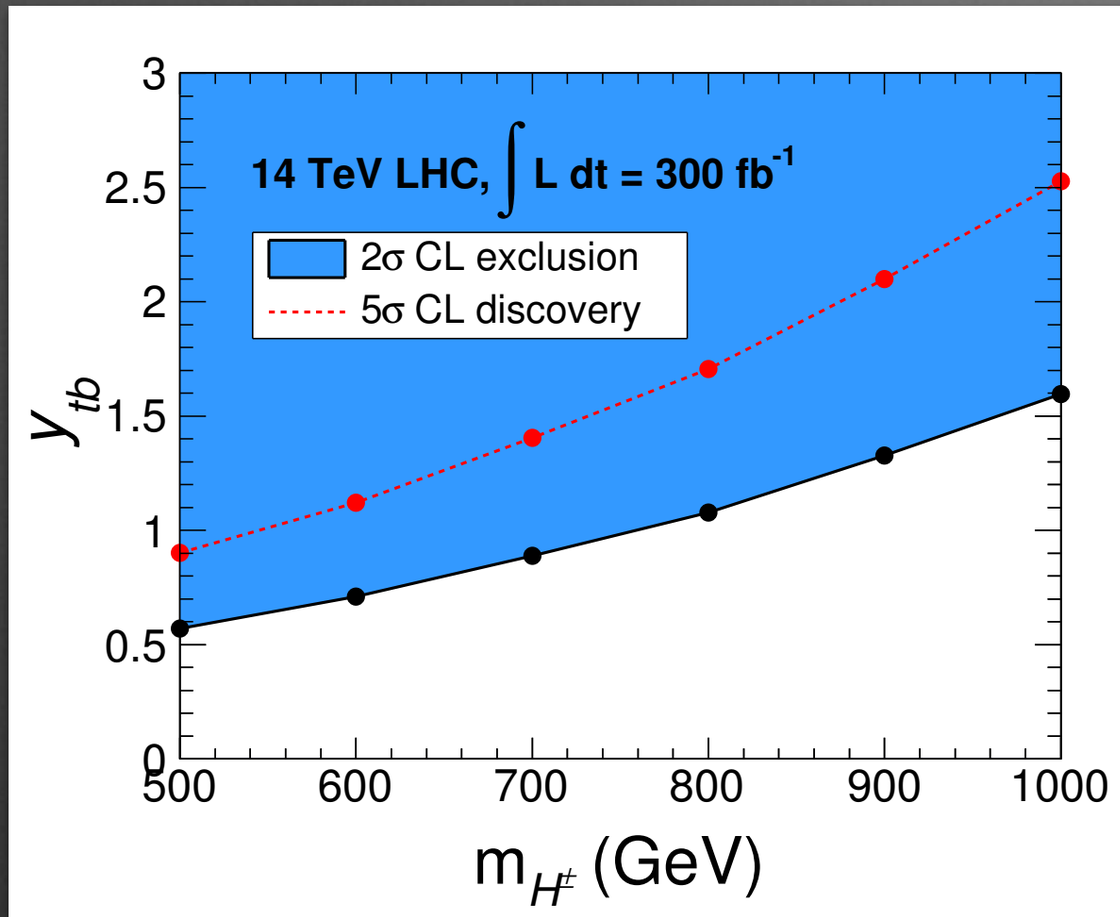
$pp \to tbH^{\pm} \to tbtb$

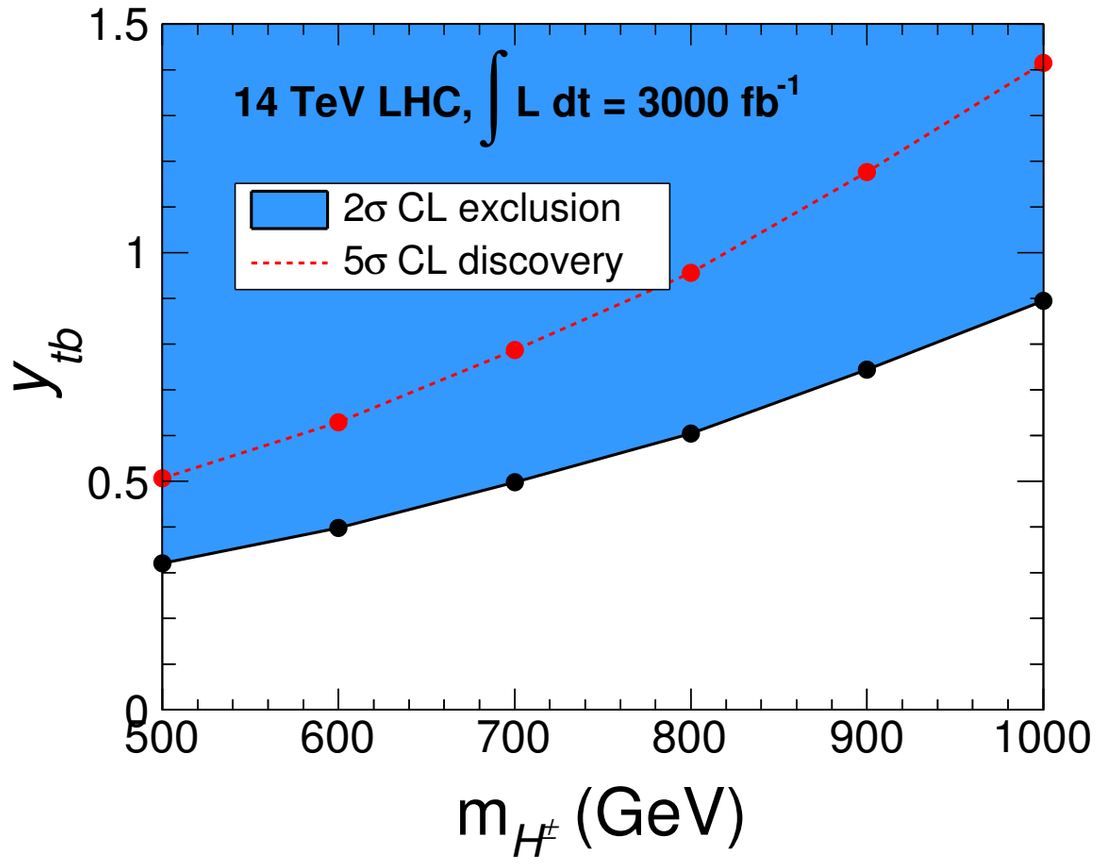
- Invariant mass distribution of the leading top and the leading b-jet



$pp \to tbH^{\pm} \to tbtb$

- Constraint to the 2HDM

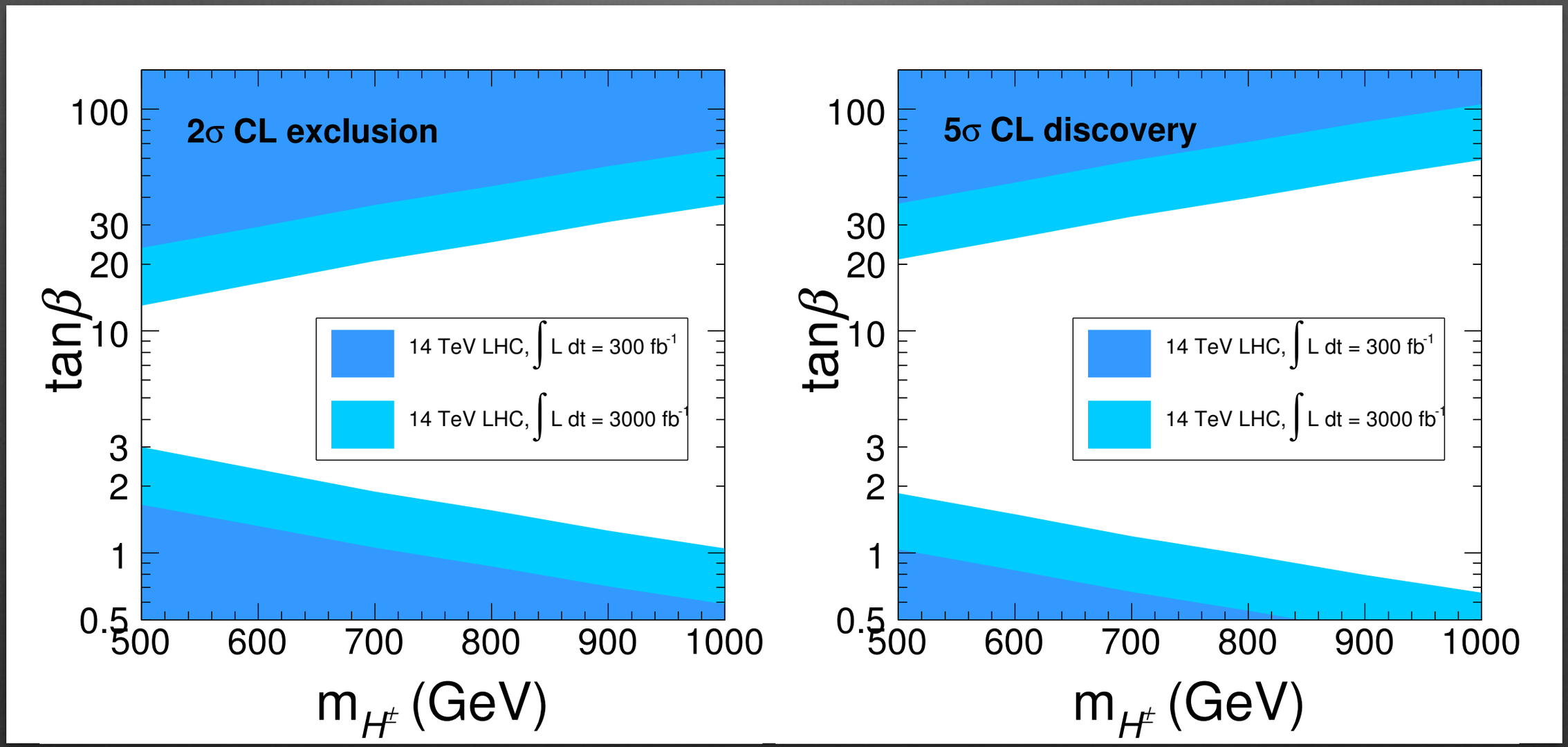




$pp \to tbH^{\pm} \to tbtb$

- Constraint to the 2HDM (Type II)

$$\mathcal{L}_{\text{Type II}} = \frac{\sqrt{2}}{v} H^{+} \bar{t}(P_L m_t \cot\beta + P_R m_b \tan\beta) b + \text{h.c.}$$



With boosted-top tagging tech. and BDT method, see J. Hajer, Y.-Y Li, T. Liu, and J. F. H. Shiu, arXiv: 1504.07617[hep-ph]

Conclusion

- A lot of new physics models predict the extension of the SM Higgs sector.

- The direct and indirect constraints from the LHC to the additional Higgs bosons are investigated in detail.

- Searching for the heavy additional Higgs bosons at the 14 TeV LHC via their interactions with the SM top quark and bottom quark are studied.

- We are on the way of hunting for the rest of Higgs bosons.

Thank you!