International Symposium on Higgs Boson and Beyond Standard Model Physics

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BSM HIGGS PHYSICS

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Why An Extended Higgs Sector?

- Often arises in ``natural" theories for various symmetry requirements:
  - supersymmetric models: MSSM/NMSSM
  - Composite Higgs models / little Higgs models
  - Twin Higgs models
  - … …
- In relation to this, the discovery of a second light Higgs may help disprove anthropic principle, since its existence could be irrelevant to EWSB directly

Why An Extended Higgs Sector?

- Dark matter: e.g., interaction mediator
- Baryon asymmetry in the Universe, e.g., new Jarlskog invariants
  - Yukawa sector: Yukawa couplings misaligned with fermion mass $\sim \mathrm{Im}[\mathrm{Tr}[MY^\dagger]]$
  - Higgs potential: relative phases of Higgs interactions
- … …

Search for an extended Higgs sector => **One of top priorities at LHC**

A Experimental Guideline - Rho Parameter

- If there are n Higgs multiplets, at tree level [P. Langacker, 1981]

$$\rho = \frac{m_W}{m_Z \cos\theta_{\mathrm{EW}}} = \frac{\sum_{i=1}^{n}[I_i(I_i+1) - \frac{1}{4}Y_i^2]v_i}{\sum_{i=1}^{n}\frac{1}{2}Y_i^2 v_i} \approx 1$$

- In the SM, $I = \frac{1}{2}, Y = 1 \Rightarrow \rho = 1$

- Can be extended in multiple ways
  - SM + singlet
  - SM + doublets with Y = +1 or -1
  - Georgi-Machacek model: SM + Higgs triplets
  - … …
- For concreteness and representativeness, let's focus on THDM (type II)

Type II THDM

- ``Physical'' reasons: free of FCNC problem (with Glashow-Weinberg condition satisfied), well-motivated at UV (MSSM), etc.

- ``nonphysical'' reason: convenient parametrization, not hard to project sensitivities to other related scenarios

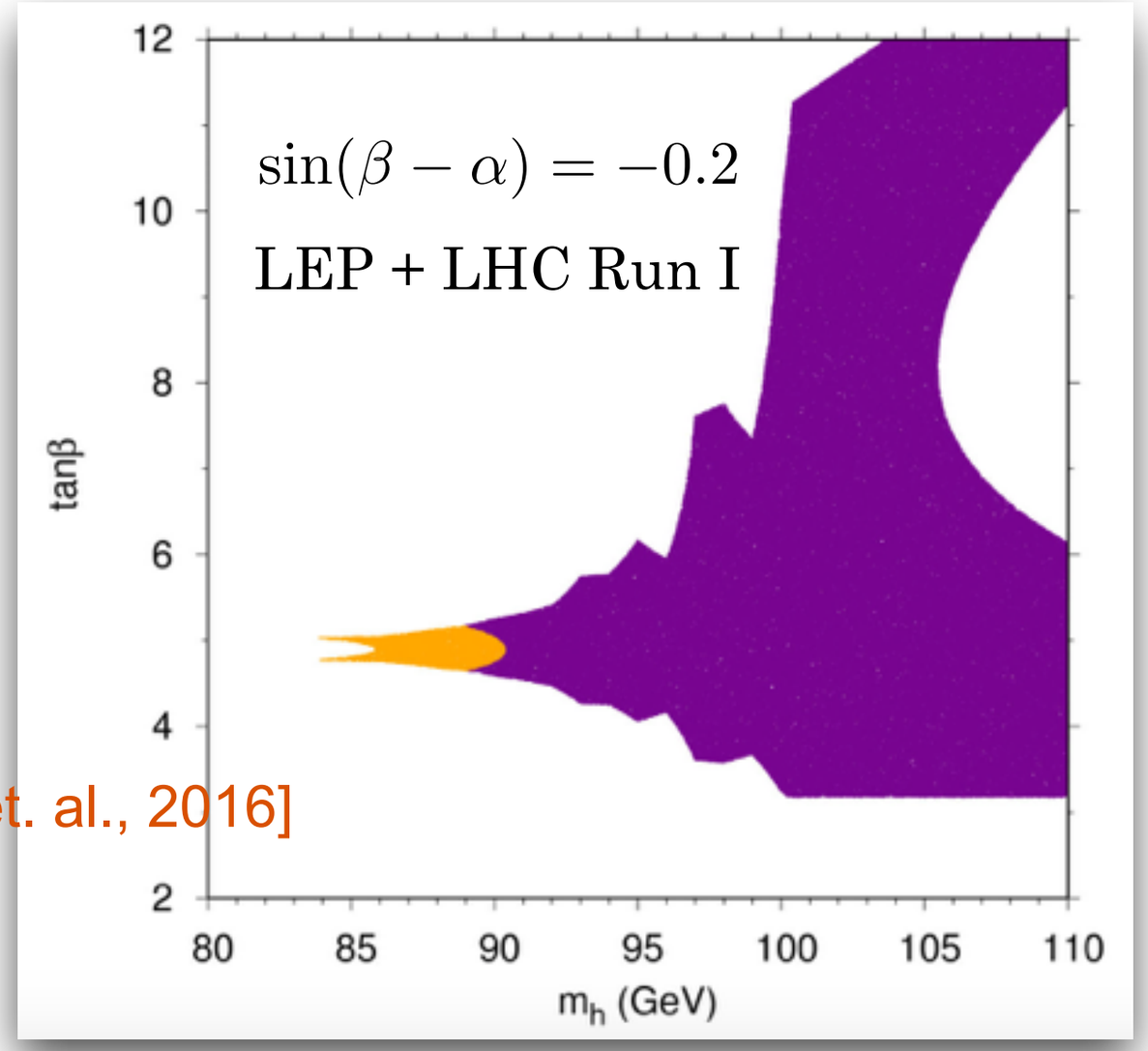
- Seven parameters after EWSB (with no CP-violation assumed): coupling of (Phi1*Phi2)^2

$$m_h, m_H, m_A, m_{H^\pm} \qquad \tan\beta \equiv \langle\Phi_2\rangle / \langle\Phi_1\rangle$$

$$\alpha: \begin{pmatrix} \sqrt{2}\,\mathrm{Re}(\Phi_2^0) - v_2 \\ \sqrt{2}\,\mathrm{Re}(\Phi_1^0) - v_1 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

- Tree-level couplings of scalars with fermions and vectors only depend on alpha and tanb.

Sub-EW Scale Scalar and Pseudoscalar



[G. Cacciapaglia et. al., 2016]

- Sub-EW scale scalar: strongly constrained by LEP measurements
- Sub-EW scale pseudoscalar: interacts with WW, ZZ via higher dimensional operator => weakly constrained by LEP

The Probe of Exotic Higgs Decay

arXiv.org > hep-ph > arXiv:1312.4992

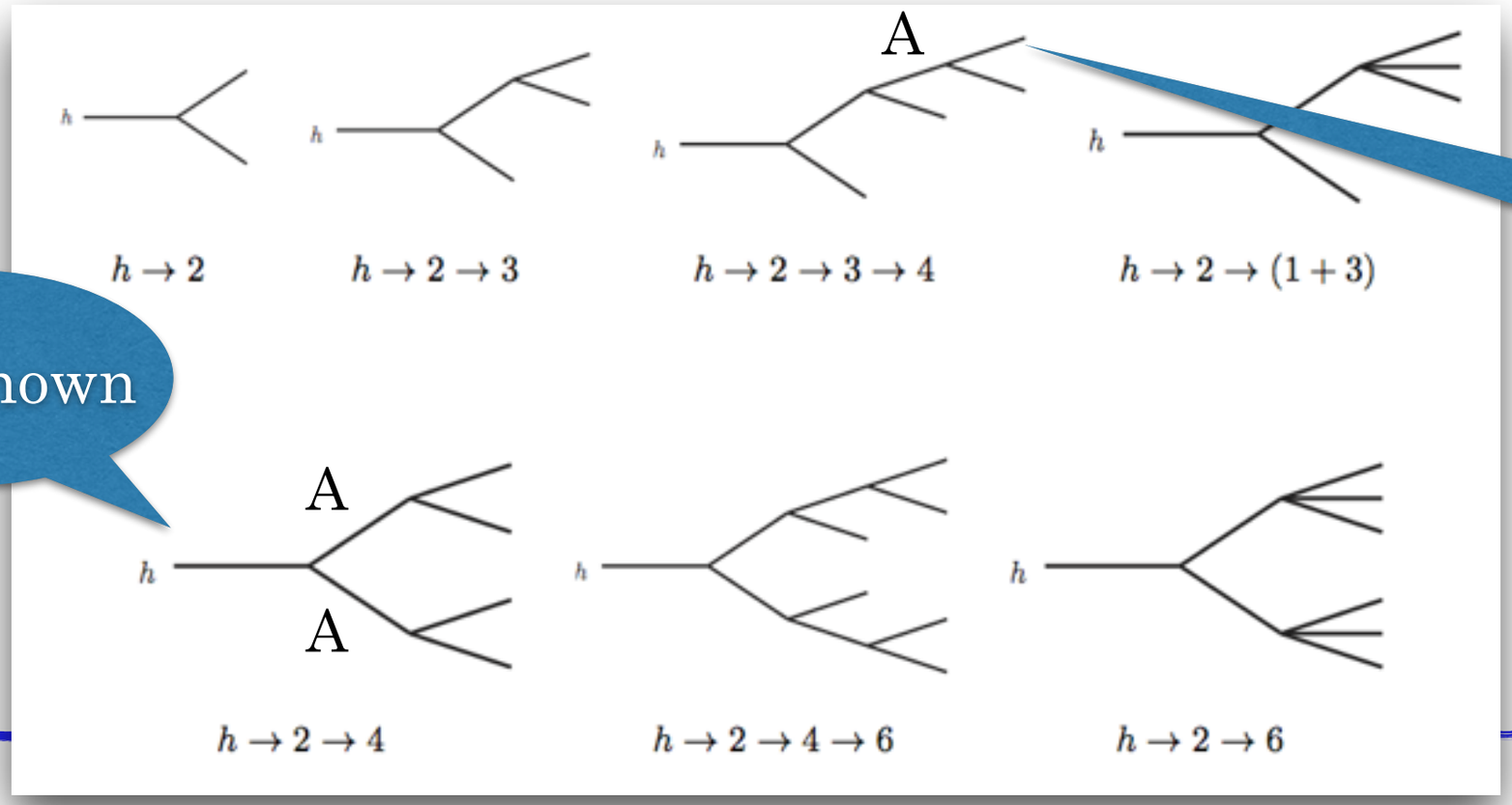
Search or

High Energy Physics - Phenomenology

Exotic Decays of the 125 GeV Higgs Boson

David Curtin, Rouven Essig, Stefania Gori, Prerit Jaiswal, Andrey Katz, Tao Liu, Zhen Liu, David McKeen, Jessie Shelton, Matthew Strassler, Ze'ev Surujon, Brock Tweedie, Yi-Ming Zhong

(Submitted on 17 Dec 2013 (v1), last revised 2 Sep 2015 (this version, v5))



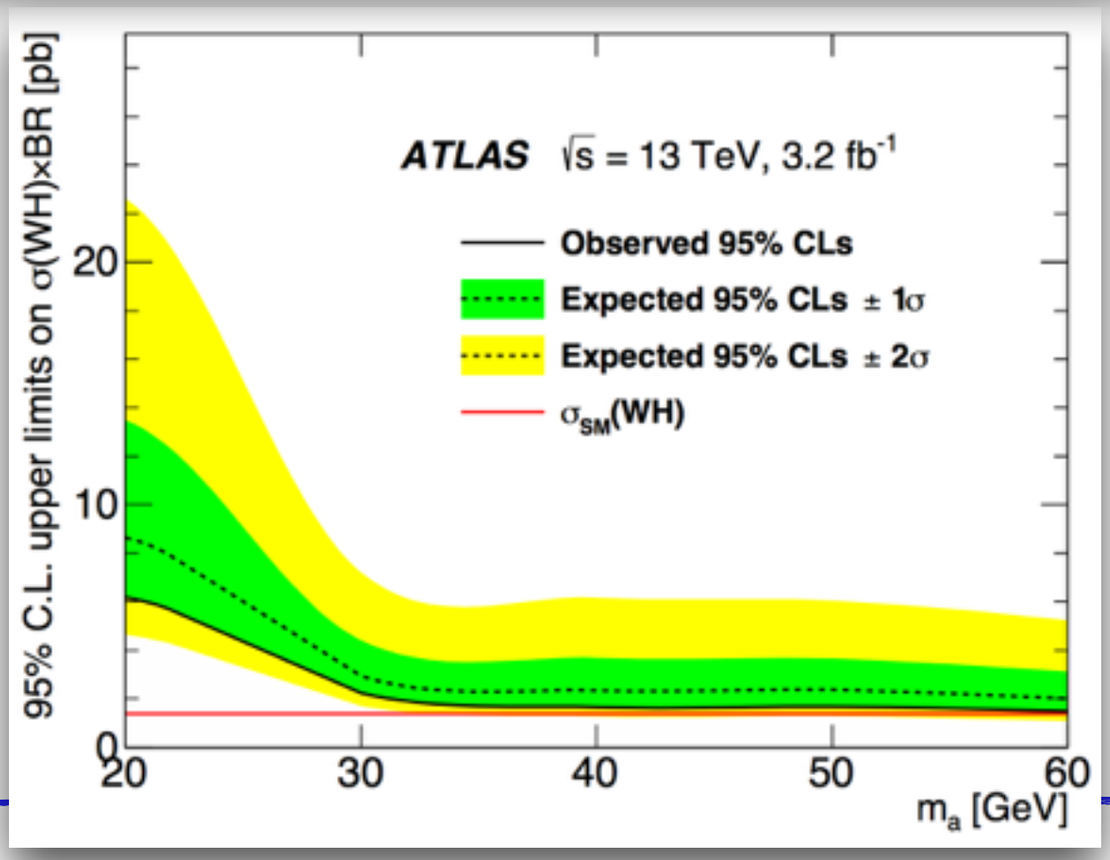
Well-known

PQ-limit of NMSSM

[J. Huang, TL, L.-T. Wang and F. Yu, PRL 112(2014)]

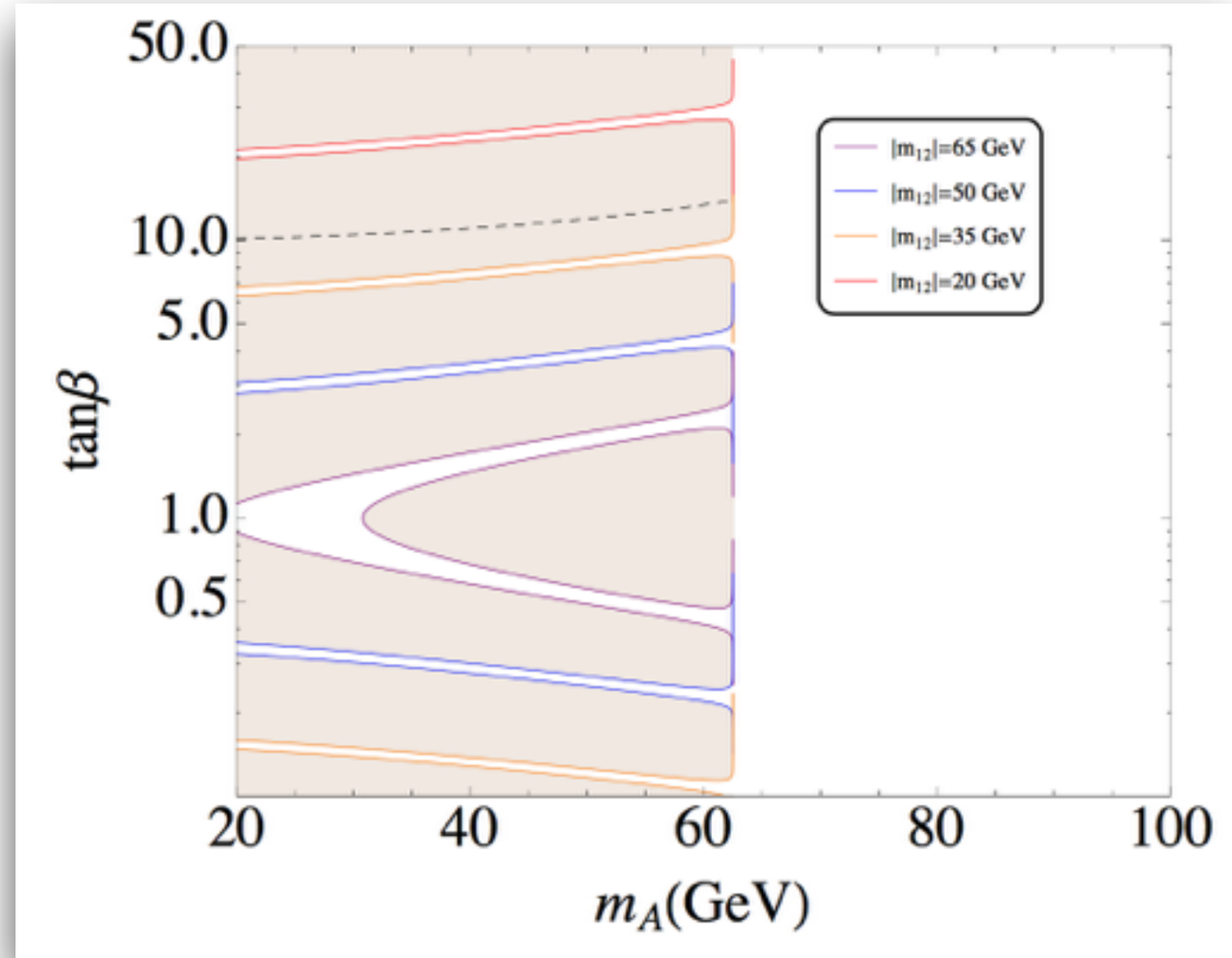
Exotic Higgs Decay at LHC

h(125) to pseudo-scalars		
h→aa→2μ2b	Run I full dataset summary of results (CMS-PAS-HIG-16-007)	
h→aa→4μ		
h→aa→2μ2τ		
h→aa→4τ		
W(h→aa→bτ)		3.2 fb^{-1} (arXiv:1606.08391)



[Florencia Canelli, ICHEP, 2016]

Limitations of the Probe via Exotic Higgs Decay

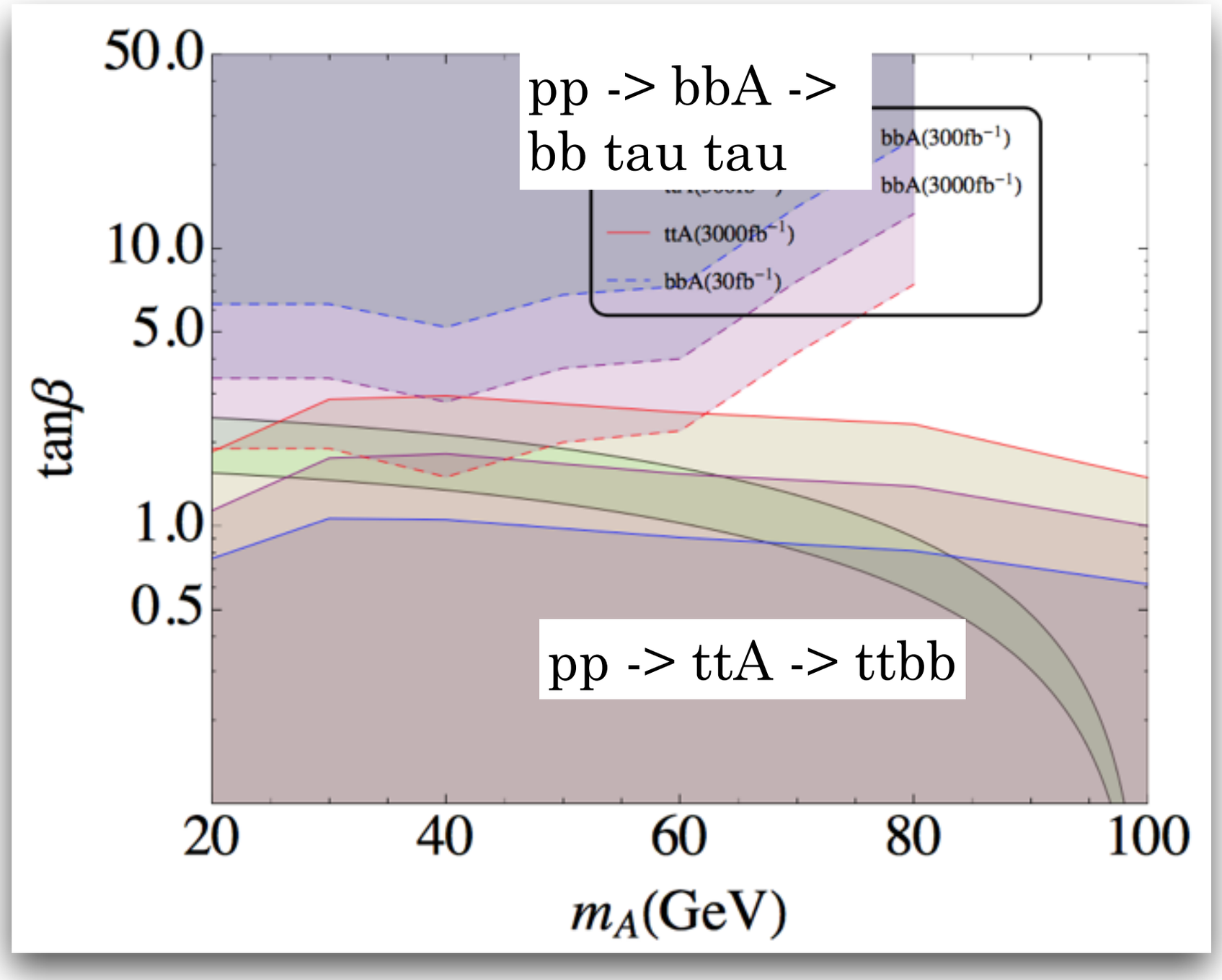


- Phase space availability
- Accidental suppression of the coupling g_hAA and hence Br(h -> AA)
- For detailed study, see [J. Bernon, J. Gunion, Y. Jiang and S. Kraml'14]

[M. Casolino, T. Farooque, A. Juste, TL, M. Spannowsky, arXiv: 1507.07004]

$$g_{hAA} = -\frac{2m_A^2 + m_h^2 - 2m_{12}^2 \sec\beta \csc\beta}{v}$$

Complementary Approach - Direct Production



- To fully cover the low mass region, => a combined search for bbA and ttA
- Using a jet substructure tool, a full coverage below 100 GeV could be achieved at HL-LHC, except a small ``wedge''

[M. Casolino, T. Farooque, A. Juste, TL, M. Spannowsky, arXiv: 1507.07004]

THDM Higgs Bosons at 13 TeV

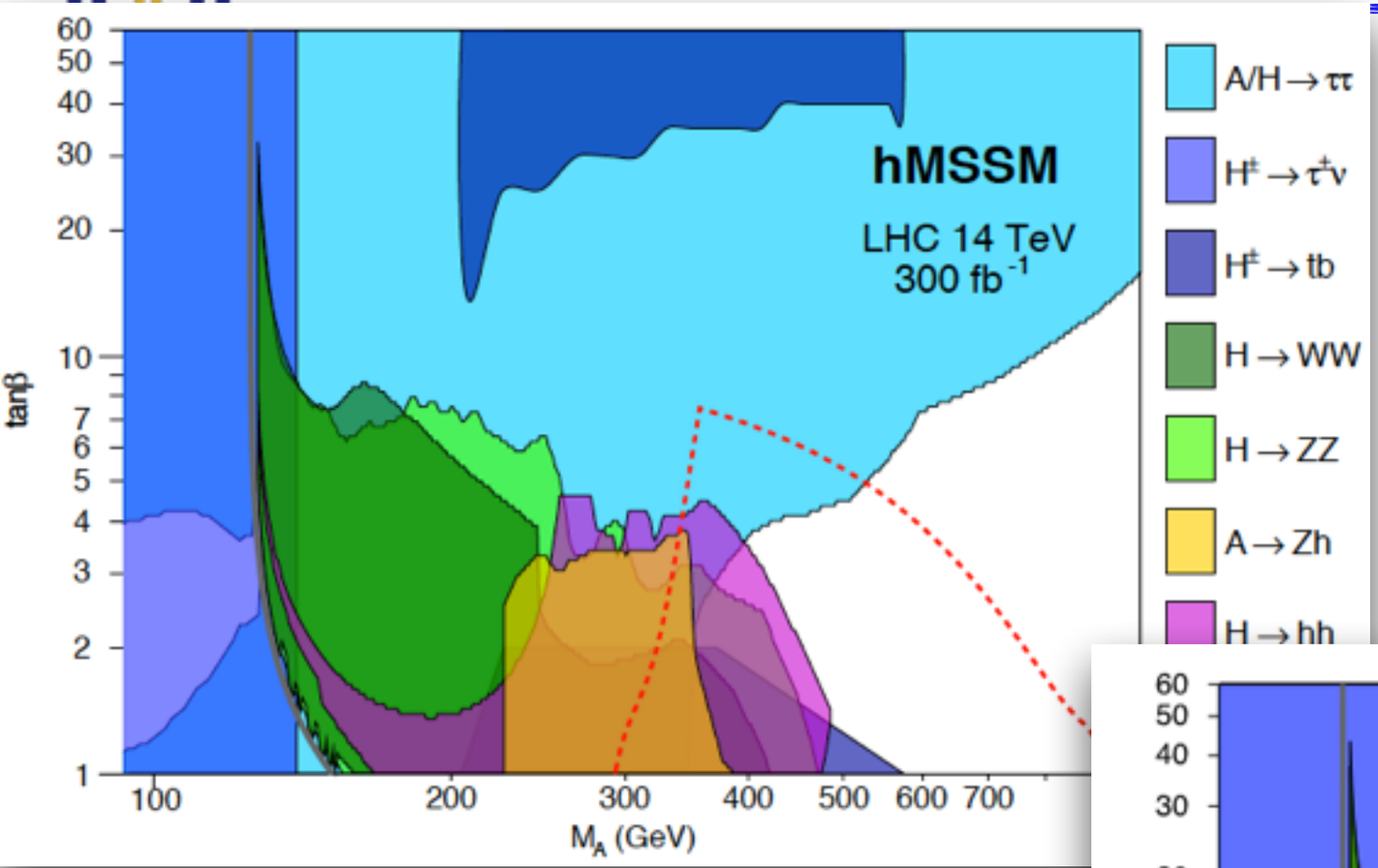
Higgs to fermions		
H→ττ	2.3 fb^{-1} (CMS-PAS-HIG-16-006)	13.3 fb^{-1} (ATLAS-CONF-2016-085)
H→bb	2.7 fb^{-1} (CMS-PAS-HIG-16-025)	
Higgs to vector bosons		
H→ZZ→4l	12.9 fb^{-1} (CMS-PAS-HIG-16-033)	14.8 fb^{-1} (ATLAS-CONF-2016-079)
H→ZZ→llvv	2.3 fb^{-1} (CMS-PA	
H→ZZ→llqq	included exotic	
H→ZZ→qqvv	included exotic	
H→WW→lvlv	2.3 fb^{-1} (CMS-PA	
H→WW→lvqq	included exotic	
H→Zγ		
Higgs to Higgs (diHiggs)		
H→hh→bbbb	2.3 fb^{-1} (CMS-PAS-HIG-16-002)	13.3 fb^{-1} (ATLAS-CONF-2016-049)
H→hh→bbττ	12.9 fb^{-1} (CMS-PAS-HIG-16-029)	
H→hh→bbWW	2.3 fb^{-1}(CMS-PAS-HIG-16-011)	
H→hh→γγWW*		13.3 fb^{-1} (ATLAS-CONF-2016-071)
H→hh→γγbb		13.3 fb^{-1} (ATLAS-CONF-2016-004)

Charged Higgs		
H^+→τν		14.7 fb^{-1} (ATLAS-CONF-2016-088)
H^+→tb		13.2 fb^{-1} (ATLAS-CONF-2016-089)
H^+→WZ	15.2 fb^{-1} (CMS-PAS-HIG-16-025)	

[Florencia Canelli, ICHEP, 2016]

- For H/A of EW scale or above, more channels are turned on

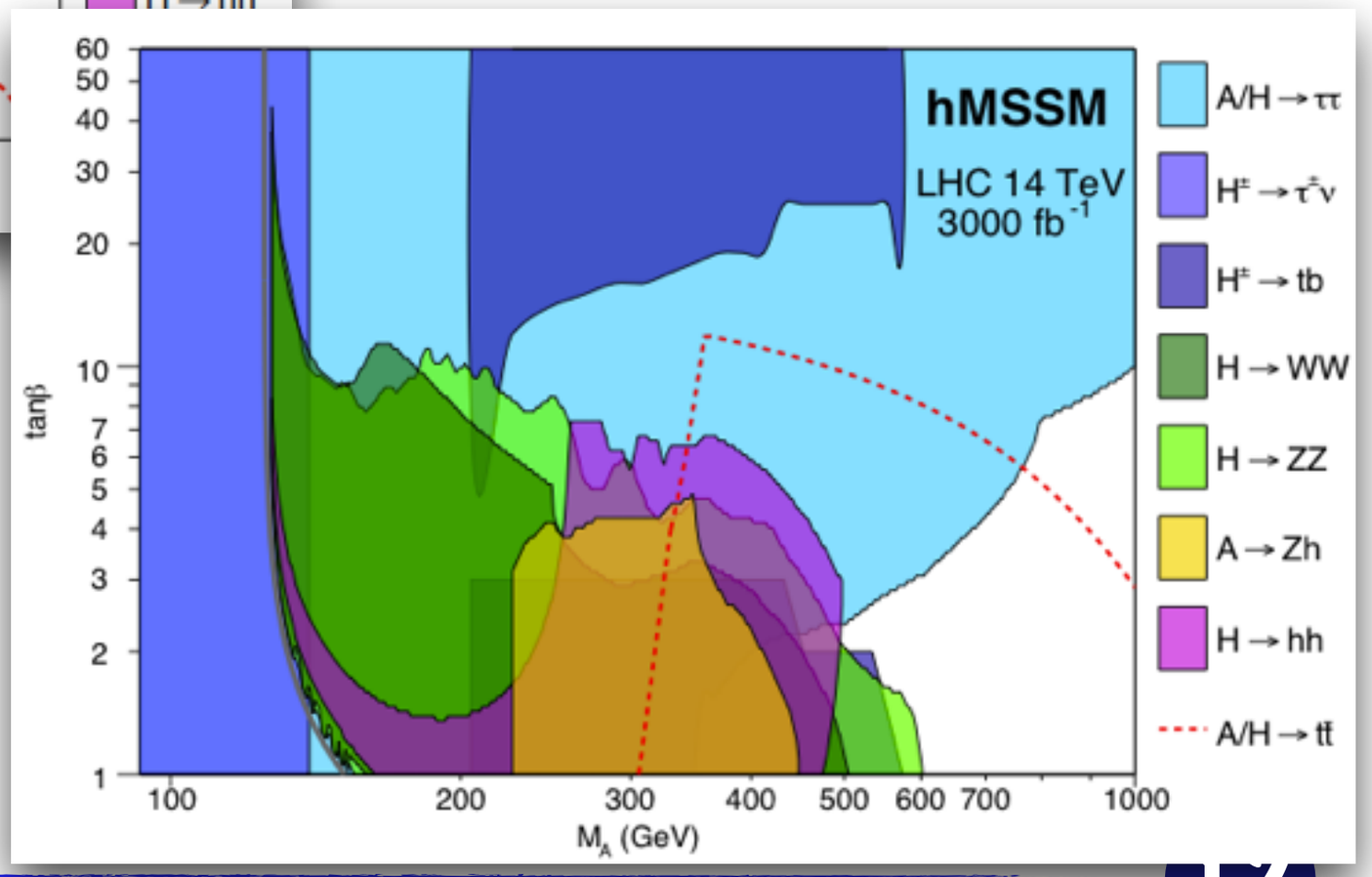
MSSM Higgs Bosons at 14 TeV



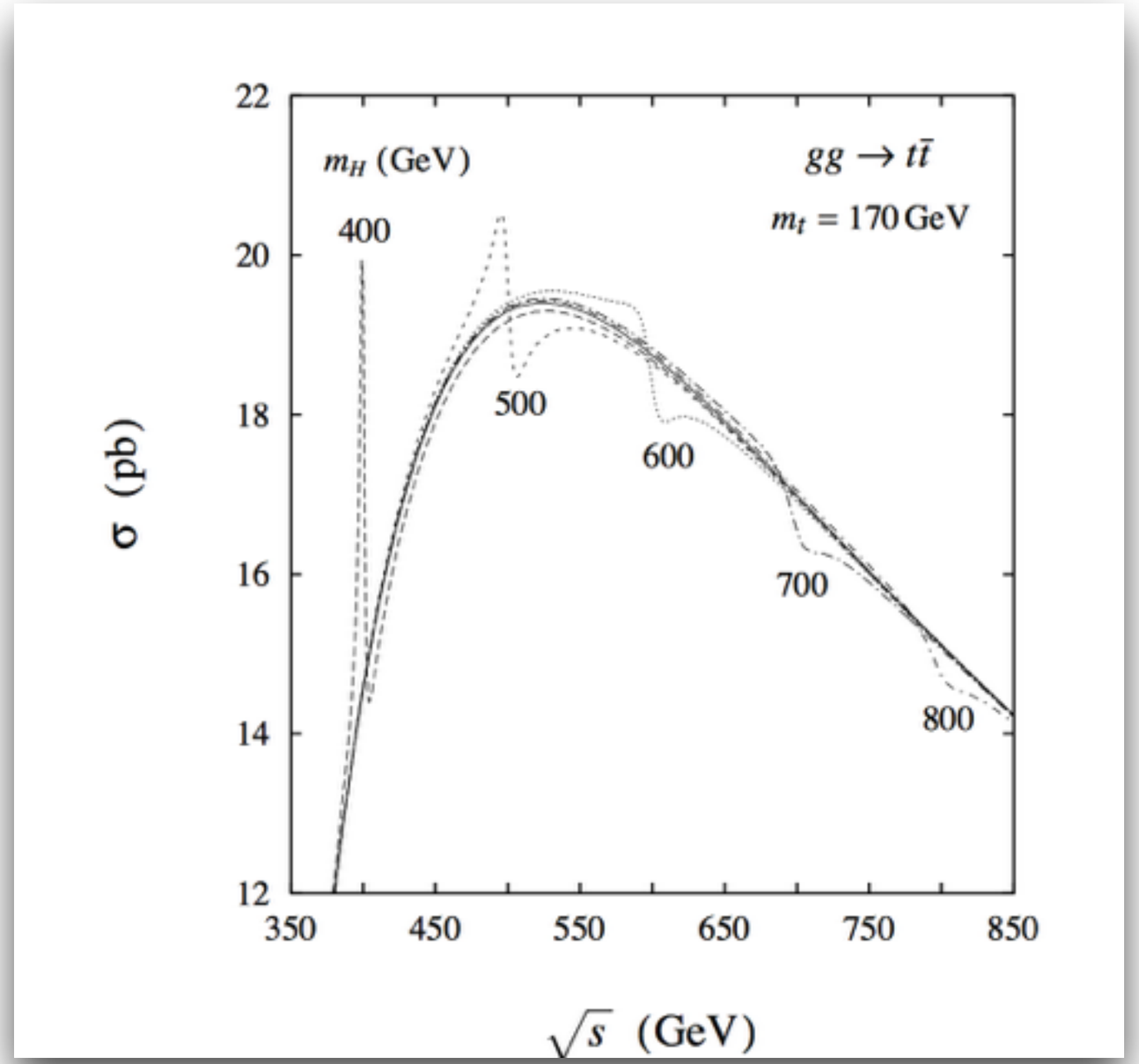
- Sensitivity projection at 14 TeV, by rescaling the 7 and 8 TeV results
- => Highly challenging to probe moderate and low tanb regions in decoupling limit

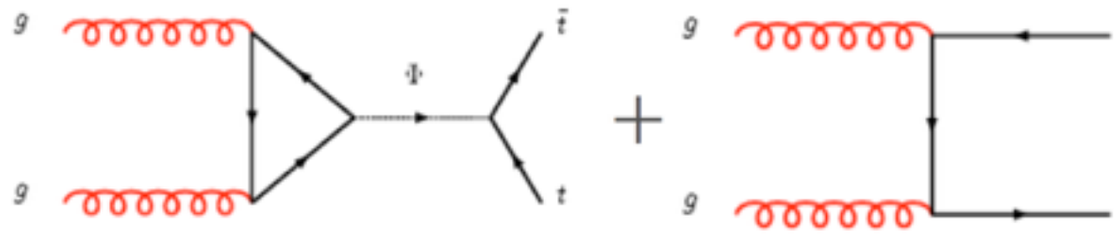
[A. Djouadi et. al.'15]

- Keep it in mind: the current tt resonance search at LHC is not mainly designed for heavy Higgs bosons



Difficulty at Low tanb Region





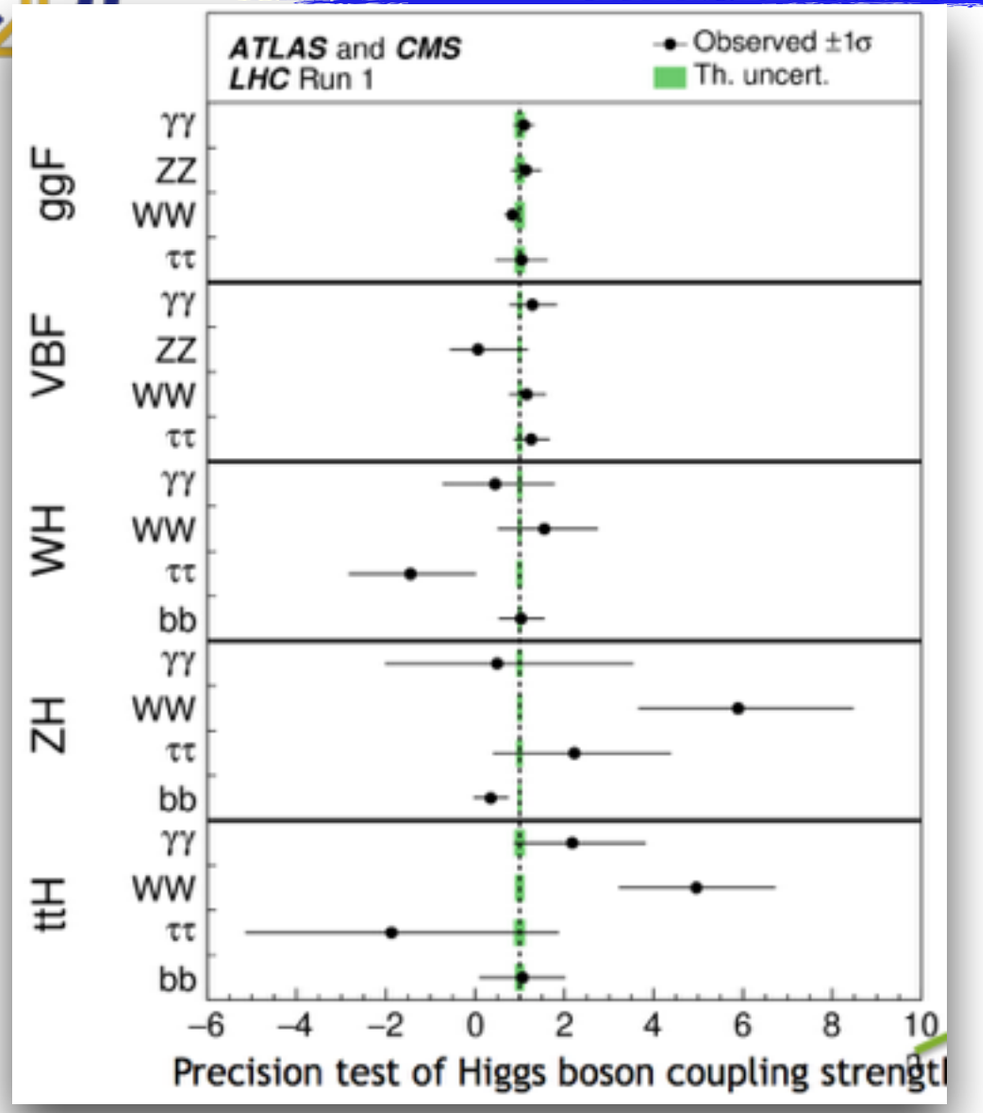
- Interference with QCD tt =>

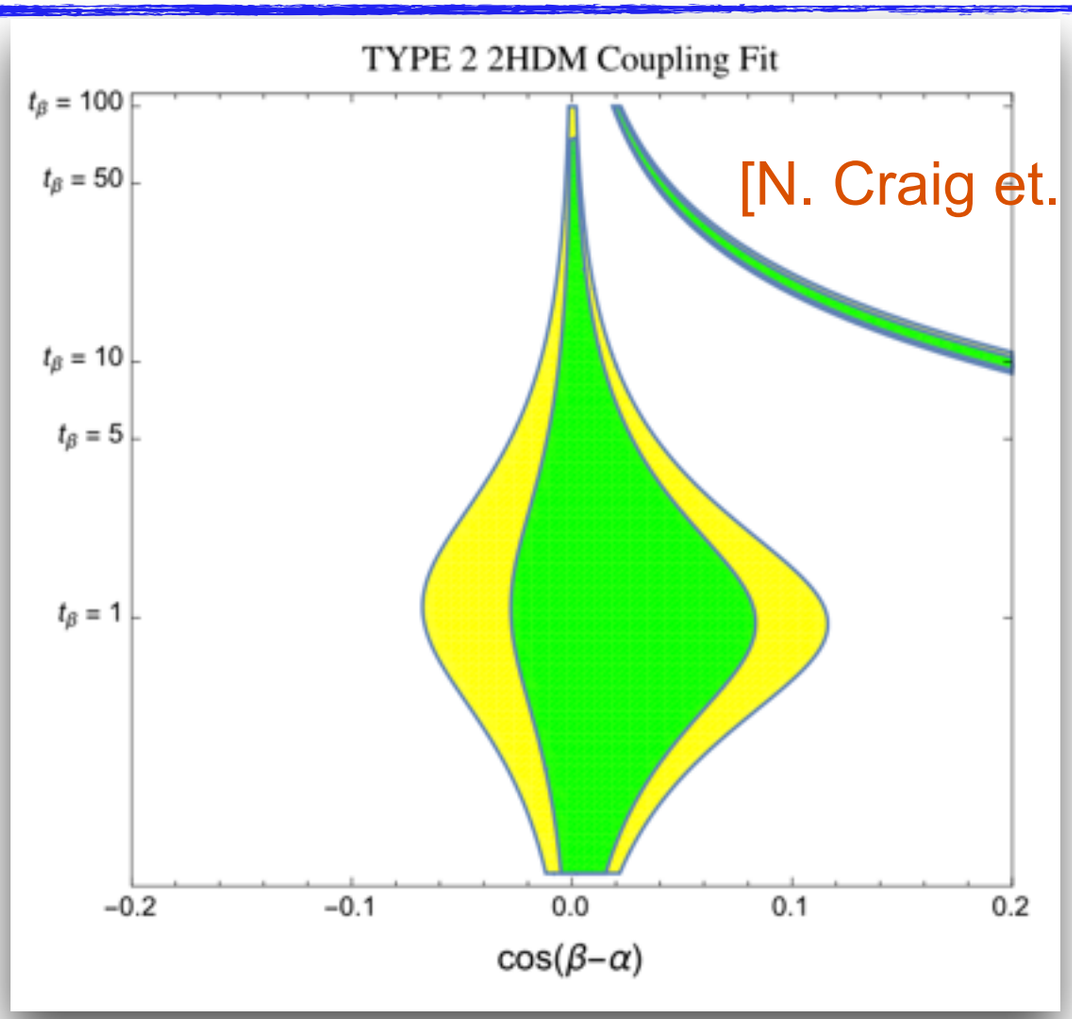
  a resonance structure of peak,

  dip or nothing

[Dicus, Stange & Willenbrock 1994]

Higgs Profile in Run I





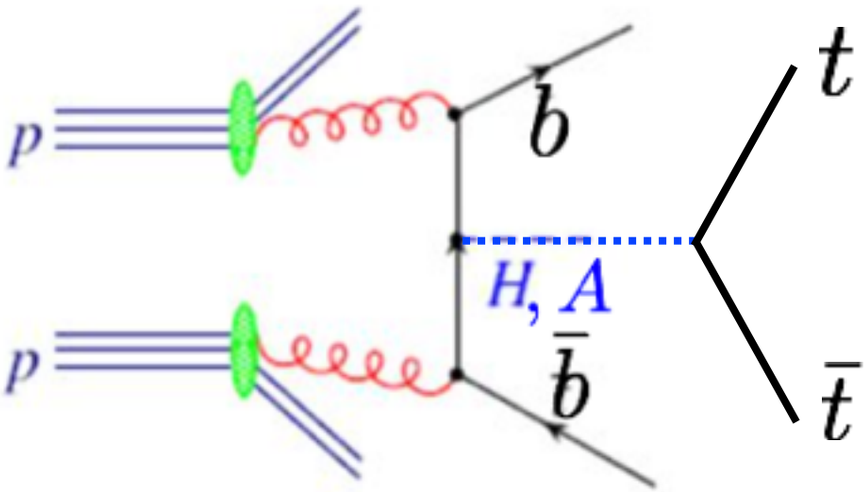
[N. Craig et. al, 2015]

$$\cos(\beta-\alpha) = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}}$$

- Alignment limit is favored
  - An vanishing Z6 is fine-tuning (e.g., can't be achieved in the MSSM at tree level) and lack of symmetry protection
  - More easily achieved in decoupling limit (mH >> EW scale)

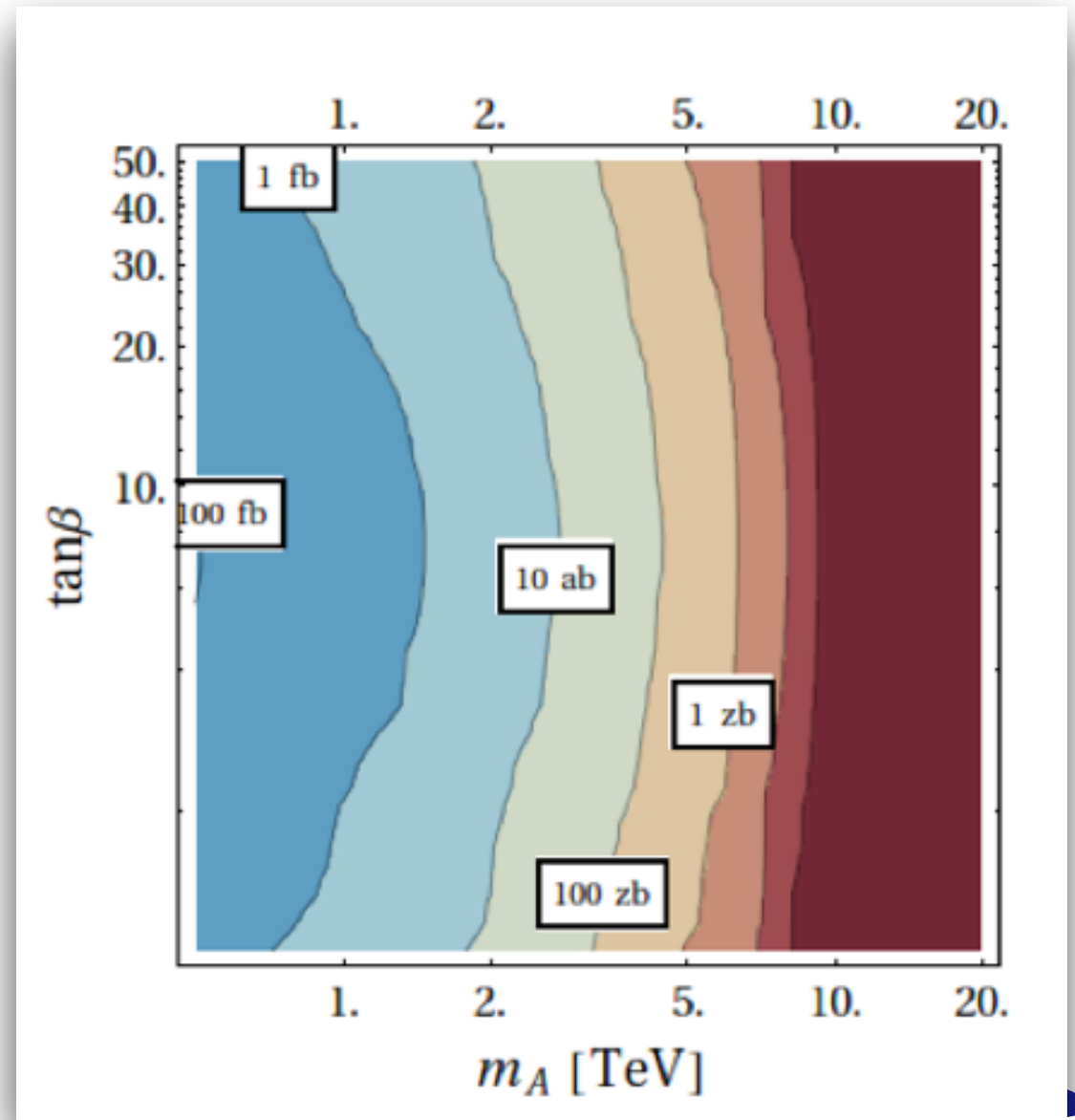
Neutral Higgs - Moderate tanb

- In the decoupling limit, $g_{HVV} = g_{hZA} = g_{hW^{\mp}H^{\pm}} \propto \cos(\beta - \alpha) \to 0$
- H, A, Hc retain couplings to the SM fermions, enable us to probe them at collider!

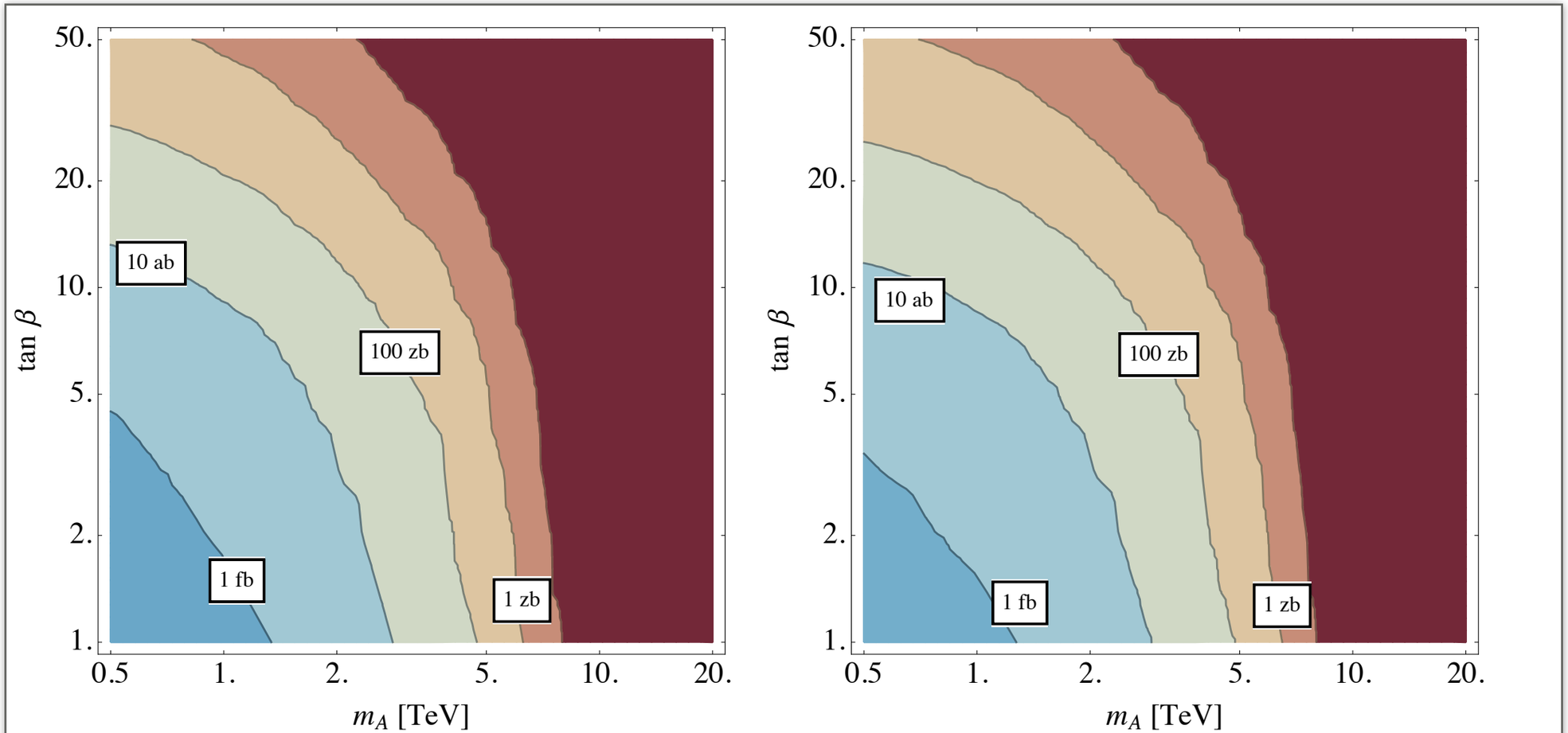


- Proposal: bbH/A -> bbtt
- Enhanced cross section at moderate tanb

[J. Hajer, Y.-Y. Li, TL and F.-H. Shiu, arXiv: 1504.07617]



Neutral Higgs - Low tanb

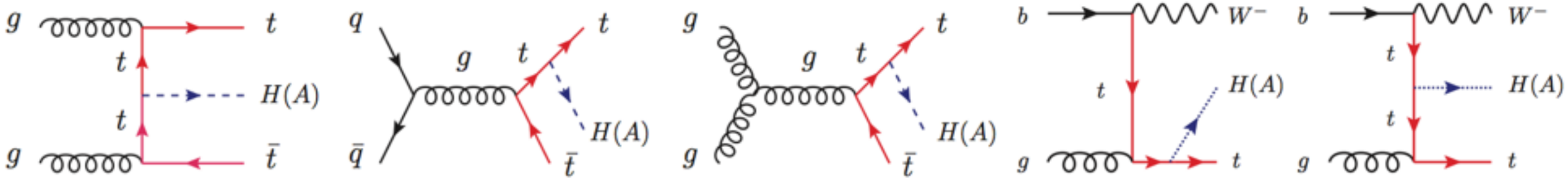


$\sigma(pp \to H/Att)\,\mathrm{Br}(H/A \to t\bar{t})$ $\sigma(pp \to H/AtW)\,\mathrm{Br}(H/A \to t\bar{t})$

[N. Craig, J. Hajer, Y.-Y. Li, TL, H. Zhang, arXiv: 1605.08744]

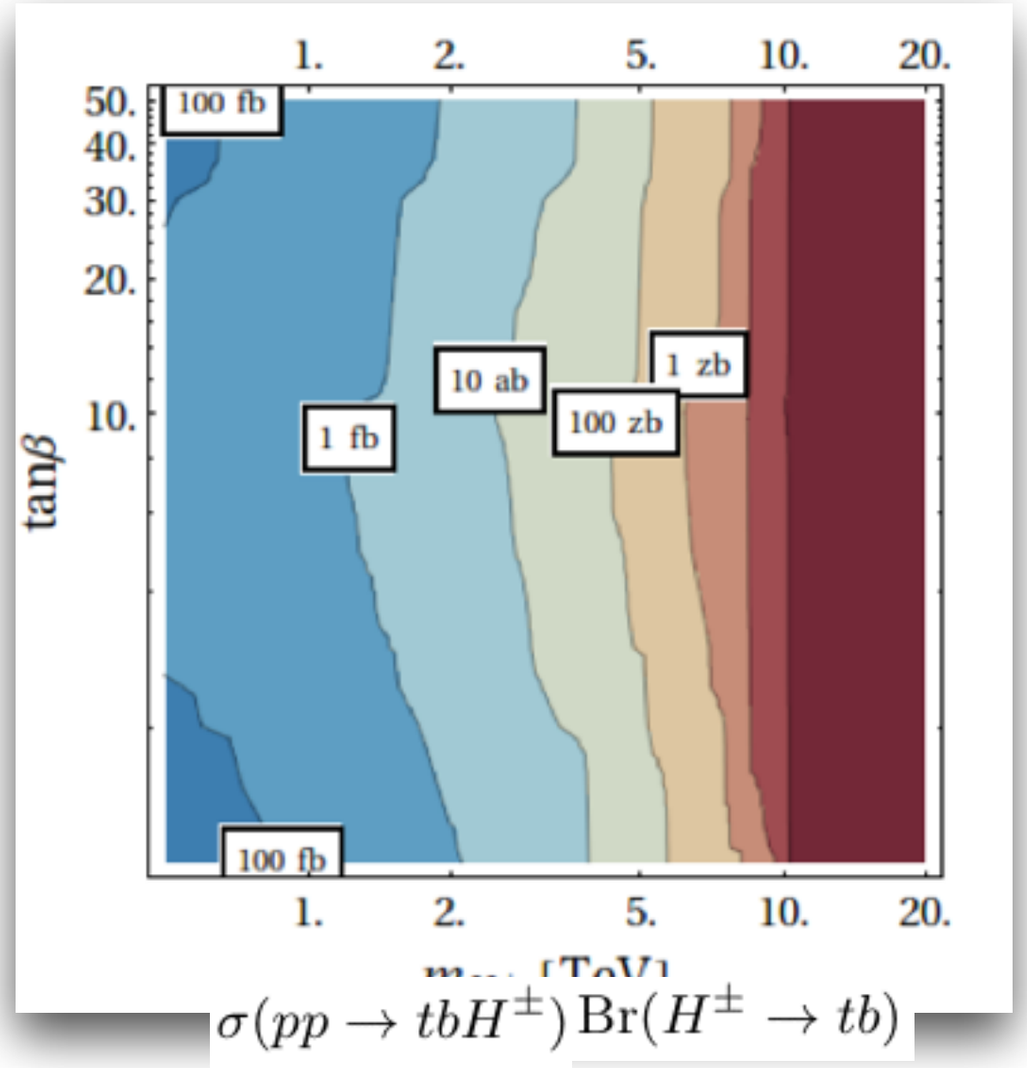
- Proposal: ttH/A + tWH/A
- Three top channel should not be ignored

Neutral Higgs - Low tanb



- tWH cross section becomes comparable to or even larger than that of ttH/A as mA/mH increases
  - the asymptotic freedom of alpha_s
  - the faster falloff in x of the gluon PDF relative to the bottom-quark PDF

Charged Higgs



- Production: tbHc is dominant, enhanced by both low and high tan_beta
- Dominant decay mode (mHc > 200 GeV): Hc -> bt

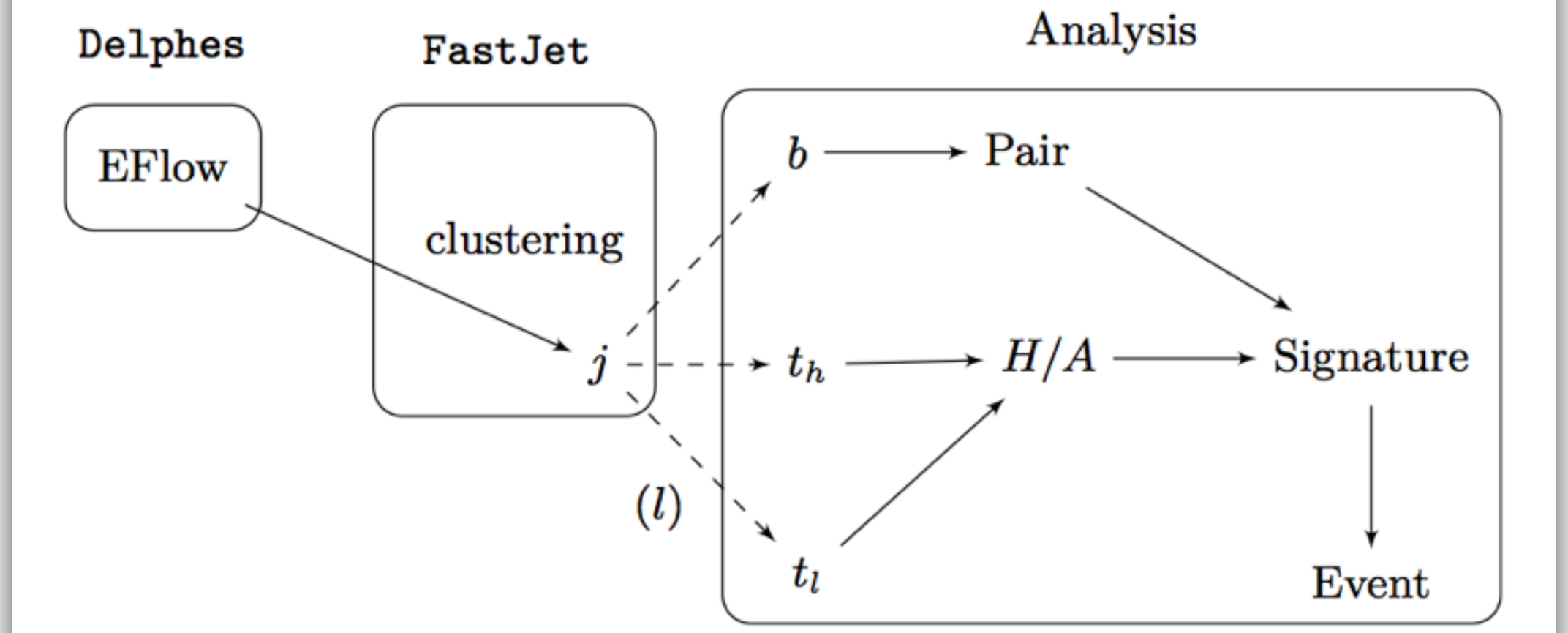
$$g_{H^+\bar{u}d} = \frac{1}{\sqrt{2}v} V_{ud}^* [m_d \tan\beta(1+\gamma_5) + m_u \cot\beta(1-\gamma_5)]$$

General Comments on Kinematics

	$\tan\beta$	Channels
Neutral Higgs (H/A)	High	$pp \to bbH/A \to bb\tau\tau, bbbb$
	moderate	$pp \to bbH/A \to bbtt$
	Low	$pp \to tH(A) + X \to ttt + X$
Charged Higgs $(H^{\pm})$	High	$pp \to tbH^{\pm} \to tbtb, tb\tau\nu_{\tau}$
	Low	$pp \to tbH^{\pm} \to tbtb$

- Multiple top and b quarks => A busy final state
- Top quarks could be highly boosted, if H/A are heavy
- b quarks accompanying the Higgs production could be forward/backward
- Combinatorial background for less-boosted top or Higgs reconstruction
- Challenges or opportunities?

Overall Strategies - bbH/A with Boosted Tops



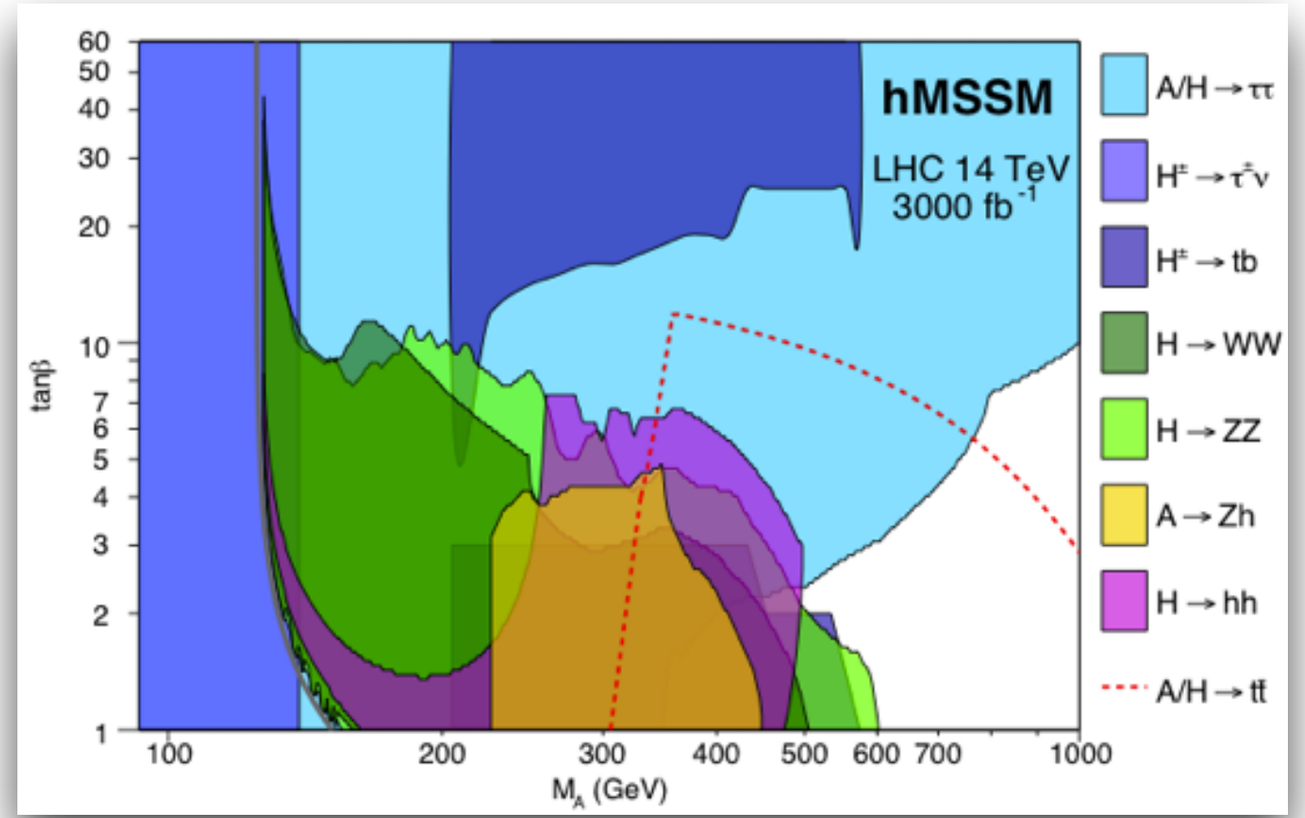
(a) BDT-based event reconstruction in the case of boosted tops.

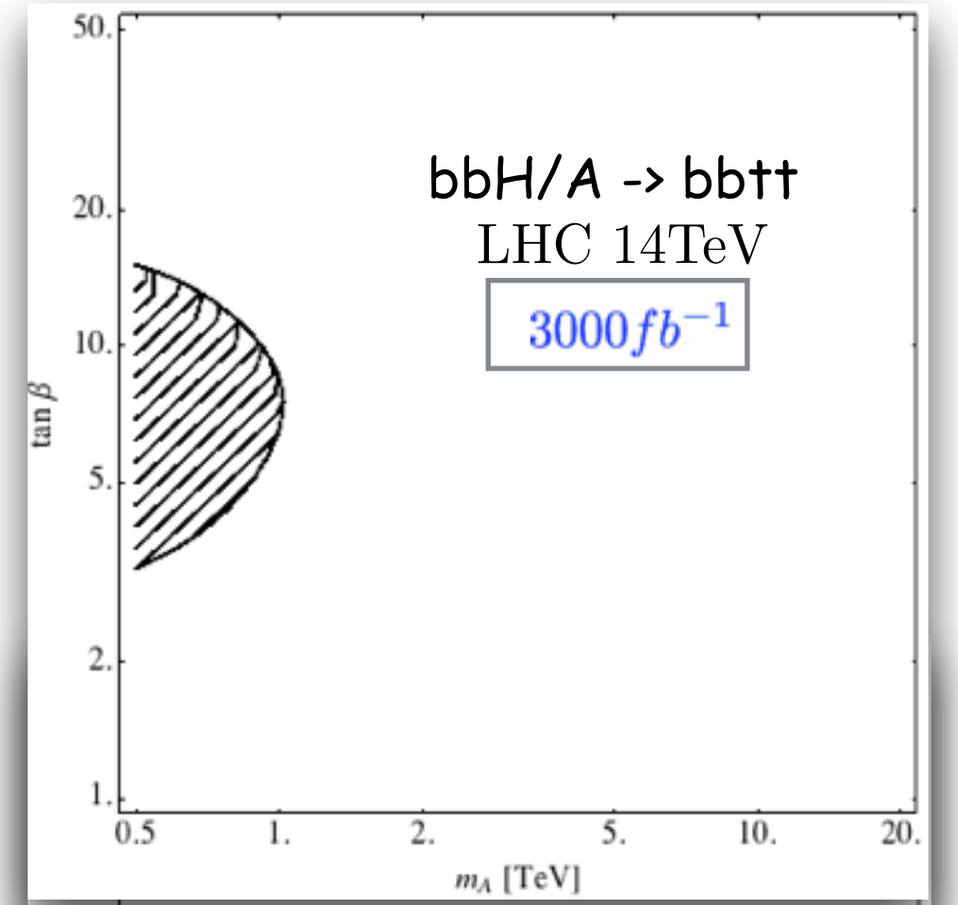
[J. Hajer, Y.-Y. Li, TL and F.-H. Shiu, arXiv: 1504.07617]

- Straightforward to generalize: less-boosted tops, ttH/A and tWH/A, and charged Higgs [N. Craig, J. Hajer, Y.-Y. Li, TL, H. Zhang, arXiv: 1605.08744]

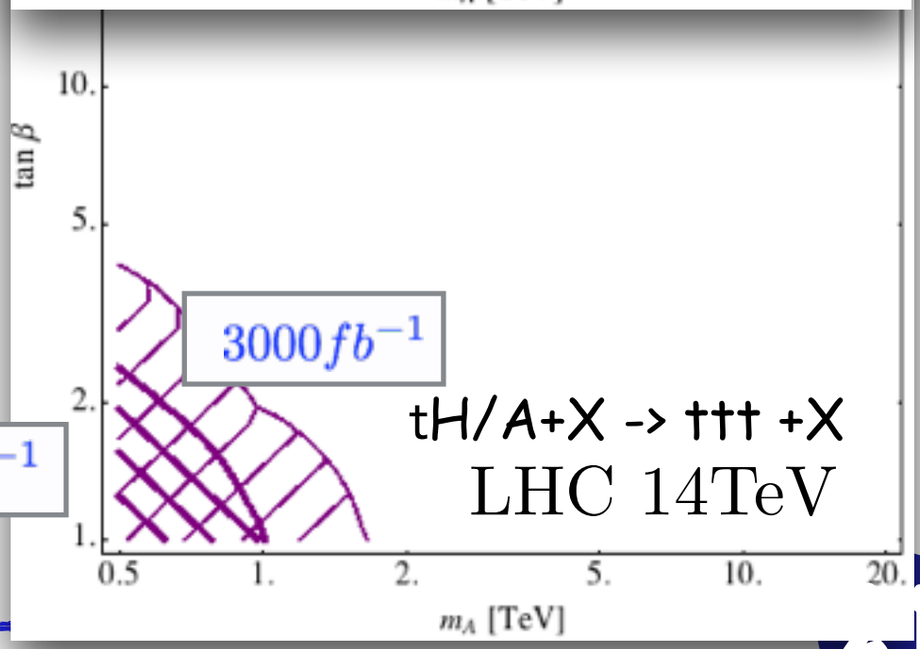
Decoupling Limit at LHC: Neutral Higgs Bosons

[A. Djouadi et. al.'15]



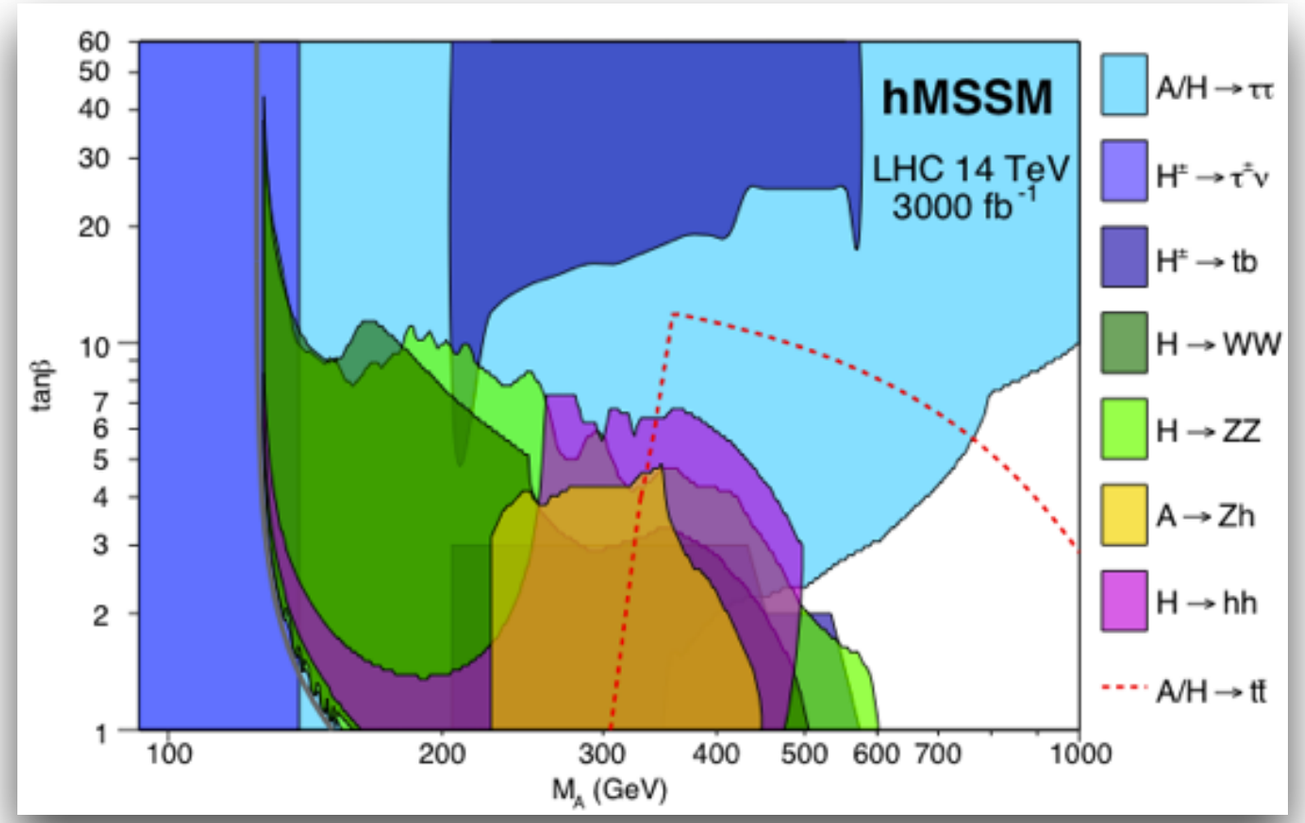


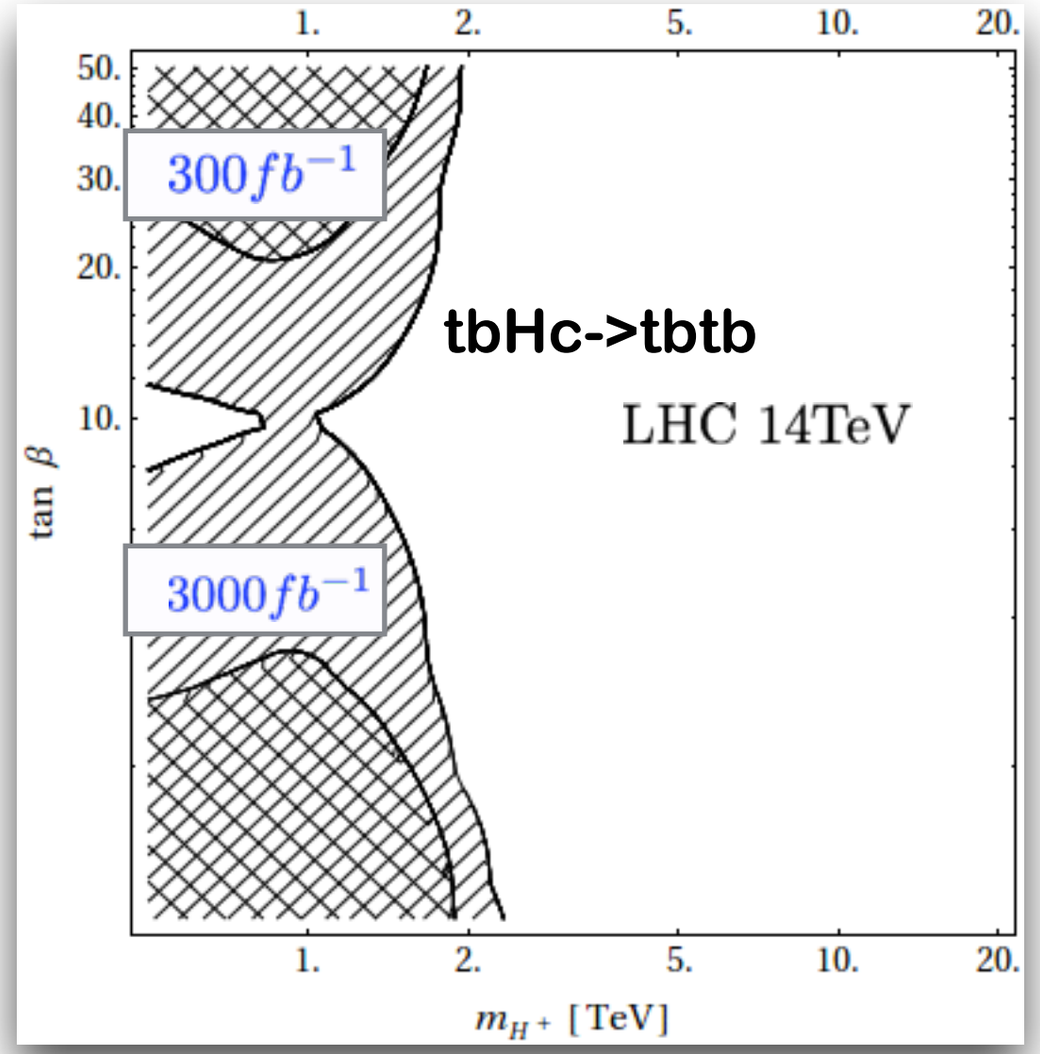
[N. Craig, J. Hajer, Y.-Y. Li, TL, H. Zhang, arXiv: 1605.08744]



Decoupling Limit at LHC: Charged Higgs Bosons

[A. Djouadi et. al.'15]

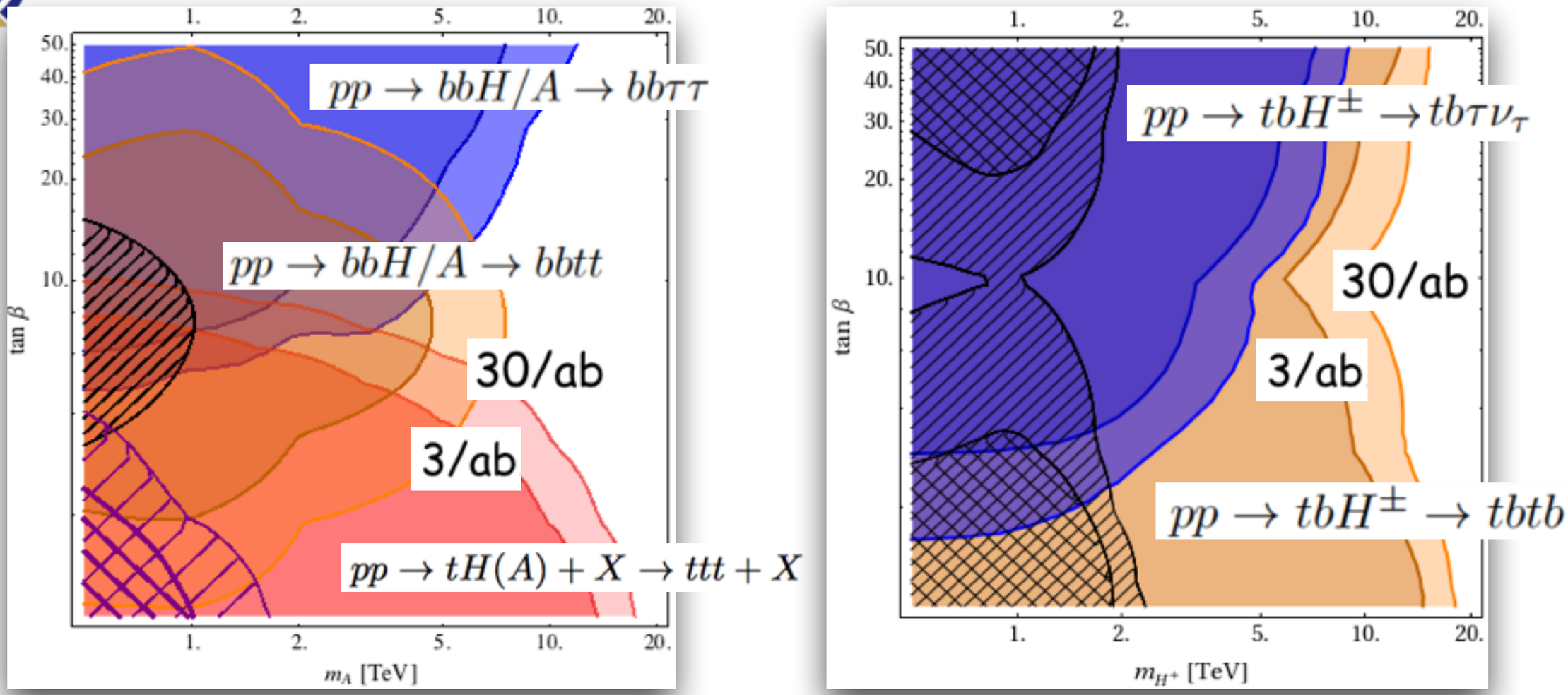




[J. Hajer, Y.-Y. Li, TL and F.-H. Shiu, arXiv: 1504.07617]

- 0.3/ab and 3/ab: high and low tb regions covered up to ~1.5 TeV and to ~2TeV, respectively

Decoupling Limit: from LHC to 100 TeV



[N. Craig, J. Hajer, Y.-Y. Li, TL, H. Zhang, arXiv: 1605.08744]

- Large tanb: bbH -> bbtautau continues to be significant
- Moderate tanb: exclude mA up to ~8TeV via bbH/A -> bbtt (semi-leptonic tt).
- Low tanb: cover up to ~15TeV via tH/A + X -> ttt + X
- Charged Higgs: dominated by tbHc -> tbtb, excluded up to ~ 10-15 TeV

Summary

- An extended Higgs sector extensively exists in BSM physics

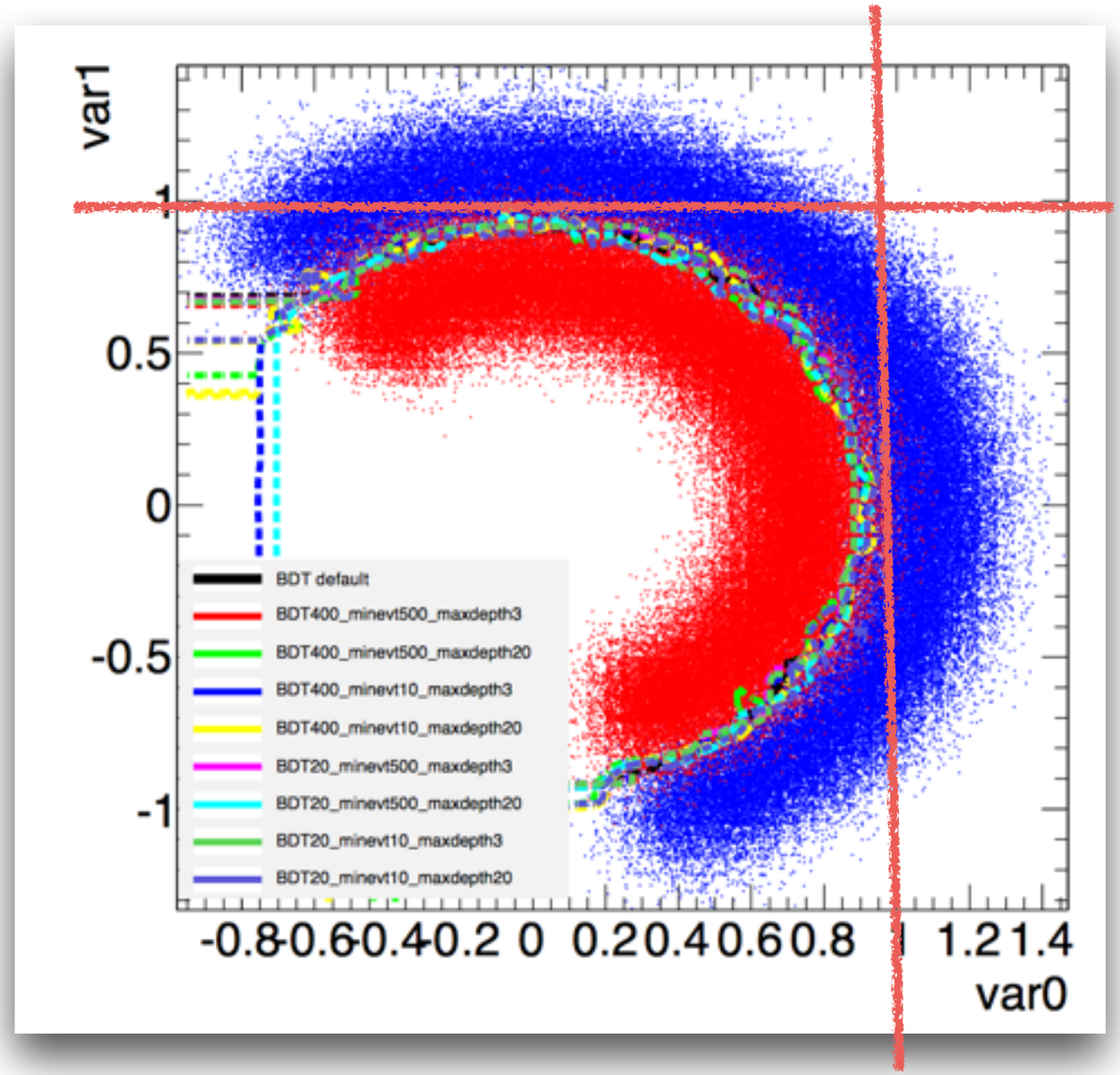
- In type II THDM, a full coverage of tanb, from sub-EW scale to ~ 1TeV, is potentially achievable (up to the uncertainty of systematic errors). The sensitivity reach could be extended roughly one order more at a 100TeV pp collider

- The discussions are not complete but typical; straightforward to generalize to other extended Higgs sectors

- The search of an extended Higgs sector is highly valuable! The profile of an extended Higgs sector may assist and deepen our understanding on ``naturalness", and many others on BSM physics

Thank you!

Boosted Decision Tree



[Yann COADOU '13]

(a) Circular correlation example

BDT: allow us to incorporate the correlation of variables to optimize the analysis.