Overlooked
(Heavy) Higgs Physics

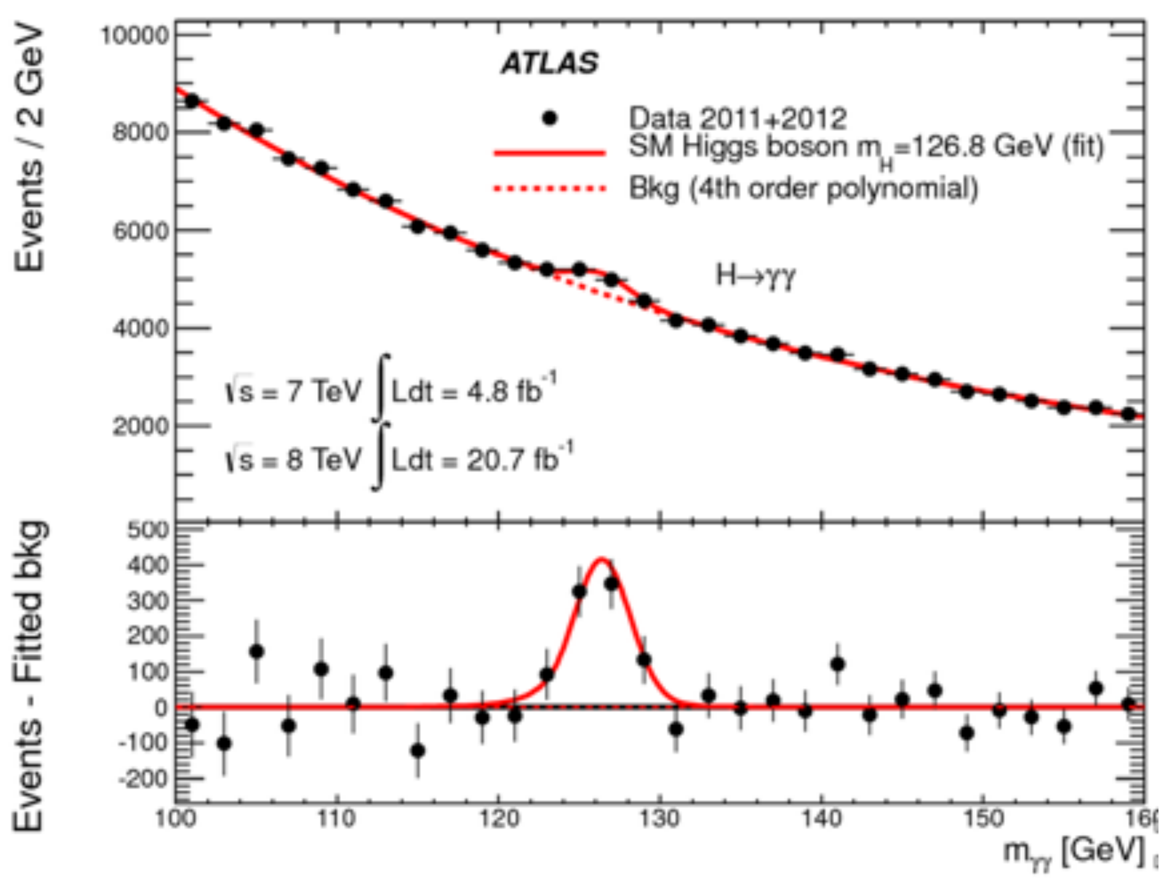
Sunghoon Jung
KIAS / SLAC

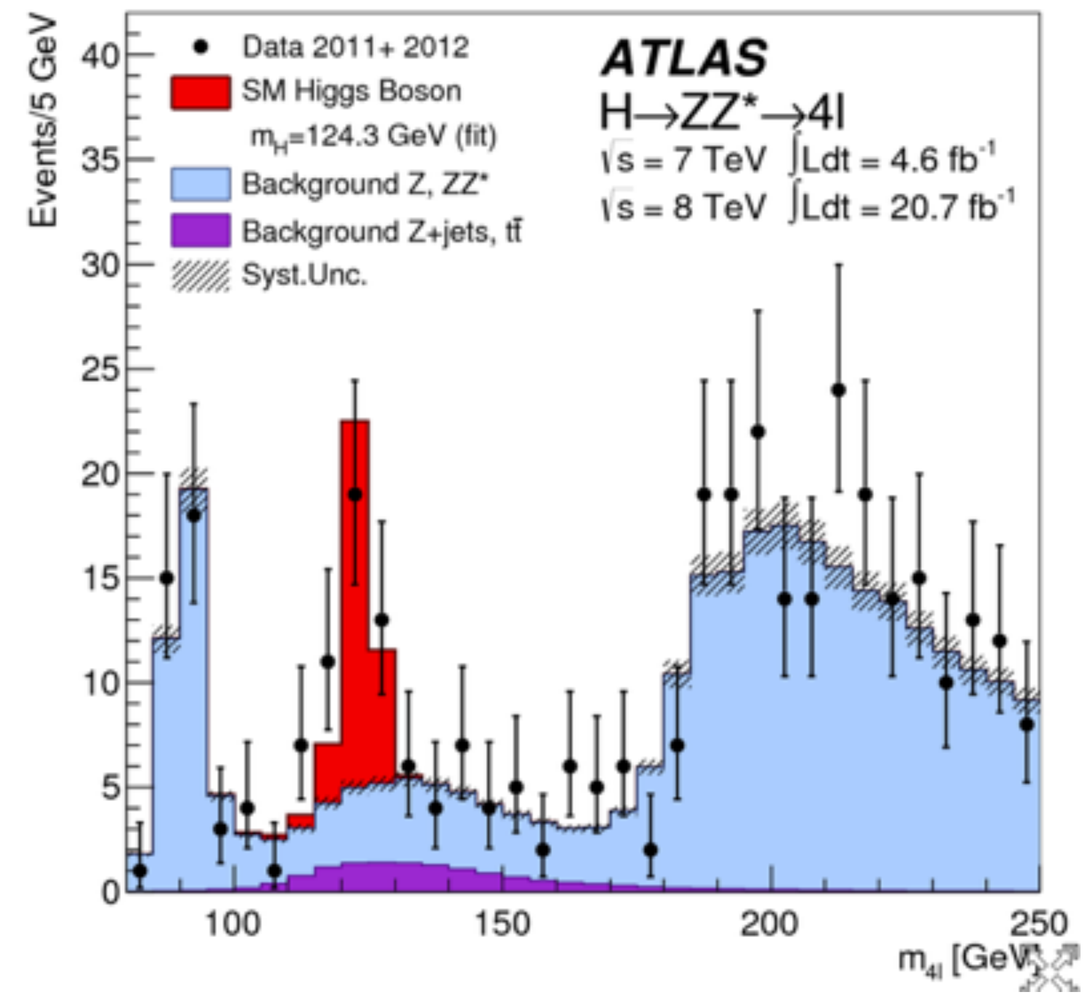
CTPU Workshop, 2015/8/18

Based on collaborations with
Eung Jin Chun, Jeonghyeon Song, Yeo Woong Yoon

1505.00291, and several works in progress

Today is a post SM Higgs era





- A great triumph.

- Having this ball, we should move beyond from it toward a more complete theory of EWSB!

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LHC beyond the SM Higgs

- One of the most important clues to a more complete theory of EWSB can come from heavy Higgs discovery.

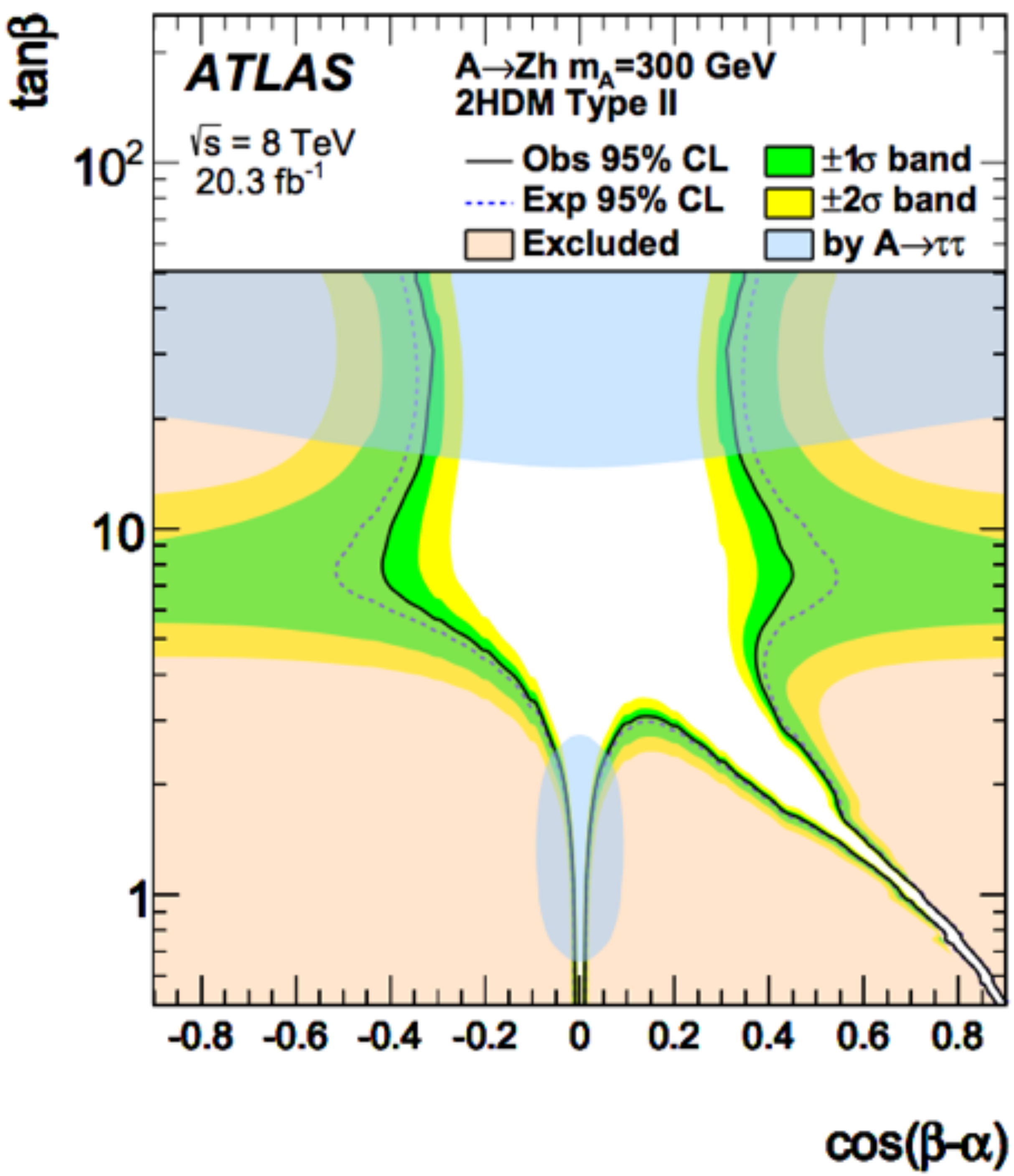
- I'll focus on MSSM (to some extent on 2HDM).

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}} R_{\beta_0} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

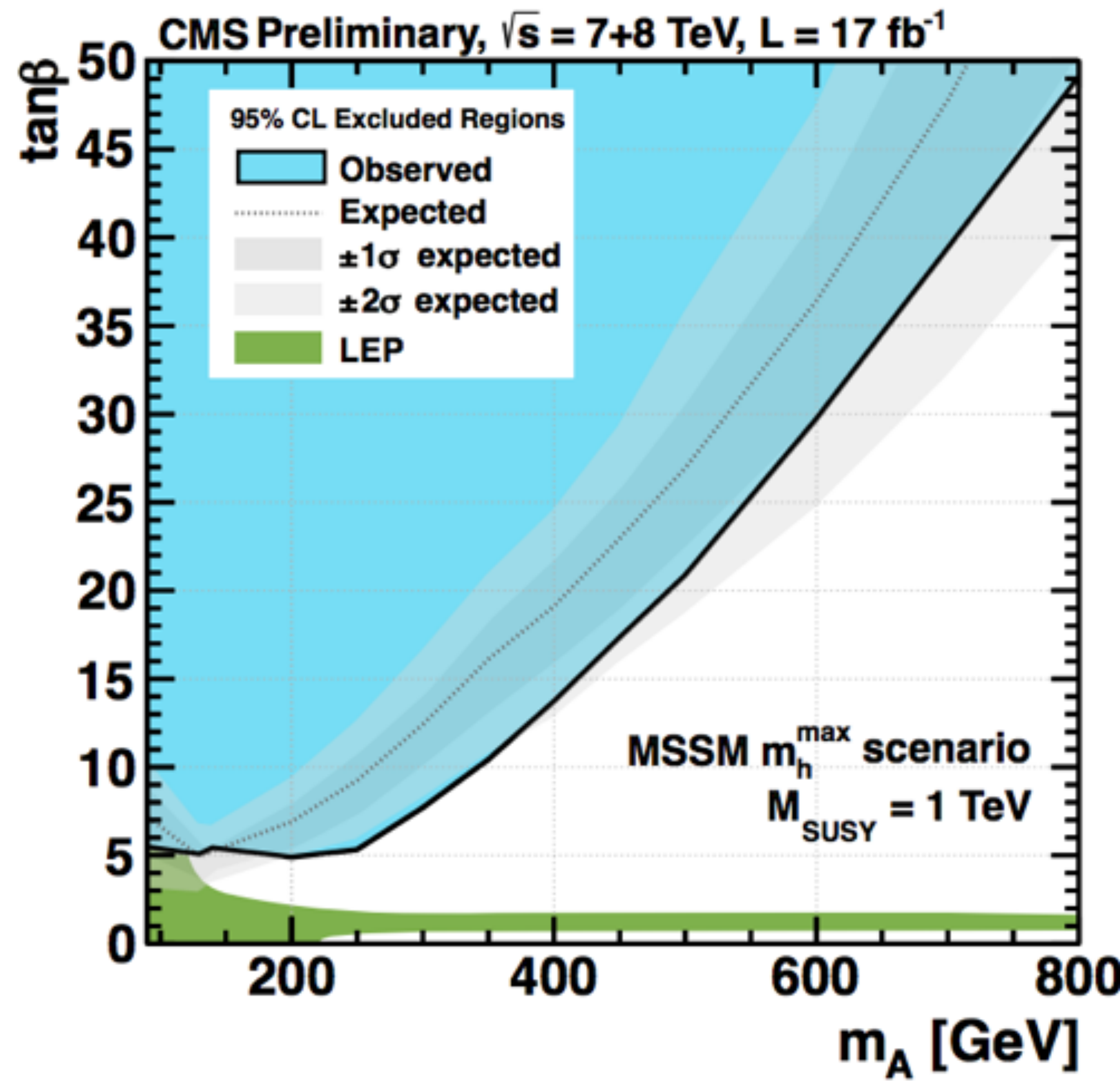
$$\begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix} = R_{\beta_\pm} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

LHC searches ongoing

A -> Zh



H/A -> tau pair



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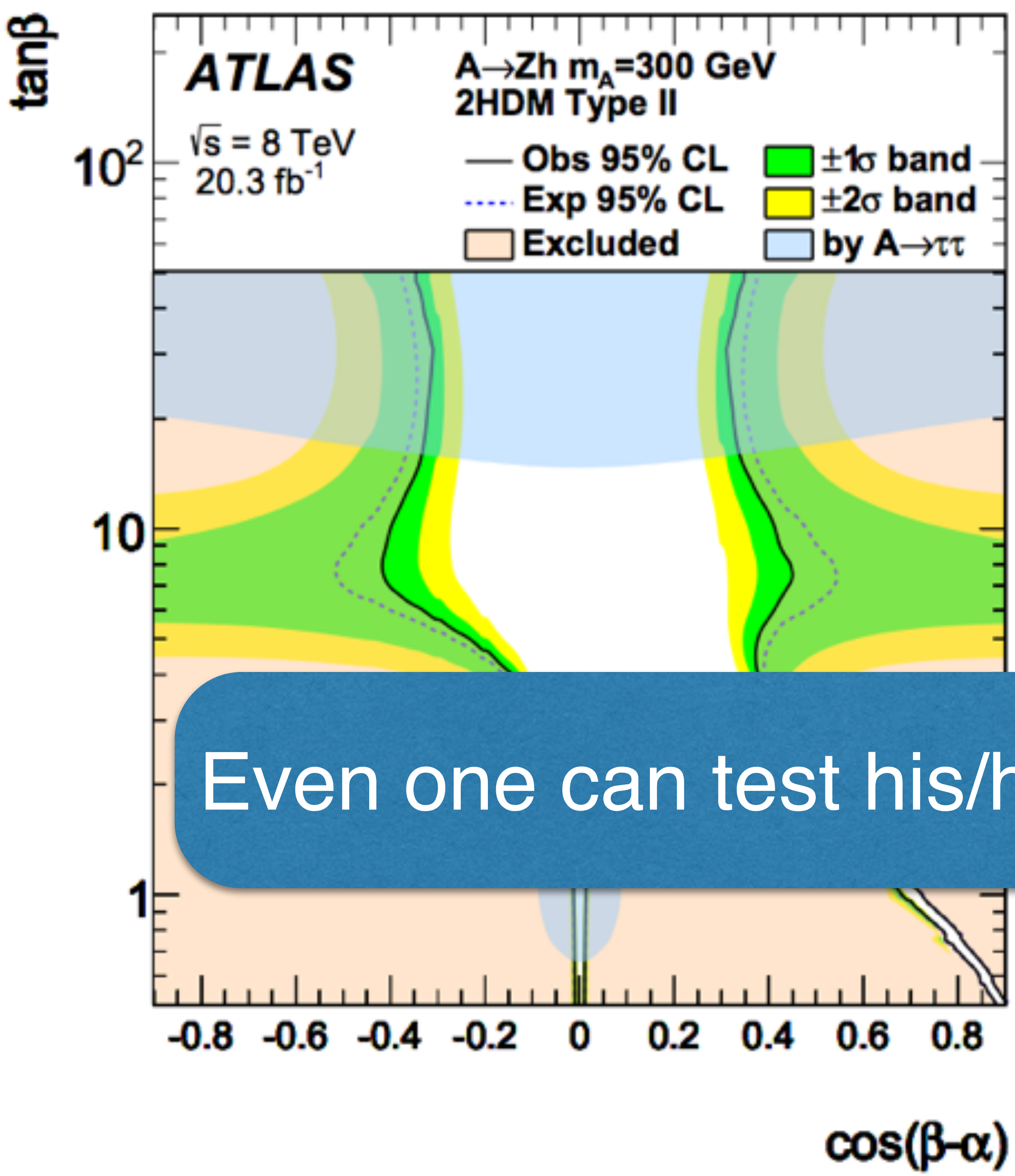
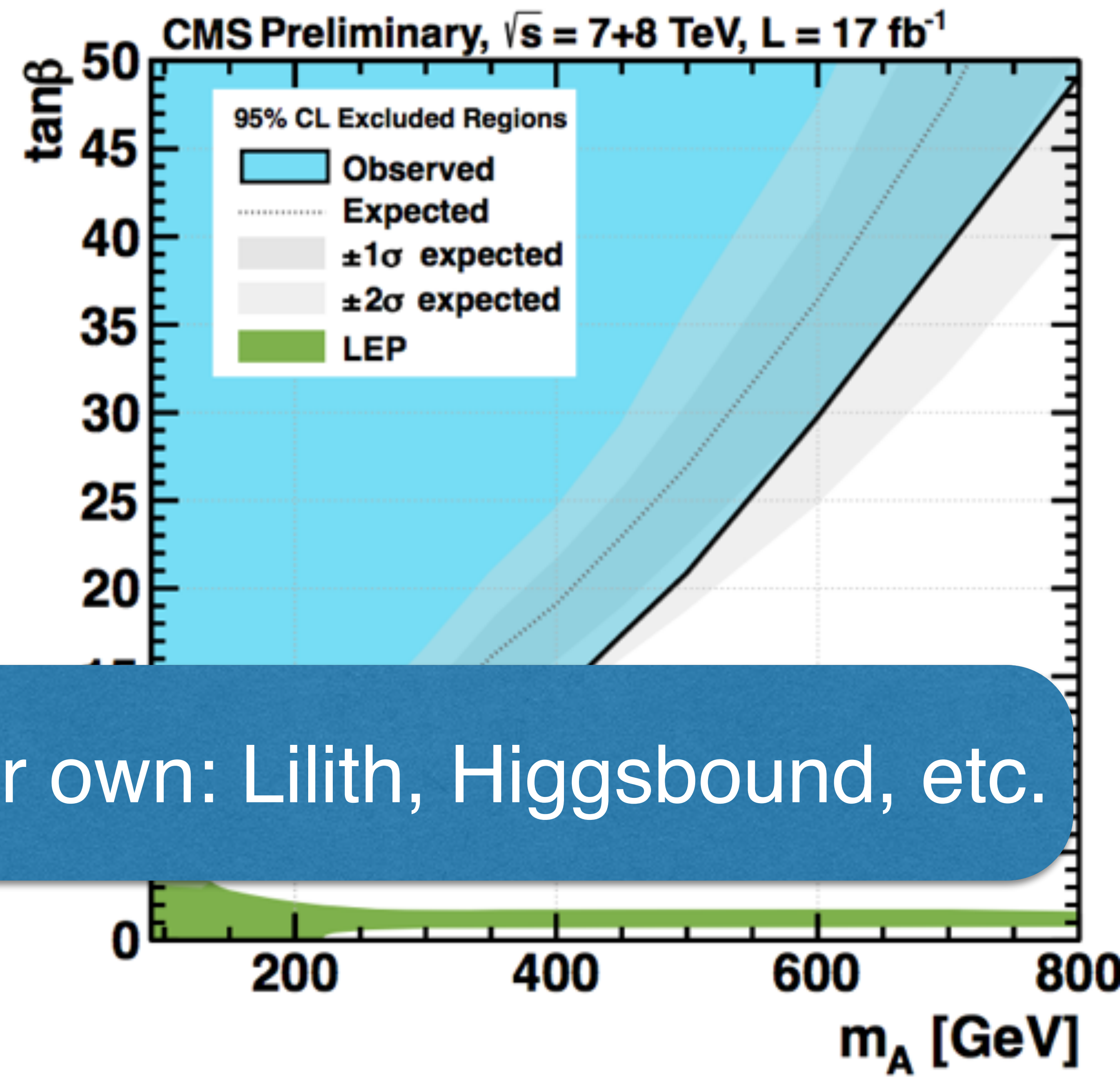
LHC searches ongoing

A -> Zh

H/A -> tau pair





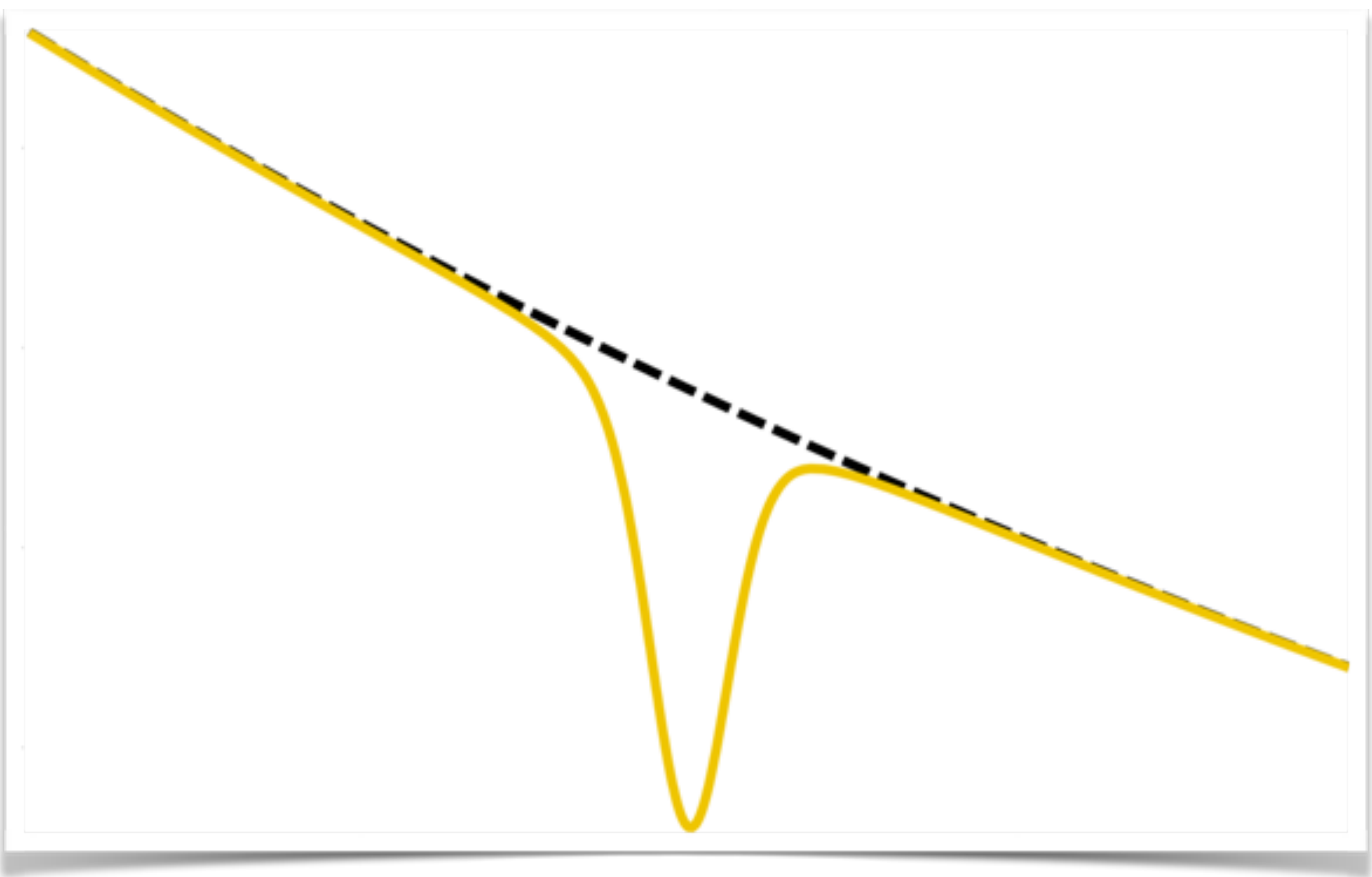
Even one can test his/her own: Lilith, Higgsbound, etc.

BUT!

Current LHC searches and theory studies overlooked two important Higgs physics.

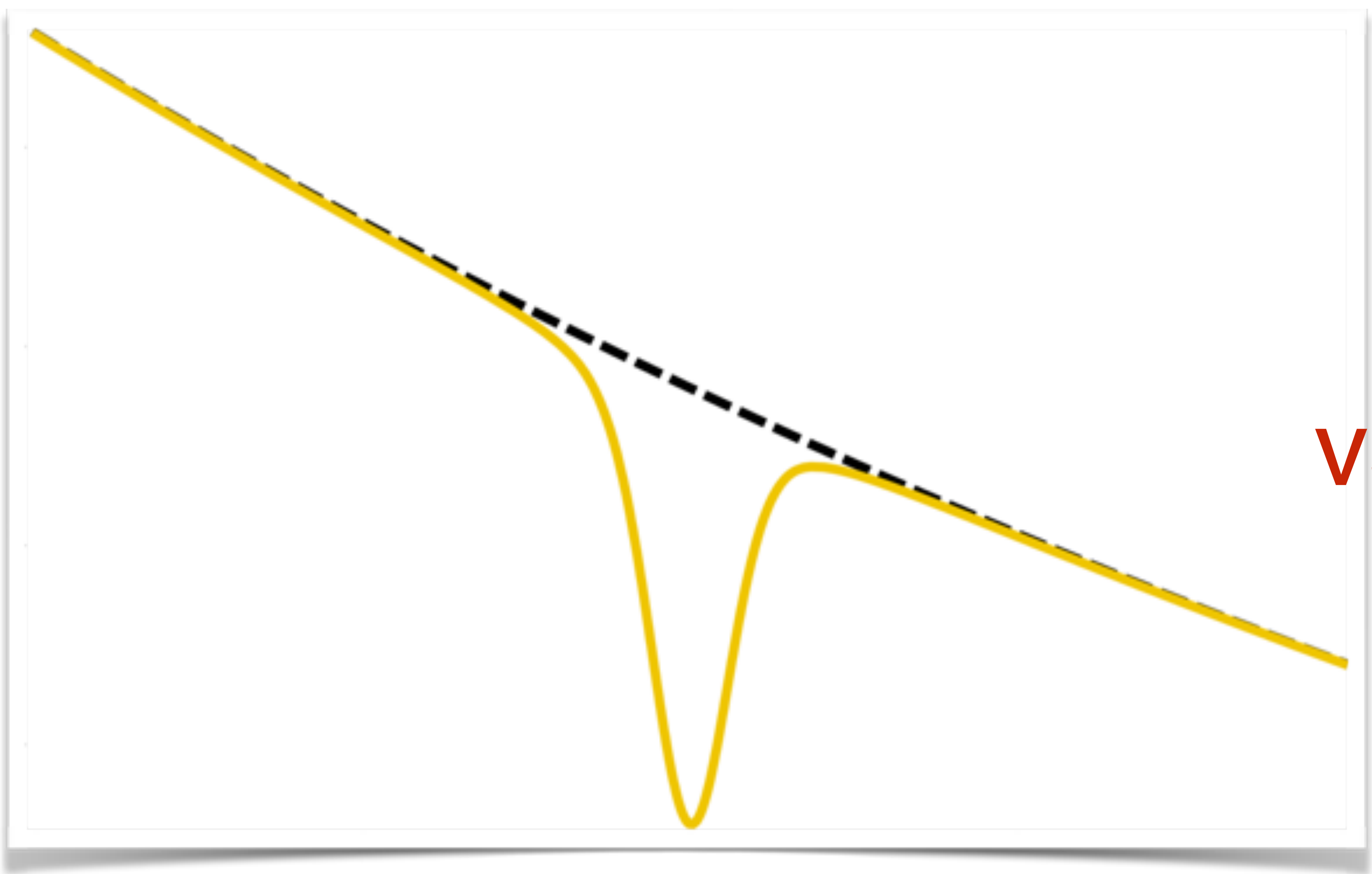
First Overlooked Heavy Higgs Physics

SJ, Song, Yoon

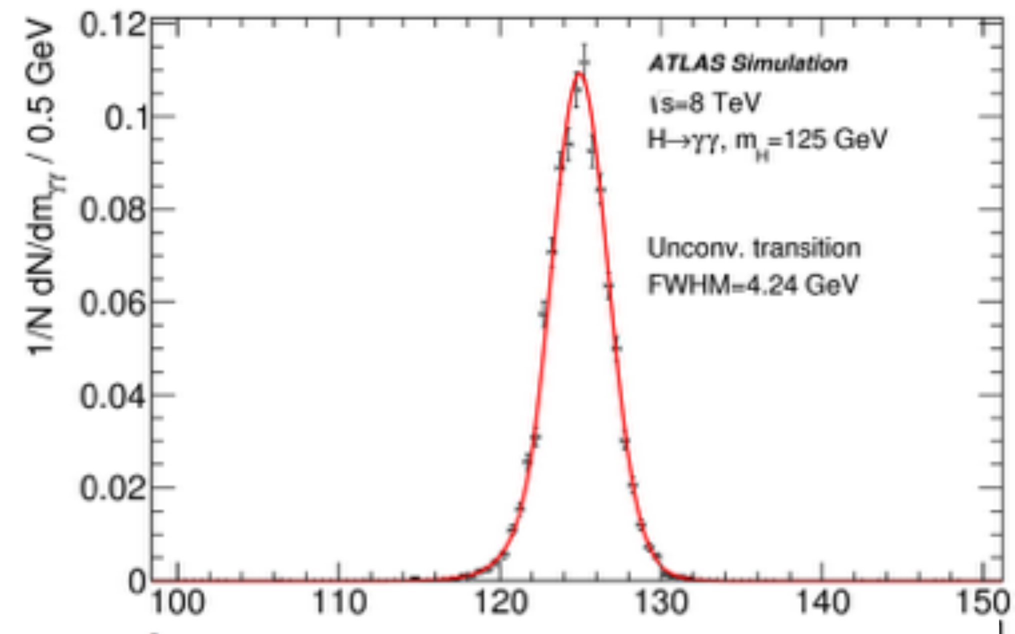


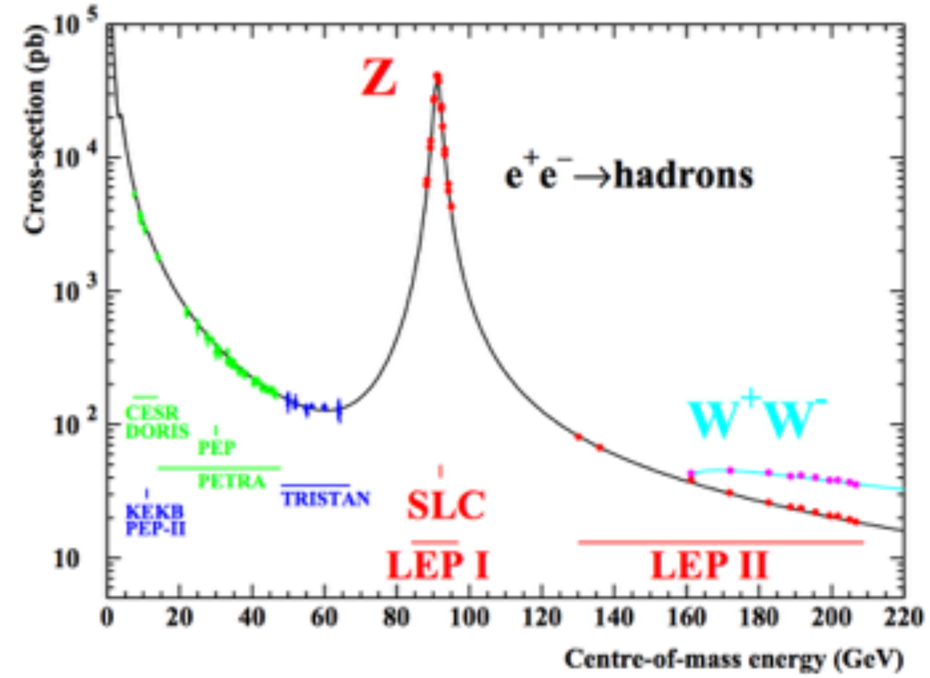
First Overlooked Heavy Higgs Physics

SJ, Song, Yoon



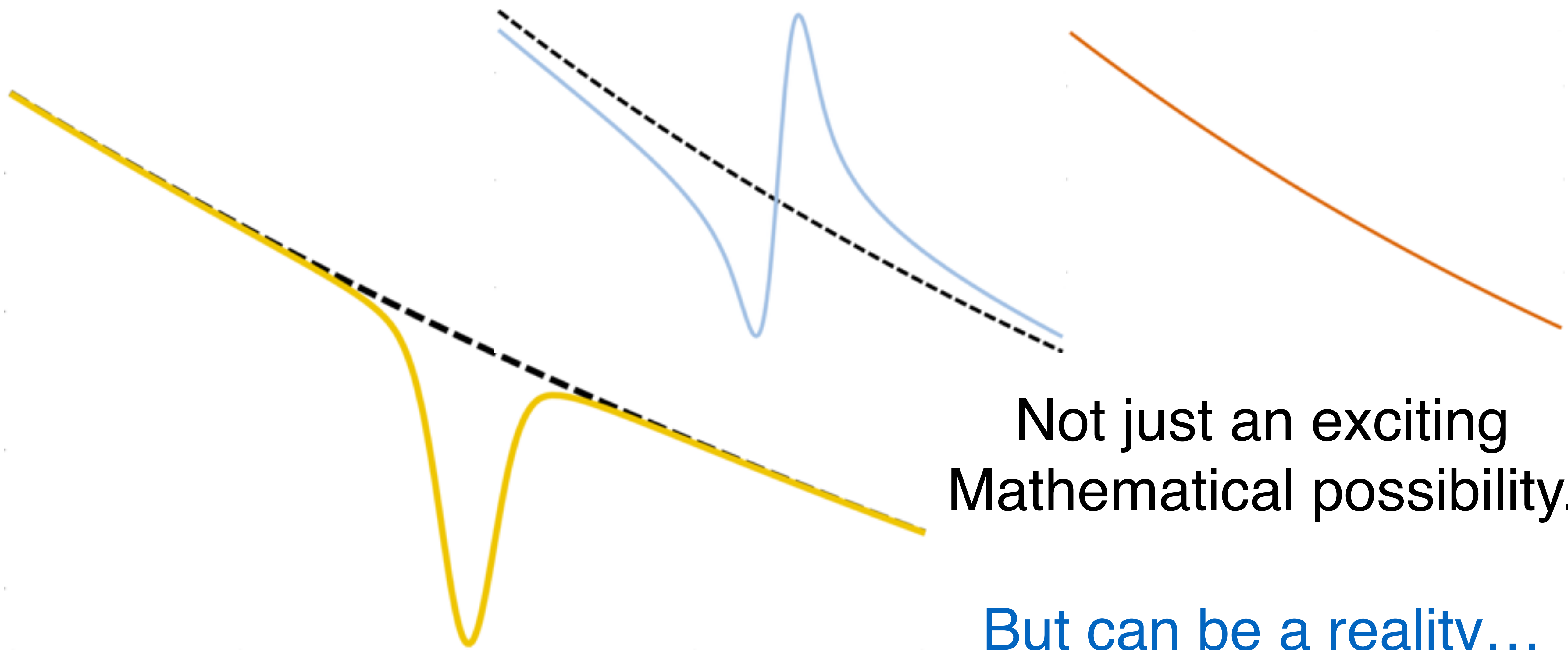
VS.





First Overlooked Heavy Higgs Physics

SJ, Song, Yoon



Not just an exciting Mathematical possibility.

But can be a reality…

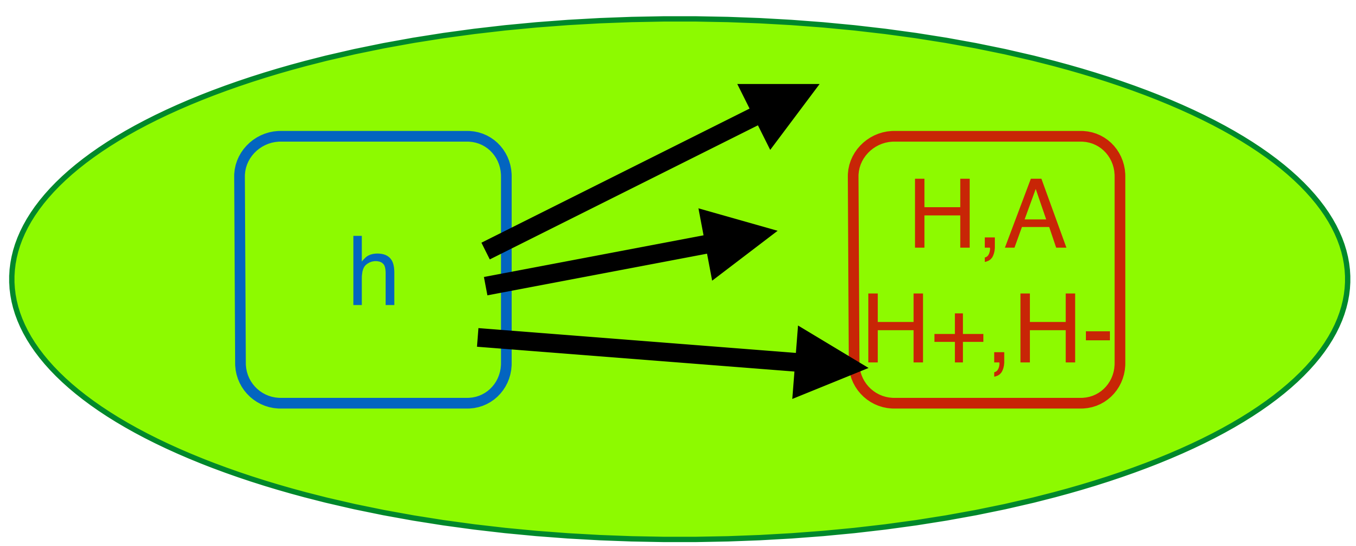
(see also YeoWoong's talk. I'll present with different emphasis and views.)

Second Overlooked Heavy Higgs Physics

SJ, Chun, Yoon

We now have the SM Higgs boson.

This trivial fact can't be overlooked.



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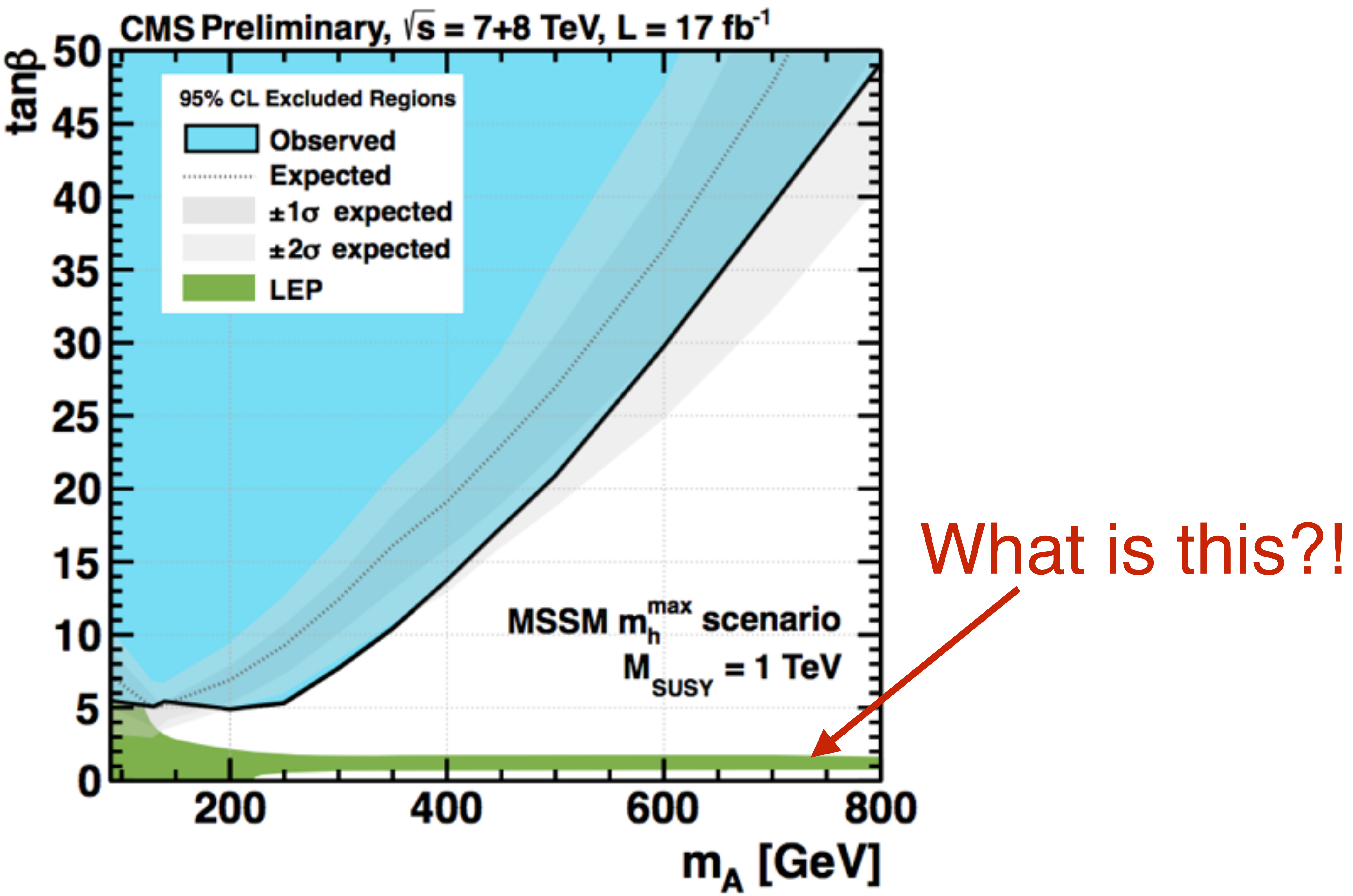
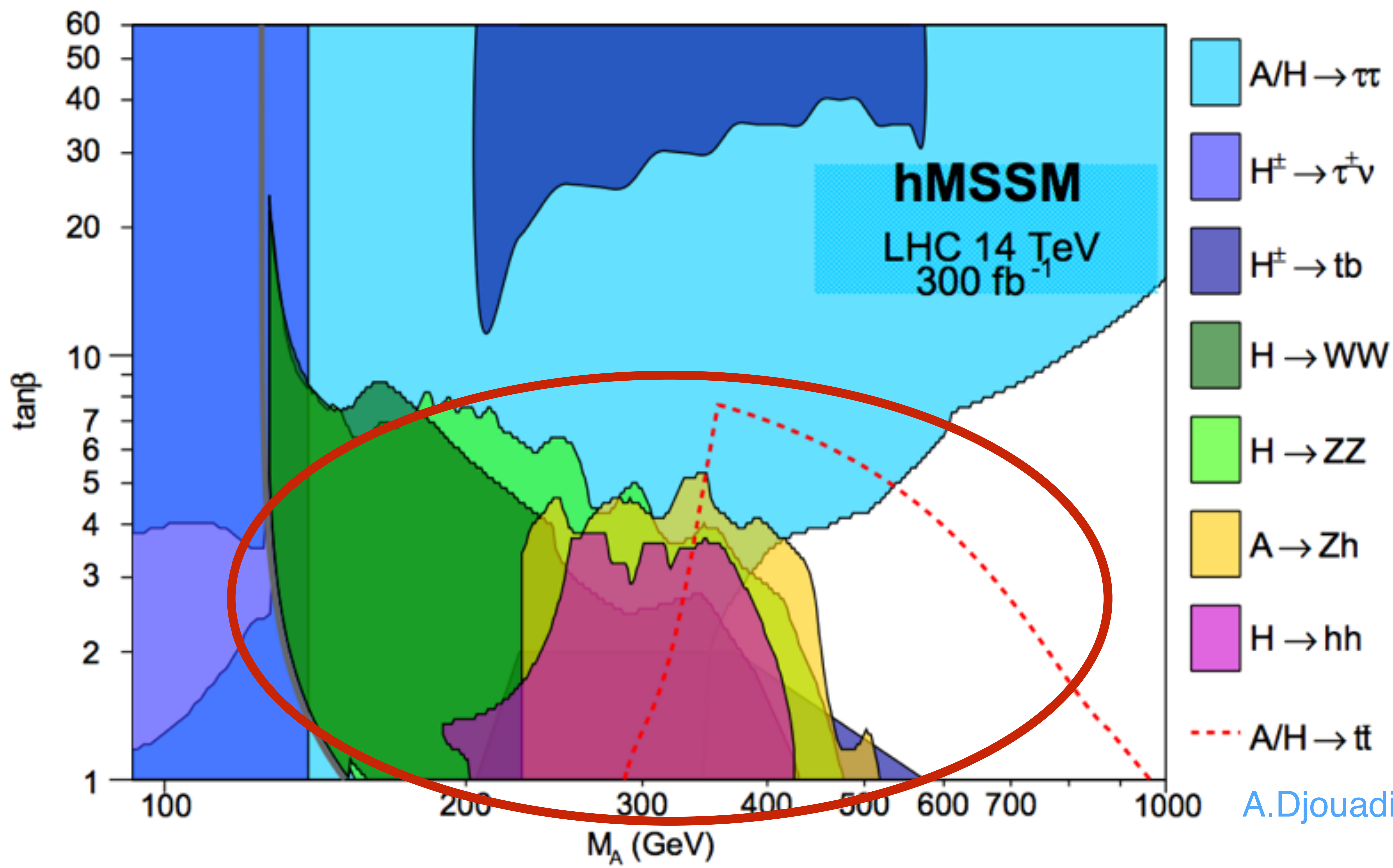
Ex 1) misleading standard searches!



PART 1:

Heavy Higgses not resonance peaks

Heavy Higgs in most channels are not peaks!



A.Djouadi et al.

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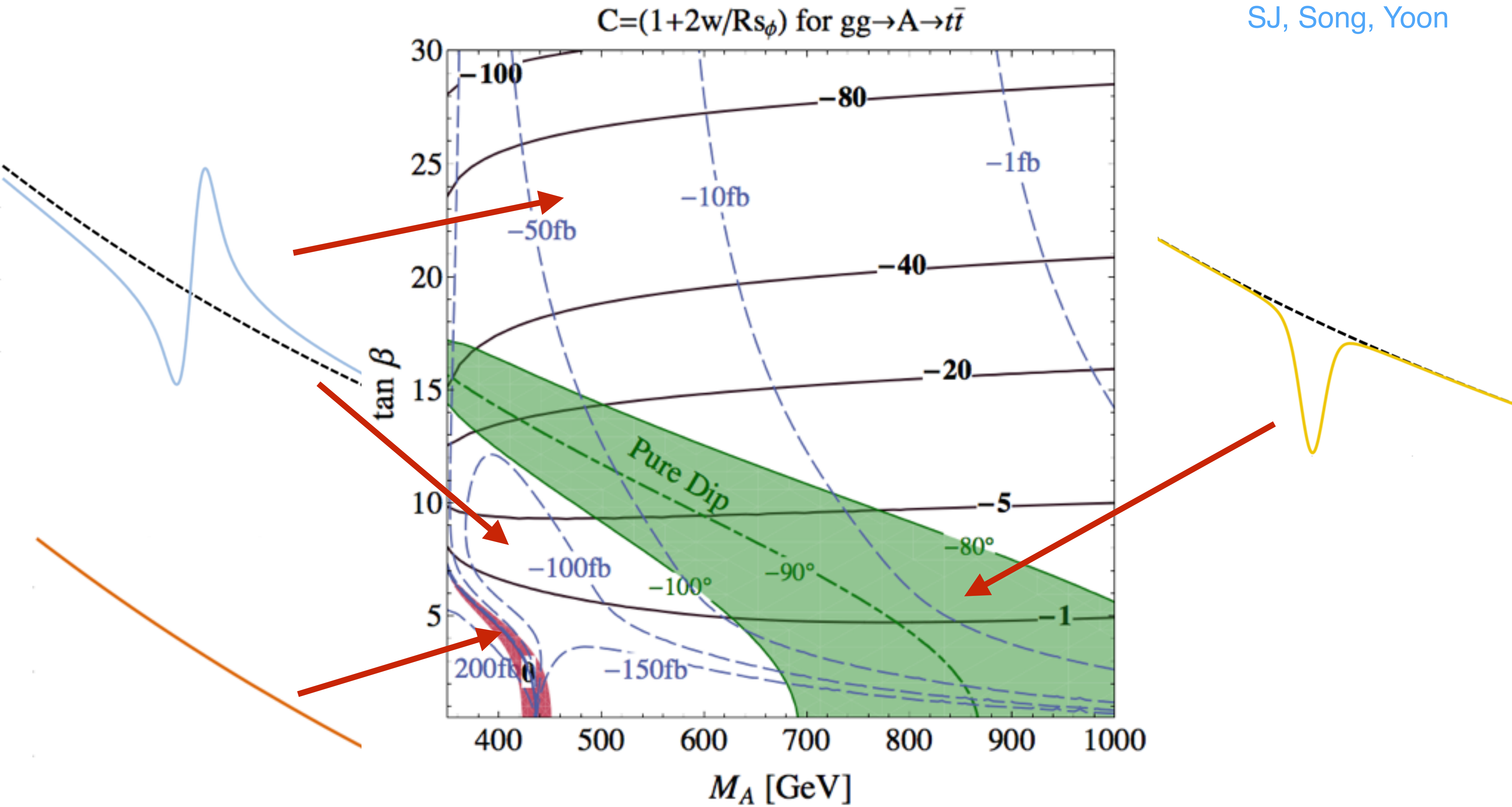
Heavy Higgs in ttbar

SJ, Song, Yoon



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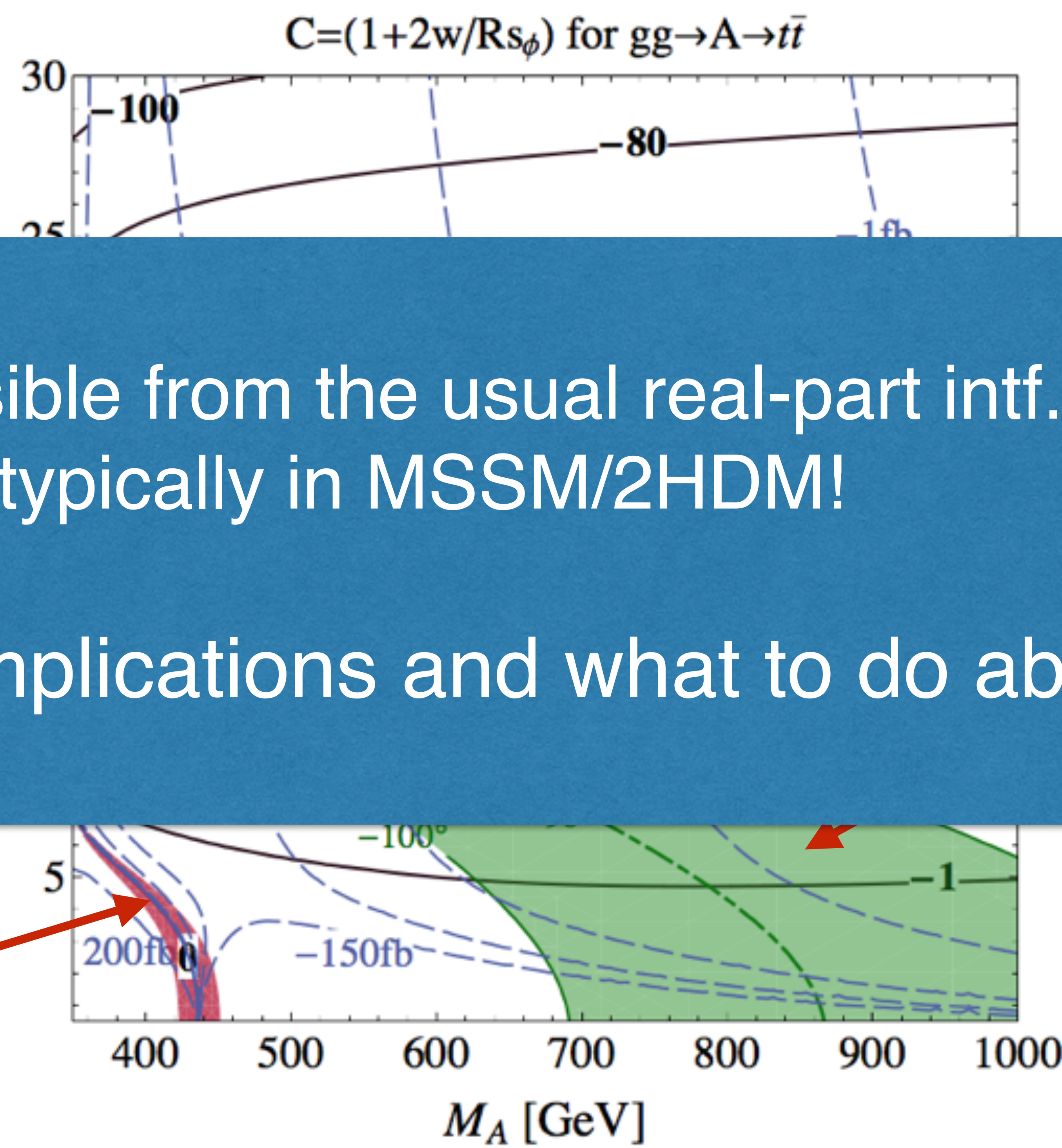
Heavy Higgs in ttbar

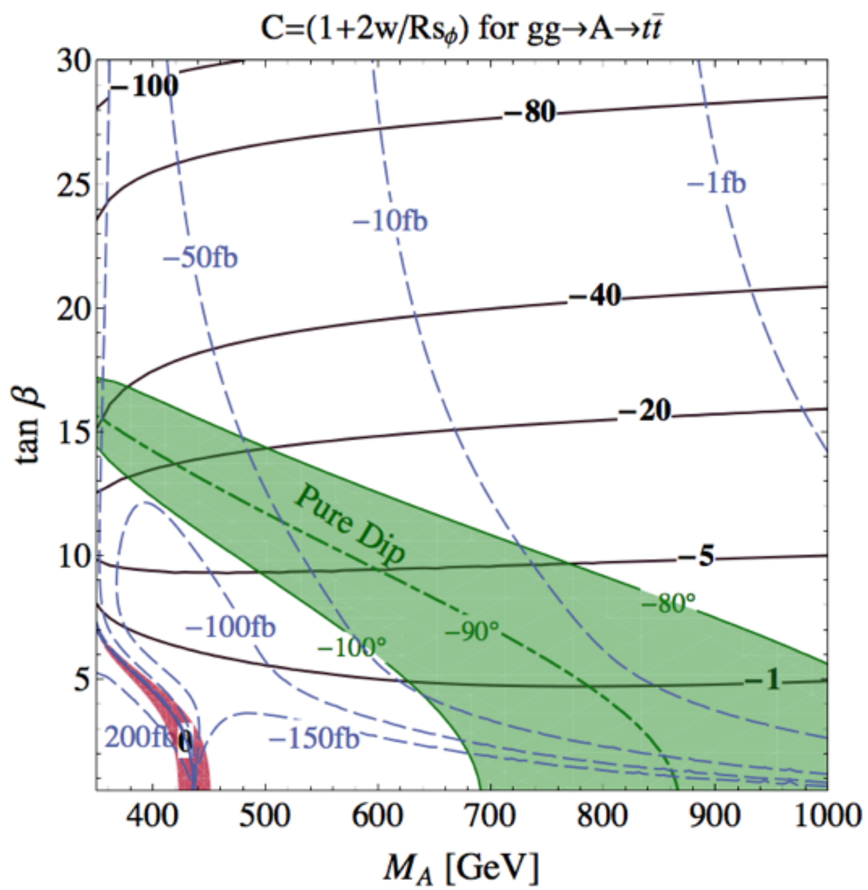
SJ, Song, Yoon



- Never possible from the usual real-part intf.
- It happens typically in MSSM/2HDM!

What are implications and what to do about it?!

LHC search challenged



vs.

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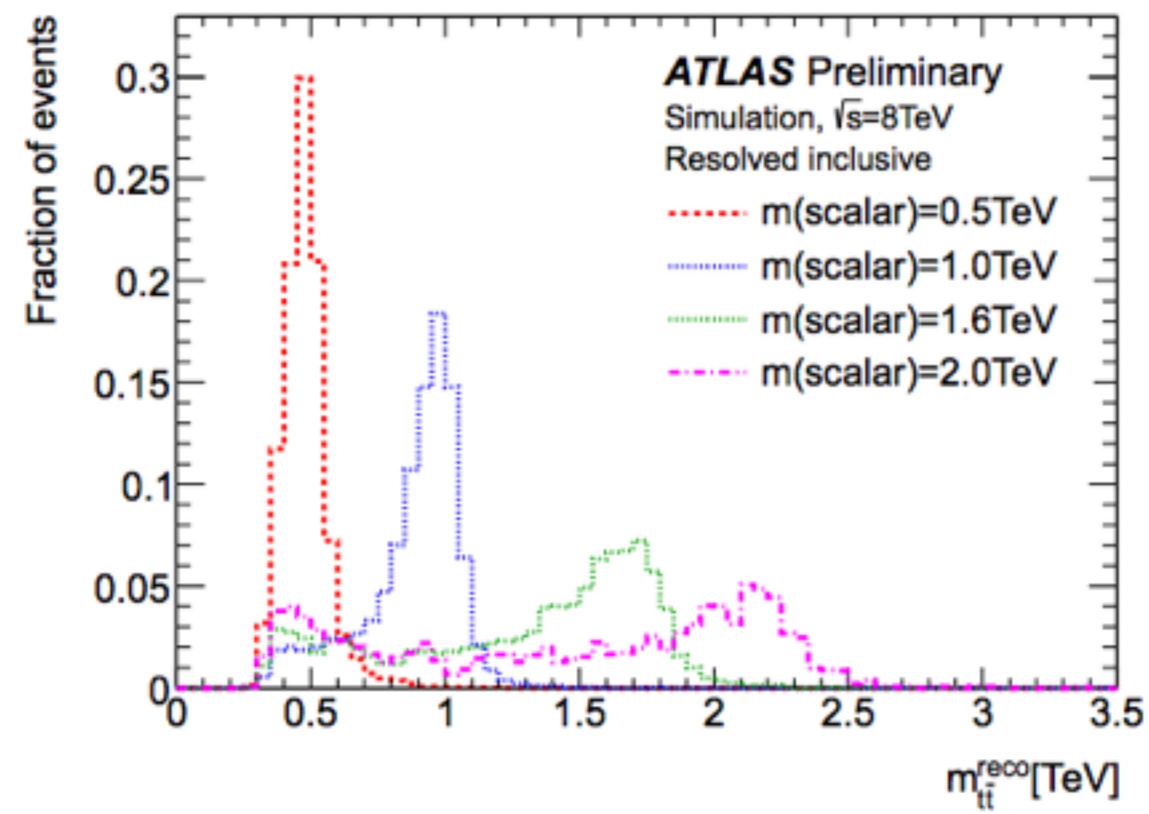


- LHC search is crucially complicated and challenged:

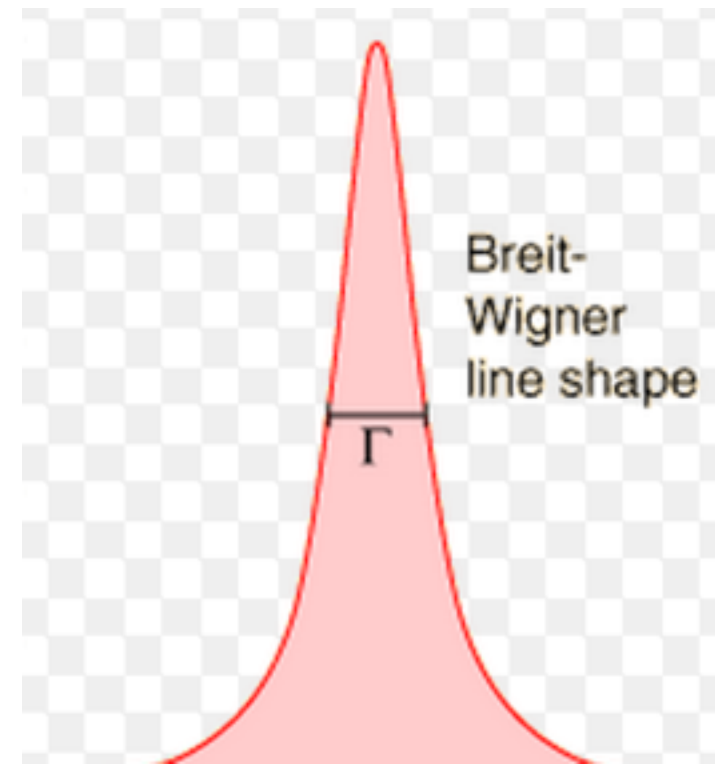
  1) Optimisation for each param space;

LHC search challenged

SJ, Song, Yoon

$$\frac{1}{(\hat{s}-M^2)^2+M^2\Gamma^2} \quad \rightarrow \quad \frac{\pi}{M\Gamma}\delta(\hat{s}-M^2)$$

$$\sigma(H/A)\cdot BR(H/A\rightarrow t\bar{t})$$

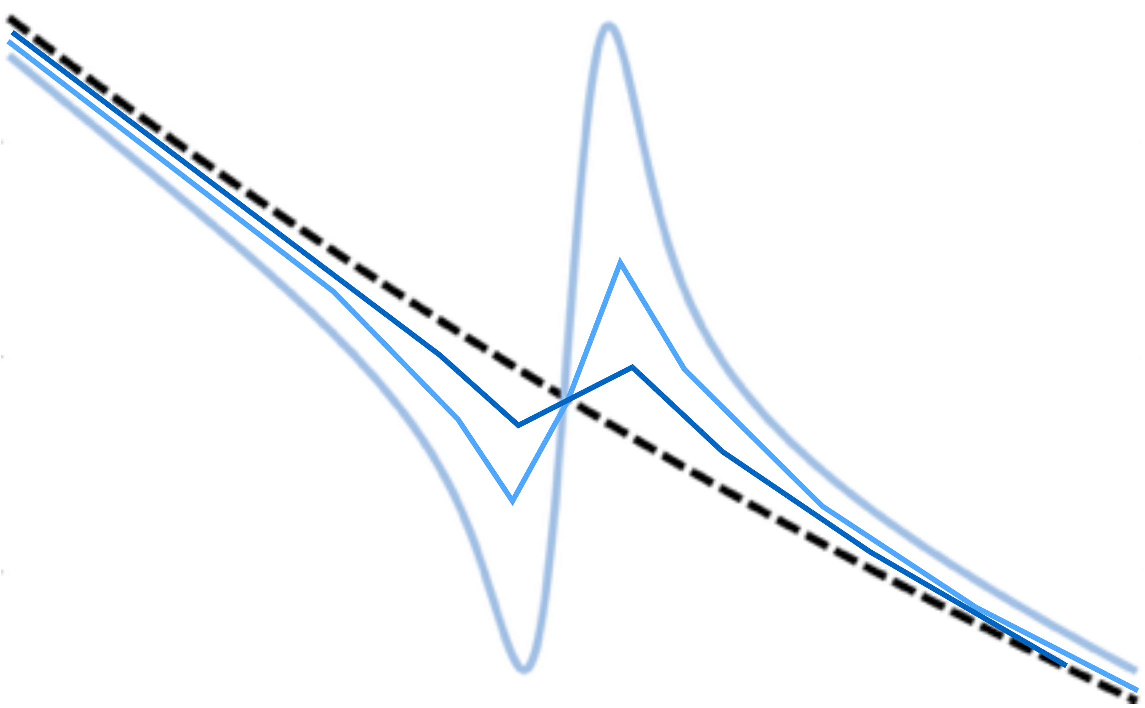


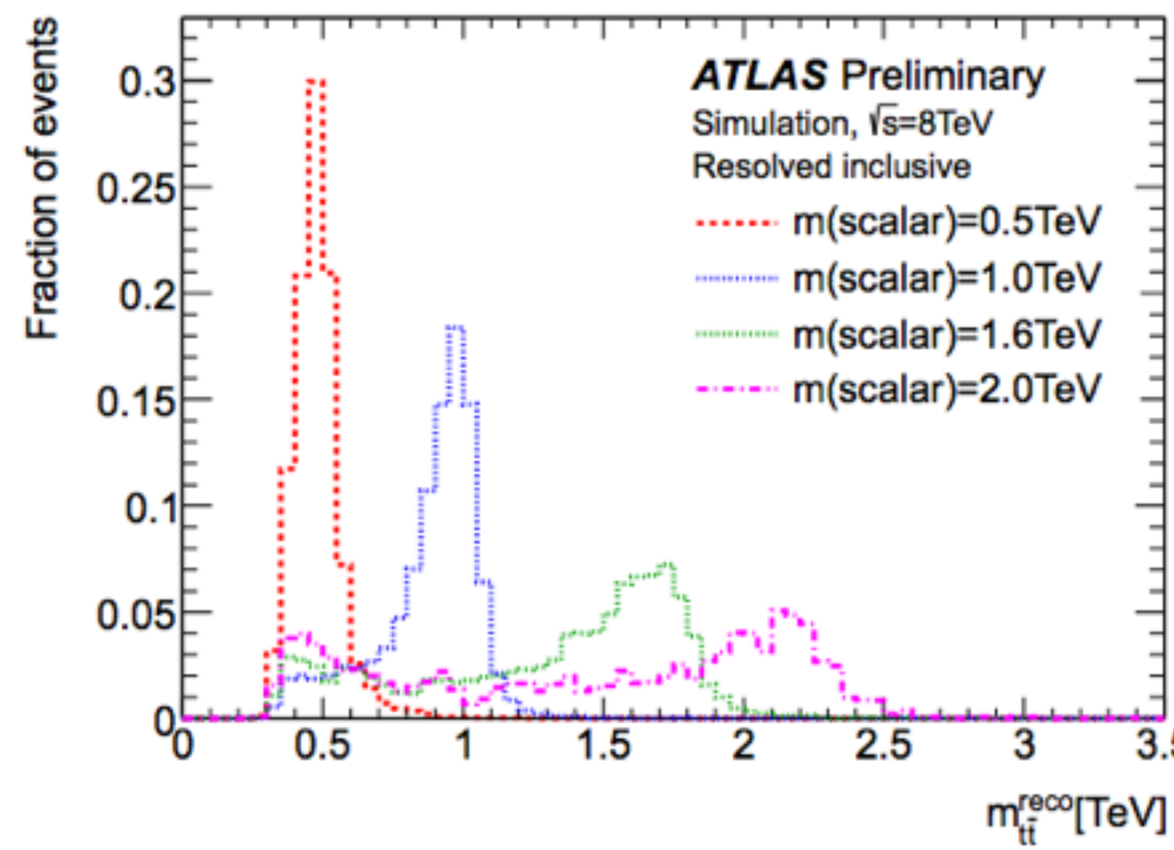
- LHC search is crucially complicated and challenged:

  1) Optimisation for each param space;
  2) NWA breaks down!;

LHC search challenged

SJ, Song, Yoon





- LHC search is crucially complicated and challenged:

  1) Optimisation for each param space;
  2) NWA breaks down!;
  3) Good resolution more essential.

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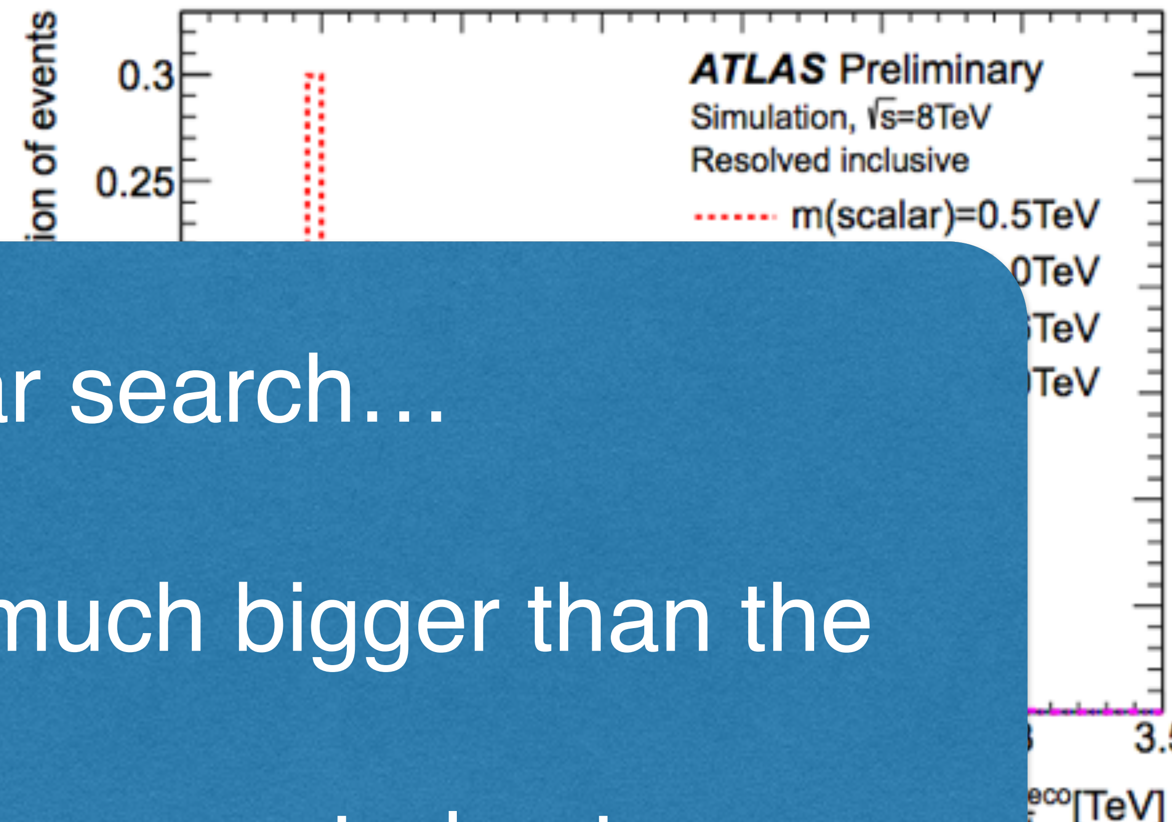
LHC search challenged

SJ, Song, Yoon



Unfortunately, in current ttbar search…

- The mtt resolution is bad (much bigger than the natural width);
- No interference effects are accounted yet.

d:

1) Optimisation for each param space;
2) NWA breaks down!;
3) Good resolution more essential.

Some history

- First glimpsed by Gaemers et al in 1984, in gg>h>QQ.
- In 1994, just around the top discovery, Dicus et al revisited gg>h>tt study in MSSM/2HDM. Underlying physics is clarified.
- Since then, various Higgs channels initiated by gg and diphoton were calculated to find that various shapes do appear.
- But no universal description of various shapes, applicable to even uncalculated processes, aiding easier thy/exp studies was available.

It's time to revisit it

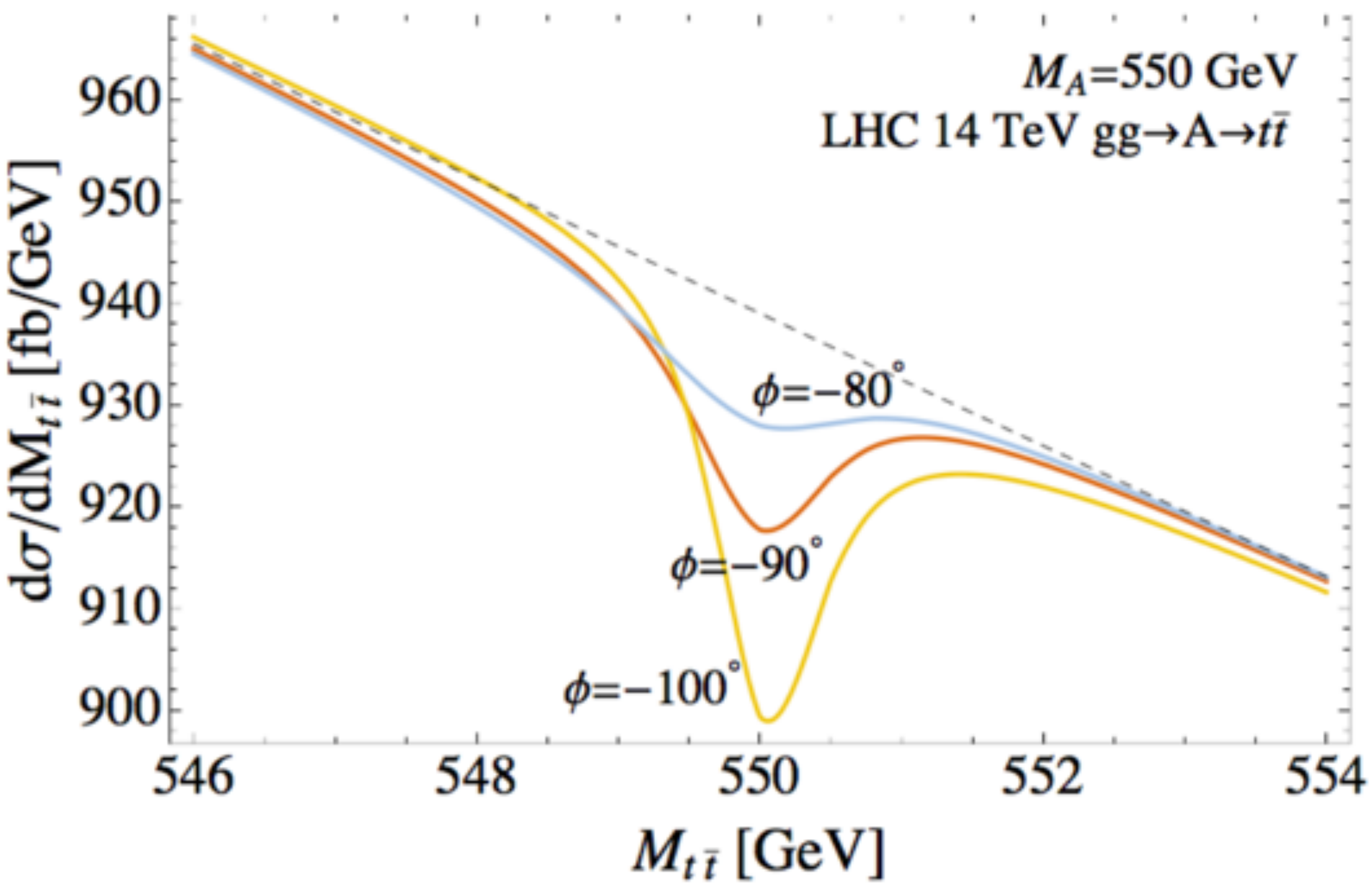
- LHC is now getting sensitivity to heavy Higgs!
- On theory side,,,

SJ, Song, Yoon
(see also YW's talk)

- We formulated a general description of Higgs resonance shapes. Translation of MSSM params to resonance-shape params significantly ease collider studies.
- Successfully modified NWA.
- Could identify potential heavy Higgs channels that could produce dips w/o calculating them.

On practical side,,, Partial solution

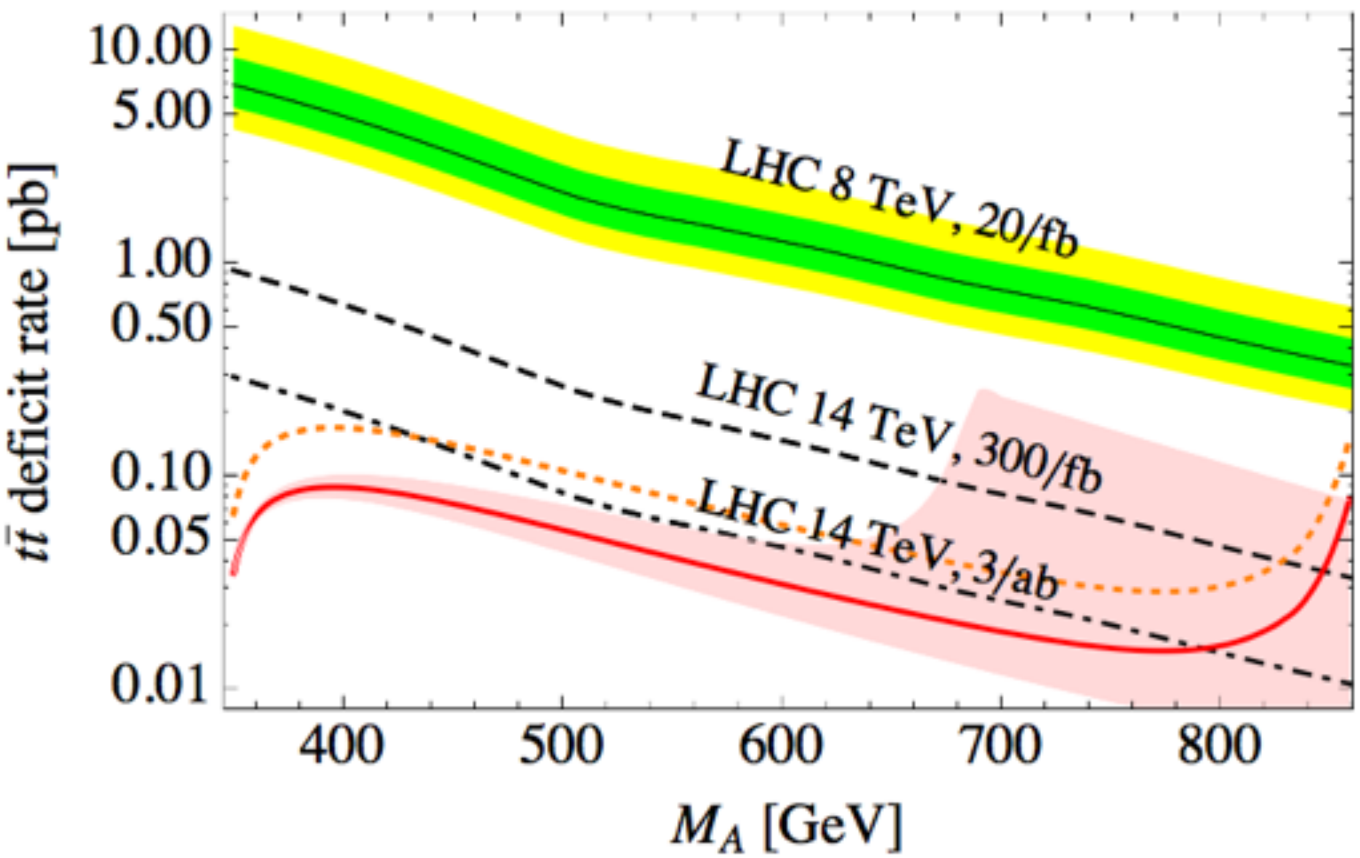
SJ, Song, Yoon

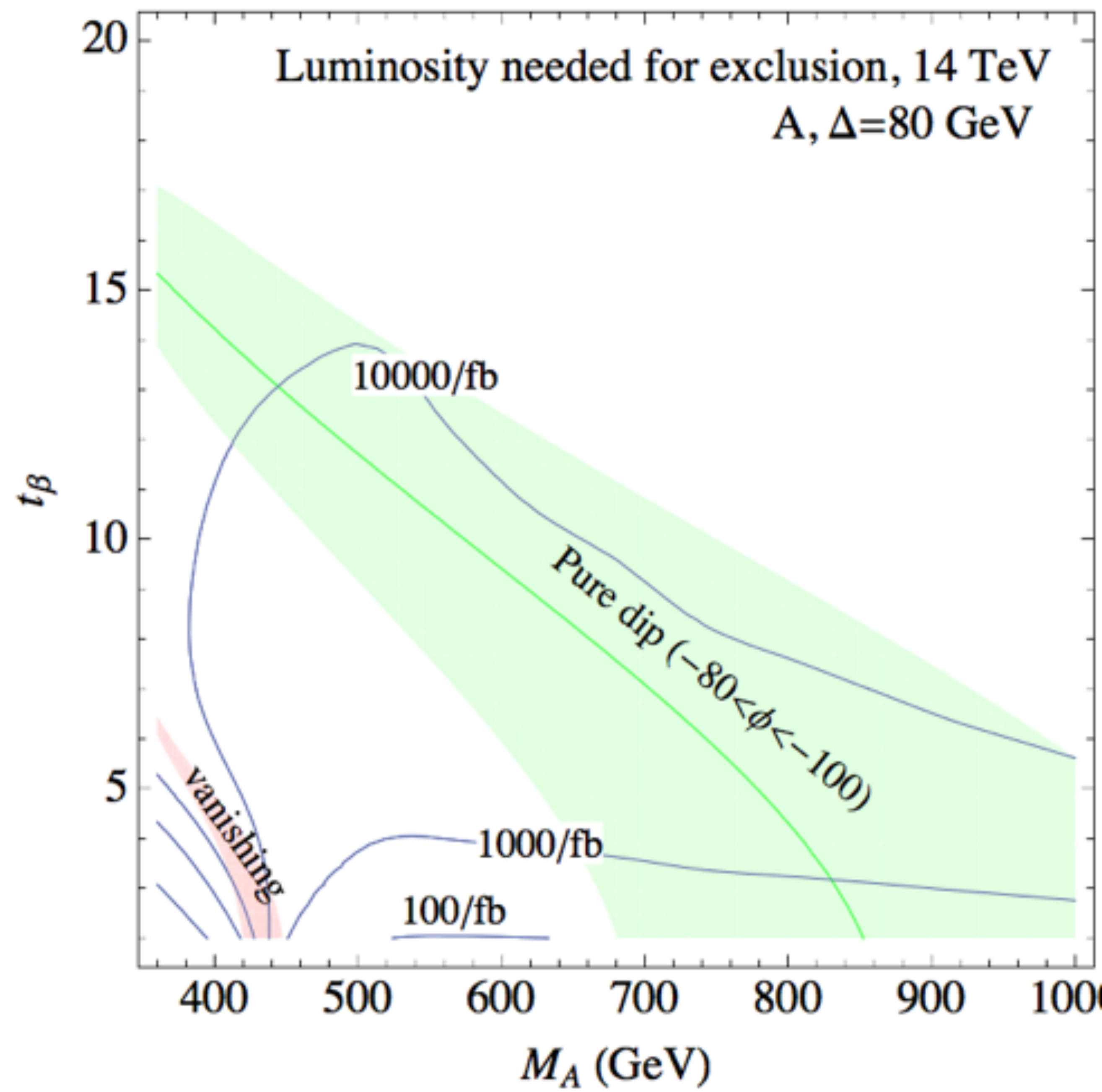


- Look for pure dips instead!
- Current LHC analyses, assuming a pure peak, apply as is now.

On practical side,,,
Partial solution

SJ, Song, Yoon





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PART 2:

Necessary Implications of SM Higgs mass on heavy Higgses

MSSM Higgs sector

- 2 Higgs doublets:
  8 real scalars - 3 Goldstones = 5 physical Higgs bosons. (4 more in addition to the SM Higgs)

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}} R_{\beta_0} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

$$\begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix} = R_{\beta_\pm} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

- Two CP-even neutral scalars are primary concern.

Higgs(Runge) basis

- Always possible to rotate to the Higgs/Runge basis:

$$\Phi_{vev} = \begin{pmatrix} G^{\pm} \\ \frac{1}{\sqrt{2}}(v + \varphi_1' + iG^0) \end{pmatrix}, \quad \text{and} \quad \Phi_{\perp} = \begin{pmatrix} H^{\pm} \\ \frac{1}{\sqrt{2}}(\varphi_2' + iA^0) \end{pmatrix}$$

beta

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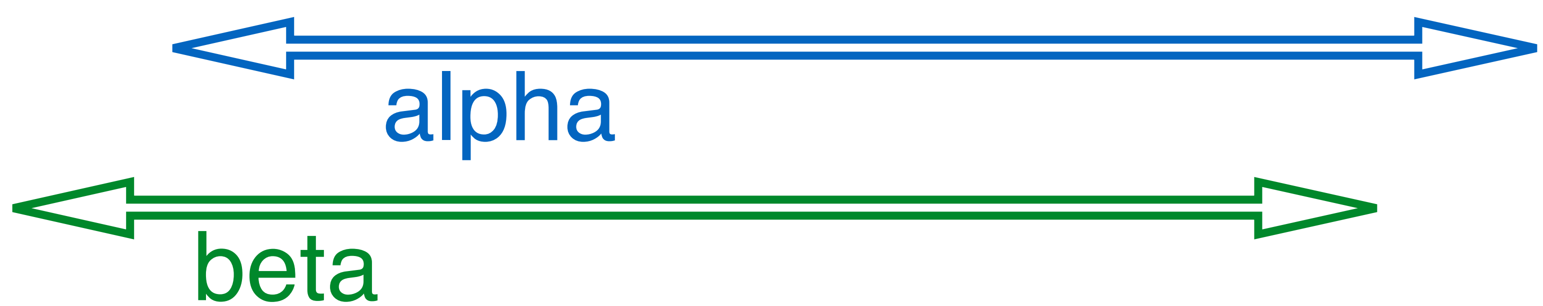

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Alignment limit

- Always possible to rotate to the Higgs/Runge basis:

$$\Phi_{vev} = \begin{pmatrix} G^{\pm} \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \text{and} \quad \Phi_{\perp} = \begin{pmatrix} H^{\pm} \\ \frac{1}{\sqrt{2}}(H + iA^0) \end{pmatrix}$$

cos(beta - alpha) =0

- Alignment when the "Higgs basis = mass eigenbasis". (allegedly obtained in decoupling limit.)

- Clearly SM-like h. No gauge couplings of H and A.

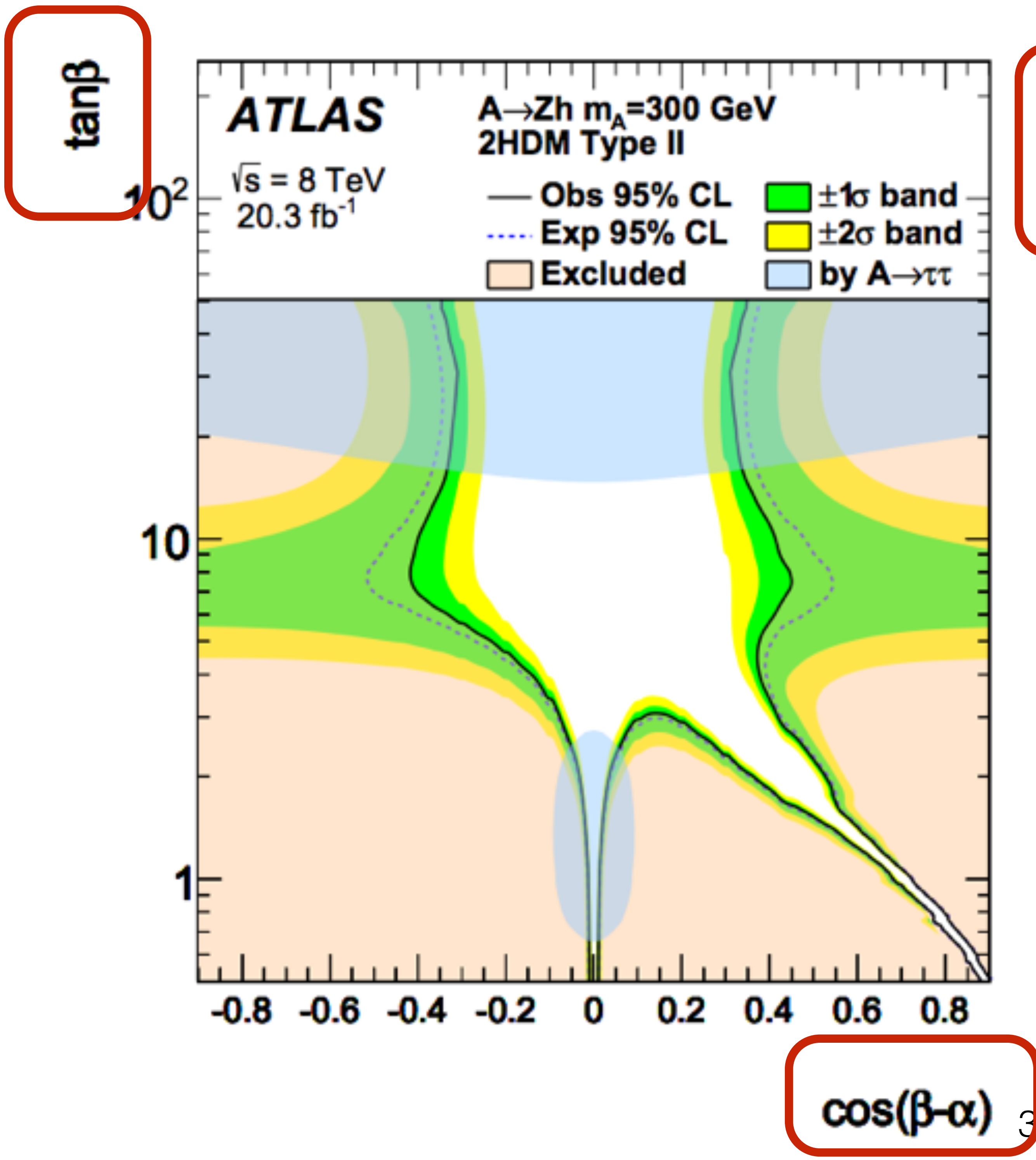
Typical independent parameters

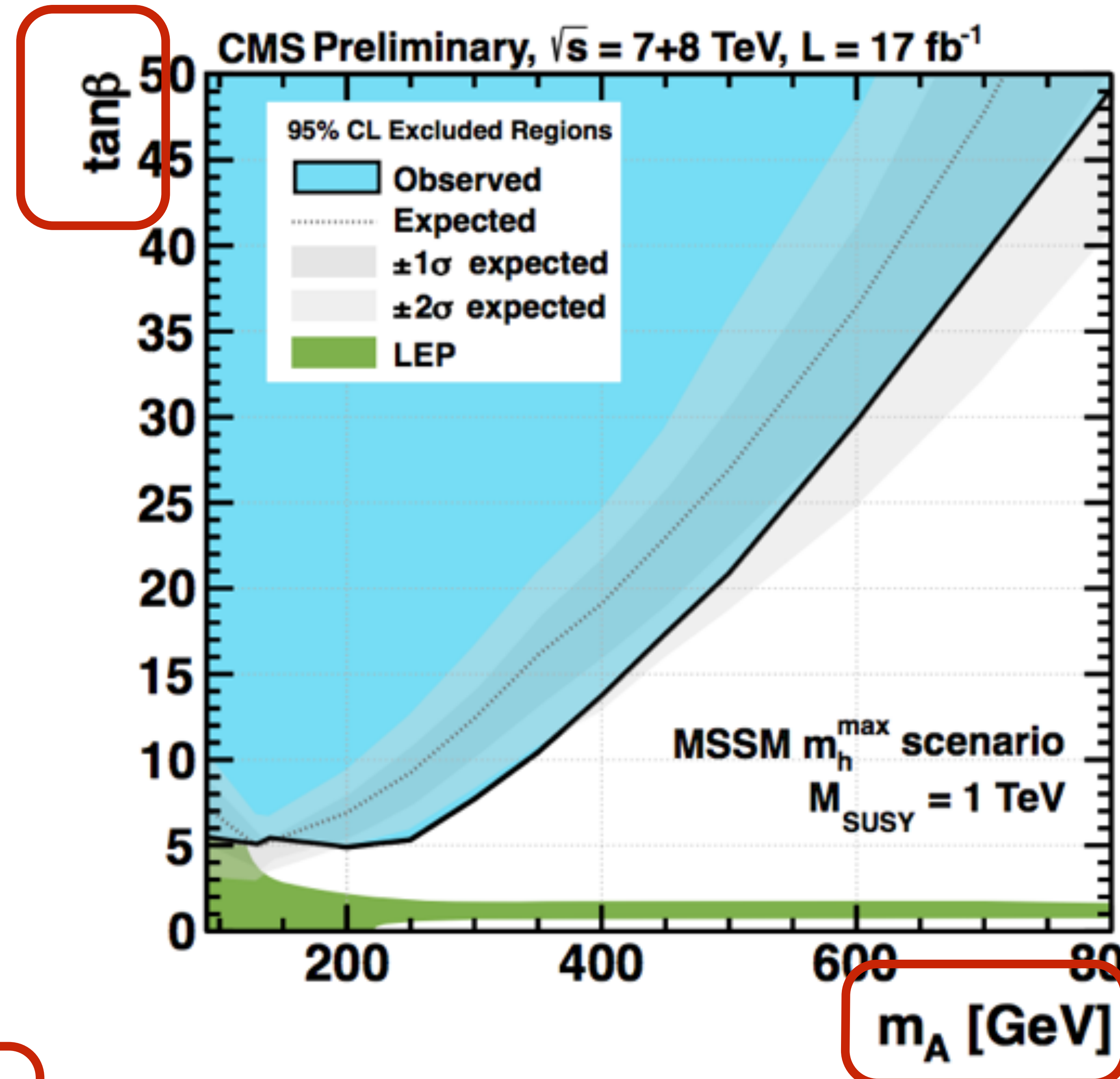
- Following three are taken to be independent params as is done in standard searches and most thy studies:

$$\{ \ m_A, \quad \tan\beta, \quad \cos(\beta - \alpha) \ \}$$

Mass, couplings and deviations from alignment

as done in standard searches





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MSSM Higgs mass (tree-level)

$$M^2 = \begin{pmatrix} M_{11}^2 & M_{12}^2 \\ M_{12}^2 & M_{22}^2 \end{pmatrix}$$

$$\begin{aligned} M_{11}^2 &= s_\beta^2 \underline{M_A^2} + \underline{m_Z^2} c_\beta^2, \\ M_{12}^2 &= -s_\beta c_\beta (\underline{M_A^2} + \underline{m_Z^2}), \\ M_{22}^2 &= c_\beta^2 \underline{M_A^2} + \underline{m_Z^2} s_\beta^2, \end{aligned}$$

$$M_A > m_Z$$

- Lighter mass eigenvalue, the SM Higgs mass, is upper bounded by ~ mZ. 125 GeV is never possible!

125 GeV

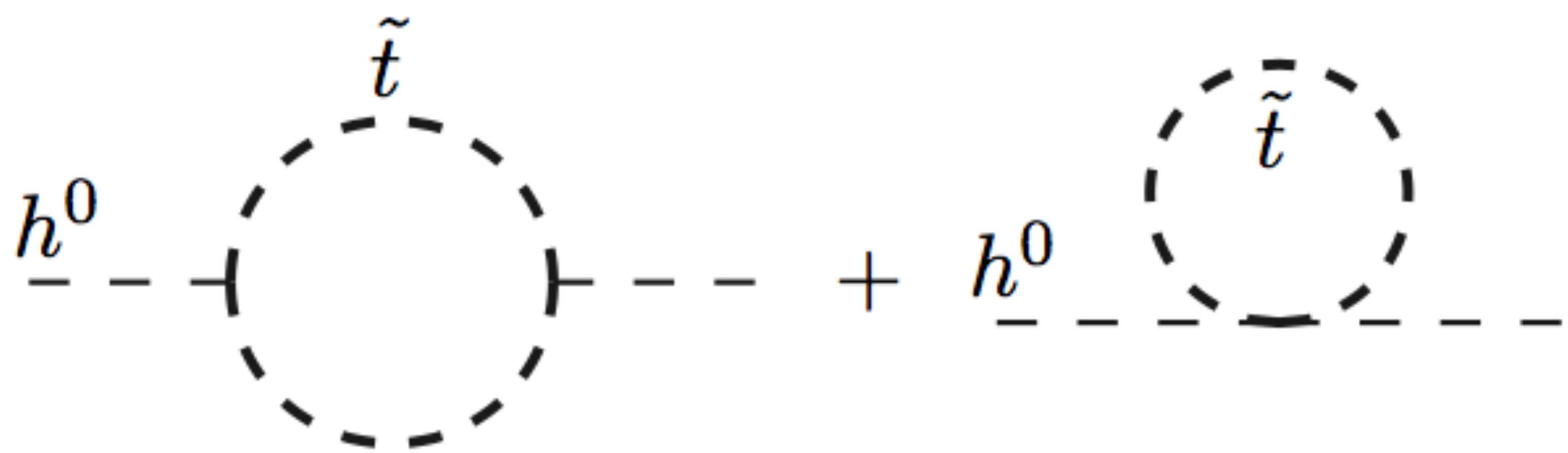
$$M^2 = \begin{pmatrix} M_{11}^2 + \Delta_{11} & M_{12}^2 + \Delta_{12} \\ M_{12}^2 + \Delta_{12} & M_{22}^2 + \Delta_{22} \end{pmatrix}$$

- One necessarily needs non-zero Deltas for the 125 GeV.
- Mixing alpha not only modified, but not a free parameter anymore (once 125 is imposed and model is specified).

Ex) 125 from stops

A.Djouadi et al

$$M^2 = \begin{pmatrix} M_{11}^2 & M_{12}^2 \\ M_{12}^2 & M_{22}^2 + \Delta_{22} \end{pmatrix}$$



$$\alpha = -\arctan\left(\frac{(M_Z^2 + M_A^2)\cos\beta\sin\beta}{M_Z^2\cos^2\beta + M_A^2\sin^2\beta - M_h^2}\right)$$

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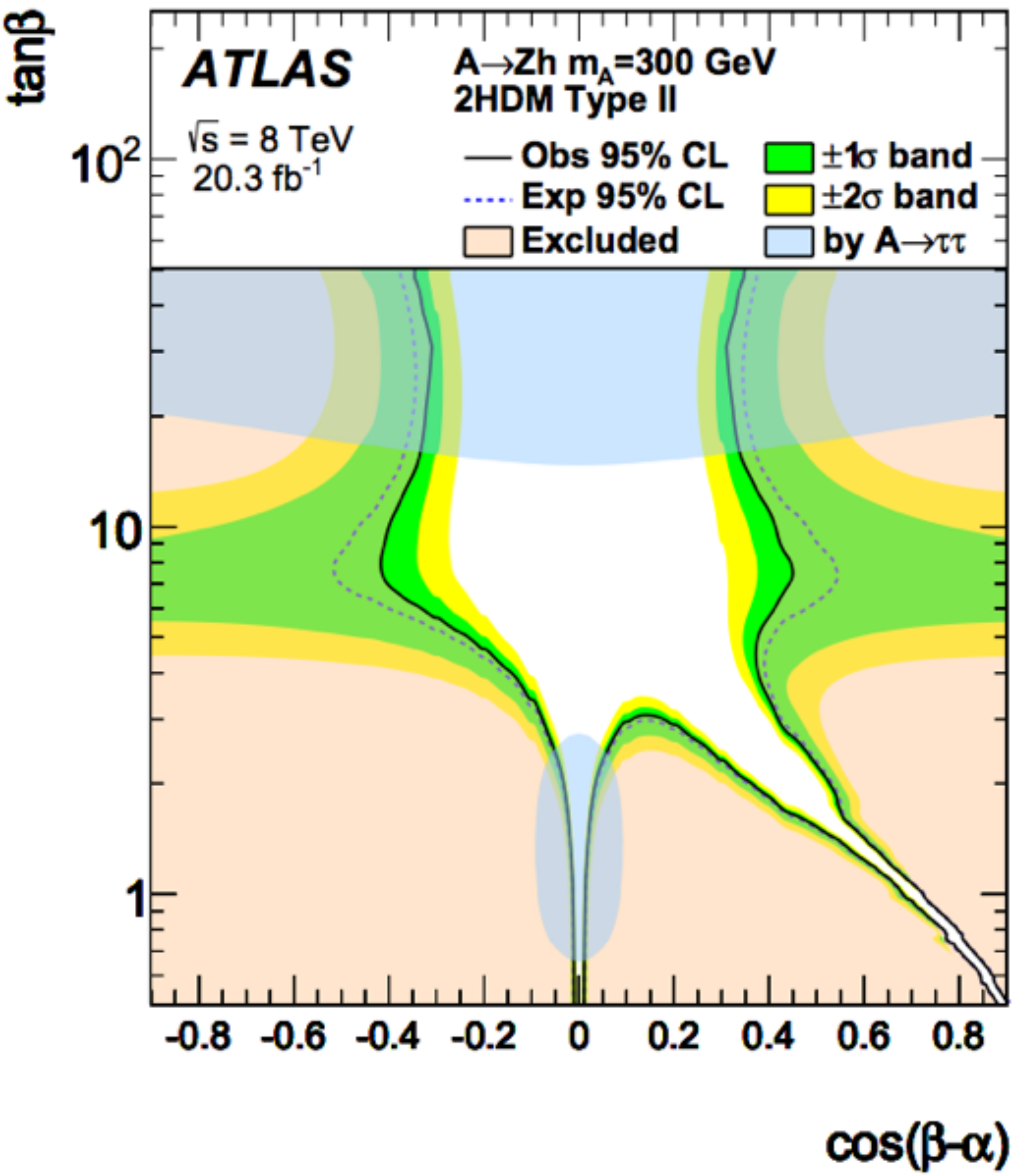
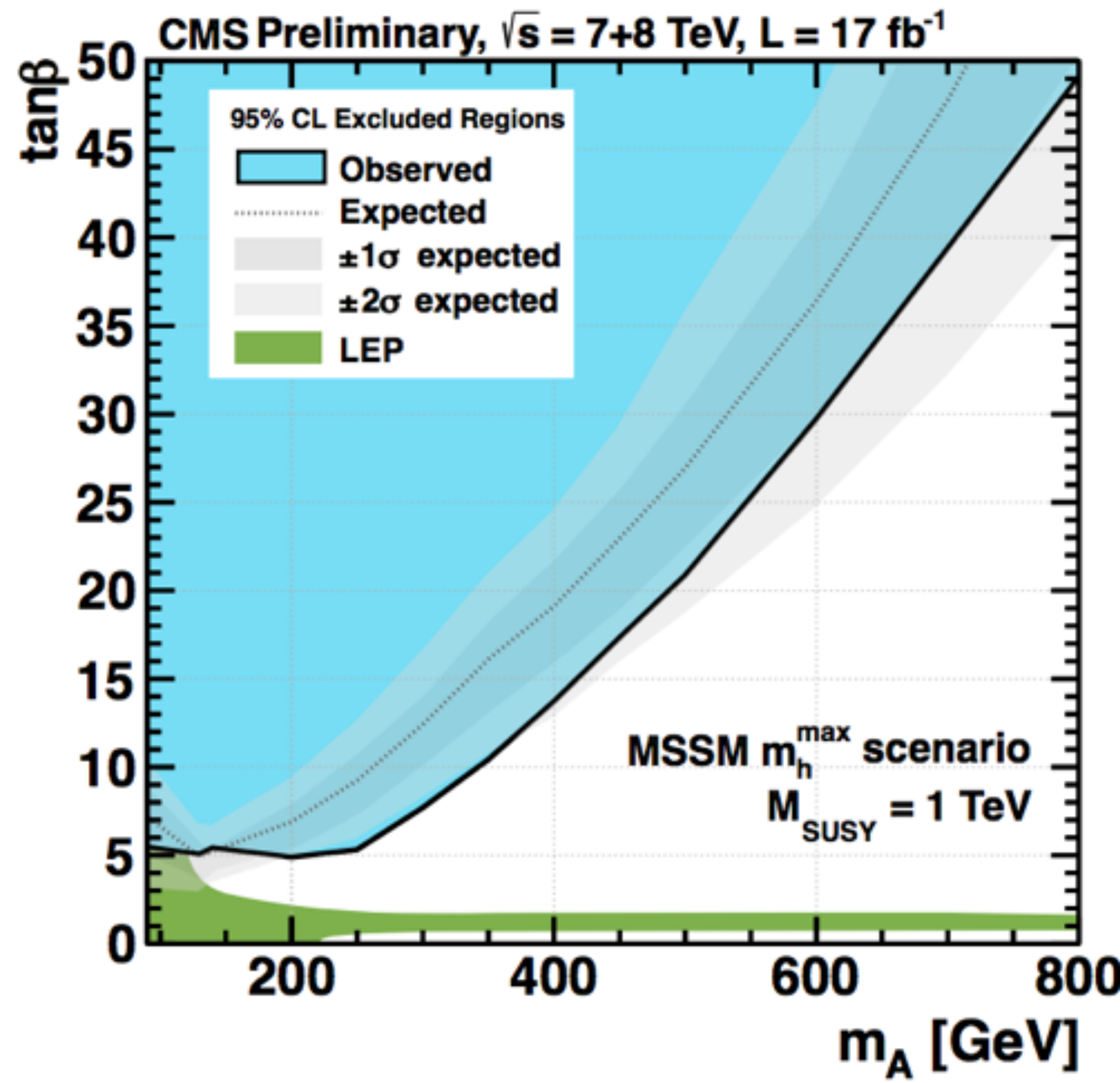
What’s misleading here





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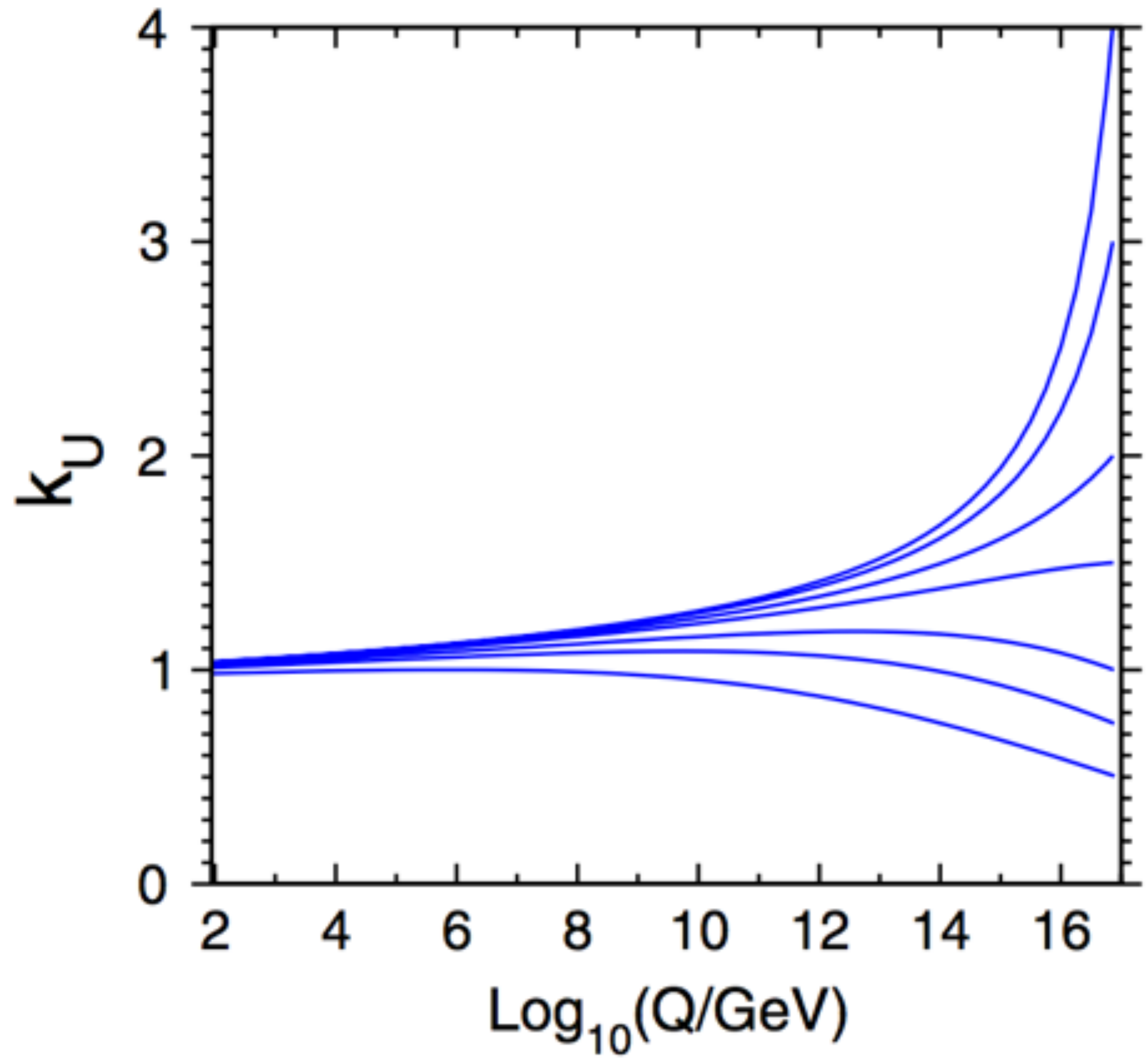
MSSM + Vectorlike fermions

S.Martin et al
SJ, Chun, Yoon

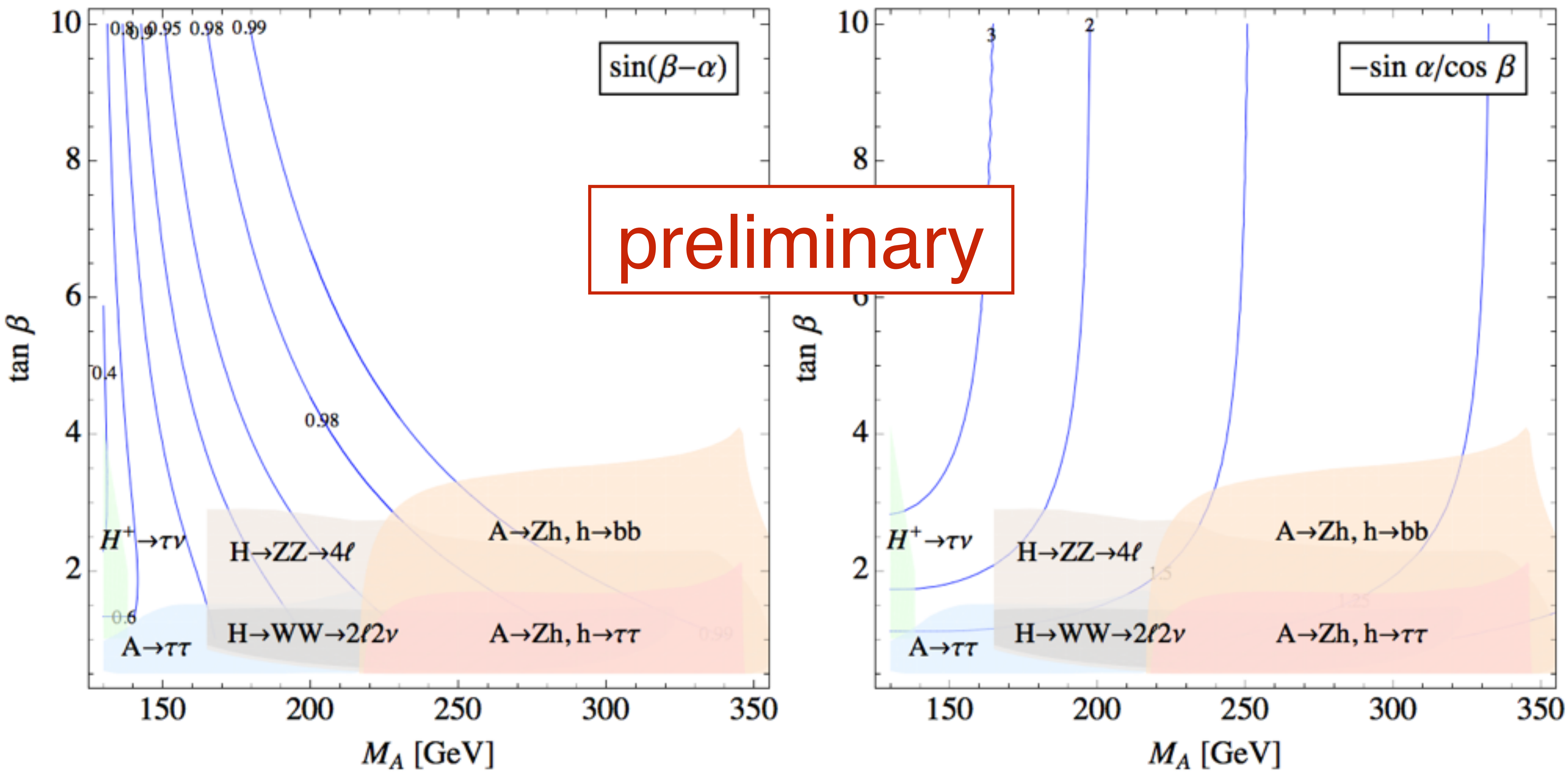
$$W = M_\Phi \Phi \bar{\Phi} + M_\phi \phi \bar{\phi} + k H_u \Phi \bar{\phi} - h H_d \bar{\Phi} \phi,$$



Naturally big enough Yukawa

Collider + Higgsicion

SJ, Chun, Yoon



Similar studies in MSSM have been carefully done by Carena, Haber, Low, Wagner, and Djouadi et al.

D-flat at low tan beta

$$V = (|\mu|^2 + m^2_{H_u})|H_u^0|^2 + (|\mu|^2 + m^2_{H_d})|H_d^0|^2 - (b\,H_u^0 H_d^0 + \text{c.c.})$$
$$+\frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.$$

- D-flat direction at tan beta = 1. Larger corrections needed.
- What I talk about is most important here—coinciding with rich heavy Higgs collider physics region.

Summary

- Heavy Higgs often not resonance peaks.

  => Pure dip search can partially resolve LHC challenges. Many more to come.
  => Applies to various new physics models.

- 125 GeV indicates a certain relation of alpha and beta.

  => Powerful (model dependent) Collider+Higgsicion.