Extra Higgs bosons and tanβ

P R E S E N T A T I O N

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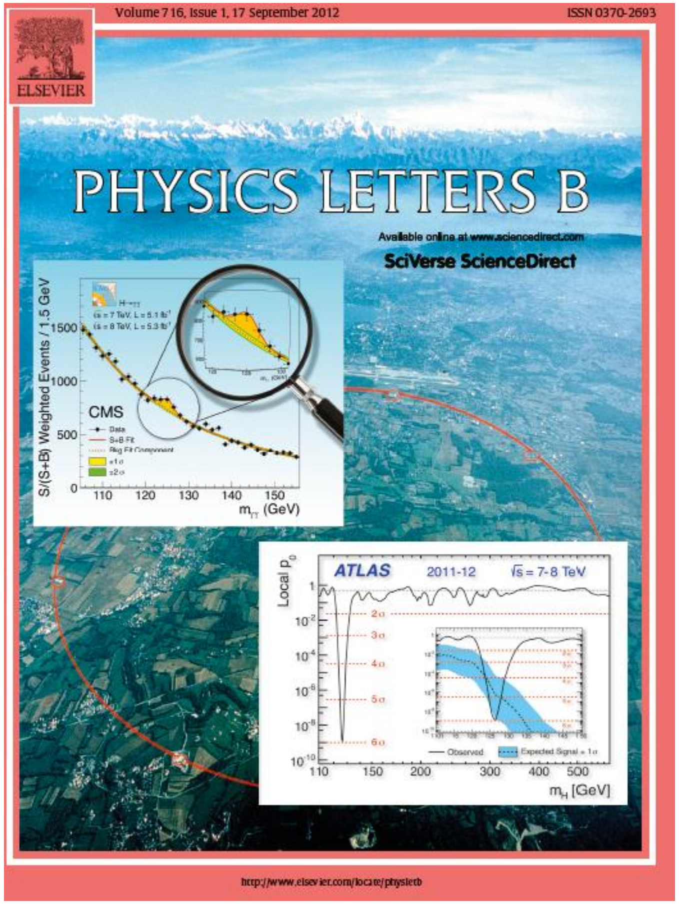
The Workshop of Future Linear Colliders (LCWS 2012), Arlington, Texas, USA
22-26/10/2012

Outline:

- Extended Higgs sector
- 2HDMs @ ILC
- Summary

Is it the end of story ?

- We found 125 GeV object !!



It is not the end of story

- Is it scalar ?
- Is it elementary ?
- Is it SM one?

- Hierarchy problem
- DM
- Neutrino mass
- Baryogenesis

- There is no reason to consider the minimal Higgs sector (SM)
- …

Guideline for Ext. Higgs sector

- Custodial symmetry: $$\rho = \frac{\sum_\alpha (I_\alpha(I_\alpha+1) - Y_\alpha^2) v_\alpha^2}{\sum_\beta 2Y_\beta^2 v_\beta^2}$$ Veltman (1977)

  - singlet/doublet VEV (or inert multiplets) preserves ρ=1

- Minimal SM
- (Main) contrib. to EWSB
- Yukawa int.
- (SUSY extension)

- DM candidate
- No contrib. to EWSB

- Minimal extension
- Mix w/ Higgs
- No contrib. to EWSB

  - higher rep. $(d \geq 3)$ has less contributions to EWSB

triplet, quadruplet, quintuplet, $\cdots$

- Neutrino mass generation
- No direct interaction w/ SM particles

Disclaimer

I could not cover all extensions

Focus on 2HDM (two Higgs doublet model)

- singlet/doublet VEV (or inert multiplets) preserves ρ=1

  - Minimal SM
  - (Main) contrib. to EWSB
  - Yukawa int.
  - (SUSY extension)

- higher rep. $(d \geq 3)$ has less contributions to EWSB

  triplet, quadruplet, quintuplet, $\cdots$

2HDM (two-Higgs-doublet model)

- **2HDM is an effective theory**

$$\Phi_1 = \begin{pmatrix} \omega_1^+ \\ \frac{v_1 + h_1 + i\, z_1}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \omega_2^+ \\ \frac{v_2 + h_2 + i\, z_2}{\sqrt{2}} \end{pmatrix}$$

- **Softly Z_2 broken 2HDM**

$$V_{2HDM} = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - \left(m_3^2 \Phi_1^\dagger \Phi_2 + \mathrm{H.c.} \right) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \mathrm{H.c.} \right]$$

- **5 Physical Higgs bosons** (assume CP inv.) m_3^2, λ_5 real

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \mathrm{R}(\alpha) \begin{pmatrix} H \\ h \end{pmatrix}, \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \mathrm{R}(\beta) \begin{pmatrix} z \\ A \end{pmatrix}, \begin{pmatrix} \omega_1^+ \\ \omega_2^+ \end{pmatrix} = \mathrm{R}(\beta) \begin{pmatrix} \omega^+ \\ H^+ \end{pmatrix}, \mathrm{R}(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

2HDM

- **Mass spectrum** (in the nearly SM-like limit)

$$m_h^2 \sim 2\lambda v^2$$ **~ 125 GeV**

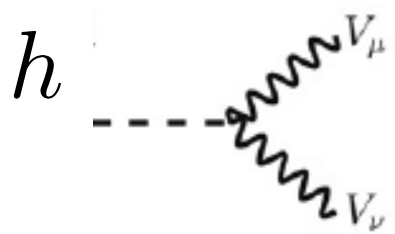
$$m_{H,A,H^\pm}^2 \sim M^2 + \frac{\lambda v^2}{2}$$ **~Not yet observed**

$$M^2 \equiv m_3^2/(\sin\beta\cos\beta)$$

M^2 characterizes non-decoupling effects

(Only important for scalar interactions, eg., hH^+H^- coupling in $h \to \gamma\gamma$)

- **gauge-gauge-Higgs coupling: sin(β−α)(~1)**



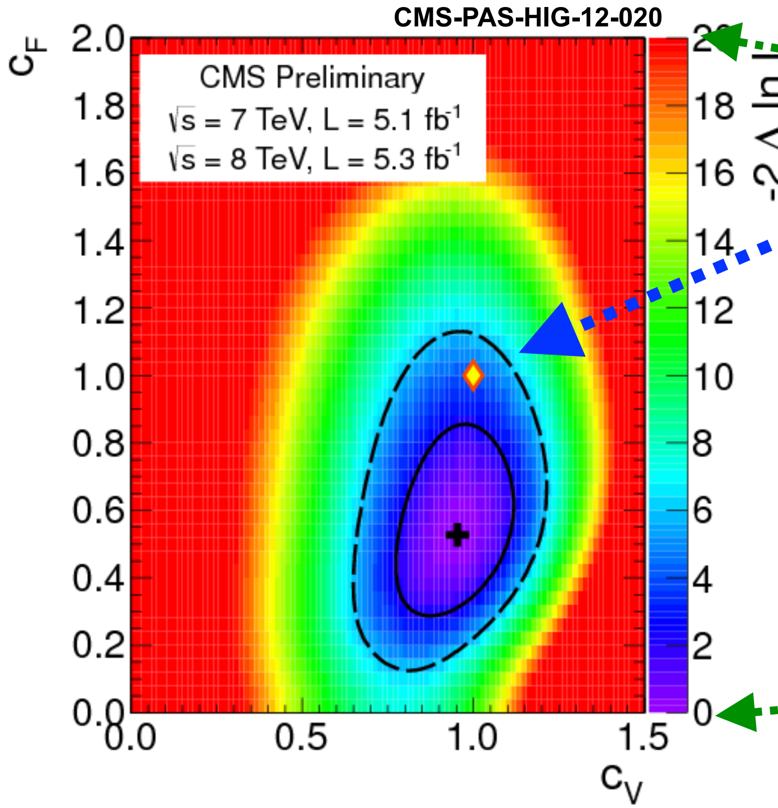
$$i\, g_V M_V \sin(\beta-\alpha) g_{\mu\nu}$$

- **tanβ (=v_2/v_1) is a free parameter**

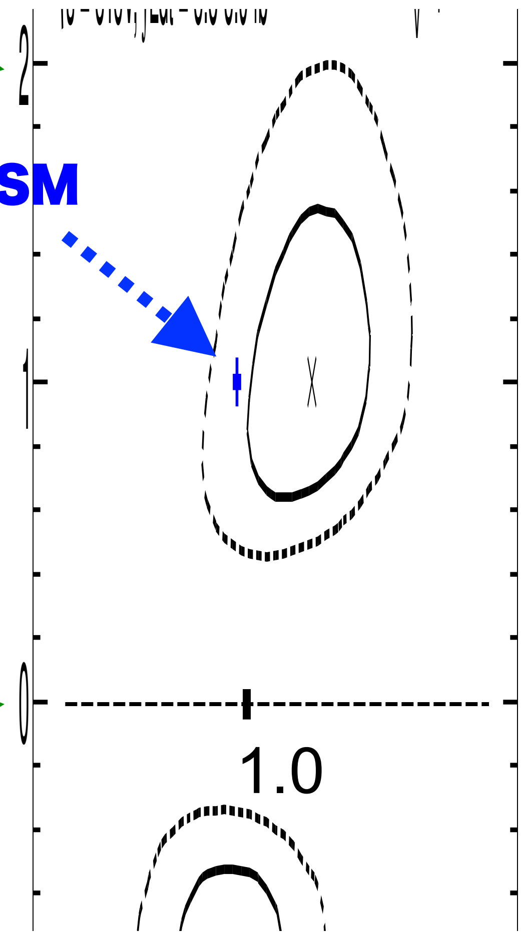
Is it SM-like?

- 125 GeV boson

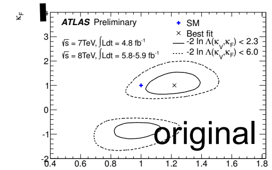
CMS-PAS-HIG-12-020



SM



ATLAS-CONF-2012-127

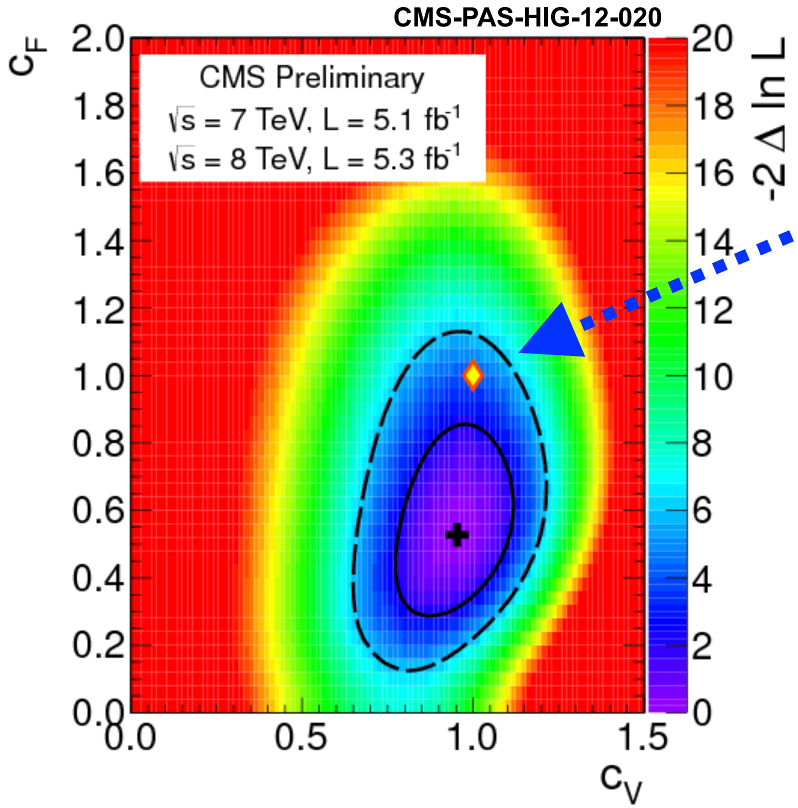


$C_F = Y/Y(SM)$
$C_V = g/g(SM) = \sin(\beta-\alpha)$

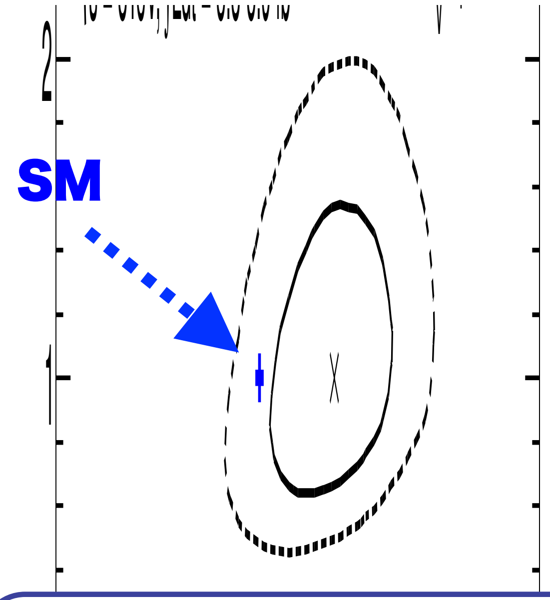
Is it SM-like?

- 125 GeV boson

CMS-PAS-HIG-12-020



SM



CMS: $C_F < 1$, $C_V \sim 1$
ATLAS: $C_F \sim 1$, $C_V > 1$

$C_V = \sin(\beta-\alpha)$ in 2HDM

sin(β−α) can be different from unity

(Of course, it is too early to say something)

SUSY Higgs search

- SUSY Higgs sector is the most popular 2HDM
  - Type-II Yukawa interaction w/ SUSY relation $\sin(\beta-\alpha) \simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$

$$\begin{cases} \Phi_u : u, \\ \Phi_d : d, \ell \end{cases}$$

$$\frac{g_{htt}}{g_{htt}^{\rm SM}} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) \simeq 1 - \frac{2m_Z^2}{m_A^2\tan^2\beta}$$

$$\frac{g_{hbb}}{g_{hbb}^{\rm SM}} = \frac{g_{h\tau\tau}}{g_{h\tau\tau}^{\rm SM}} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \simeq 1 + \frac{2m_Z^2}{m_A^2}$$

$$\frac{g_{Htt}}{g_{htt}^{\rm SM}} = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha) \simeq -\frac{1}{\tan\beta}$$

$$\frac{g_{Hbb}}{g_{hbb}^{\rm SM}} = \frac{g_{H\tau\tau}}{g_{h\tau\tau}^{\rm SM}} = \cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha) \simeq \tan\beta$$

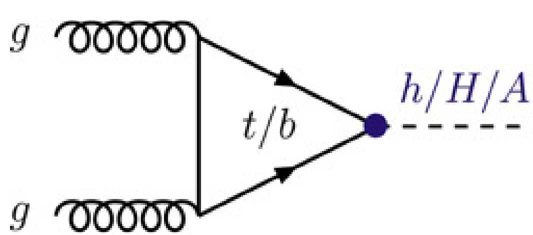
u $\quad$ d, ℓ

Yukawa int. for H, A, H^+ is suppressed/enhanced for large tanβ

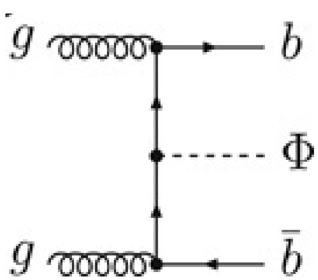
SUSY Higgs production @ LHC

$$\frac{g_{Hbb}}{g_{hbb}^{\mathrm{SM}}} = \frac{g_{H\tau\tau}}{g_{h\tau\tau}^{\mathrm{SM}}} \simeq \tan\beta$$

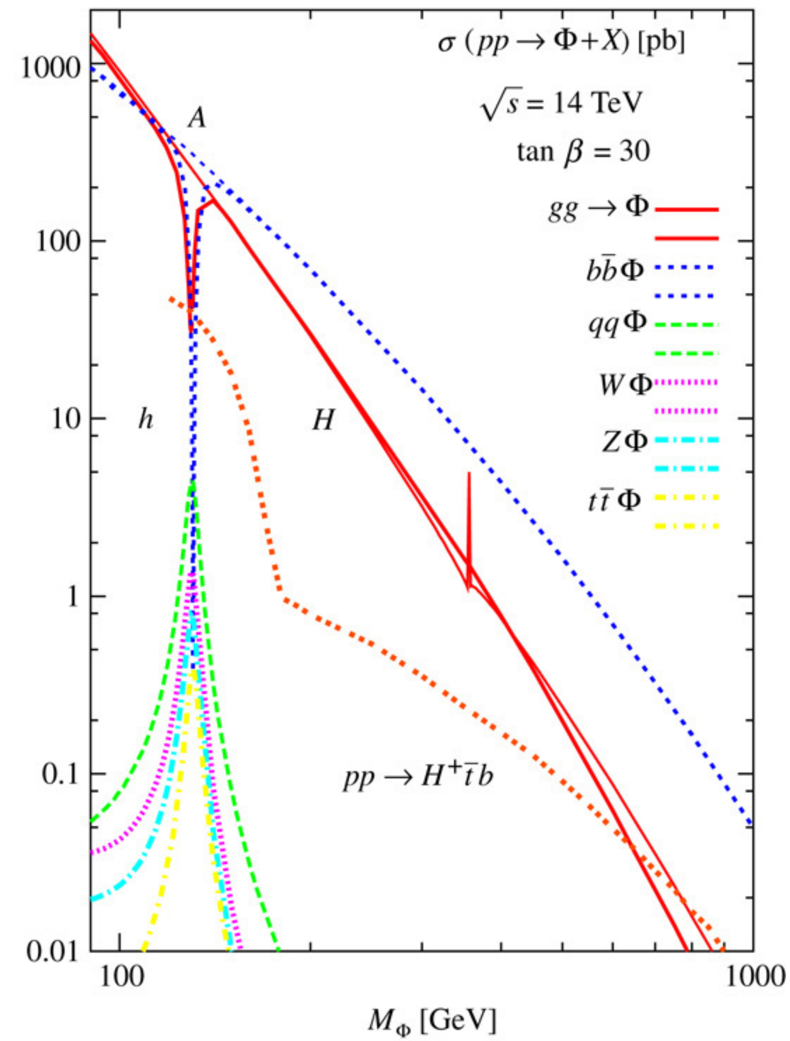
- gg→h/H/A wtith h/H/A→ττ



- bbh/H/A with h/H/A→ττ

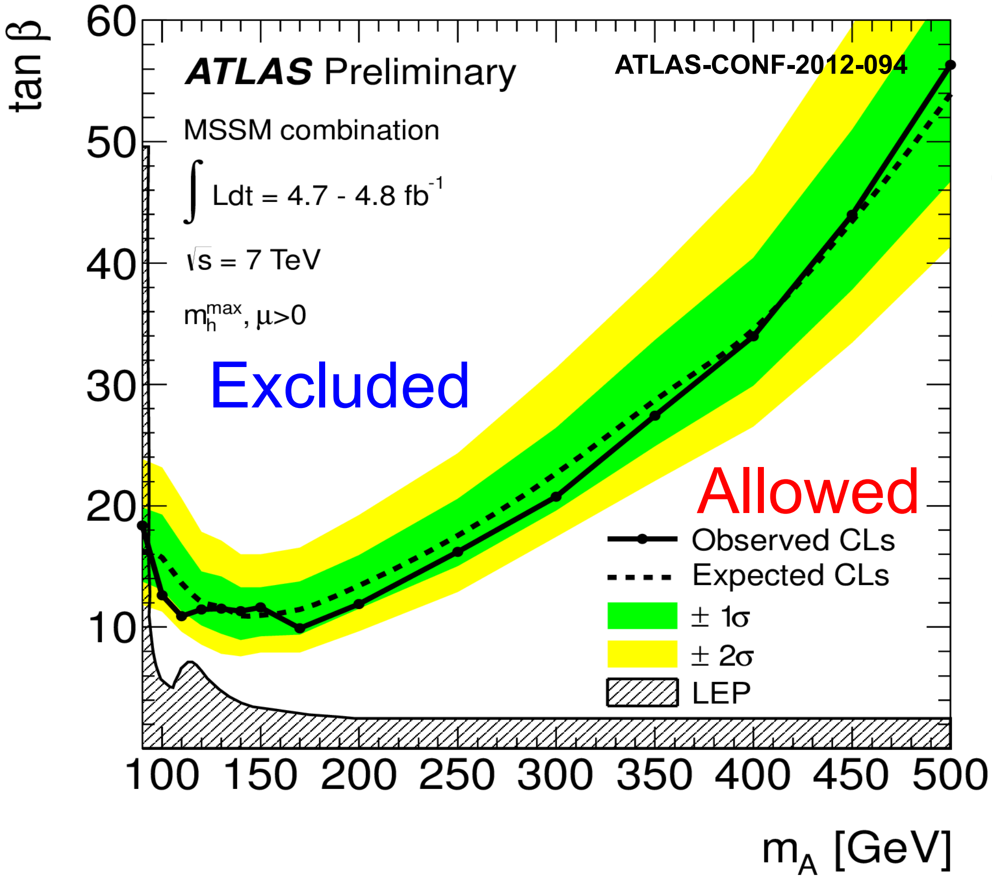


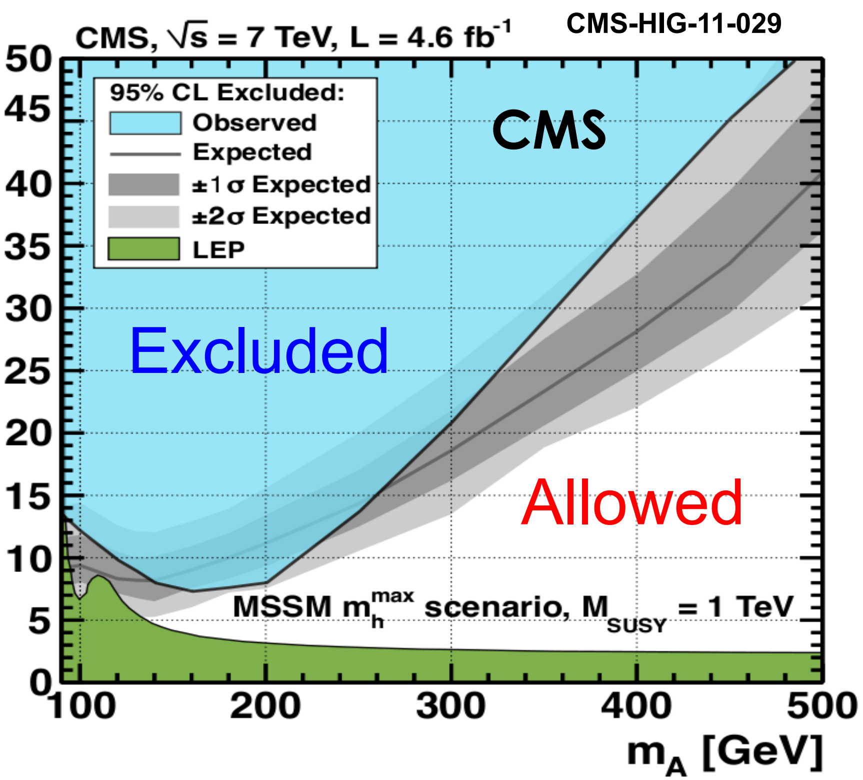
Djouadi (2008)



SUSY Higgs search @ LHC

- LHC results (H/A→ττ)



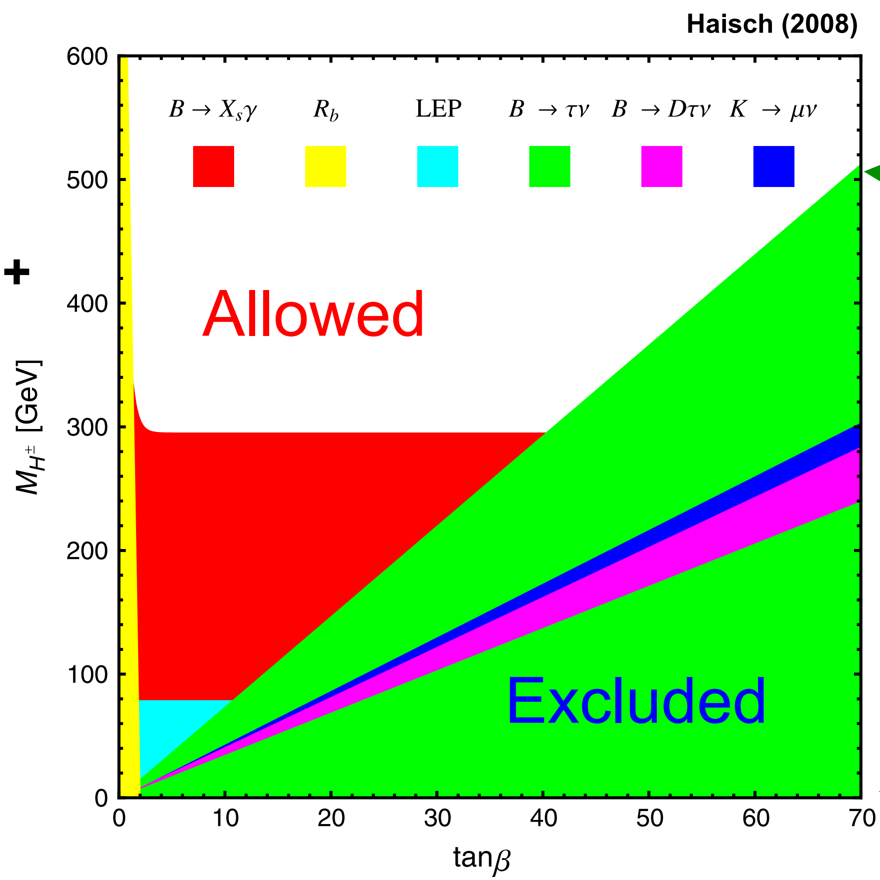


- Small m_A and large tanβ are constrained

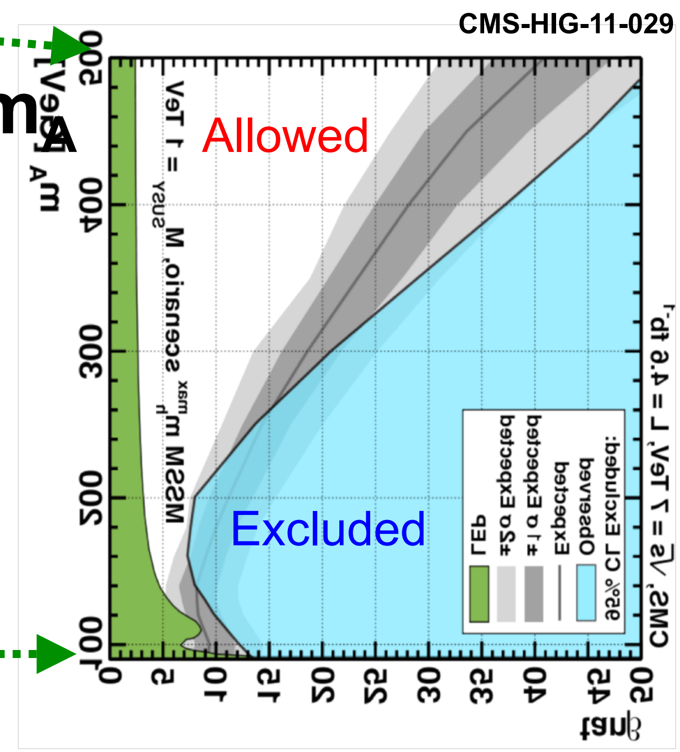
Other constrains on 2HDM-II

- Flavor data are competitive

m_{H+}

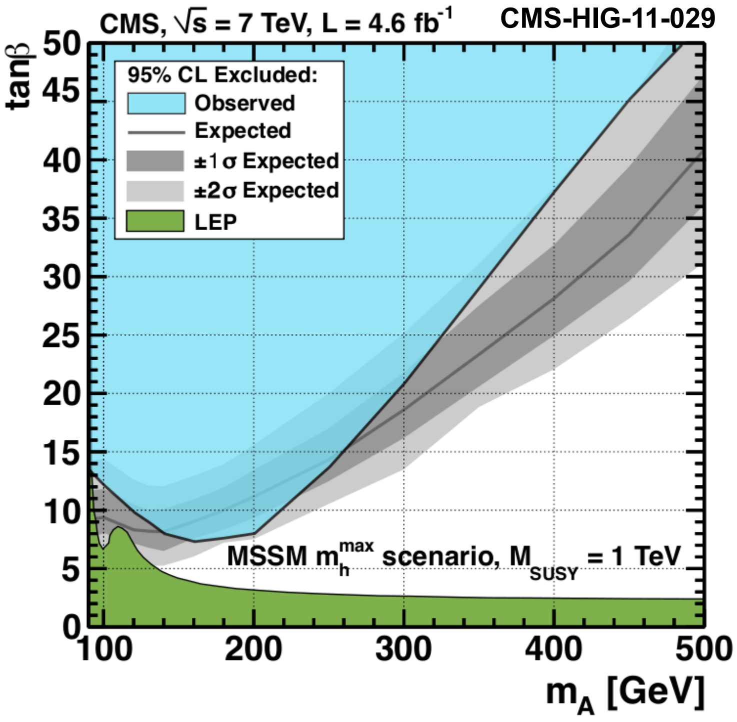


m_A



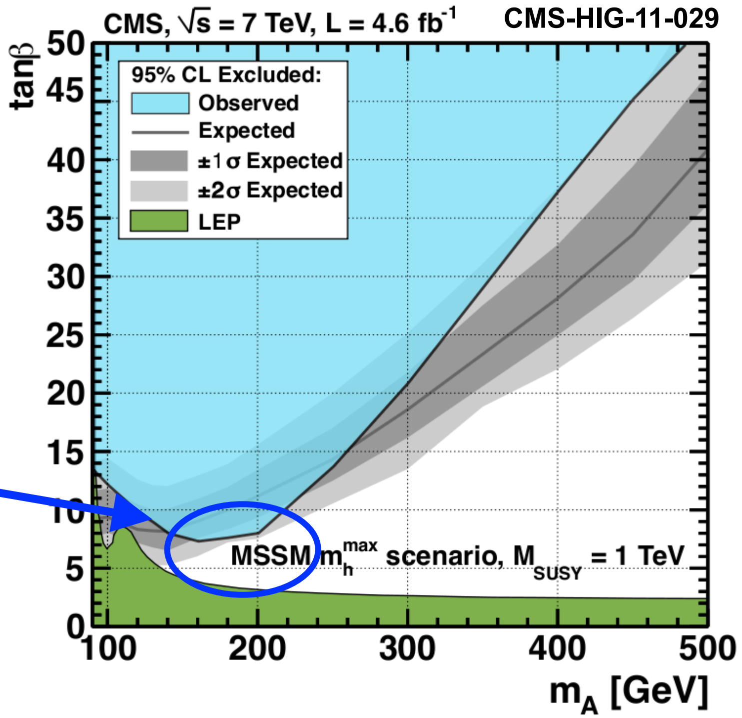
❖ **Small m_A, m_{H+} and large tanβ are constrained**

What can LC do?

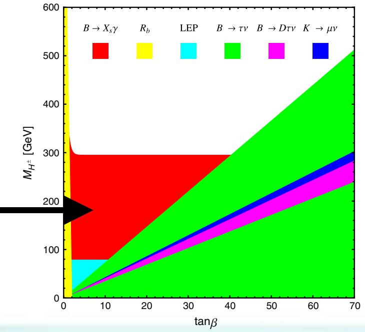


What can LC do?

- ❖ Small m_A w/ small $\tan\beta$

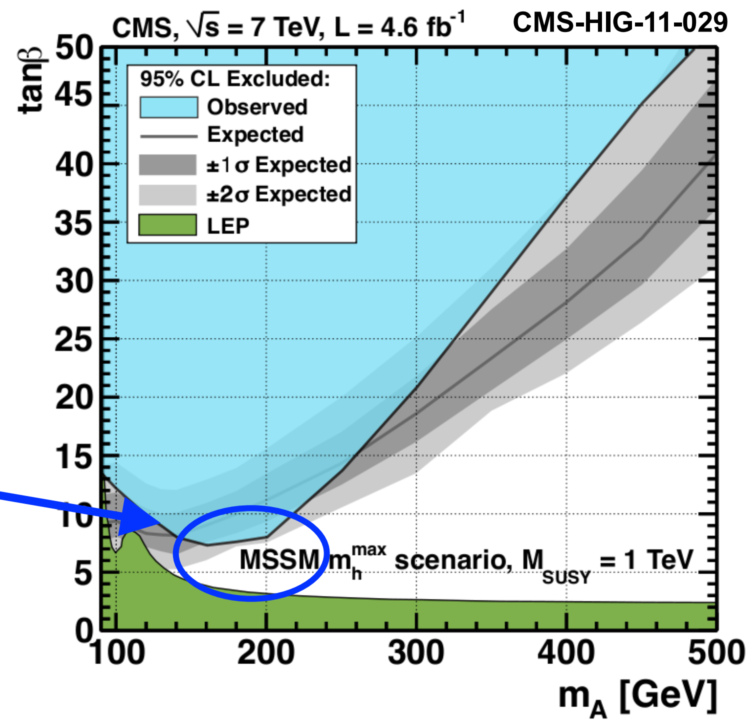


Cancellation mechanism is necessary for b→sγ



Haisch (2008)

What can LC do?

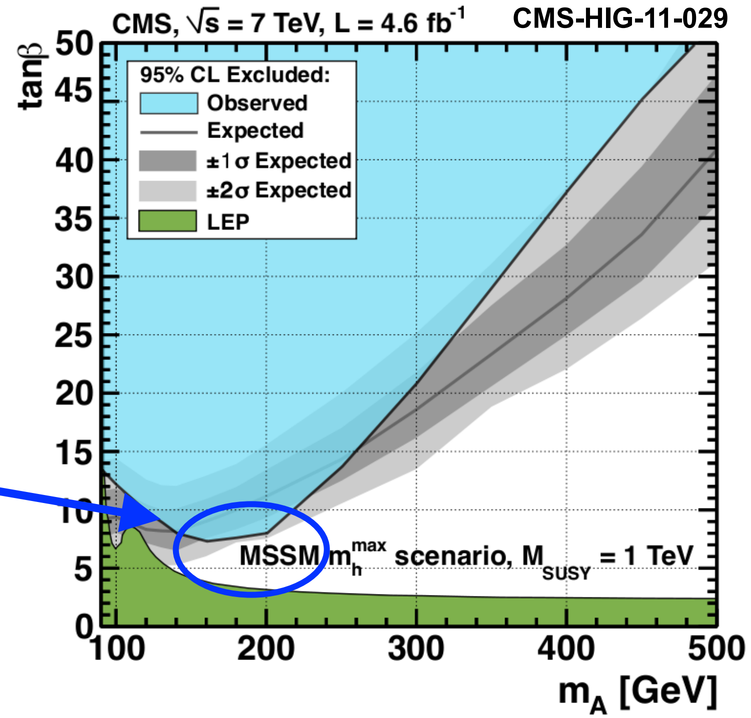


- Small m_A w/ small $\tan\beta$
- Leptophilic Higgs

Beat quark interaction !!
(Less LHC & B phys. Constraints)

What can LC do?

❖ Small m_A w/ small tanβ



❖ Leptophilic Higgs

Beat quark interaction !!
(Less LHC & B phys. Constraints)

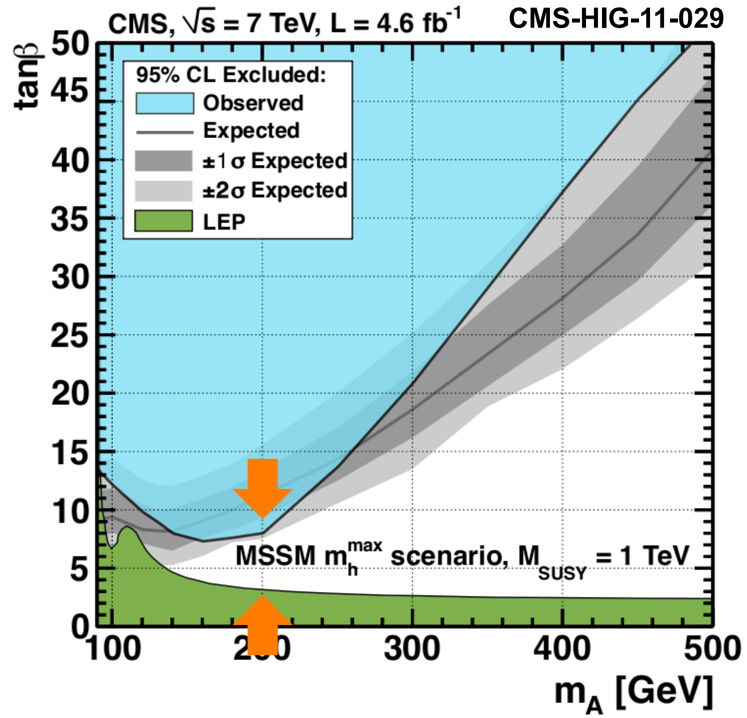
❖ Precision SM-like Higgs study

Small m_A w/ small tanβ

tanβ @ LHC

Once Extra Higgs

is discovered, then…



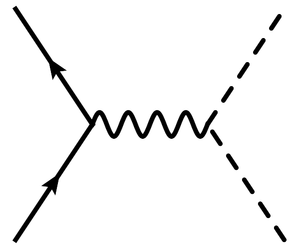
For example,

m_A=200GeV → 3 < tanβ < 8

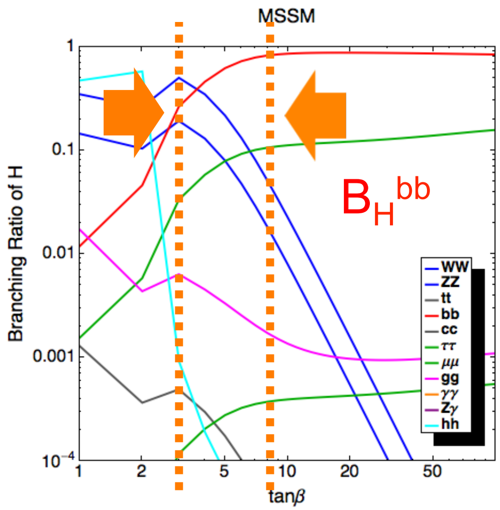
by assuming MSSM(2HDM-II)

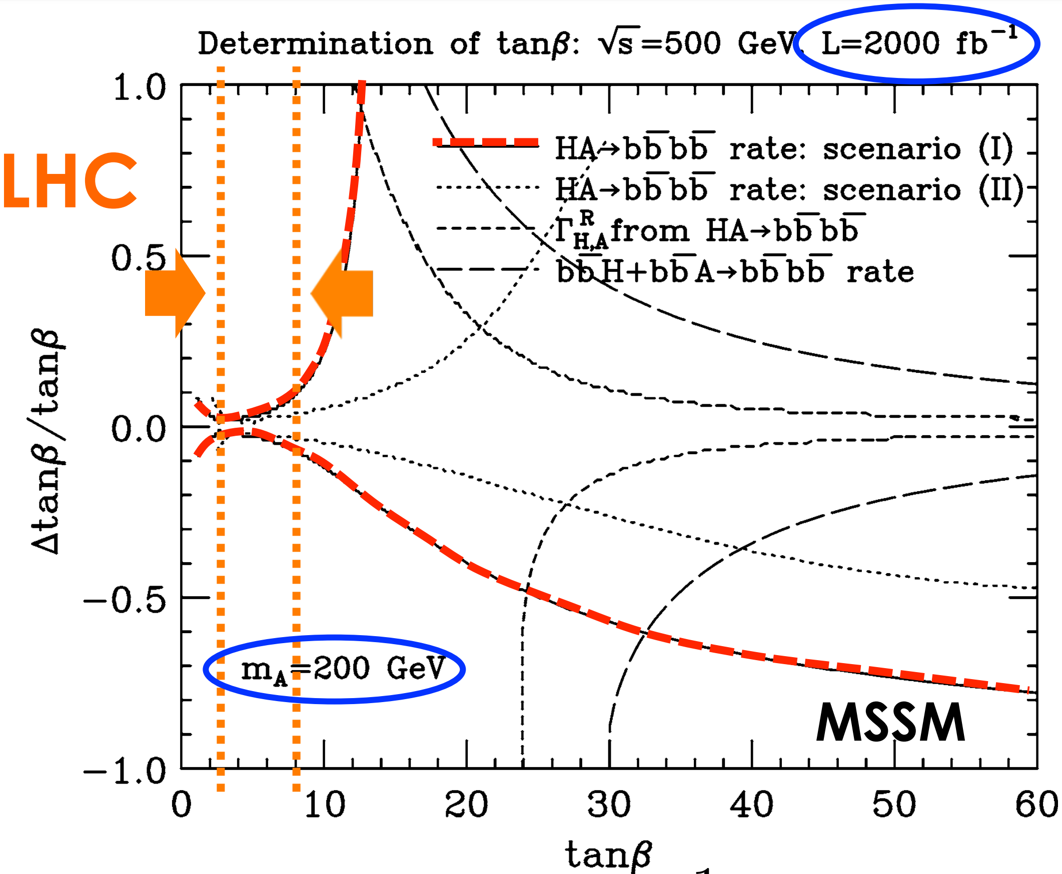
tanβ in MSSM @ LC

Gunion et.al. (2003)



HA production @ LC





$$\mathcal{B}_H^{bb} \simeq \frac{1}{1+\frac{0.0016}{0.012}+\frac{0.35+0.14}{0.012}\left(\frac{1}{1+t_\beta s_{\beta-\alpha}/c_{\beta-\alpha}}\right)^2}$$

$$\sim 1/\tan^4\beta$$

B_H^{bb} strongly depends on tanβ

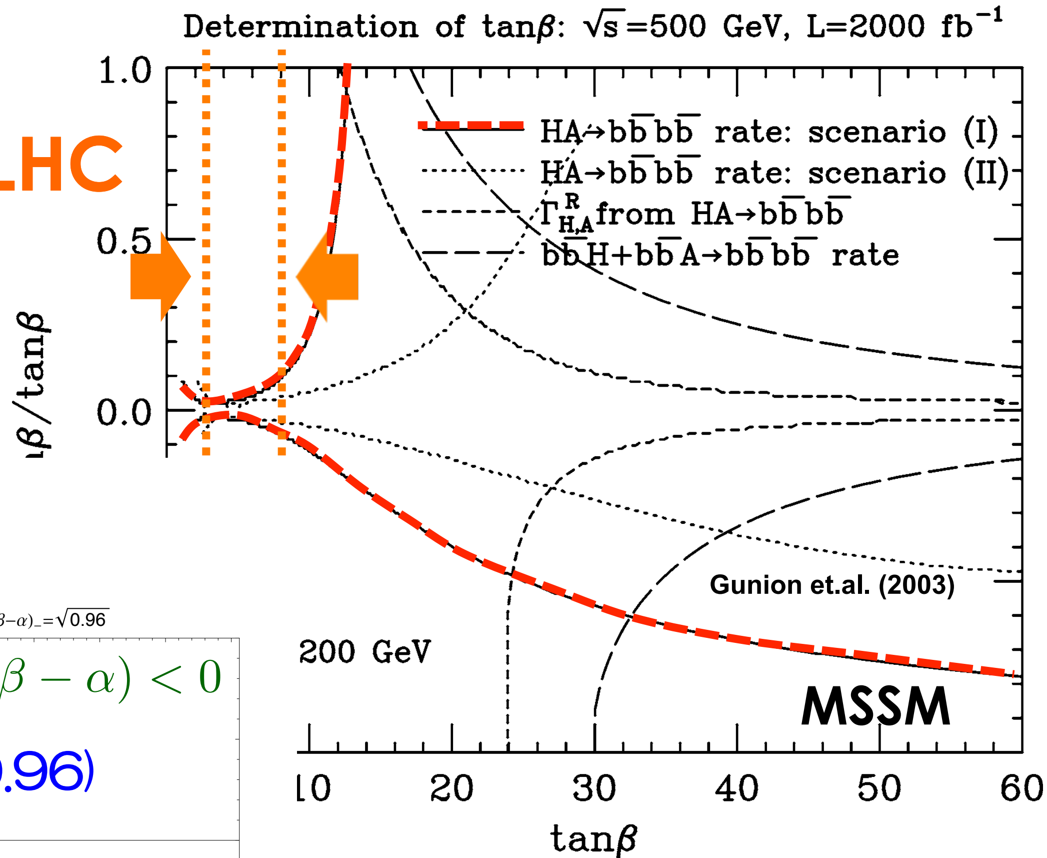
→ BR measurement can probe tanβ very precisely

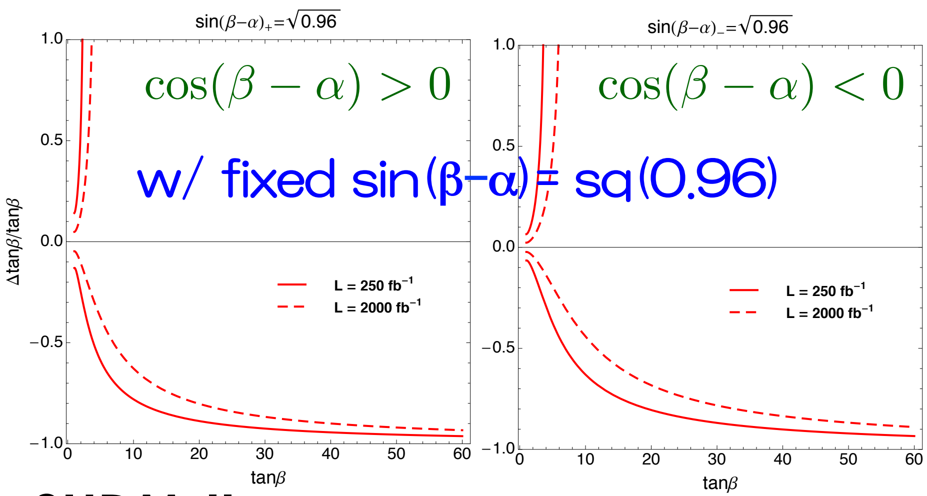
tanβ in 2HDM-II @ LC

$$\sin(\beta-\alpha) \not\simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$

LHC

- Without SUSY relation
- cos(β-α) can be positive
- Different tanβ dependence





$$\mathcal{B}_H^{bb} \simeq \frac{1}{1+\frac{0.0093}{0.078}+\frac{0.66+0.24}{0.078}\left(\frac{1}{1+t_\beta\sqrt{0.96/0.04}}\right)^2}$$

$$\sim 1/\tan^2\beta$$

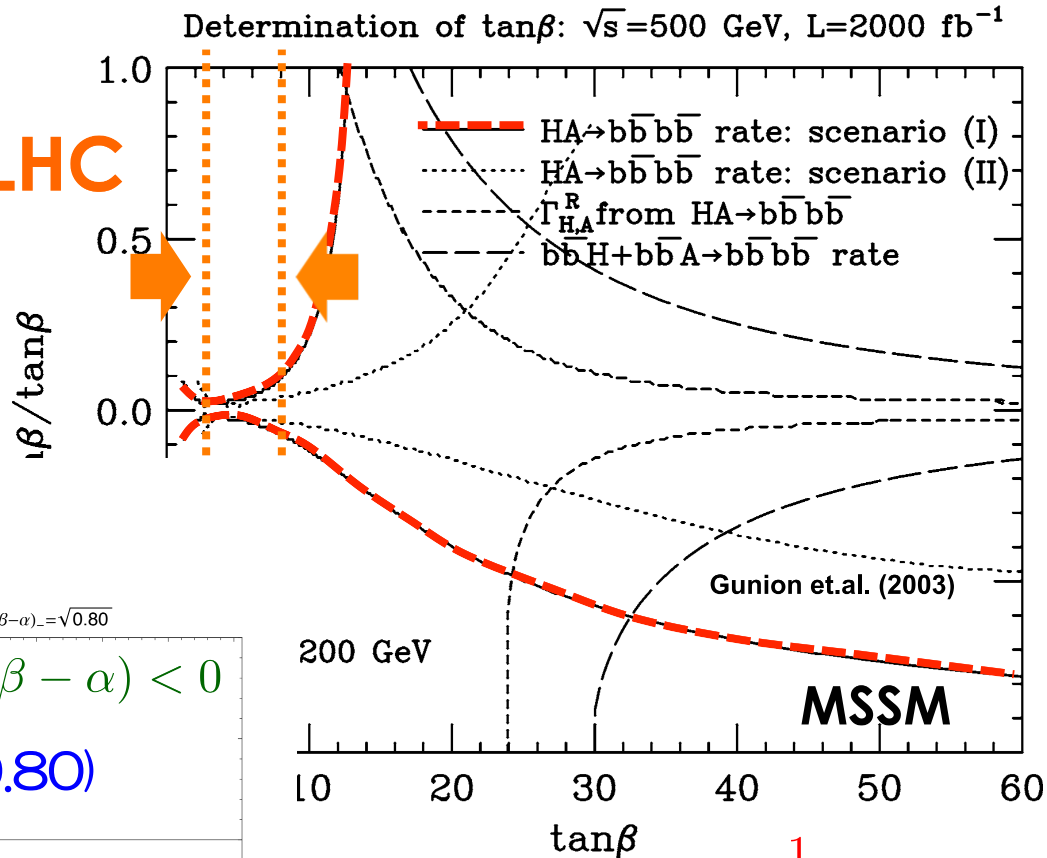
2HDM-II

Kanemura, KT, Yokoya, Yagyu

tanβ in 2HDM-II @ LC

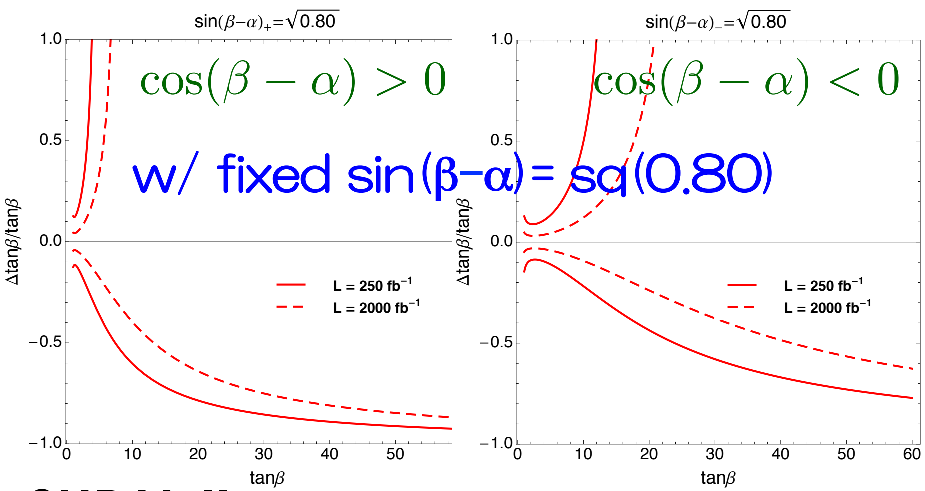
$$\sin(\beta-\alpha) \not\simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$

- Without SUSY relation
- cos(β−α) can be positive
- Different tanβ dependence



$$\frac{bb}{H} \simeq \frac{1}{1+\frac{0.0093}{0.078}+\frac{0.66+0.24}{0.078}\left(\frac{1}{1+t_\beta\sqrt{0.96/0.04}}\right)^2}$$

$$\sim 1/\tan^2\beta$$



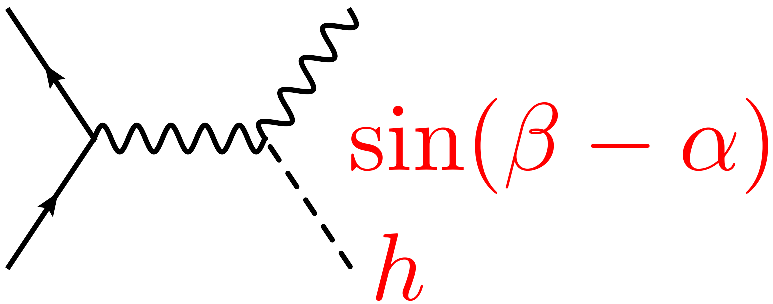
2HDM-II

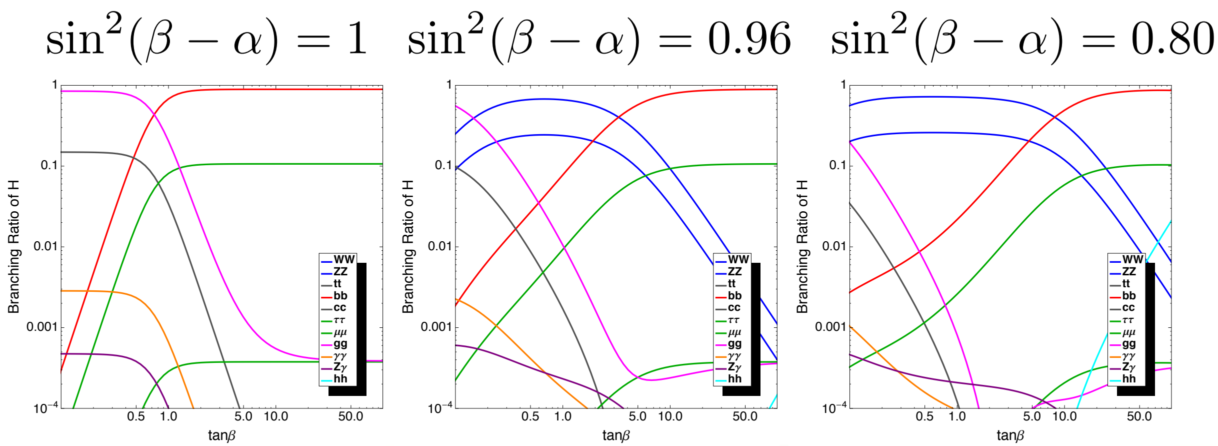
Kanemura, KT, Yokoya, Yagyu

tanβ @ LC

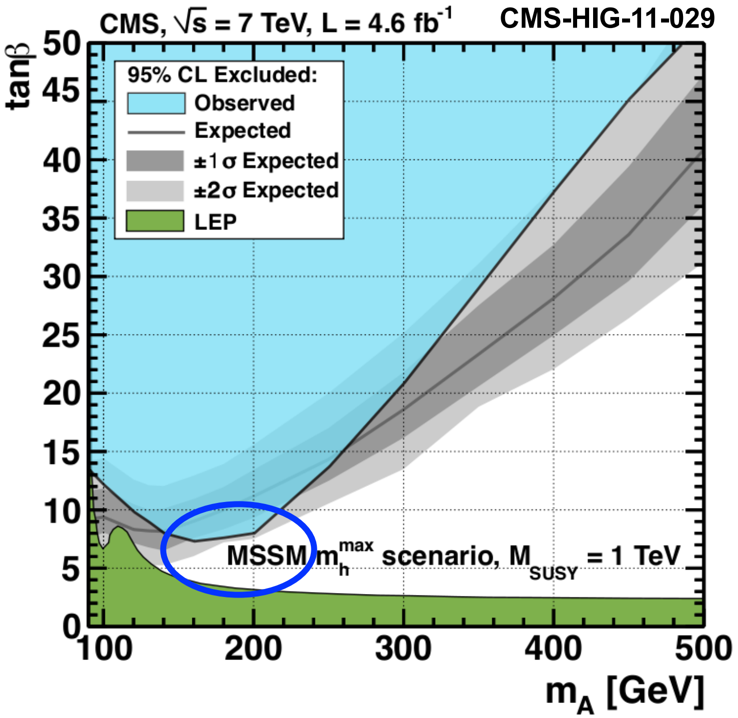
❖**Precise measurement of sin(β−α)**
makes BR prediction better in 2HDMs

→ **Key observable for determining tanβ**





What can LC do?



- ❖ Small mA w/ small tanβ
- ❖ Leptophilic Higgs

  Beat quark interaction !!
  (Less LHC & B phys. Constraints)
- ❖ Precision SM-like Higgs study

Leptophilic 2HDM

FCNC problem of 2HDM

- **Flavor changing neutral current (FCNC)**

$$\mathcal{L} = \overline{L}\,(Y_{\ell 1}\Phi_1 + Y_{\ell 2}\Phi_2)\,\ell_R + \text{H.c.}$$

Yukawa int. is not simultaneously diagonalized with mass matrix.

→ Generate **tree level FCNC**(, highly constrained by data)

- **Adding extra Z2 sym. to avoid FCNC**

$$\begin{array}{ll} \Phi_1 \to +\Phi_1, & L \to +L \\ \Phi_2 \to -\Phi_2, & \ell_R \to -\ell_R \end{array}$$

$$\mathcal{L} = \overline{L}\,(\quad\; + Y_{\ell 2}\Phi_2)\,\ell_R + \text{H.c.}$$

4 types of Yukawa int.

- 4 independent combinations of Z2 charges

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q, L
Type-I	+	-	-	-	-	+
Type-II	+	-	-	+	+	+
Type-X	+	-	-	-	+	+
Type-Y	+	-	-	+	-	+

- **Type-II: 2HDM structure in SUSY**

$$\mathcal{L} = +\overline{Q} Y_u u_R H_u + \overline{Q} Y_d d_R H_d + \overline{L} Y_\ell \ell_R H_d + \text{H.c.}$$

4 types of Yukawa int.

- 4 independent combinations of Z2 charges

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q, L
Type-I	+	-	-	-	-	+
Type-II	+	-	-	+	+	+
Type-X	+	-	-	-	+	+
Type-Y	+	-	-	+	-	+

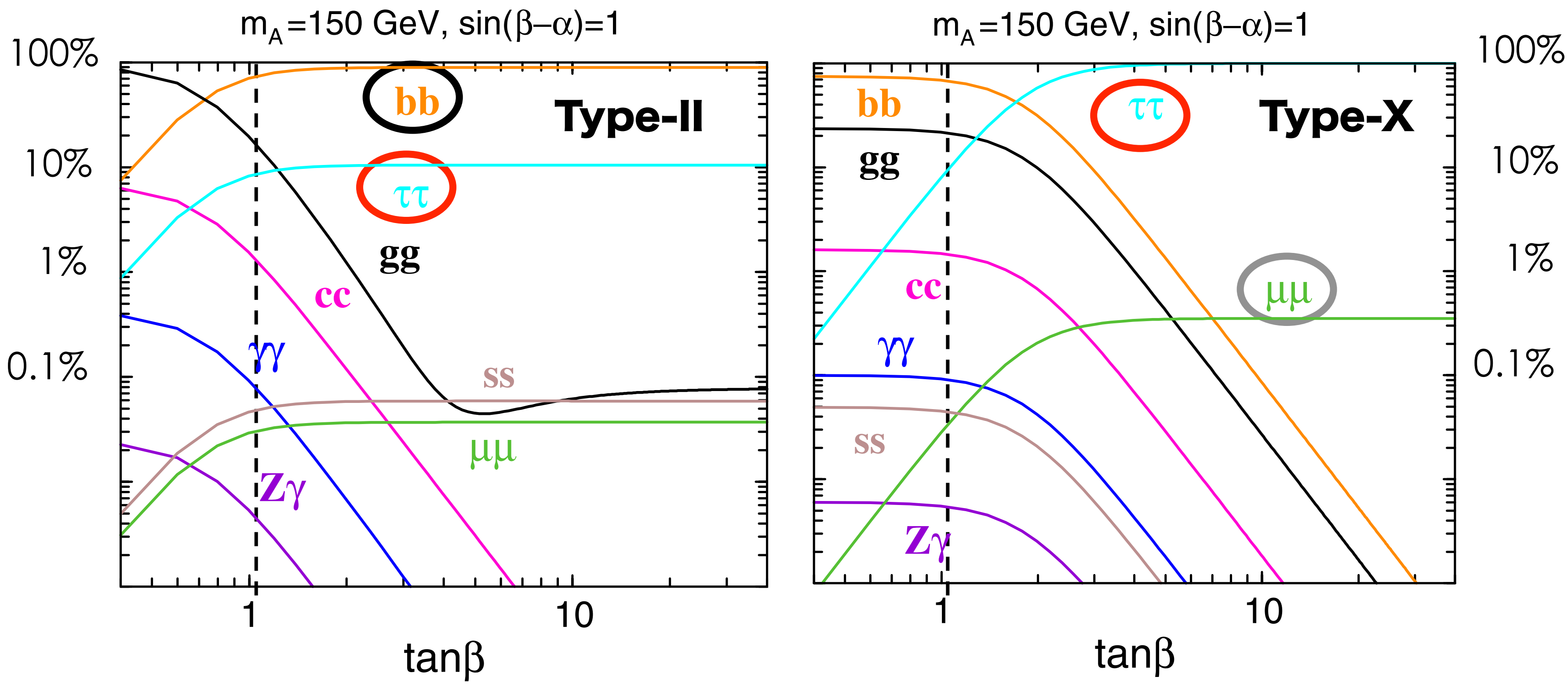
- **Type-X: Leptophilic 2HDM for tanβ>1**

$$\mathcal{L} = +\overline{Q}Y_u u_R H_q + \overline{Q}Y_d d_R H_q + \overline{L}Y_\ell \ell_R H_\ell + \text{H.c.}$$

Higgs doublets distinguish quarks and leptons!!

Higgs decays in 2HDMs

Aoki, Kanemura, KT, Yagyu (2009)



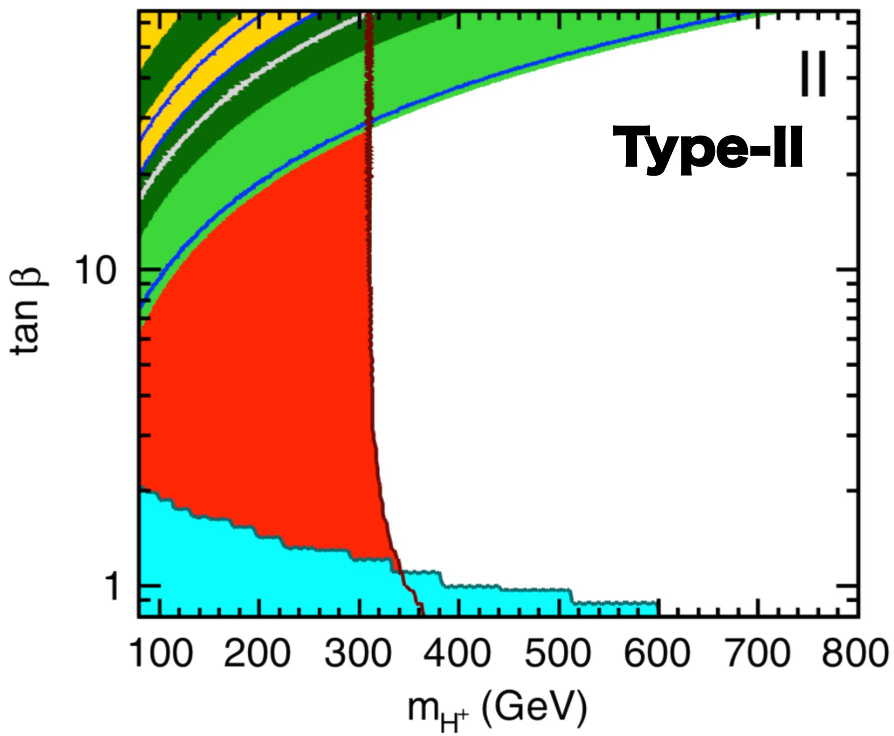
2HDM-X: Enhance leptonic Yukawa int. by tanβ

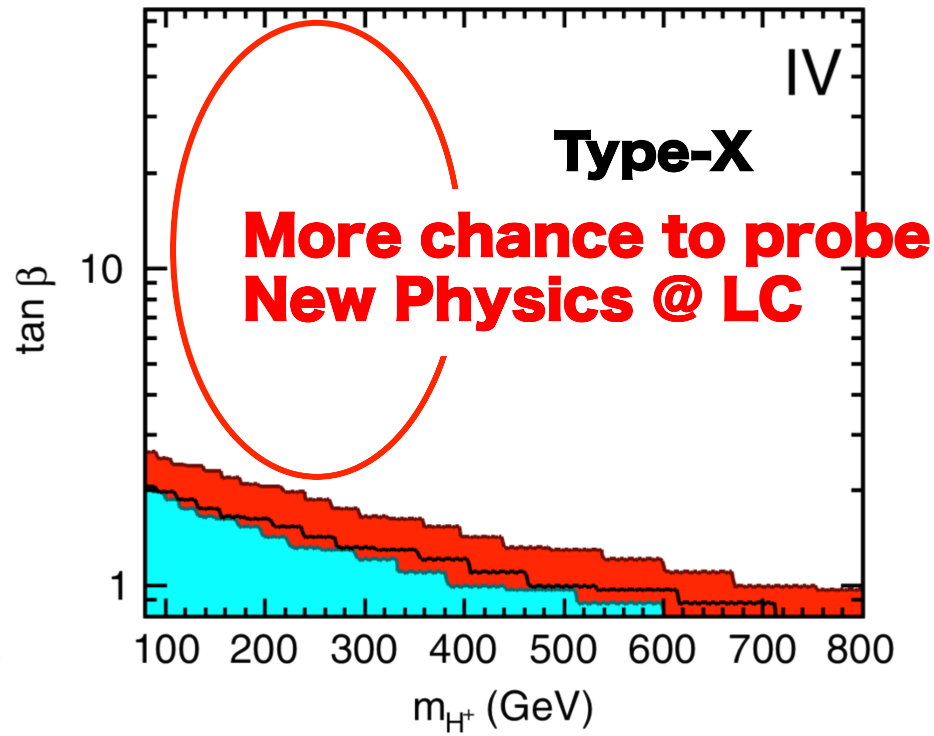
- **More than 99% of H/A decay into ττ**
- **Sizable μμ [$(m_\mu/m_\tau)^2=1/300$] mode**

Flavor constraint on 2HDM-X

- No LHC results, and weaker flavor constraints

Mahmoudi, Stal (2009)



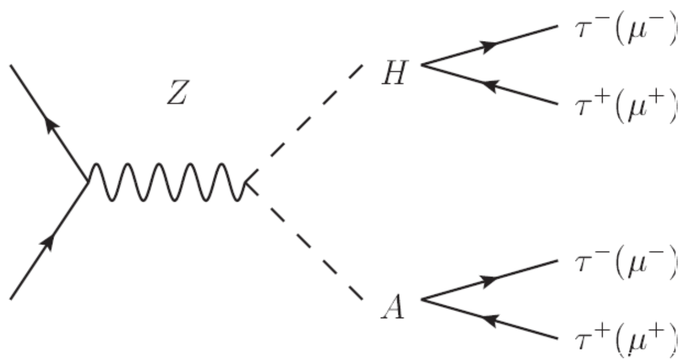


small m_{H+} and
very large $\tan\beta$ are allowed

2HDM-X @ colliders

Kanemura, KT, Yokoya (2012)

- DY production with leptonic decay modes

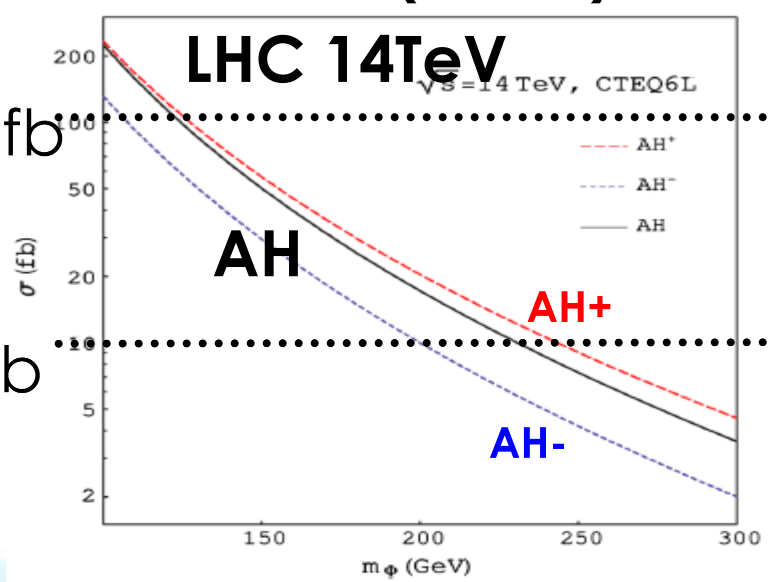


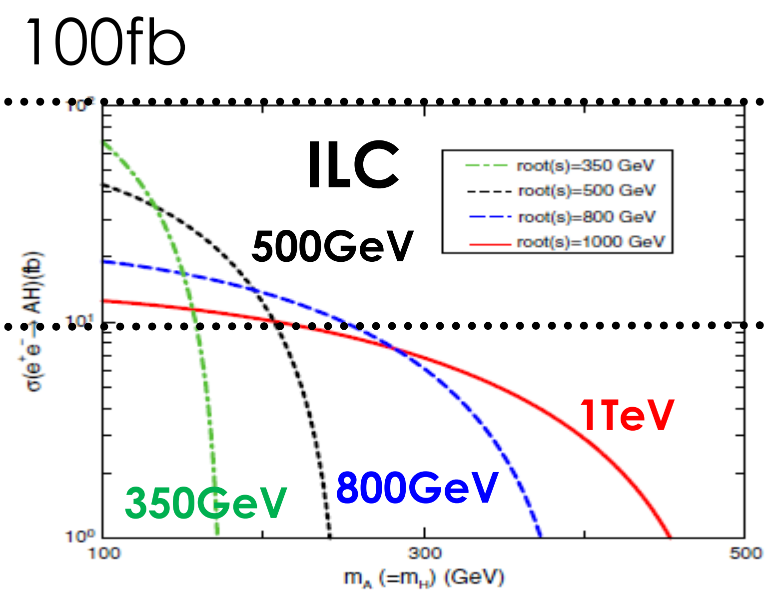
Multi-tau signature

4τ: more than 99%

$2\mu2\tau$: $\sigma(4\tau)$ x 1/300 x 2!

Cross sections are O(10-100)fb

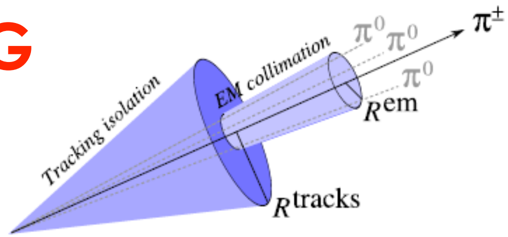




2HDM-X @ LHC

Kanemura, KT, Yokoya (2012)

High multiplicity of tau jet reduces BG



τ ID is important

(1 or 3 prong, narrow cone, less QCD activity)

→ The excess can be seen!!

An example for $4\tau \to 4\tau^h$
m_A=130GeV, m_H=170GeV

$4\tau_h$ event analysis	HA	$\phi^0 H^\pm$	VV	$t\bar{t}$	V+jets	s/b	S (100 fb^{-1})
Pre-selection	324.	52.8	147.	797.	5105.	0.1	4.7
$p_T^{\tau_h} > 40$ GeV	67.2	4.9	2.0	14.7	21.7	1.9	9.4
$\not{E}_T > 30$ GeV	48.6	4.4	1.1	7.6	10.4	2.8	9.3
$H_T^{\rm jet} < 50$ GeV	34.2	3.4	0.5	0.8	8.2	3.9	8.7
$H_T^{\rm lep} > 350$ GeV	27.6	2.7	0.4	0.5	3.1	7.5	9.3

But, mass reconstruction is difficult due to missing ν's

→ "HA→2μ2τ" is reconstructable (w/ collinear approx.)

Huge lumi. is necessary due to $\mathcal{B}^{\mu\mu}/\mathcal{B}^{\tau\tau} \times 2! \simeq 0.7\%$

2HDM-X @ LC

Kanemura, KT, Yokoya (2012)

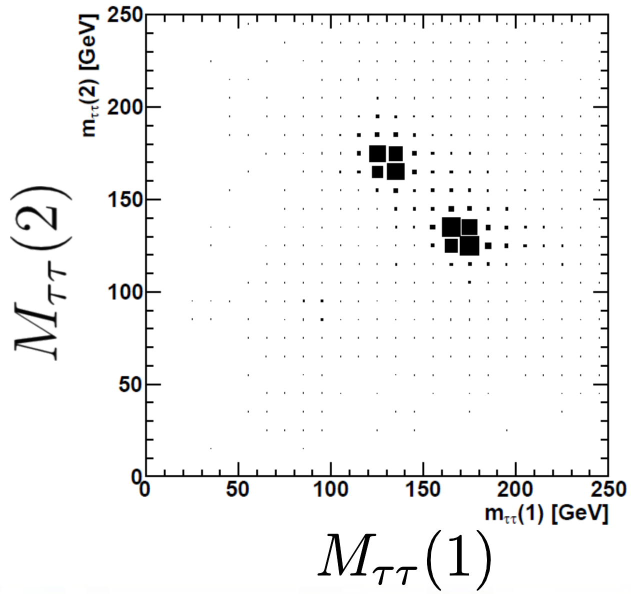
- **4τ momontum are fully reconstructable from taujets & missing ν's** [We know initial 4 momenta @ LC (only p_T @ LHC)]

An example for 4τ → 4τh
m_A=130GeV, m_H=170GeV

for 5σ ~ 2/fb @ LC

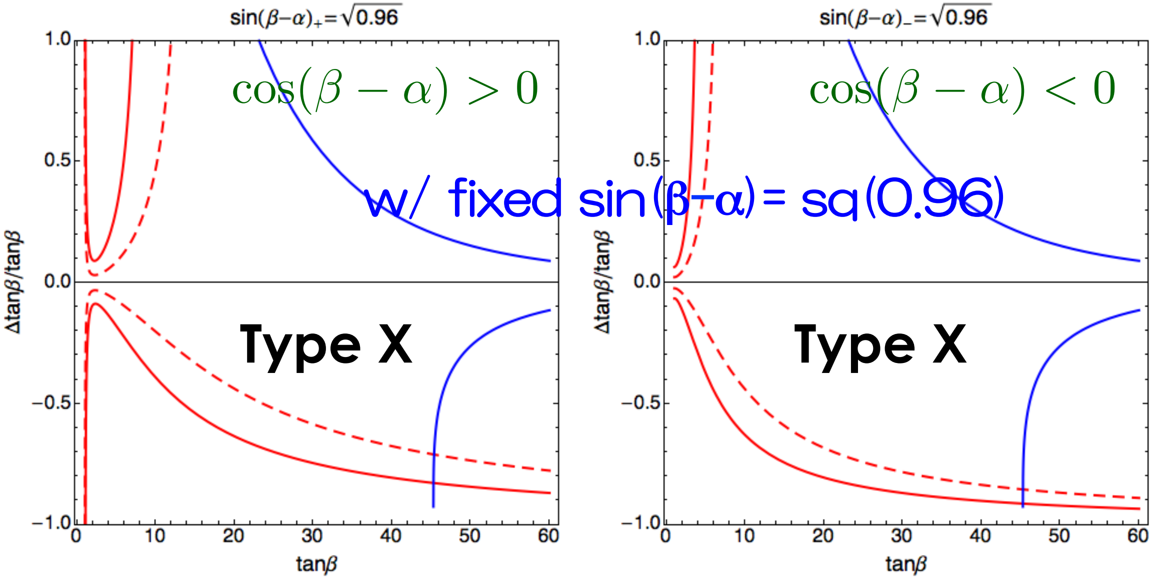
$4\tau_h$ event analysis	HA	VV	$t\bar{t}$	S (100 fb^{-1})
Pre-selection	300.	10.6	1.2	38.
$0 \leq z_{1-4} \leq 1$	251.	6.2	0.1	38.
$(m_Z)_{\tau\tau} \pm 20$ GeV	238.	1.8	0.	43.

Not only mass reconstruction, but also **directly probe pair production!!**



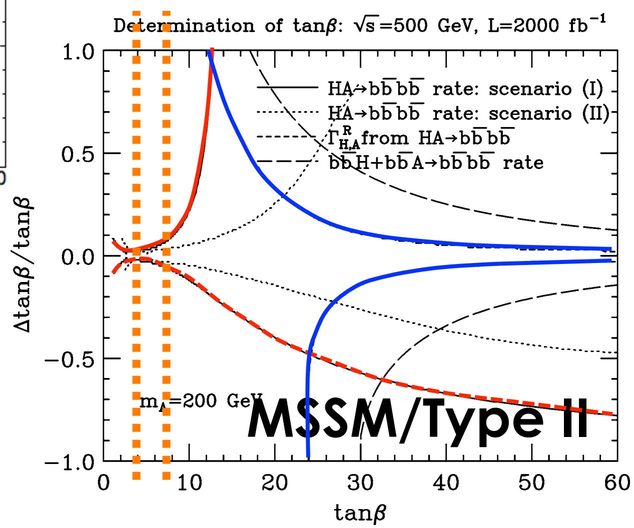
tanβ in 2HDM-X

- BR measurement w/ 4τ final states
- Width measurement of H/A: $\Gamma^{H,A}_{\rm tot} \simeq \frac{G_F m_{H,A} m_\tau^2}{4\sqrt{2}\pi} \tan^2\beta$



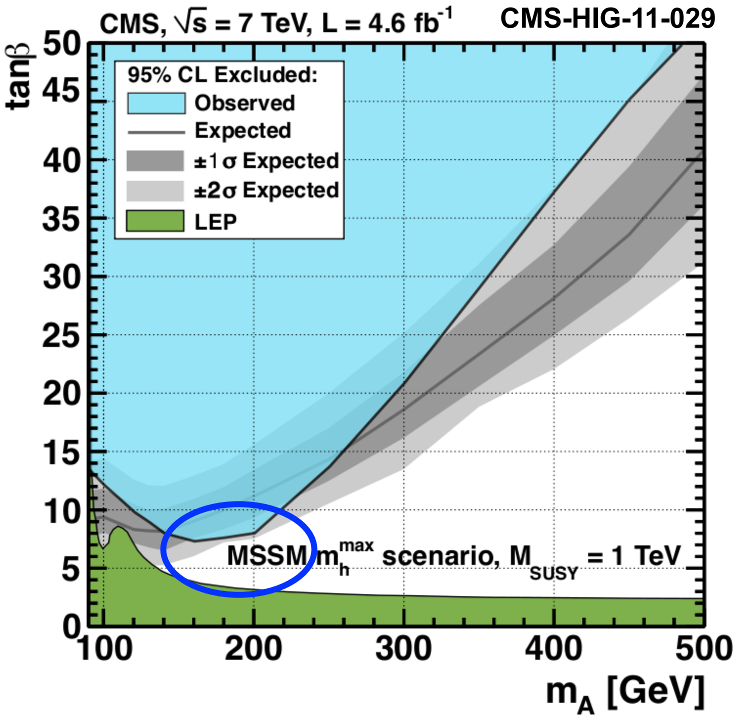
Wider parameter regions
should be examined by LC

Gunion et.al. (2003)



What can LC do?

- ❖ Small mA w/ small tanβ



- ❖ Leptophilic Higgs

  Beat quark interaction !!
  (Less LHC & B phys. Constraints)

- ❖ Precision SM-like Higgs study

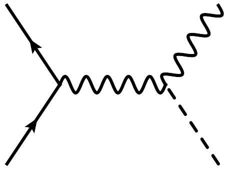
Precision SM-like Higgs study

SM-like Higgs in SUSY

- SUSY Higgs sector is the most popular 2HDM
  - Type-II Yukawa interaction w/ SUSY relation

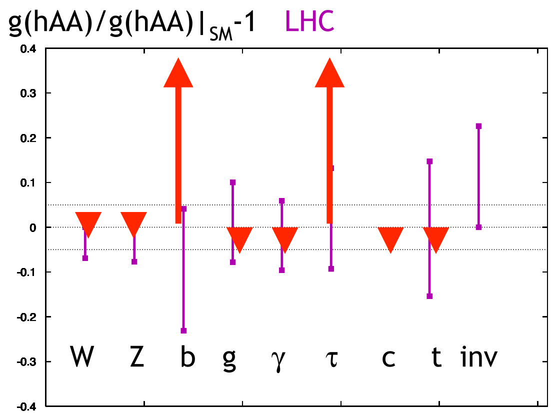
$$\begin{cases} \Phi_u : u, \\ \Phi_d : d, \ell \end{cases}$$

$$\sin(\beta-\alpha) \simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta} \approx 1$$

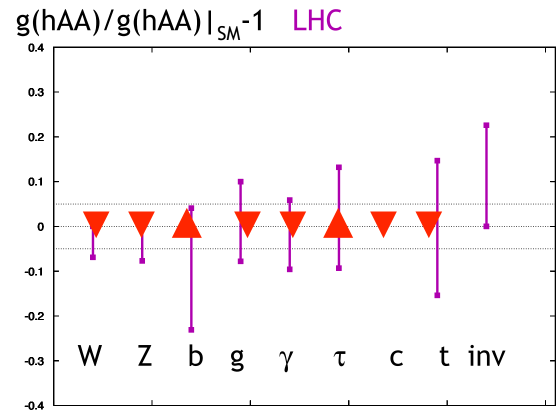


$$\frac{g_{hbb}}{g_{hbb}^{\rm SM}} = \frac{g_{h\tau\tau}}{g_{h\tau\tau}^{\rm SM}} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \simeq 1 + \frac{2m_Z^2}{m_A^2}$$

$$\frac{g_{htt}}{g_{htt}^{\rm SM}} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) \simeq 1 - \frac{2m_Z^2}{m_A^2 \tan^2\beta}$$



m_A=200GeV
w/ tanβ=5



m_A>>m_Z
w/ tanβ=5

BG figure is taken from 1207.2516 by Peskin

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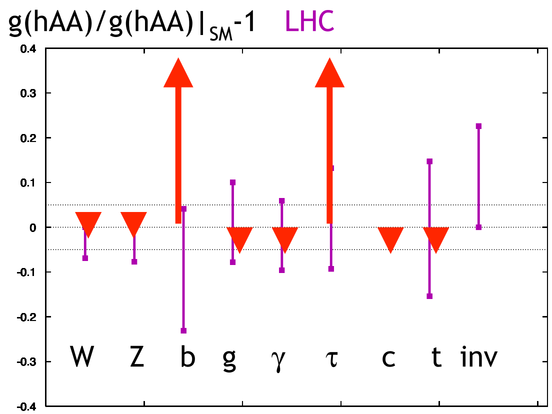
hbb deviation can probe m_A scale



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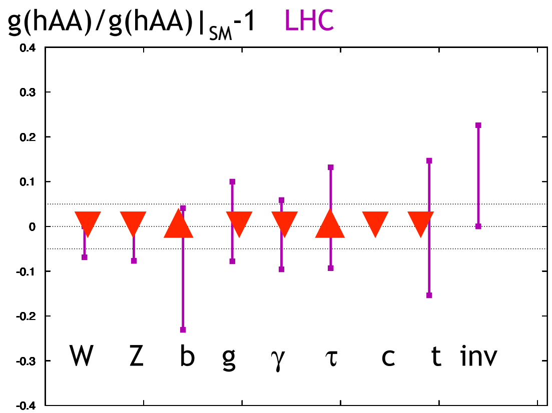

m_A>>m_Z
w/ tanβ=5

SM-like Higgs in 2HDMs

2HDM-II

$$\sin(\beta-\alpha) \not\simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$

- Type-II Yukawa interaction w/o SUSY relation

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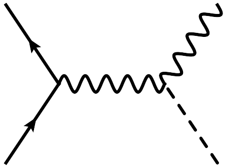
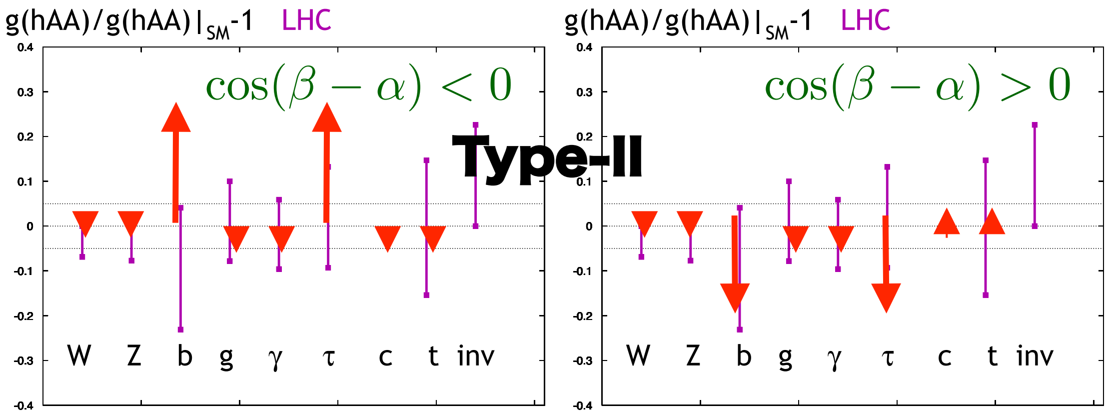
$$\frac{g_{htt}}{g_{htt}^{\rm SM}} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$

❖ No m_A dependence [$\sin(\beta-\alpha)$ is determined by ]

❖ $\cos(\beta-\alpha)$ can be sizable and positive



SM-like Higgs in 2HDMs

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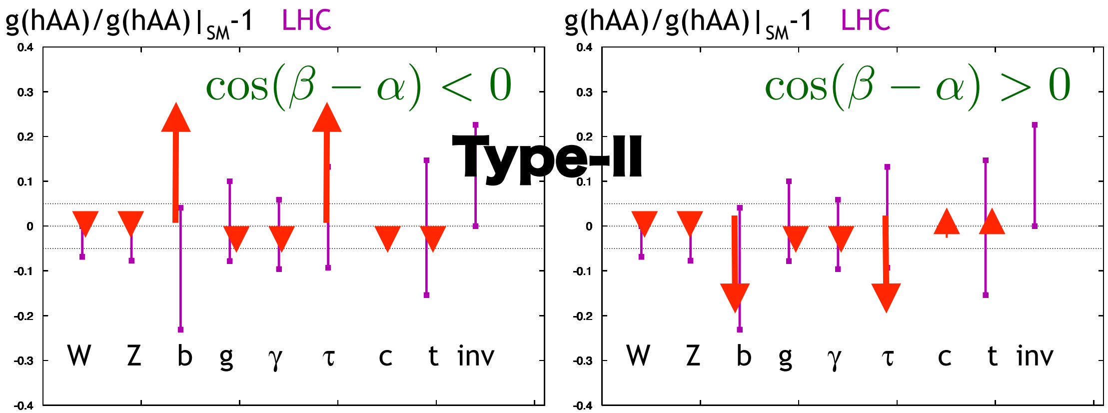
sin(β−α) + hff deviations (w/o m_A)

→ detemination of tanβ



SM-like Higgs in 2HDMs

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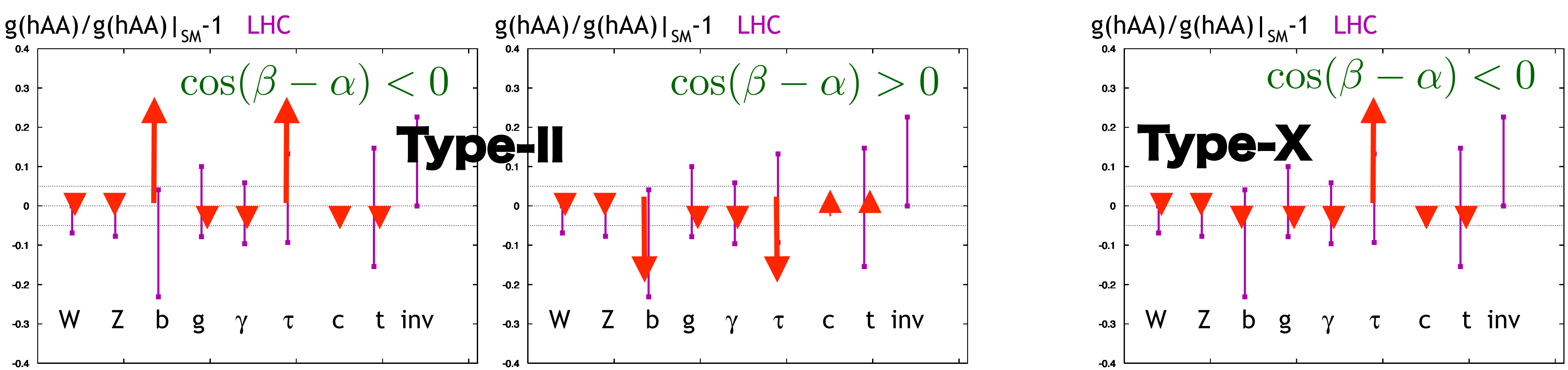
sin(β−α) + hff deviations (w/o m_A)

→ discrimination of types of Yukawa



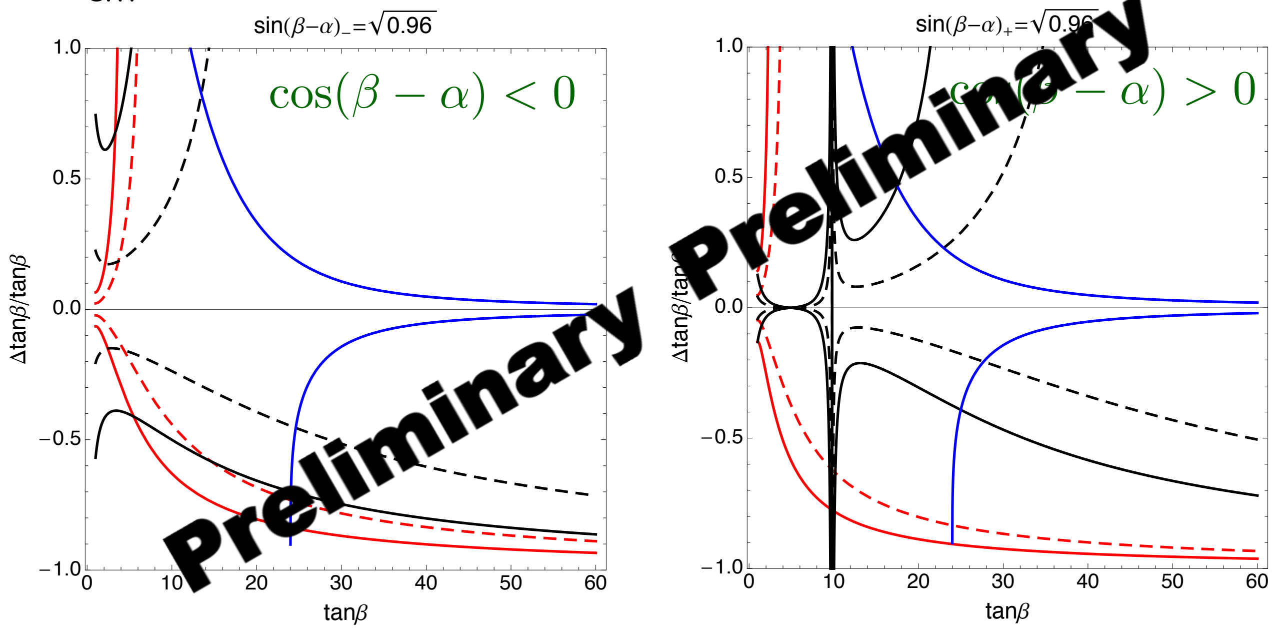
tanβ in SM-like Higgs decay

- Assume precise measurement of BR(h→bb)

$$\mathcal{B}_h^{bb} \simeq \frac{1}{1+\frac{0.052}{0.50}+\frac{0.26+0.031}{0.50}\left(\frac{1}{1-t_\beta\sqrt{0.04/0.96}}\right)^2}$$

ΔB/B = 0.03 (0.01) is chosen.
[250/fb @ E_{cm} = 250GeV] (See, talk by Dr. Ono)

Kanemura, KT, Yokoya, Yagyu



Type-II

tanβ in SM-like Higgs decay

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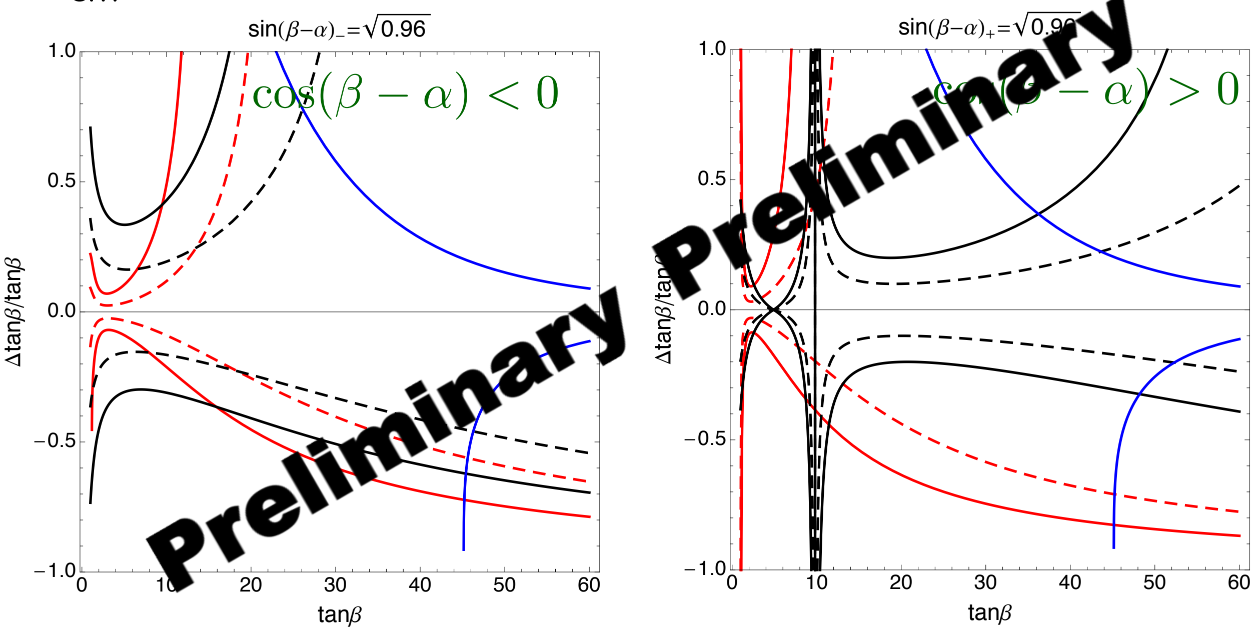


Type-X

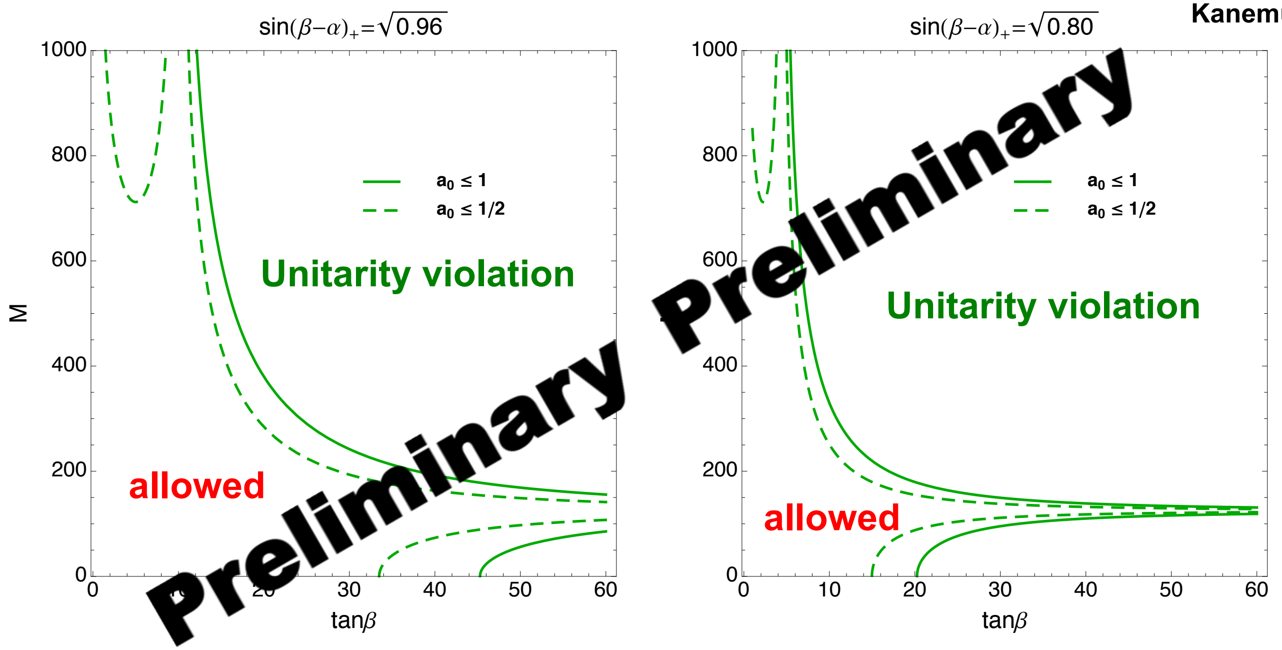
Unitarity bound

- Potential largest eigenvalue:

Kanemura et,al, (1993)

$$a^{\pm} = -\frac{1}{32\pi}\left[3(\lambda_1+\lambda_2) \pm \sqrt{9(\lambda_1-\lambda_2)^2 + 4(2\lambda_3+\lambda_4)^2}\right]$$

Kanemura, KT, Yokoya, Yagyu



There are implicit upper mass bounds

[a deviation of sin(β-α) requires non-decoupling]

Summary

- Extra Higgs bosons
  - **Direct search**
    - ❖ SUSY/2HDM-II Higgs has been searched
      (small m_A w/ $3 < \tan\beta < 8$ @ LC)
    - ❖ Leptophilic Higgs
      (4τ signature @ LHC)
      (4τ signature & $\tan\beta$ @ LC)
  - **Indirect search**
    - ❖ Precision SM-like Higgs study
      ($\tan\beta$ from $h \to bb$ @ LC)
      (discriminate types of Yukawa in 2HDMs)

Summary

- Extra Higgs bosons
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  - Indirect search
    - ❖ Precision SM-like Higgs study
      ($\tan\beta$ from $h \to bb$ @ LC)
      (discriminate types of Yukawa in 2HDMs)

LC can probe extra Higgs bosons, directly and indirectly.

Back up slides

- Type-II Higgs interactions
  - SM-like Higgs h and additional Higgs H w/o sin(β-α)=1

$$g_{hbb} = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$

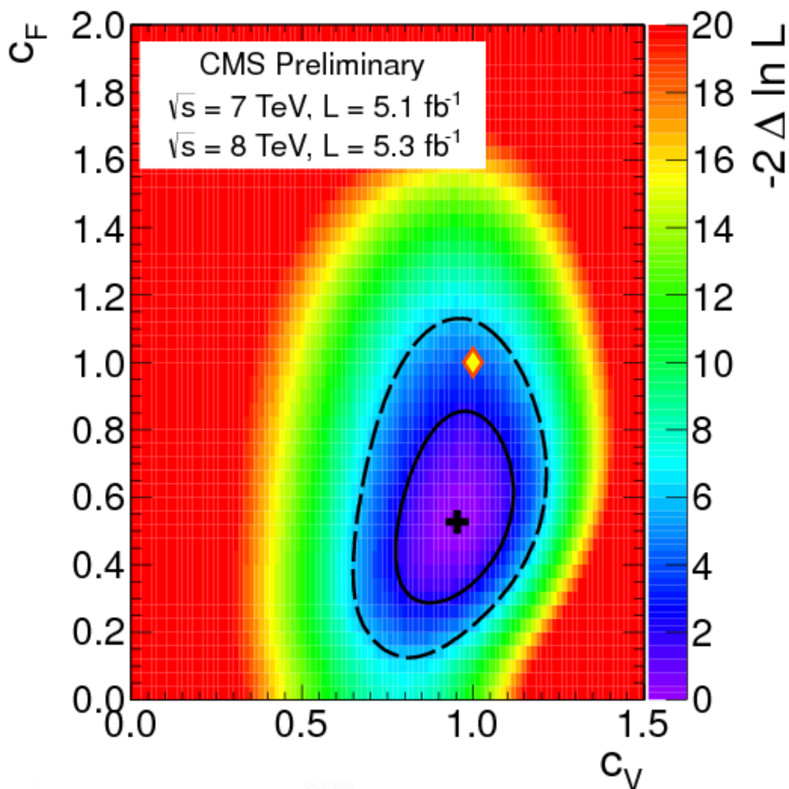
$$g_{htt} = \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$

$$\tan\beta\cos(\beta-\alpha) = \begin{cases} \pm 0.2\tan\beta & \text{for} \quad \sin(\beta-\alpha) = \sqrt{0.96} \\ \pm 0.45\tan\beta & \text{for} \quad \sin(\beta-\alpha) = \sqrt{0.80} \end{cases}$$

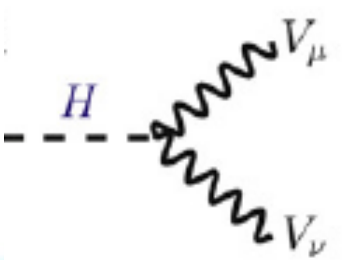
The factor can be <u>much larger</u> than unity

SM-like?

- SM-like gauge-gauge-Higgs coupling is favored

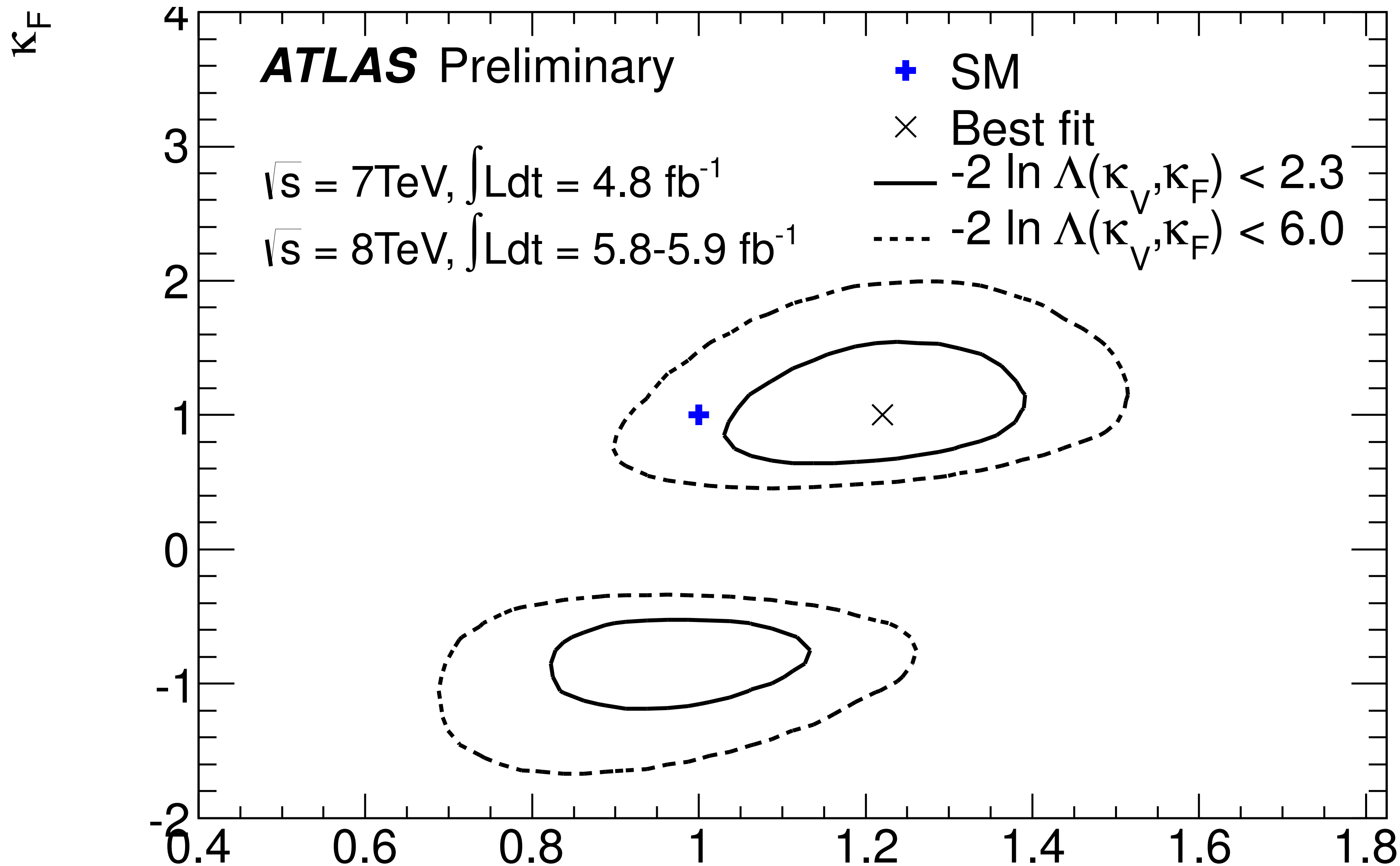


Production	Decay	LO	SM
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF/VH	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF/VH	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4/C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^4/C_F^2$



$$W^+_\mu W^+_\nu h : i g_W M_W \sin(\beta - \alpha) g_{\mu\nu}$$

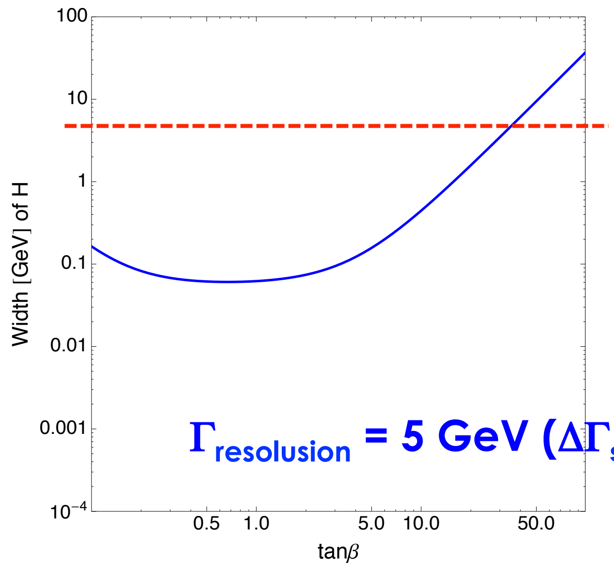
sin(β−α) can be different from unity

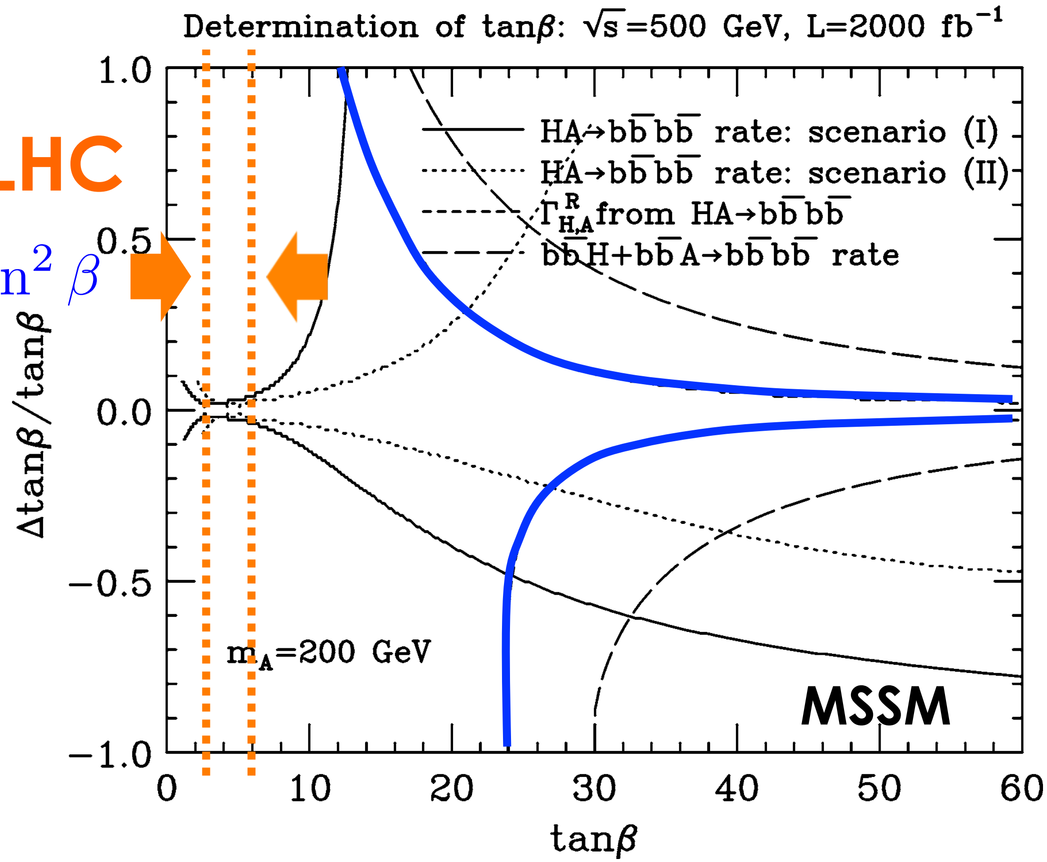

ATLAS Preliminary
$\sqrt{s}$ = 7TeV, $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8TeV, $\int Ldt$ = 5.8-5.9 fb^{-1}
SM
Best fit
$-2 \ln \Lambda(\kappa_V,\kappa_F) < 2.3$
$-2 \ln \Lambda(\kappa_V,\kappa_F) < 6.0$
κ_F
4
3
2
1
0
-1
-2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

- Gunion et.al. (2003)

Width measurement

$$\Gamma^{H,A}_{\rm tot} \simeq N_C \frac{G_F m_{H,A} m_b^2}{4\sqrt{2}\pi} \tan^2\beta$$





$\Gamma_{\rm resolution}$ **= 5 GeV (**$\Delta\Gamma_{\rm sys}$ **= 0.5 GeV) is taken**

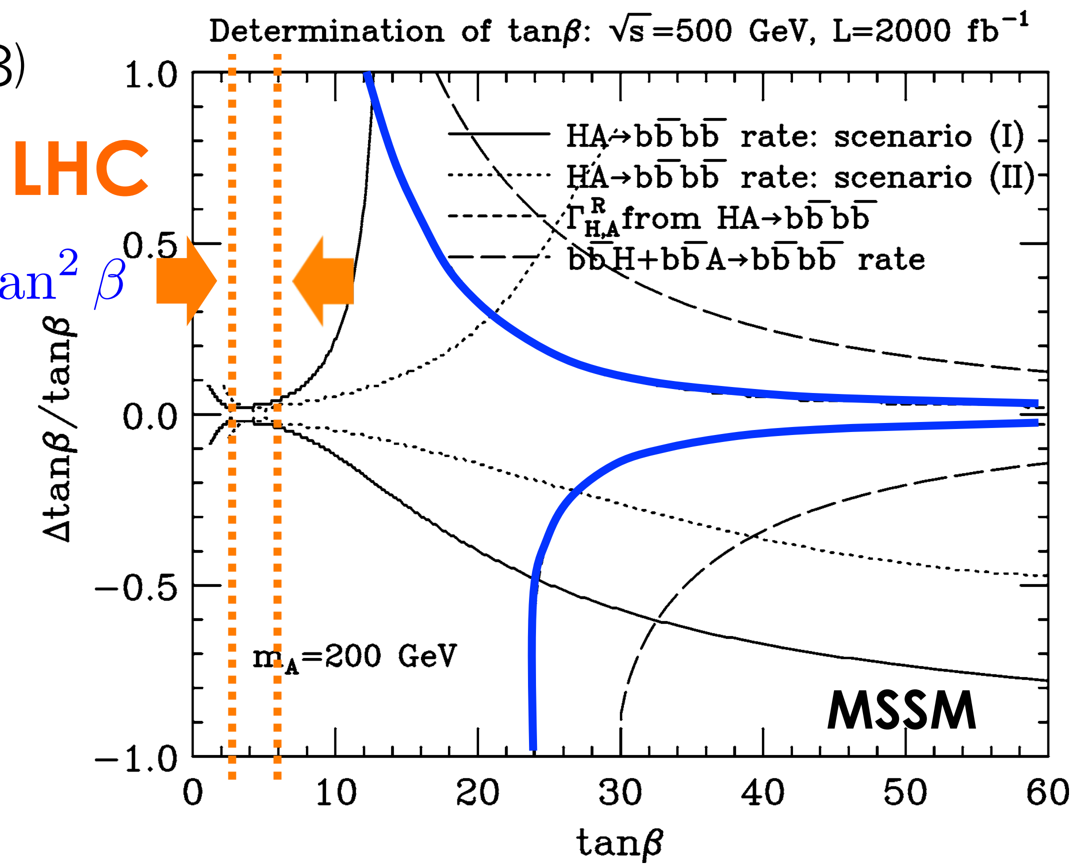
Width measurement is sensitive **for high tanβ**

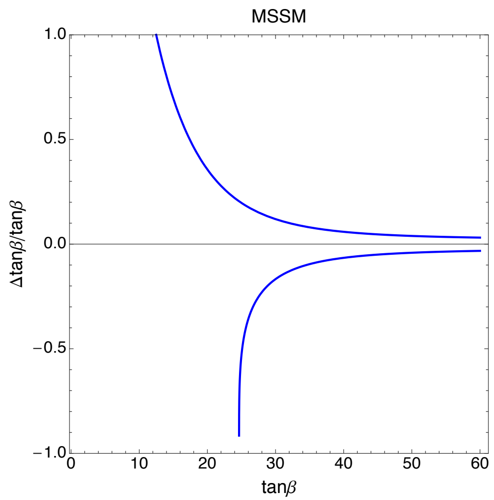
tanβ @ LC

- Gunion et.al. (2003)

Width measurement

$$\Gamma_{\rm tot}^{H,A} \simeq N_C \frac{G_F m_{H,A} m_b^2}{4\sqrt{2}\pi} \tan^2\beta$$





Systematic uncertainty is dominated,
← 250/fb is sufficient

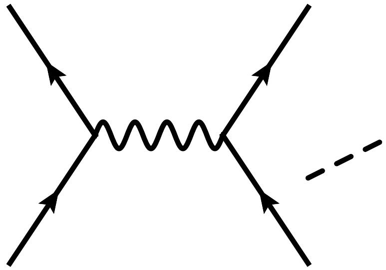
Width measurement is sensitive **for high tanβ**

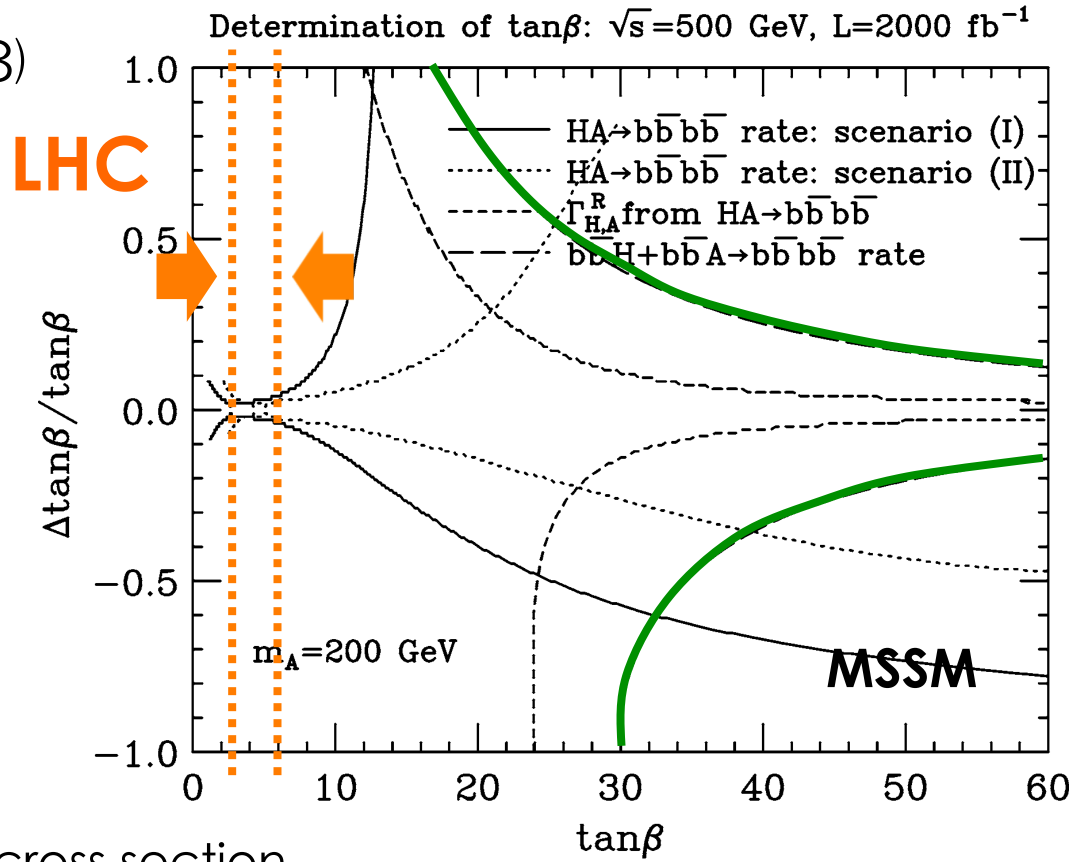
tanβ @ LC

- Gunion et.al. (2003)

bbH/bbA production

$$\sigma \propto \tan^2 \beta$$





Less sensitivity due to less cross section
(LHC would have better sensitivity)

tanβ @ LC

Gunion et.al. (2003)

- Gunion et.al. (2003)

bbH/bbA production

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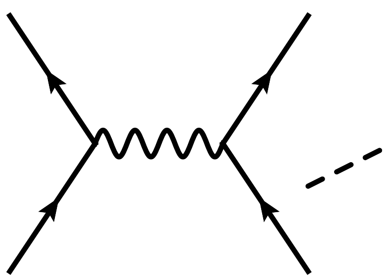

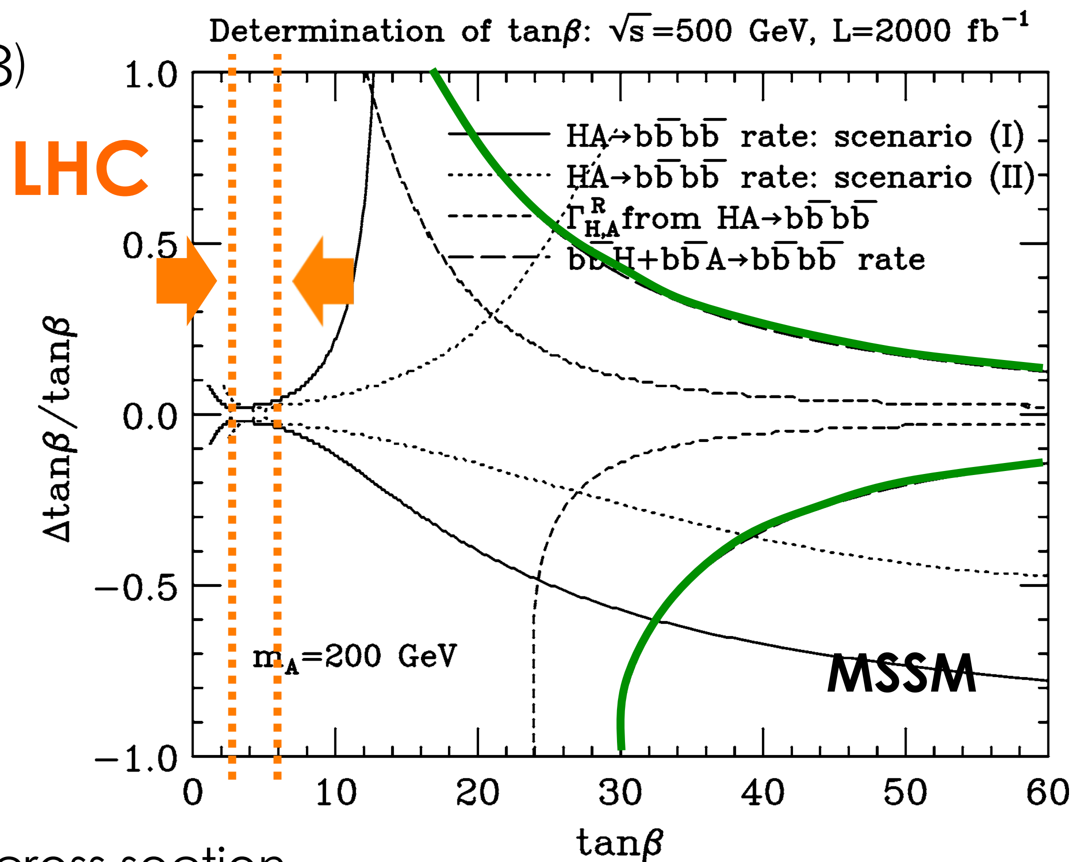

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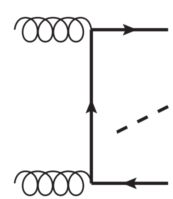
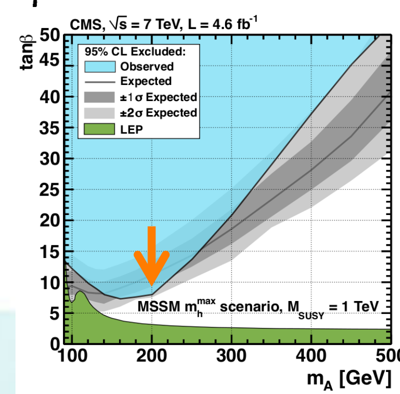
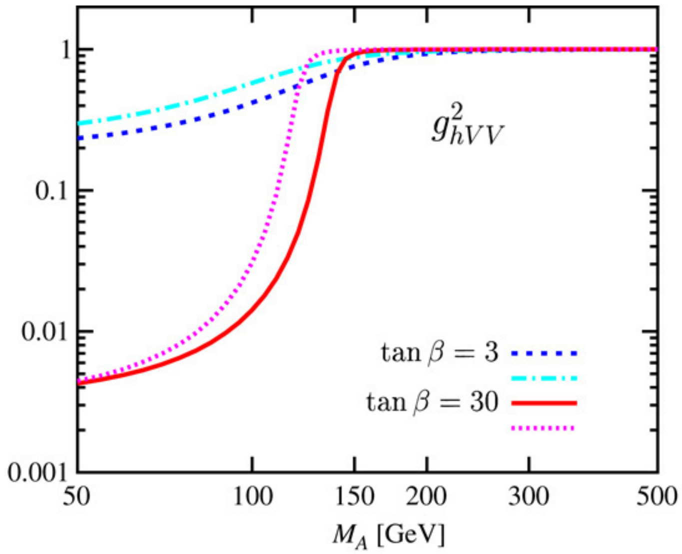
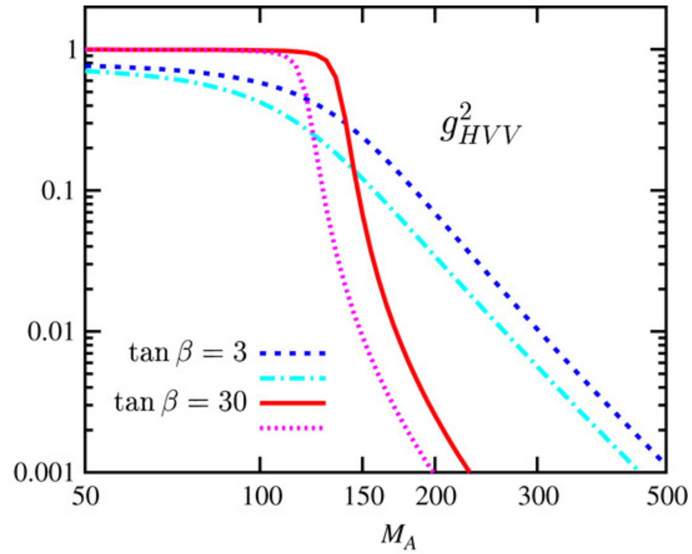




Gauge coupling in MSSM

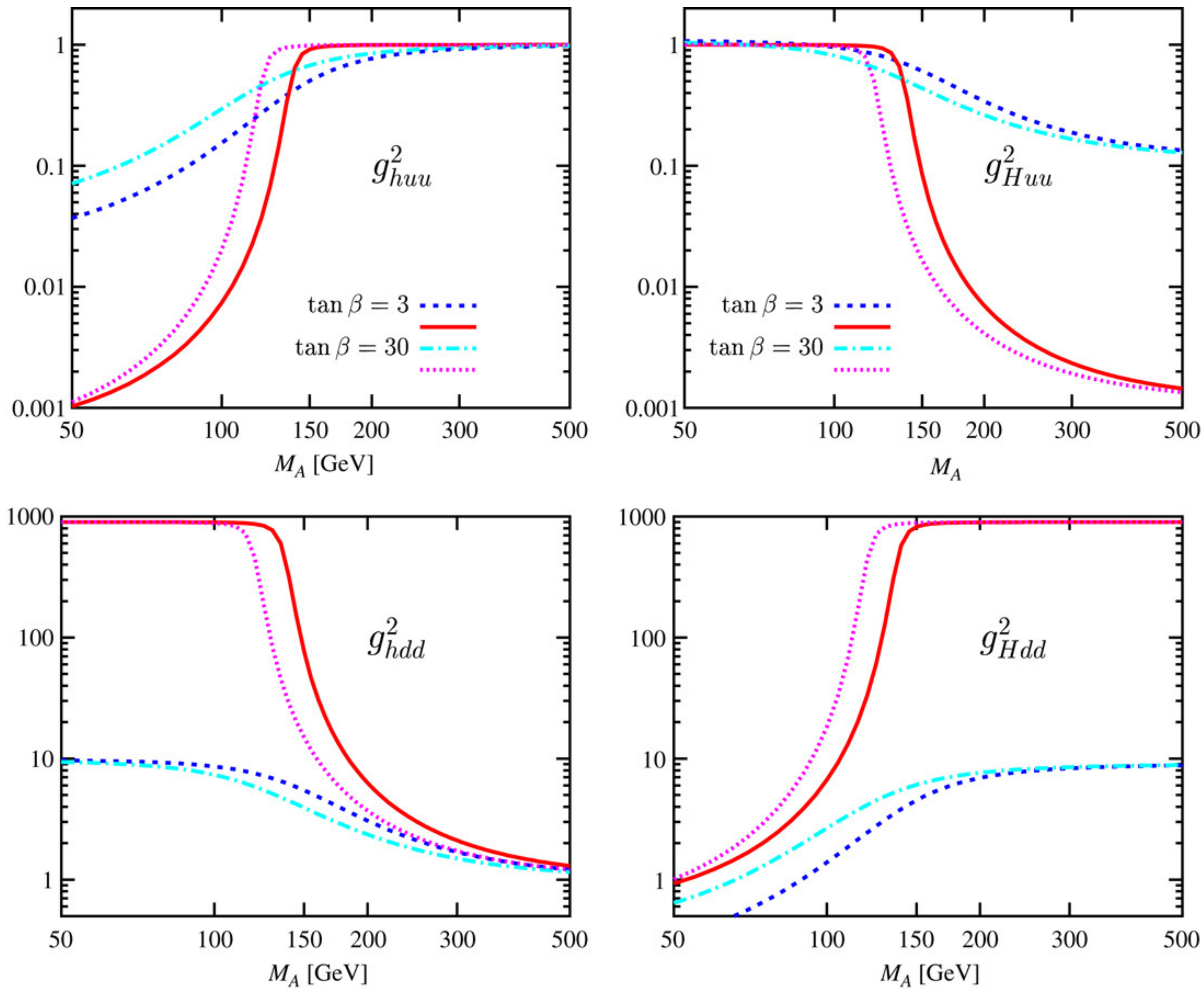
Djouadi (2008)





Yukawa coupling in MSSM

Djouadi (2008)



Kanemura, KT, Yokoya (2012)

Event analysis details

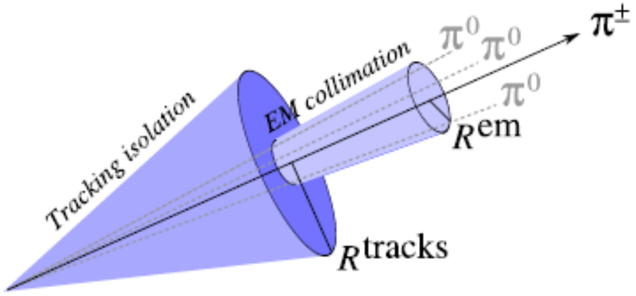
-MadGraph5: event generation, calculate (diff.) σ

-PYTHIA: hadronization (quark, $\tau \rightarrow$ hadron)

w/ TAUOLA (tau polarization)

-FastJet: (construct jets from hadrons)

jet is defined by anti-kT w/ R<0.4



→ **Detector simulation**
(construct kinematical variables such as invariant mass, etc…)

Unitarity bound

Kanemura, KT, Yokoya, Yagyu

- tanβ enhancement in λ couplings

$$\lambda_1 = \frac{1}{v^2\cos^2\beta}\left(-M^2\sin^2\beta + m_H^2\cos^2\alpha + m_h^2\sin^2\alpha\right)$$

$$\lambda_2 = \frac{1}{v^2\sin^2\beta}\left(-M^2\cos^2\beta + m_H^2\sin^2\alpha + m_h^2\cos^2\alpha\right)$$

$$\lambda_3 = \frac{1}{v^2}\left[-M^2 + (m_H^2 - m_h^2)\frac{\sin 2\alpha}{\sin 2\beta} + 2m_{H^+}^2\right]$$

nearly SM-like ($\beta-\alpha=\pi/2-\delta$), and $M=M_H=M_{H^+}$

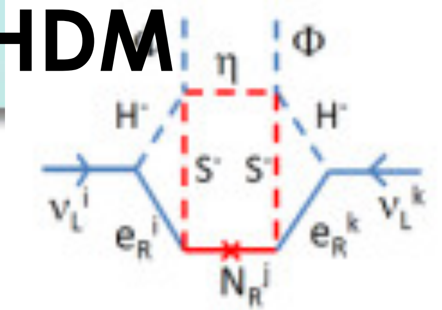
$$\lambda_1 \to +\frac{m_h^2}{v^2} - \frac{2(M^2-m_h^2)t_\beta}{v^2}\delta - \frac{(M^2-m_h^2)t_\beta^2}{v^2}\delta^2$$

$$\lambda_2 \to +\frac{m_h^2}{v^2} + \frac{2(M^2-m_h^2)/t_\beta}{v^2}\delta + \frac{(M^2-m_h^2)/t_\beta^2}{v^2}\delta^2$$

$$\lambda_3 \to +\frac{m_h^2}{v^2} + \frac{2(M^2-m_h^2)}{v^2}\delta + \frac{(M^2-m_h^2)}{v^2}\delta^2$$

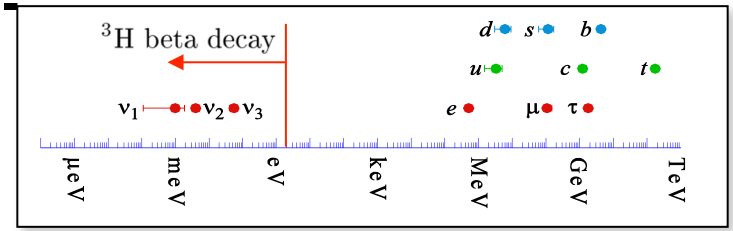
Only λ_1 diverges
@ large tanβ

Leptophilic Higgs in 2HDM



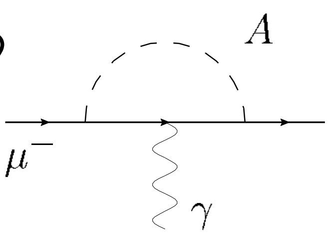
◻ Tiny neutrino mass

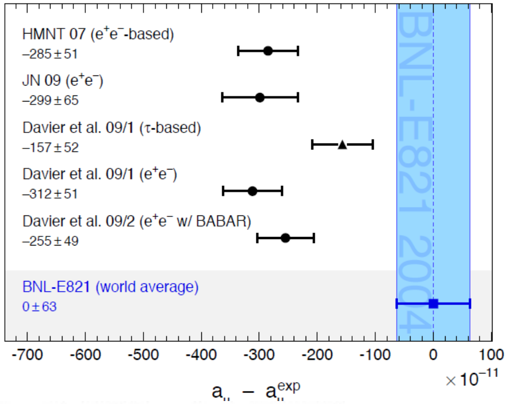
ex. 3-loop radiative seesaw w/ **light H+/-**
by Aoki et al. PRL102:051805,2009



◻ μ magnetic moment

light A(CP odd) w/ large tanB
by Cao et al. PRD80:071701,2009

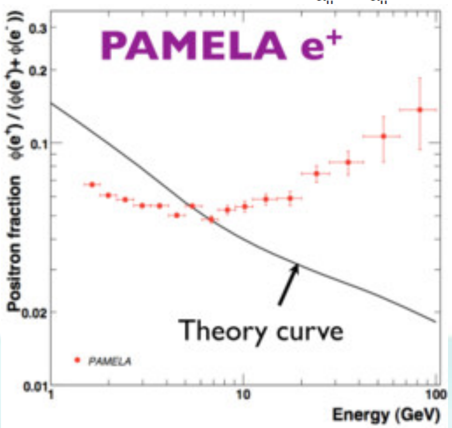




◻ e⁺ excess @ PAMELA, FERMI

scalars as a messenger to DM
by Goh et al. JHEP 0905:097,2009

DM DM → Φ’ Φ’ → ττττ

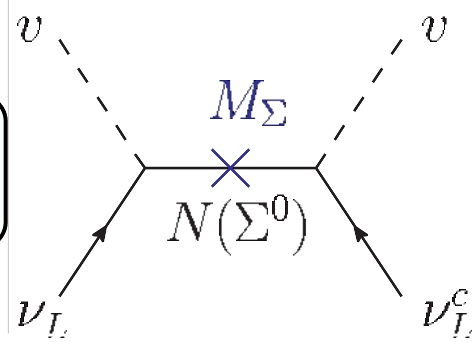


A model for tiny neutrino masses

◻ Gauged Type-III seesaw

$$\mathcal{L} = +\overline{Q}Y_u u_R \widetilde{H}_q + \overline{Q}Y_d d_R H_q + \overline{L}Y_\ell \ell_R H_\ell + \text{H.c.}$$

[B-L like] U(1) extension [in Type-I seesaw]



◻ Anomaly cancellation requires 2HDM-X

Charge assignment:

$$(u,d)_L \sim (3,2,1/6;n_1), \quad u_R \sim (3,1,2/3;n_2), \quad d_R \sim (3,1,-1/3;n_3),$$

$$(\nu,e)_L \sim (1,2,-1/2;n_4), \quad e_R \sim (1,1,-1;n_5), \quad \Sigma_R \sim (1,3,0;n_6).$$

U(1)x scalar: $\chi^0 \sim (1,1,0;-2n_6)$

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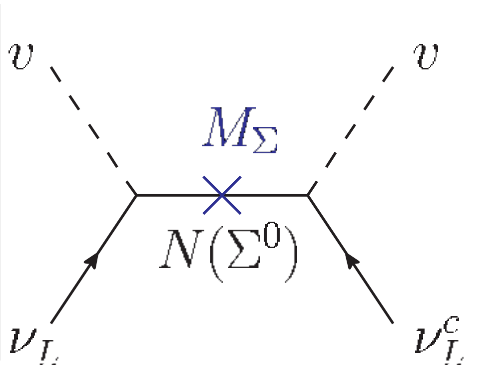

□ Anomaly cancellation requires 2HDM-X

Axial-vector anomaly:

$$[SU(3)]^2 U(1)_X : \quad +2n_1 - n_2 - n_3 = 0$$

$$[SU(2)]^2 U(1)_X : \quad +3(\tfrac{1}{2})n_1 + (\tfrac{1}{2})n_4 - (2)n_6 = 0$$

$$[U(1)_Y]^2 U(1)_X : \quad +6(\tfrac{1}{6})^2 n_1 - 3(\tfrac{2}{3})^2 n_2 - 3(-\tfrac{1}{3})^2 n_3 + 2(-\tfrac{1}{2})^2 n_4 - (-1)^2 n_5 = 0$$

$$U(1)_Y [U(1)_X]^2 : \quad +6(\tfrac{1}{6})n_1^2 - 3(\tfrac{2}{3})n_2^2 - 3(-\tfrac{1}{3})n_3^2 + 2(-\tfrac{1}{2})n_4^2 - (-1)n_5^2 = 0$$

$$[U(1)_X]^3 : \quad +6n_1^3 - 3n_2^3 - 3n_3^3 + 2n_4^3 - n_5^3 - 3n_6^3 = 0$$

gravitational anomaly:

$$+6n_1 - 3n_2 - 3n_3 + 2n_4 - n_5 - 3n_6 = 0$$

Unique solution exists!!

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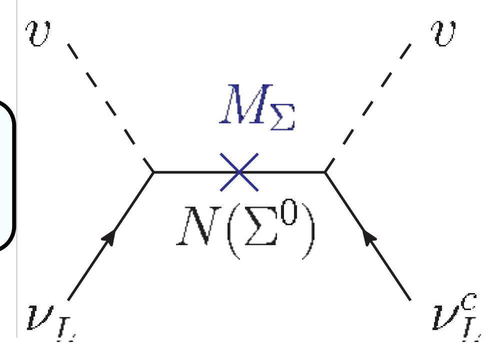

☐ Anomaly cancellation requires 2HDM-X

possible Yukawa int:

$$n_1 - n_3 = n_2 - n_1 = n_6 - n_4 = \frac{3}{4}(n_1 - n_4), \quad n_4 - n_5 = \frac{1}{4}(9n_1 - n_4),$$

$$H_q \qquad\qquad H_\ell$$

2HDM-X can also be a low energy effective theory