300 and 3000 /fb projections for 2-Higgs doublet models at the LHC

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C.-Y. C. and S. Dawson, PRD 87, 055016 (arXiv:1301.0309)
C.-Y. C., S. Dawson, and M. Sher, (arXiv:1305.1624)

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Outline

- Introduction to two Higgs doublet models (2HDMs.)
- Constraints on 2HDMs
- Projections for the LHC
- Projections for the ILC
- Conclusions

Two Higgs Doublet Models (2HDMs)

- The most general Higgs potential with two Higgs doublets, Φ_1 and Φ_2 , and a Z_2 symmetry is:

$$V = m_{11}^2\, \Phi_1^\dagger \Phi_1 + m_{22}^2\, \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3\, \Phi_1^\dagger \Phi_1\, \Phi_2^\dagger \Phi_2 + \lambda_4\, \Phi_1^\dagger \Phi_2\, \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right].$$

A good review paper: [Branco, Ferreira, Lavoura, Rebelo, Sher, Silva]

- Apply a Z_2 symmetry, such that a fermion couples only to a single Higgs doublet. Free from tree level FCNCs. [S. L. Glashow and S. Weinberg, Phys. Rev. D 15, 1958 (1977).]

$$\Phi_1 \to -\Phi_1,\ \Phi_2 \to \Phi_2 \quad \text{and} \quad d \to -d,\ u \to u,\ e \to -e.$$ for the type II model

All the possible assignments:

Model	Type I	Type II	Lepton-specific	Flipped
Φ_1	-	d, ℓ	ℓ	d
Φ_2	u, d, ℓ	u	u, d	u, ℓ

[Logan, MacLennan, PRD81, 075016]

- An example of Type II: Supersymmetry

Two Higgs Doublet Models

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \qquad \langle \phi_i^0 \rangle = \begin{pmatrix} 0 \\ \frac{v_i}{\sqrt{2}} \end{pmatrix}$$

$$\phi_i^0 = \frac{v_i}{\sqrt{2}} + \frac{1}{\sqrt{2}}(\phi_i^{0,r} + i\phi_i^{0,i})$$

- β : $\tan\beta \equiv \frac{v_2}{v_1}$
- α : The mixing angle between two CP-even neutral Higgs bosons.
- Five Higgs bosons: h, H, A, and $H^{\pm}$, $M_H > M_h$
- 6 parameters: $\alpha, \tan\beta, M_h, M_H, M_A$, and $M_{H^{\pm}}$.
- Assume that the discovered SM-like Higgs is the lightest CP-even Higgs.

  M_h =125 GeV

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  M_h =125 GeV

The couplings of h and H to fermions and gauge bosons relative to the SM couplings:

	I	II	Lepton specific	Flipped
g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
$g_{ht\bar{t}}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
$g_{hb\bar{b}}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
$g_{h\tau^+\tau^-}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$
g_{HVV}	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
$g_{Ht\bar{t}}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$
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- Universal hVV couplings $\sin(\beta-\alpha)$, and HVV couplings $\cos(\beta-\alpha)$.
- Decoupling limit: $\sin(\beta-\alpha)=1$, $\sin\alpha=-\cos\beta$ and $\cos\alpha=\sin\beta$

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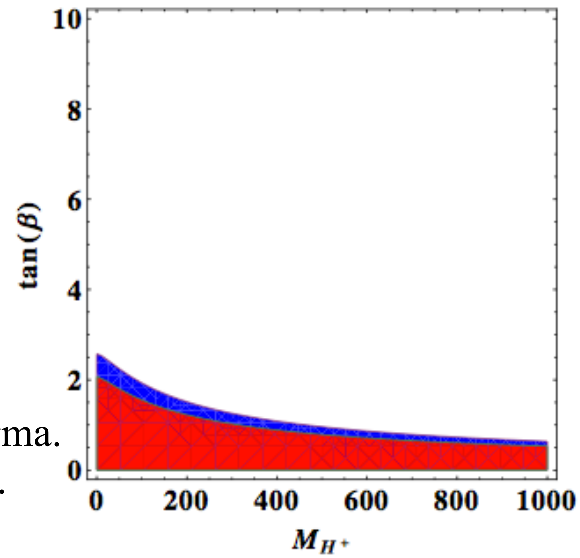
- Decoupling limit: $\sin(\beta-\alpha)=1$, $\sin\alpha=-\cos\beta$ and $\cos\alpha=\sin\beta$

Constraints

- Flavor constraints:
  - $\Delta M_{B_d} \equiv M_{B_H} - M_{B_L}$, $B_H(B_L)$ denotes the heaviest (lightest) of the mass eigenstates.
    - Model-independent bound: excludes
      $0 < \tan\beta \lesssim 0.5$

Shaded: excluded at 2 sigma.
Red: excluded at 3 sigma.

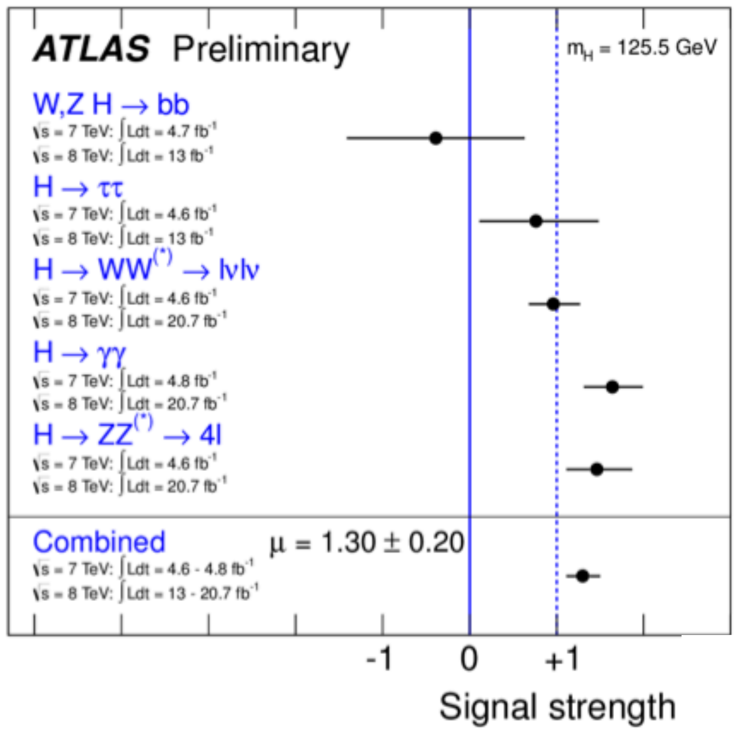


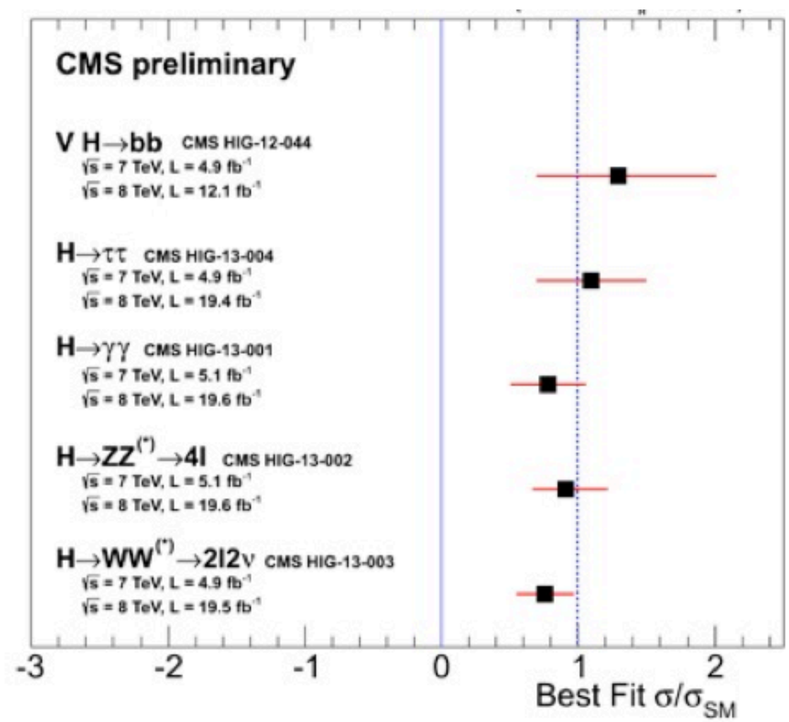
For more flavor bounds: Mahmoudi et. al, 0907.1791

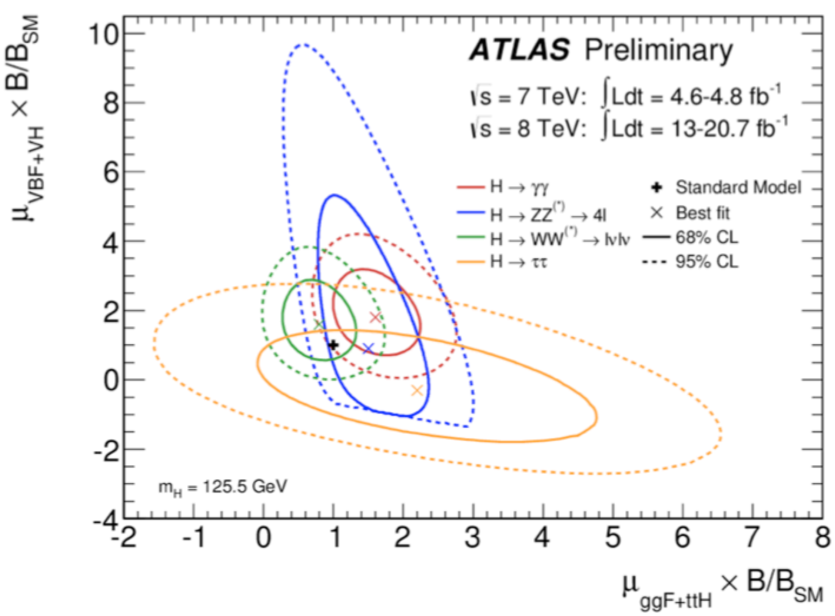
- Perturbative bound: Requiring $\frac{\lambda_1}{4\pi} < 1$, implies $\tan\beta < 7$
  - We focus on low $\tan\beta$ region in this study.

Measured signal strength

Moriond results



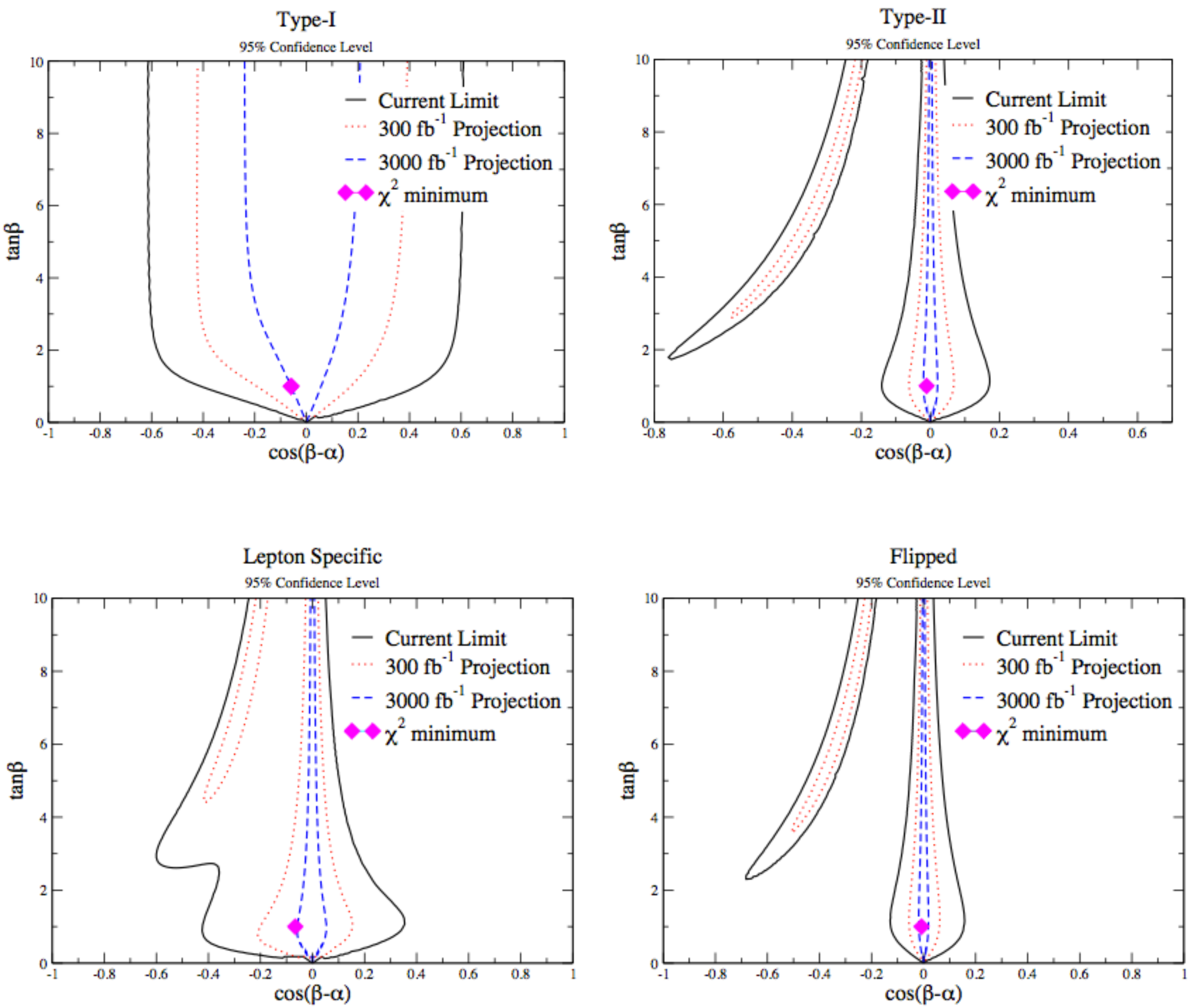




$$R_{\text{decay}} \equiv \frac{\sum_j \sigma(pp \to j \to h) \times \mathrm{B}(h \to \texttt{decay})|_{\text{observed}}}{\sum_j \sigma(pp \to j \to h) \times \mathrm{B}(h \to \texttt{decay})|_{\text{SM}}}$$

- R=1 : Standard Model Higgs
- Measuring deviations of the couplings from the SM

χ^2 fit for the light Higgs

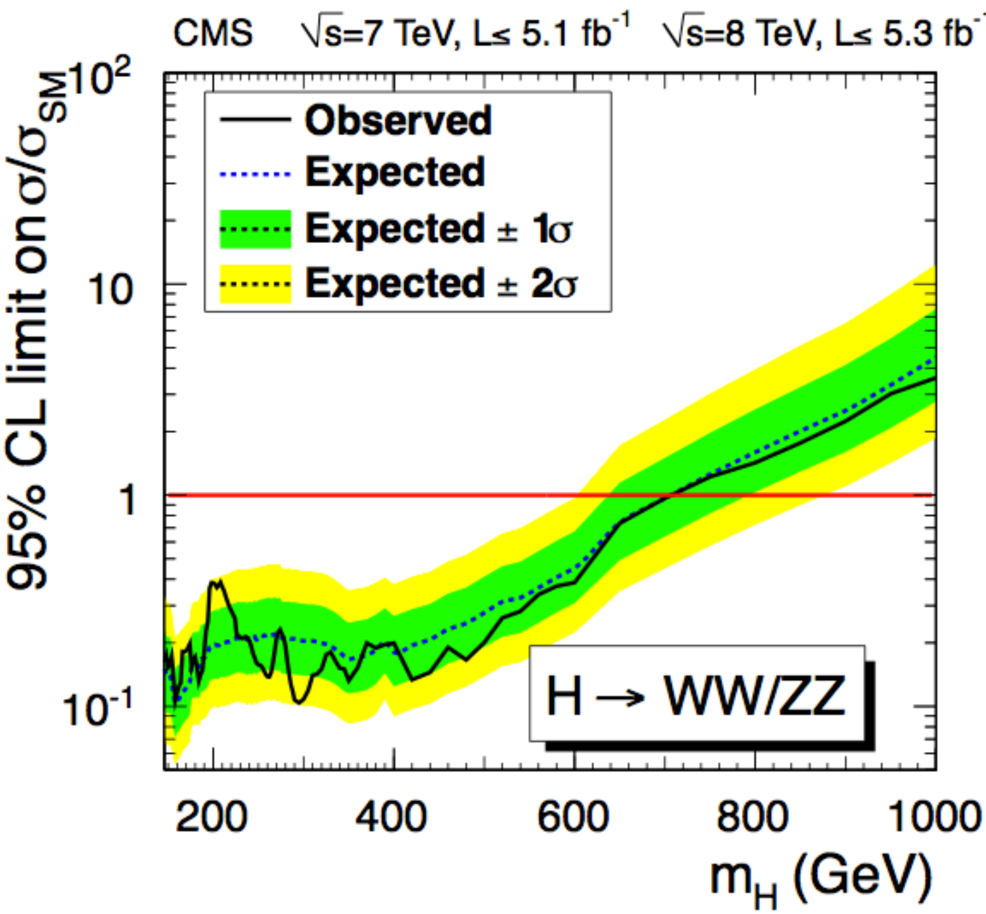


- SM limit: $\cos(\beta-\alpha)=0$
- Projection: assume that the SM is correct.
- systematics uncertainties $\sim \dfrac{1}{\sqrt{\mathcal{L}}}$

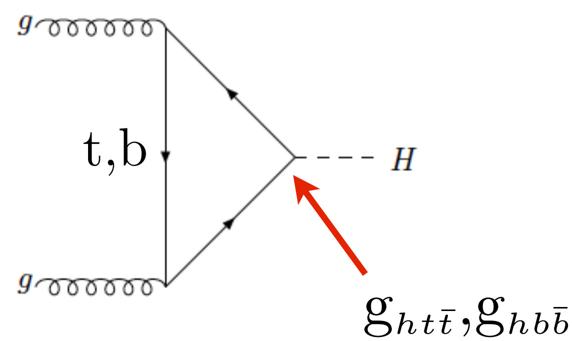
  [CMS NOTE-2012/006]
- Type-I is not very constrained, since $g_{hf\bar{f}} = \dfrac{\cos\alpha}{\sin\beta} \sim \cos\alpha$ at large $\tan\beta$ region.
- χ^2 minima: close to SM limit.

Heavy Higgs searches

[arXiv: 1304.0213]



- Only H->WW/ZZ is considered.
- Excluded mass range 145 ~ 710 GeV.
- Choose two mass points: 200 and 300 GeV, because bounds there are better.



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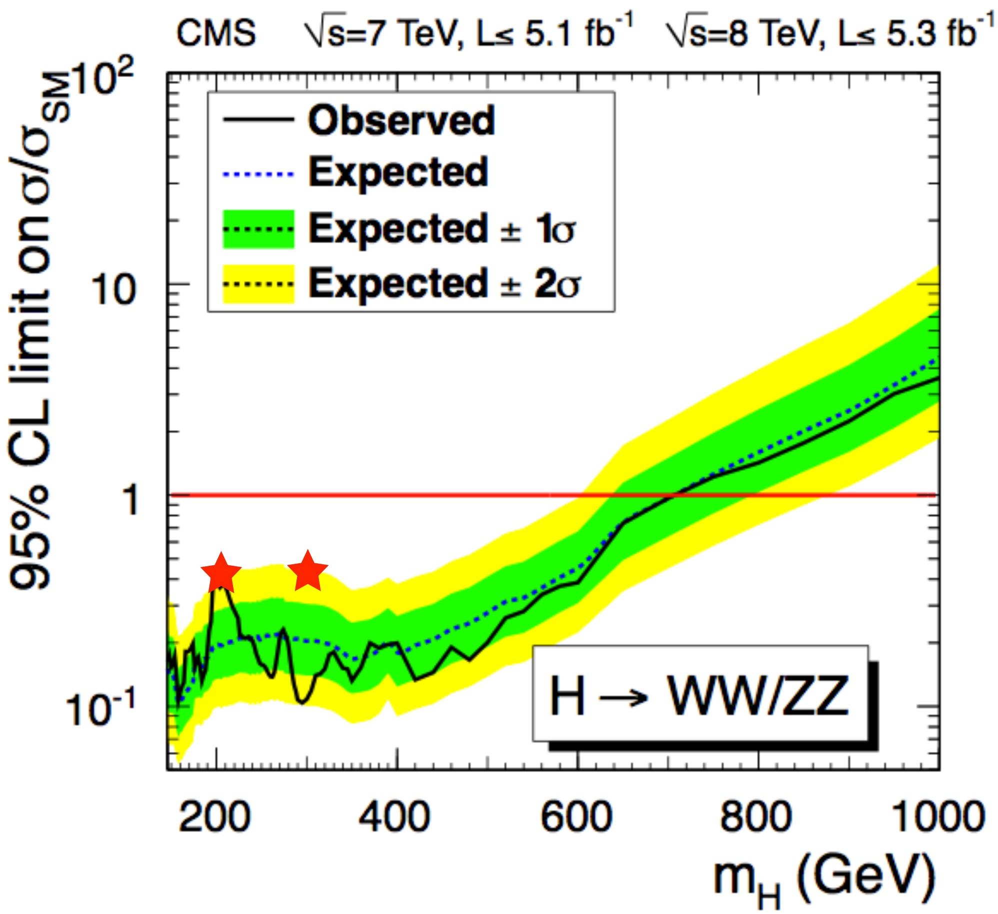

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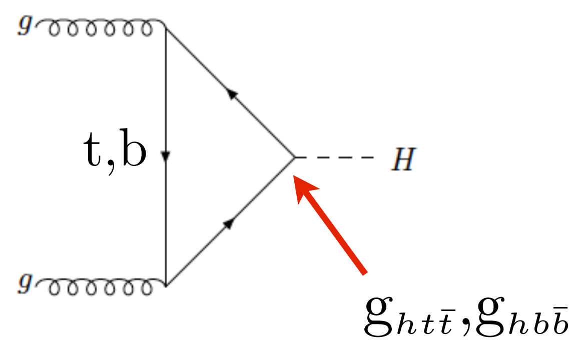
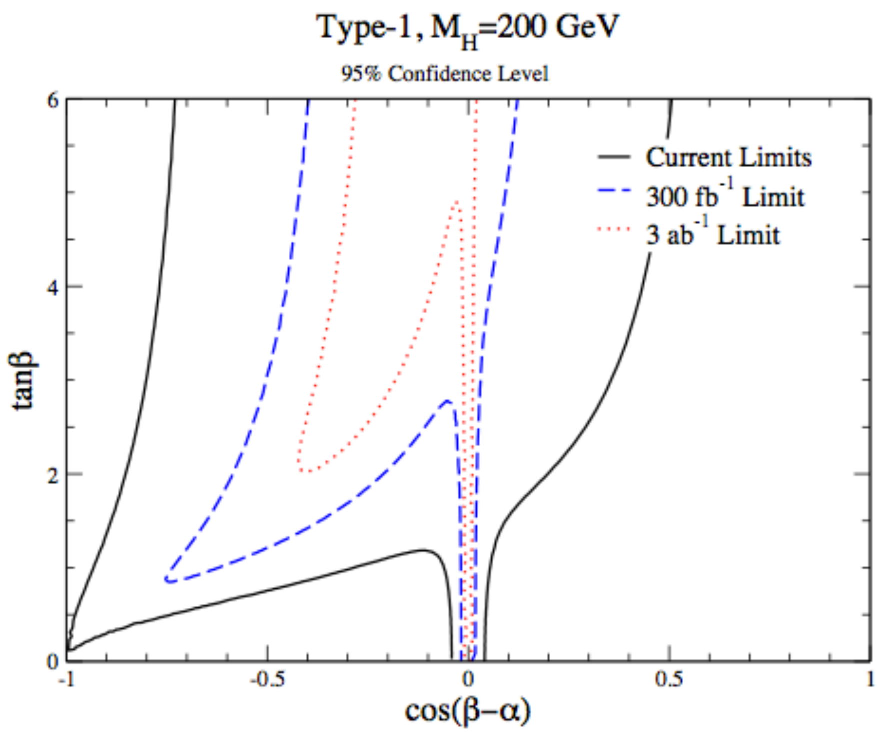
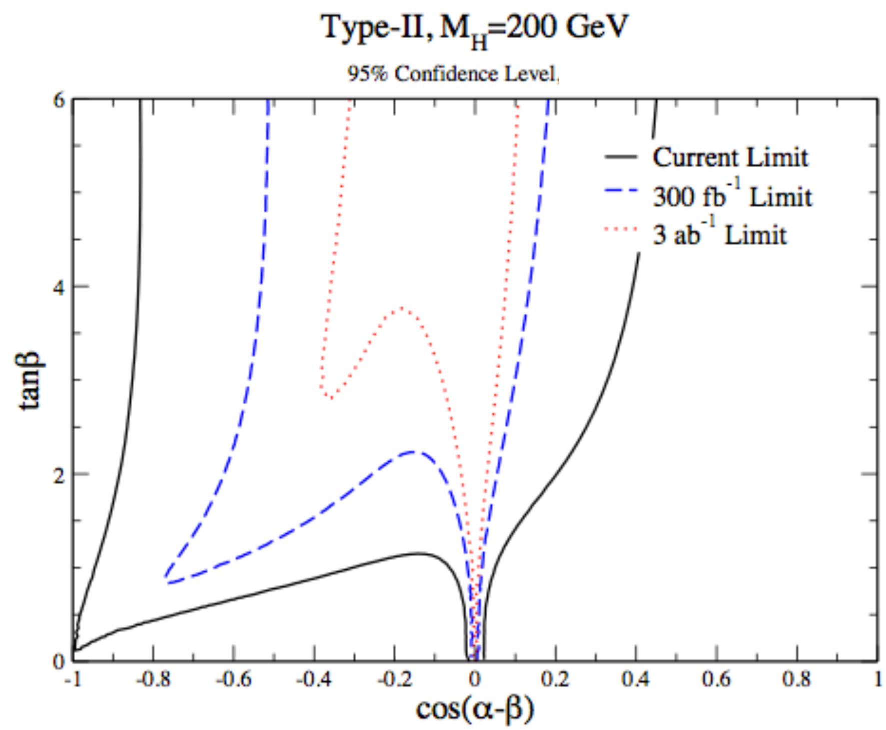


$M_H = 200$ GeV

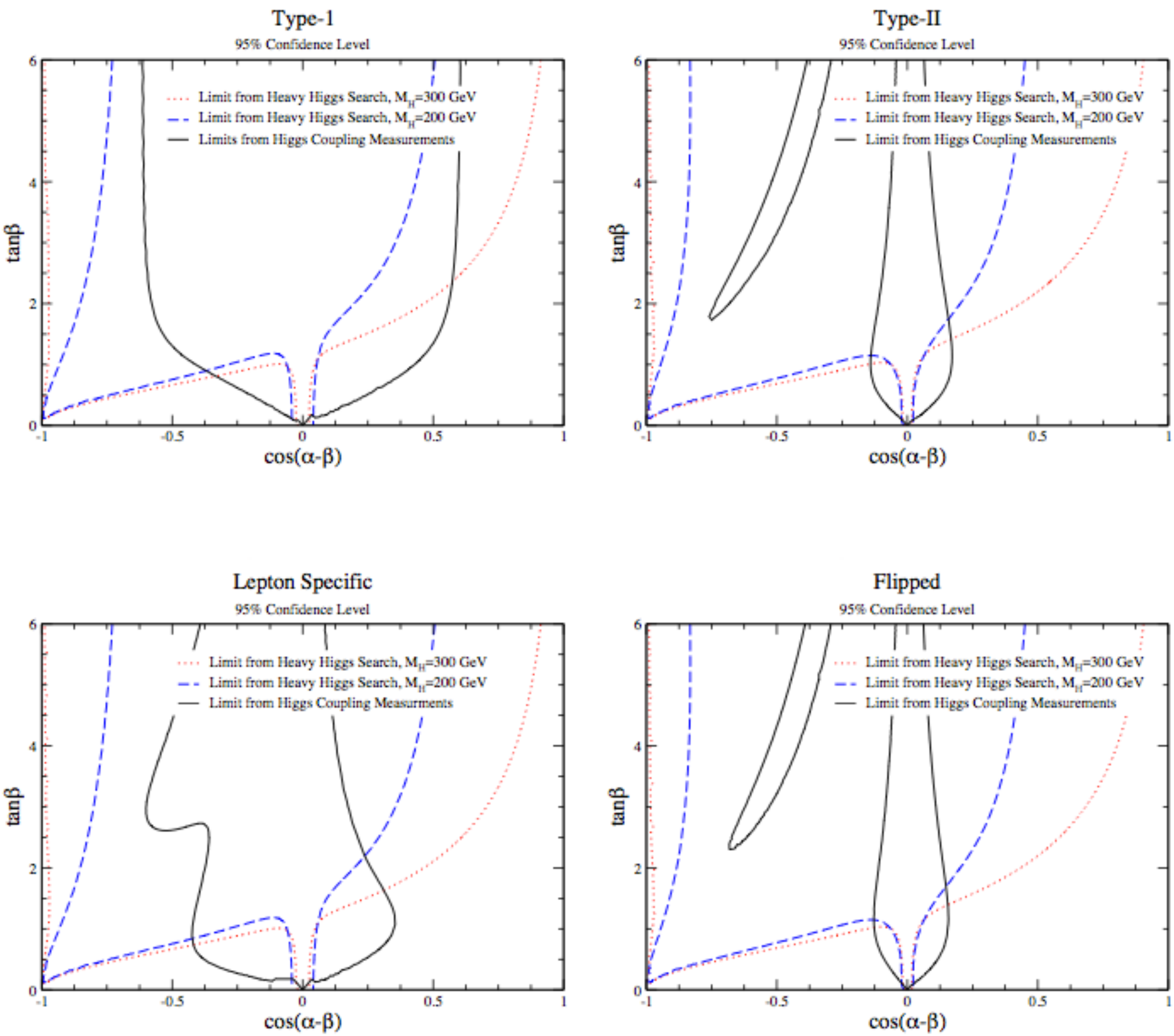
- Heavy Higgs mainly decays into WW and ZZ.
- difficult to exclude the region near $\cos(\beta-\alpha) \sim 0$, since $g_{HVV} = \cos(\beta-\alpha)$.





- Lepton-specific and flipped models give very similar results to the type-I and type-II models, respectively.
- An increase in luminosity will tightly constrain $\cos(\beta-\alpha)$ for $\tan\beta < 4$ in the type-I model and will give a sufficient constraint for $\tan\beta < 4$ in the type-II model.

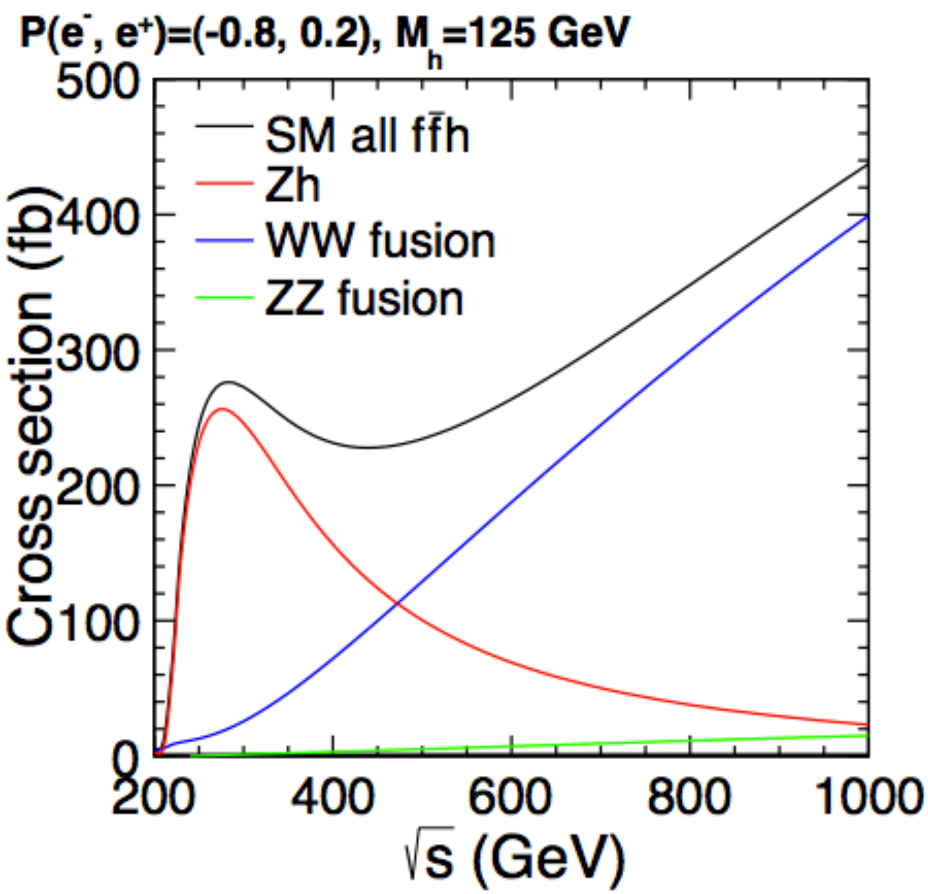
Comparisons with LHC coupling measurements



- Based on current measurements.
- A significant fraction of the previously allowed parameter-space in the type-I model is excluded by limits from heavy Higgs searches.
- For the type-II model, some of the remaining parameter-space is excluded, especially for small $\tan\beta$.
- At M_H =300 GeV, due to the opening up of the H $\rightarrow$ h h channel, the exclusion region is smaller than from M_H = 200 GeV.

Projected sensitivity for the ILC

[arXiv: 1207.2516 by M. Peskin]



[ILCTDR-VOLUME 2]

Observable	Expected Error
ILC at 500 GeV with 500 fb^{-1}	
$\sigma(Zh)\cdot BR(b\bar{b})$	0.018
$\sigma(Zh)\cdot BR(c\bar{c})$	0.12
$\sigma(Zh)\cdot BR(gg)$	0.14
$\sigma(Zh)\cdot BR(WW)$	0.092
$\sigma(Zh)\cdot BR(ZZ)$	0.25
$\sigma(Zh)\cdot BR(\tau^+\tau^-)$	0.054
$\sigma(Zh)\cdot BR(\gamma\gamma)$	0.38
$\sigma(WW)\cdot BR(b\bar{b})$	0.0066
$\sigma(WW)\cdot BR(c\bar{c})$	0.062
$\sigma(WW)\cdot BR(gg)$	0.041
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$\sigma(WW)\cdot BR(ZZ)$	0.082
$\sigma(WW)\cdot BR(\tau^+\tau^-)$	0.14
$\sigma(WW)\cdot BR(\gamma\gamma)$	0.26
$\sigma(t\bar{t}h)\cdot BR(b\bar{b})$	0.25
ILC at 1 TeV with 1000 fb^{-1}	
$\sigma(WW)\cdot BR(b\bar{b})$	0.0047
$\sigma(WW)\cdot BR(c\bar{c})$	0.076
$\sigma(WW)\cdot BR(gg)$	0.031
$\sigma(WW)\cdot BR(WW)$	0.033
$\sigma(WW)\cdot BR(ZZ)$	0.044
$\sigma(WW)\cdot BR(\tau^+\tau^-)$	0.035
$\sigma(WW)\cdot BR(\gamma\gamma)$	0.10
$\sigma(t\bar{t}h)\cdot BR(b\bar{b})$	0.087

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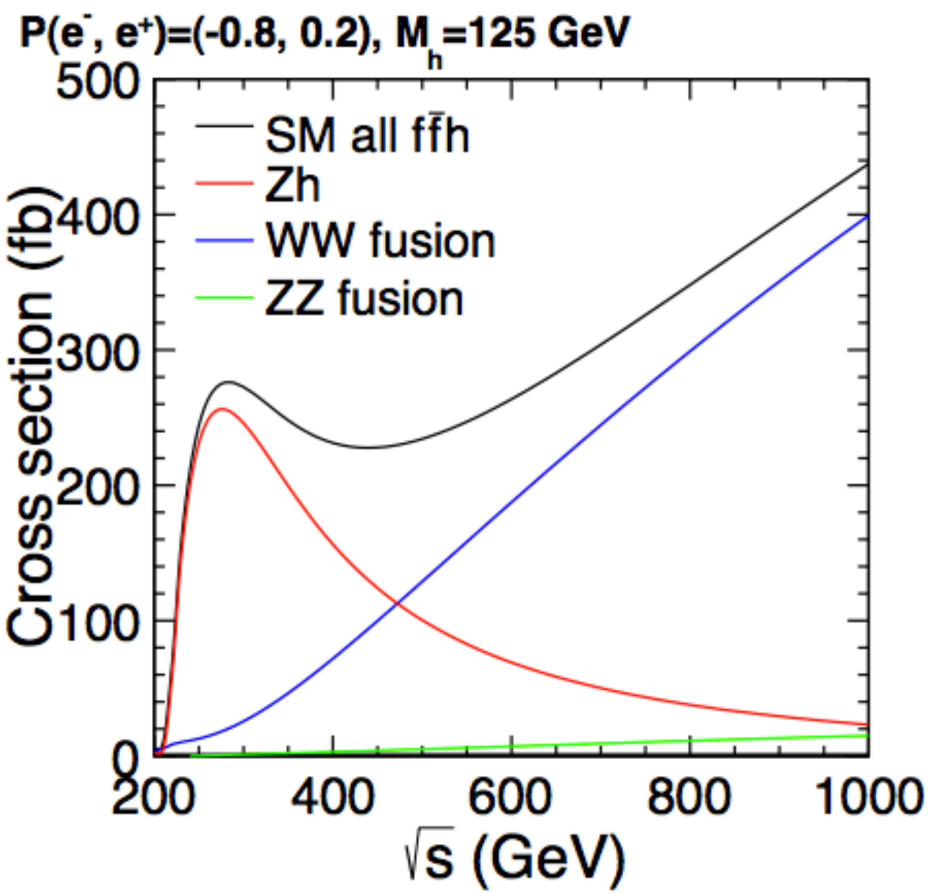

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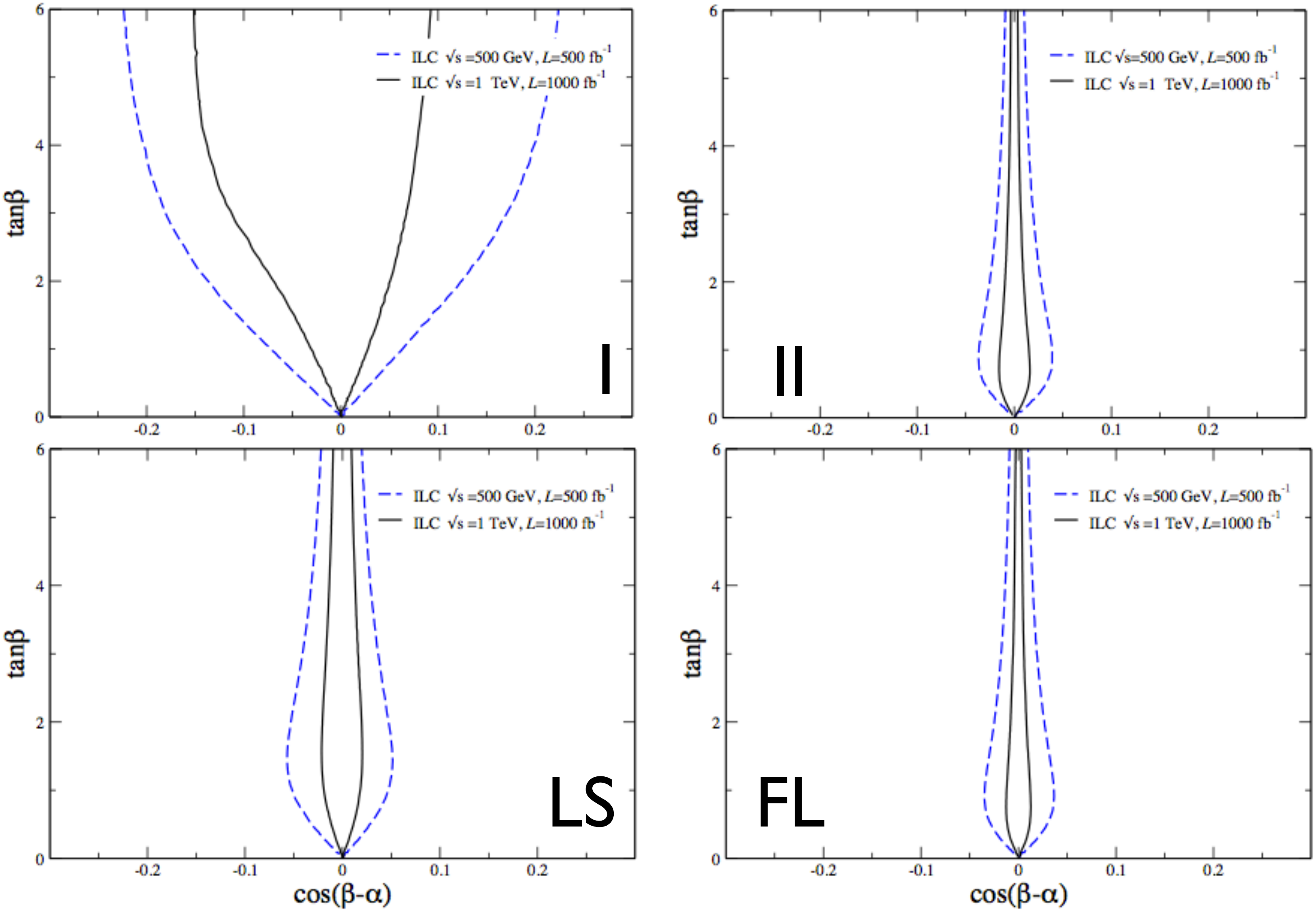
Comparison between ILC 500 GeV and 1TeV

Projections at 95% CL

ILC $\sqrt{s}$ =500 GeV, L=500 fb^{-1}

ILC $\sqrt{s}$ =1 TeV, L=1000 fb^{-1}



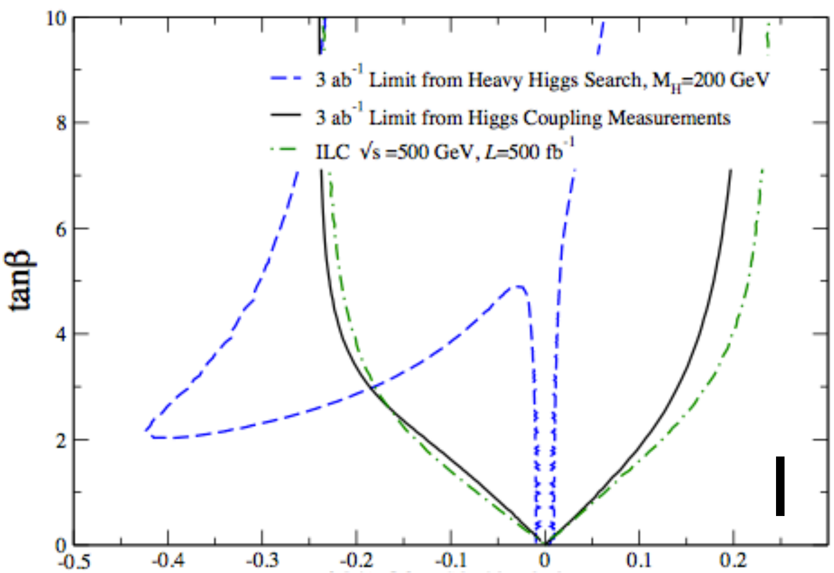
- Flipped model gives very similar result to the type II model, respectively.

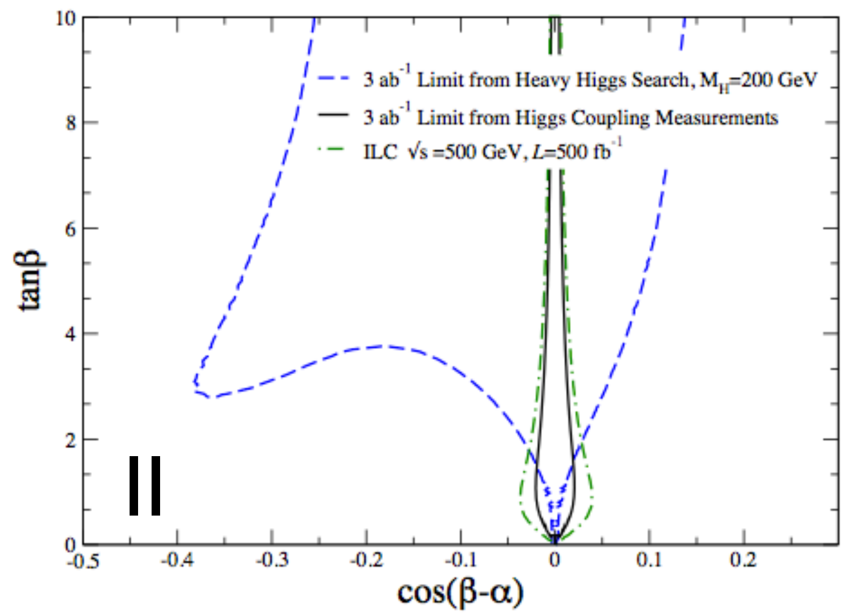
- An increase in luminosity will constrain $\cos(\beta-\alpha)$ and will give a sufficient constraint for small $\tan\beta$.

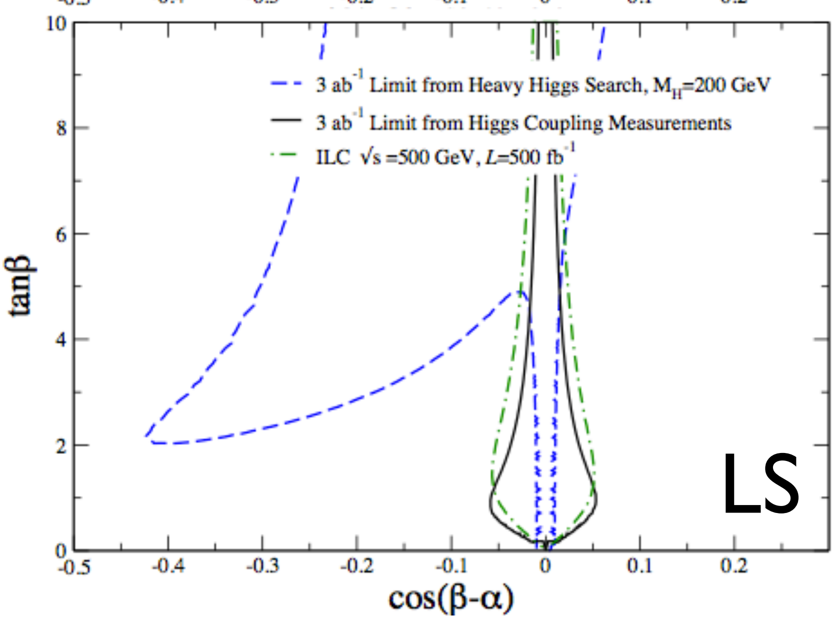
Comparison between ILC 500 TeV and LHC

Projections at 95% CL

- - 3 ab^{-1} Limit from Heavy Higgs Search, M_H=200 GeV
— 3 ab^{-1} Limit from Higgs Coupling Measurements
·- ILC $\sqrt{s}$ =500 GeV, L=500 fb^{-1}





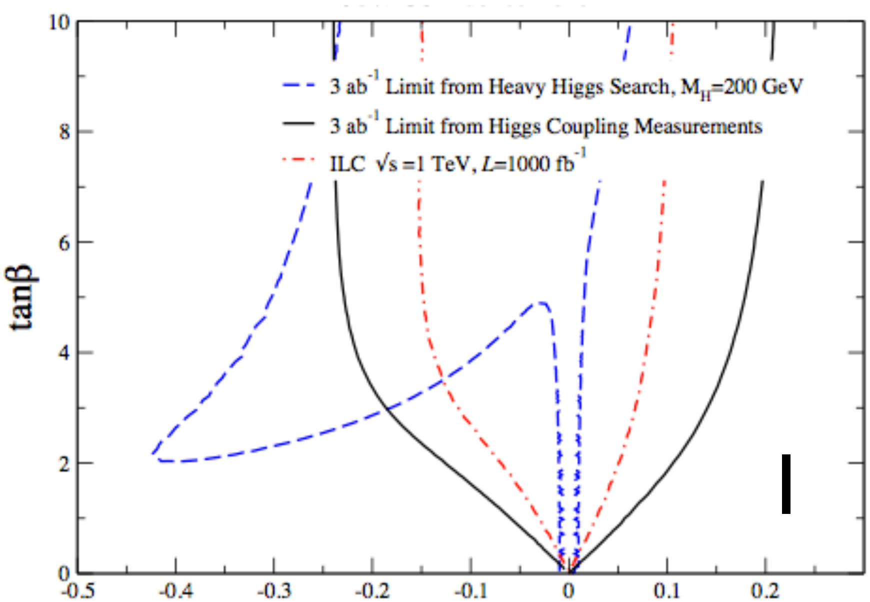


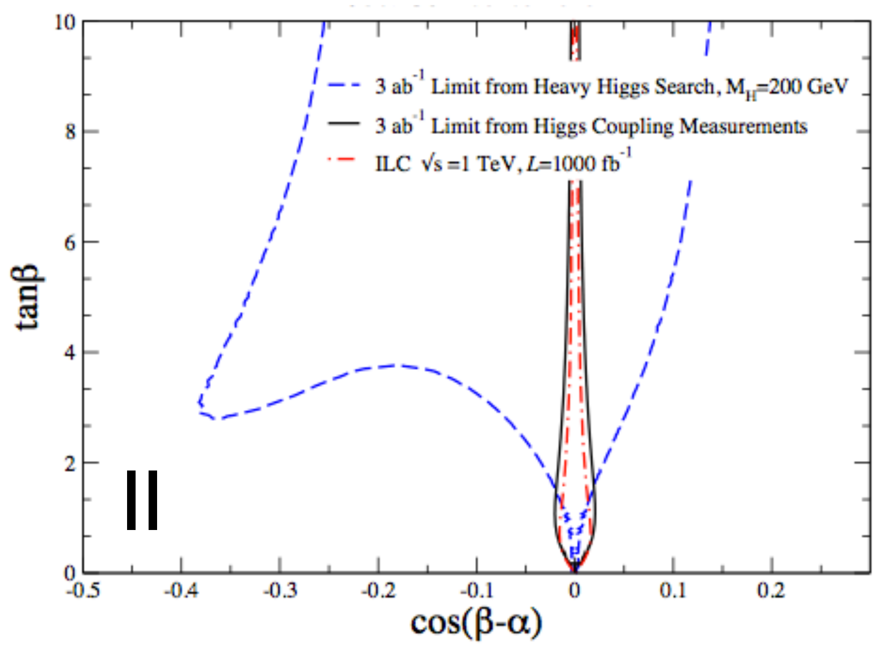
- The region between lines are allowed at 95% confidence level.
- The Flipped model has the similar results to the type-II model.
- Bounds from ILC are comparable to those from LHC.

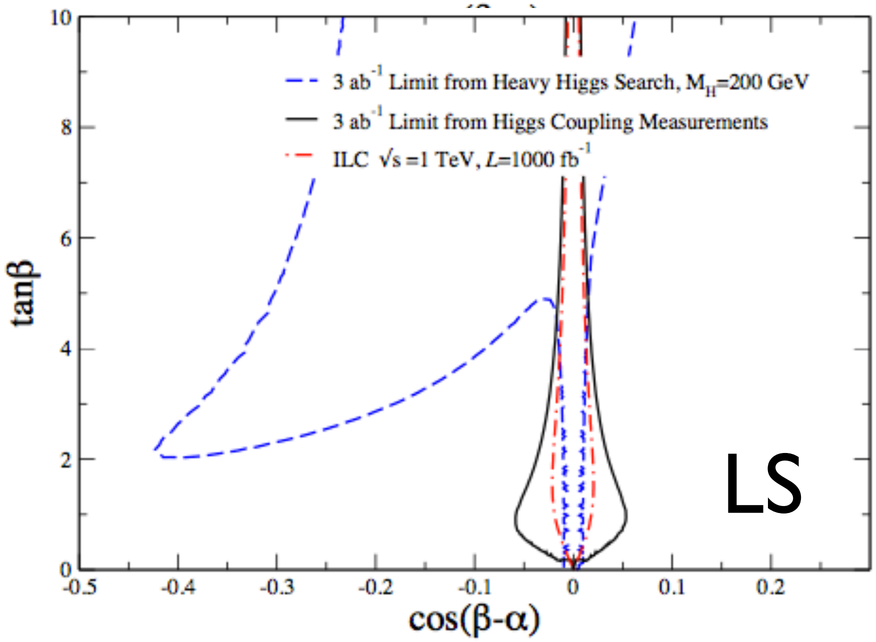
Comparison between ILC 1 TeV and LHC

Projections at 95% CL

3 ab^{-1} Limit from Heavy Higgs Search, M_H=200 GeV
3 ab^{-1} Limit from Higgs Coupling Measurements
ILC $\sqrt{s}$ =1 TeV, L=1000 fb^{-1}







- The region between lines are allowed at 95% confidence level.
- The Flipped model has the similar results to the type-II model.
- Bounds from ILC are better than those from LHC. In particular, in the type-I model a large part of the parameter-space is excluded.

Conclusions

- We have considered four variations of 2HDMs, with a Z_2 Symmetry.
- Based on the LHC Higgs data only small regions of parameter-space can produce rates which are consistent with the experiments.
- The projected sensitivity with 300/fb and 3/ab is discussed and we found that it is possible to exclude more parameter-space in the 2HDMs with higher luminosities.
- LHC bounds on a heavy Higgs searches can further restrict the parameter-space. In particular, for the type-I model the allowed region is shrunk by more than a factor of two.
- Projections for ILC show that ILC at 1TeV with 1000 /fb can give better bounds than those from LHC light Higgs coupling measurements at 14 TeV with 3/ab, especially for type-I model.

Thank you!

Backup slides

M_H=300 GeV

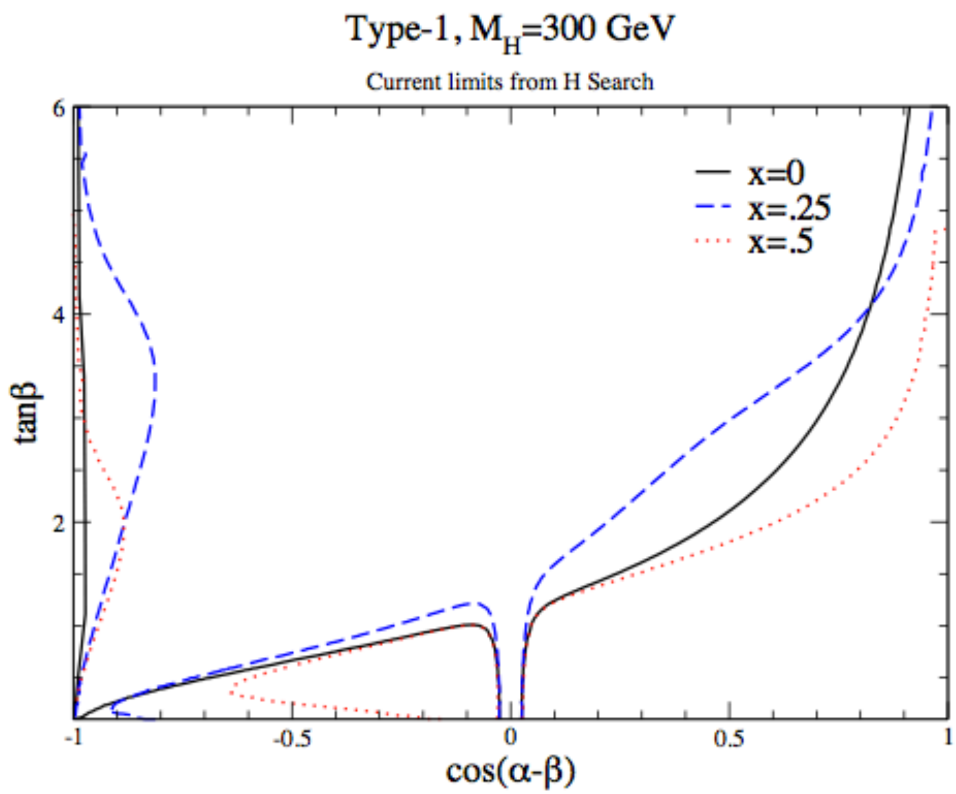
- H $\rightarrow$ h h becomes available: $\Gamma(H^0 \rightarrow h^0 h^0) = \frac{\lambda_{Hhh}^2}{8\pi M_H}\left(1 - \frac{4m_h^2}{M_H^2}\right)^{1/2}$

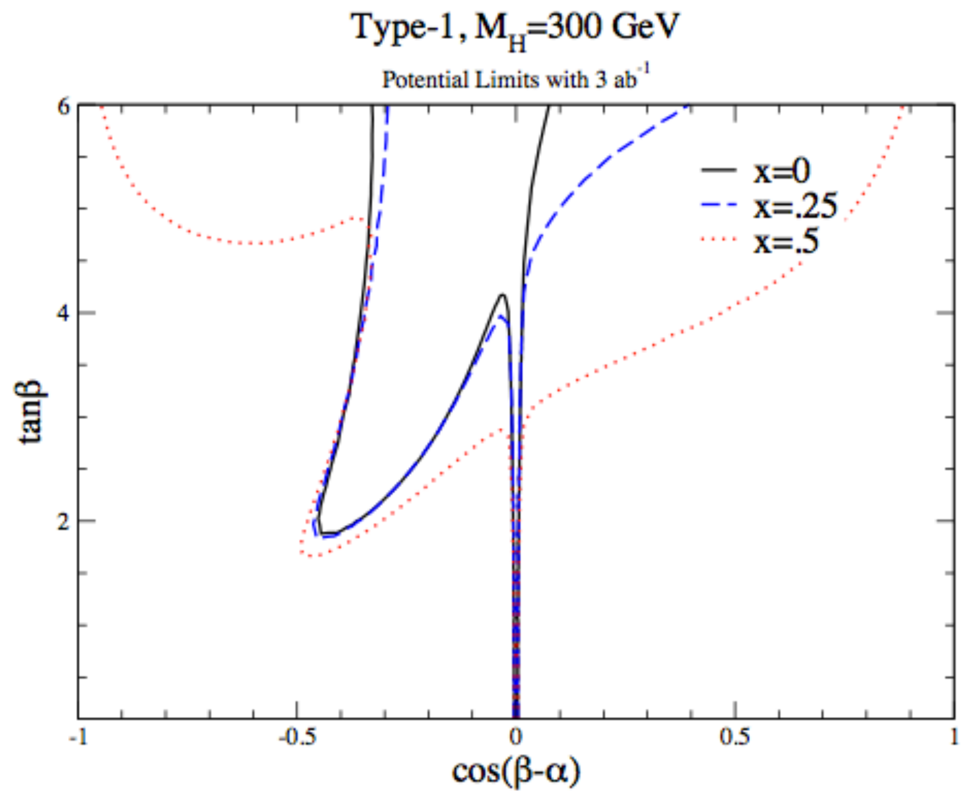
$$\lambda_{Hhh} = -\cos(\beta-\alpha)\left(\frac{\sin 2\alpha}{\sin 2\beta}\right)\frac{M_{H^0}^2 + 2M_{h^0}^2}{2v}\left\{1 - x\left(\frac{3}{\sin 2\beta} - \frac{1}{\sin 2\alpha}\right)\right\}$$

where $x \equiv 2\mu^2/(M_{H^0}^2 + 2M_{h^0}^2)$.

- x=0 case => No Flavor changing neutral current (FCNC).
- x is not equal to 0 => Z_2 symmetry is softly-broken.
- Due to the opening up of the H $\rightarrow$ h h channel, the exclusion region is smaller than from M_H = 200 GeV.

Soft-Z_2 breaking





- The region between lines are allowed at 95% confidence level.
- As x is increases above 0.25, the bounds become progressively weaker.