Multi tau lepton signatures in leptophilic 2HDM at ILC

Koji TSUMURA
(Nagoya Univ.)

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PRESENTATION

Outline:
- Leptophilic 2HDM
- Experimental constraints
- LHC search
- ILC search

NAGOYA UNIVERSITY

S. Kanemura, K. Tsumura and H. Yokoya, arXiv:1111.6089, accepted in Phys. Rev. D

M. Aoki, S. Kanemura, K. Tsumura and K. Yagyu, Phys. Rev. D80 015017 (2009)

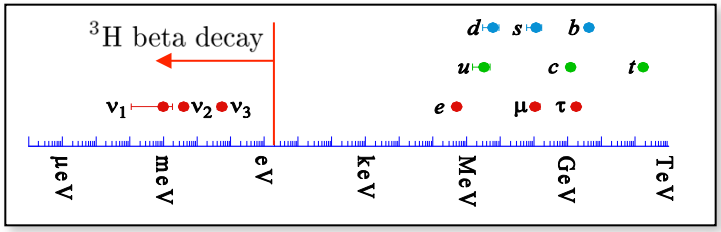
Why do we focus on Leptophilic Higgs boson?

New physics in Lepton sector

Tiny neutrino mass

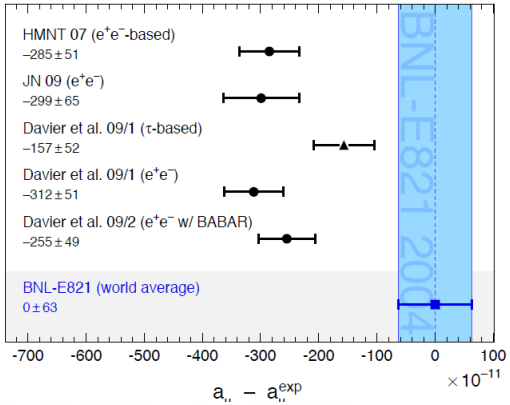
- Tree level seesaw (Type-II)
- Radiative seesaw (Zee, Zee-Babu, Ma,…)

These models introduce **new scalars**.



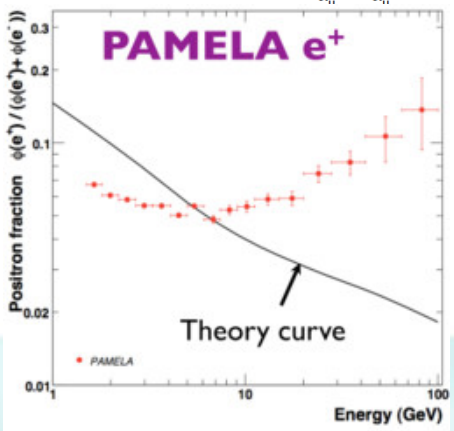
μ magnetic moment

New **LIGHT** scalars can give sizable contrib.

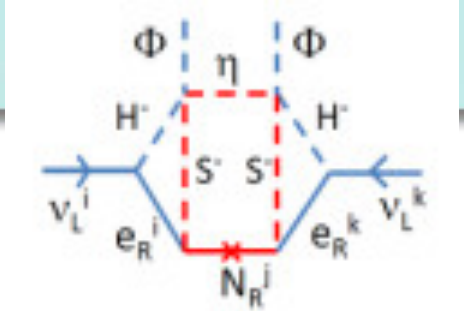


e^+ excess @ PAMELA, FERMI

New **Lepton-specific** scalar play
a role of a messenger to DM

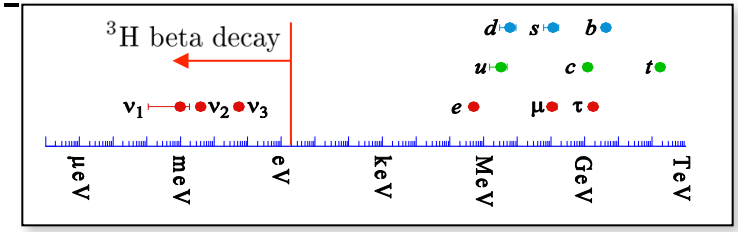


Leptophilic Higgs in 2HDM



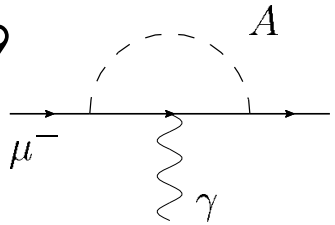
- **Tiny neutrino mass**

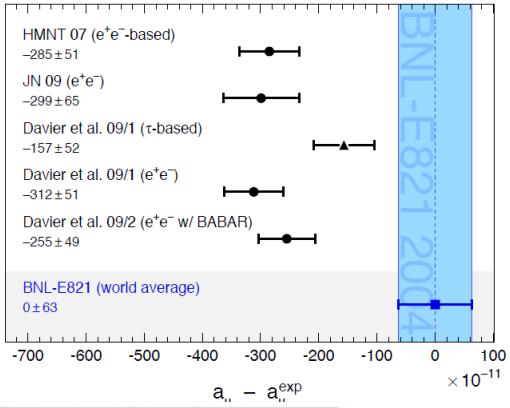
  ex. 3-loop radiative seesaw w/ light H+/-
  by Aoki et al. PRL102:051805,2009



- **μ magnetic moment**

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

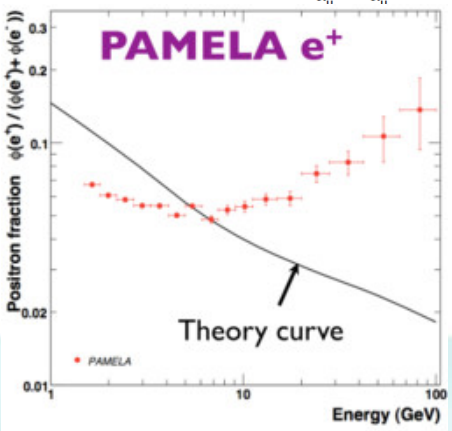




- **e^+ excess @ PAMELA, FERMI**

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

  DM DM → Φ' Φ' → ττττ



Classify 2HDMs by Yukawa

◻ General 2HDM (Type-III)

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

Yukawa int. is not simultaneously diagonalized with mass matrix.

→ Generate **tree level FCNC** (Flavor changing neutral current).

◻ Adding extra Z2 sym. to avoid FCNC

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

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

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**

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

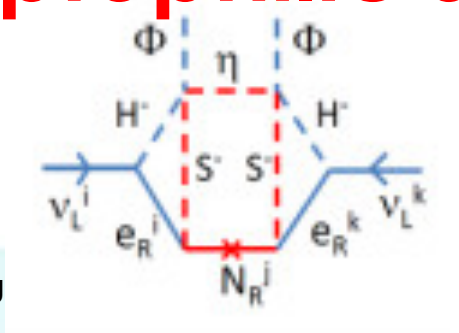
2HDM-X as a low energy effective theory

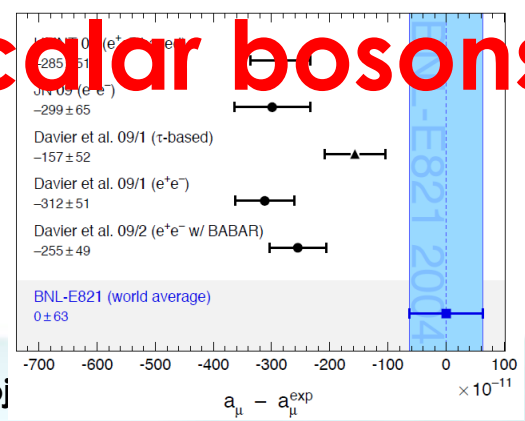
- Higgs doublets distinguish quarks and leptons

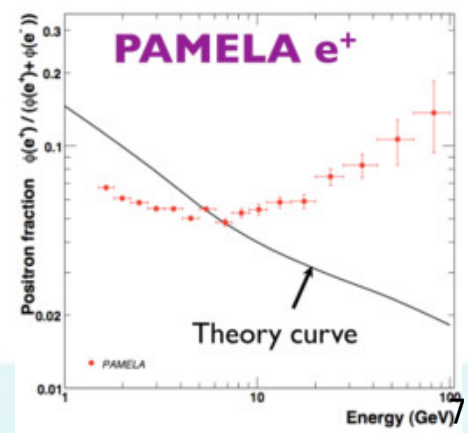
$$\mathcal{L} = +\overline{Q} Y_u u_R H_q + \overline{Q} Y_d d_R H_q + \overline{L} Y_\ell \ell_R H_\ell + \text{H.c.}$$

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

- Leptophilic scalar bosons







2HDM

- **Softly Z2 broken 2HDM**

$$\Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + i\, z_i) \end{pmatrix}$$

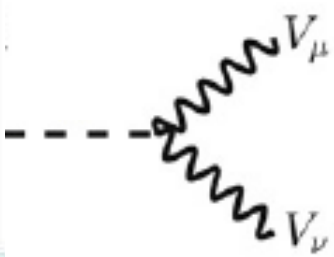
$$V_{2\mathrm{HDM}} = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - \left(m_3^2 \Phi_1^\dagger \Phi_2 + \mathrm{H.c.} \right) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2$$
$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) +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

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

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

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

$$m_h^2 \sim 2\lambda v^2, \quad m_{H,A,H^\pm}^2 \sim M^2 + \frac{\lambda v^2}{2} \quad \text{where} \quad M^2 \equiv m_3^2/(\sin\beta\cos\beta)$$



sin(β-α)(=1), **tanβ** are also free parameters

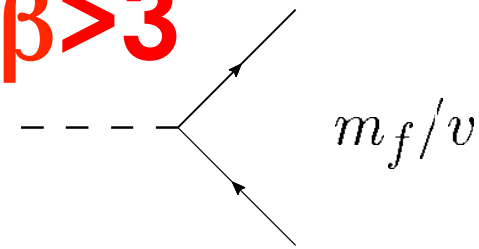
Type-X Yukawa interaction

- Yukawa int. of extra scalars (H,A,H^+) in the SM-like limit is corrected by a factor of $\tan\beta = \langle \Phi_2 \rangle / \langle \Phi_1 \rangle$

$\xi_f \times m_f/v$

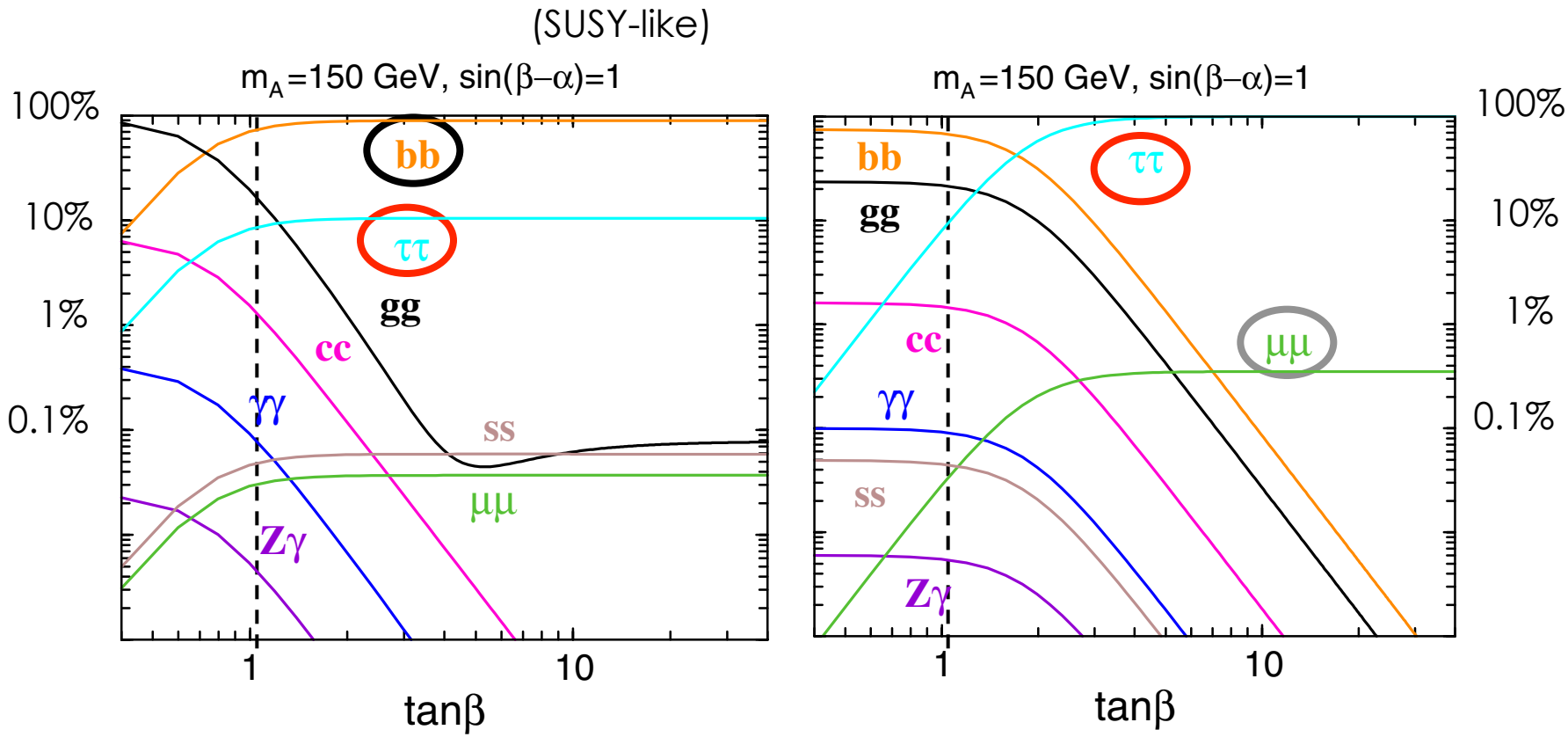
	ξ^u	ξ^d	ξ^ℓ	
Type-I	$1/\tan\beta$	$-1/\tan\beta$	$-1/\tan\beta$	SM-like
Type-II	$1/\tan\beta$	$\tan\beta$	$\tan\beta$	SUSY-like
Type-X	$1/\tan\beta$	$-1/\tan\beta$	$\tan\beta$	
Type-Y	$1/\tan\beta$	$\tan\beta$	$-1/\tan\beta$	

Type-X: Leptoplilic in tanβ>3



Higgs decays in 2HDMs

Aoki, Kanemura, Tsumura, Yagyu, PRD80, 015017 (2009)

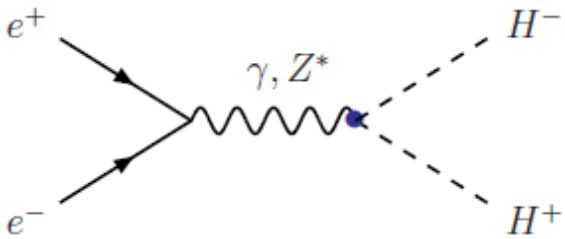


- 2HDM-X: Enhance leptonic Yukawa int. by tanβ.
  - More than 99% of H/A decay into ττ
  - Sizable μμ [$(m_\mu/m_\tau)^2$=1/300] mode

Experimental constraints

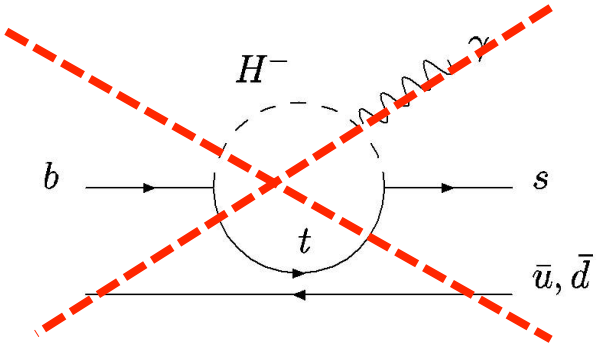
- Direct search results
- B decays
- Tau decays

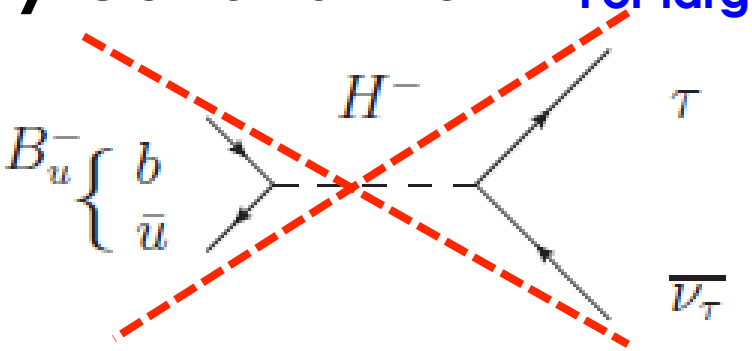
Direct search ~100GeV@LEP



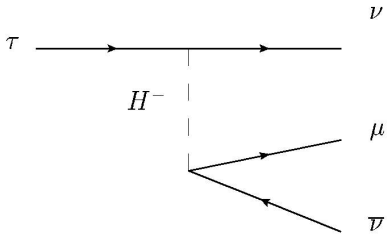
Almost free from B decay constraints

For large tanβ

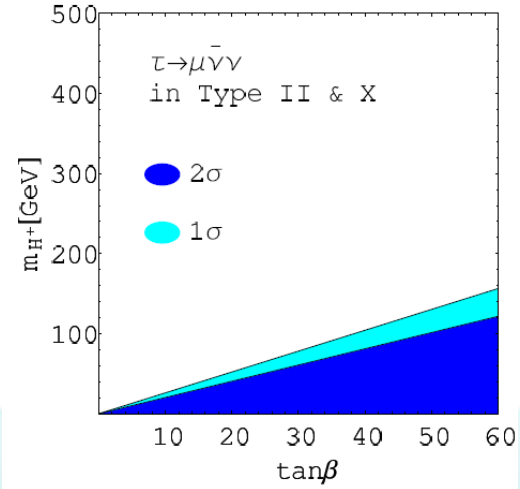




weaker constraint by τ decays



For large tanβ



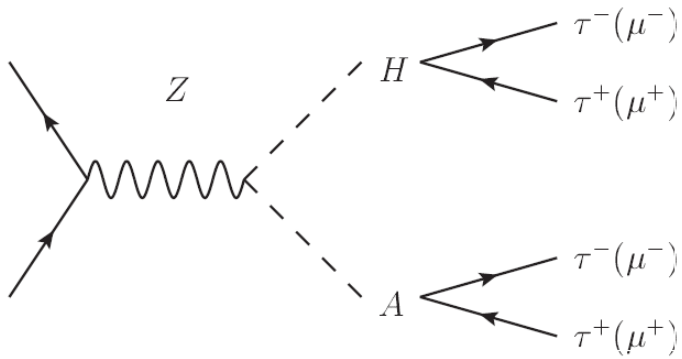
Leptophilic Higgs boson @ colliders

LHC vs ILC

Test of Leptophilic-2HDM @ LHC and ILC

Kanemura, Tsumura, Yokoya

- DY production with leptonic decay modes

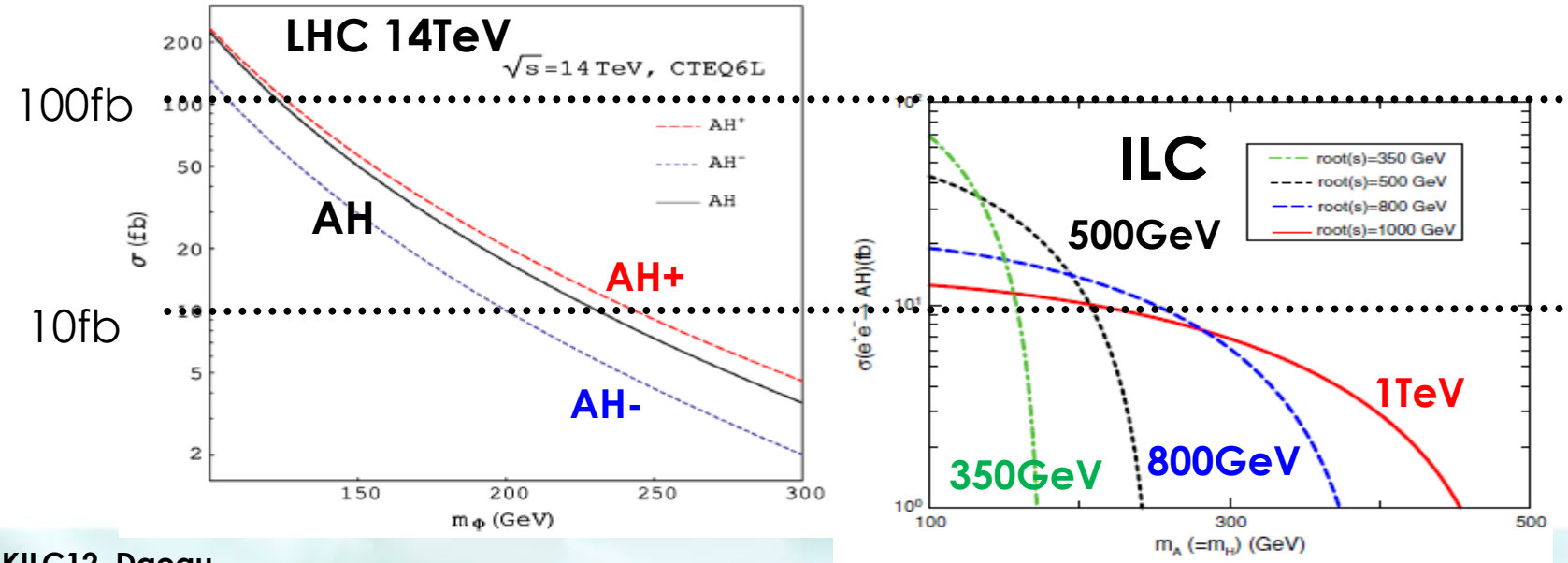


Multi tau lepton signatures

4τ: more than 99%

2μ2τ: σ(4τ) x 1/300 x 2!

- Cross sections are O(10)fb @ LHC & ILC



LHC14

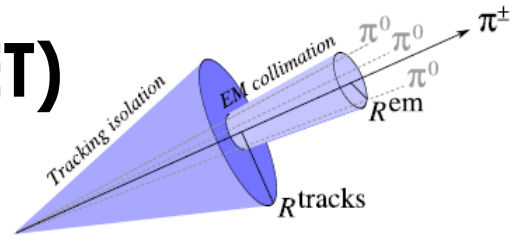
- mH=130GeV & mA=170GeV [σ=50fb]
- BG [VV(107pb), ttbar(492pb), DY(30nb)]

Event analysis details (for LHC14 and ILC500)

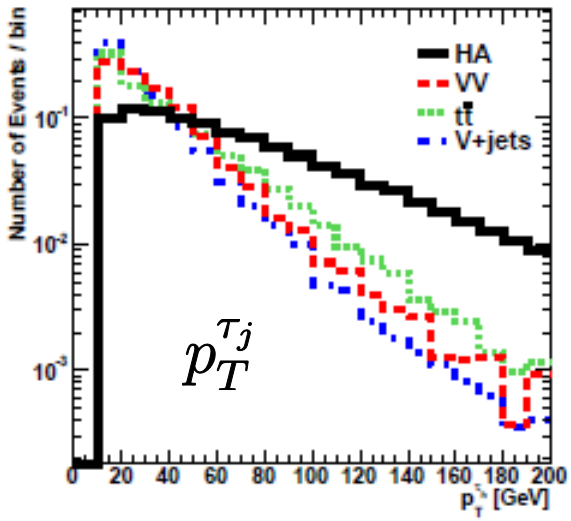
-FastJet, TAUOLA, PYTHIA, MG5 are used,
jet is defined by anti-kT w/ R<0.4

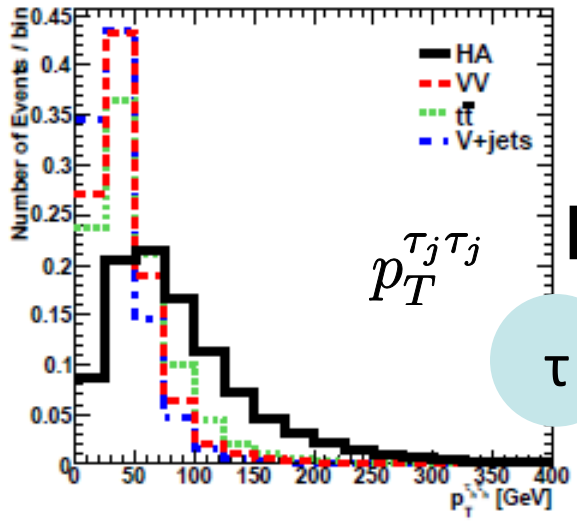
-Identification of hadronic τ

- Require 1 or 3 charged-hadron(s) (1- & 3-prong)
- **Narrow cone R<0.15 (95% of ET)**



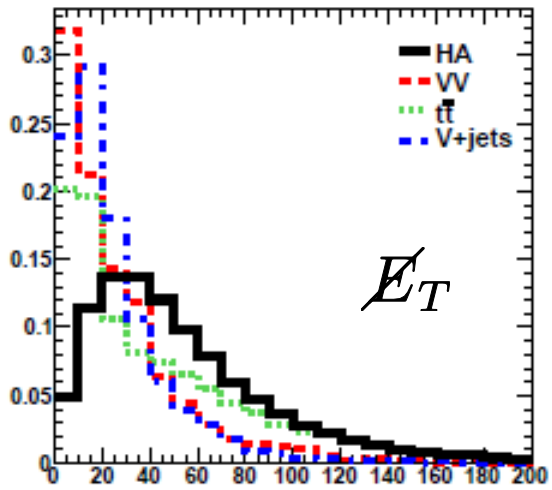
$4\tau_h$ channel : τ_h τ_h τ_h τ_h @LHC14 (an example)

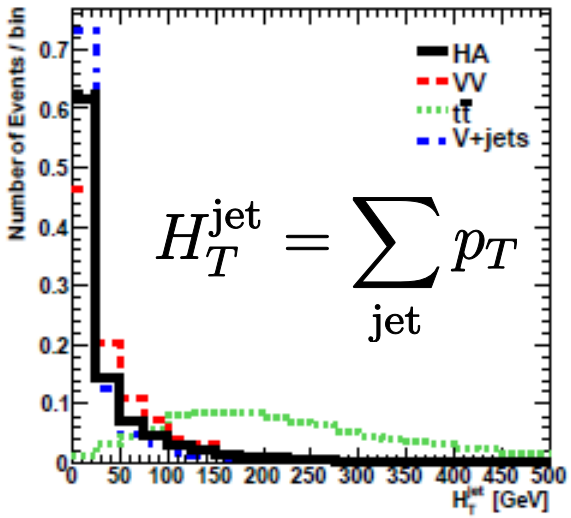


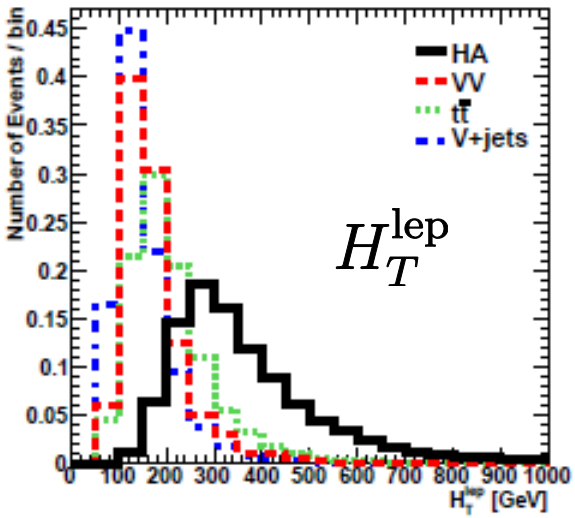


Pre-selection: 4 τ_h

τ ⇨ e μ or τ_h







$4\tau_h$ channel : τ_h τ_h τ_h τ_h @LHC14 (an example)

L=100 [fb^{-1}]

- perform selection cuts to enhance signal/background ratio

$4\tau_h$ 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

High pT cut: VV

pT cut: DY

Pre-selection: 4 τh

HTjet cut: ttbar

- Significance estimator:

$$S = \sqrt{2[(s+b)\ln(1+s/b) - s]} \simeq s/\sqrt{b} \quad (s \ll b)$$

Optimize kinematical cuts, and many channels

$4\tau_h$ event analysis	HA	$\phi^0 H^\pm$	VV	$t\bar{t}$	V+jets	s/b	S (100 fb^{-1})
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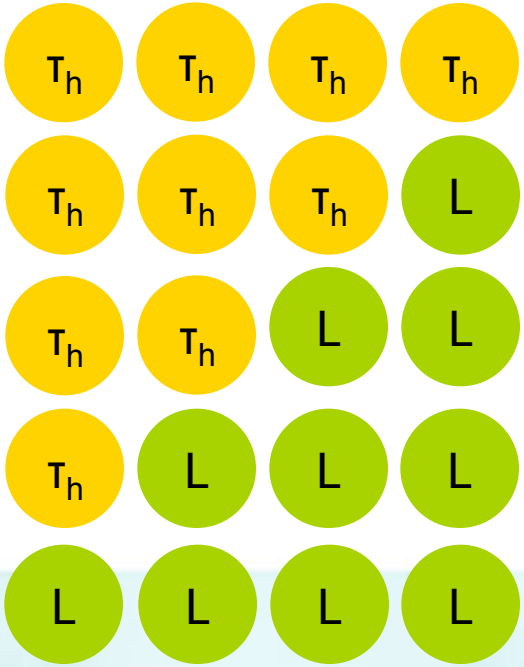
L=100 [fb^{-1}]

Lepton channels	$4\tau_h$		$3\tau_h 1\mu$		$3\tau_h 1e$		$2\tau_h 1\mu 1e$		$2\tau_h 2e$	
	s/b	(S)	s/b	(S)	s/b	(S)	s/b	(S)	s/b	(S)
Pre-selection	377./6050.	(4.8)	302./4208.	(4.6)	278./3883.	(4.4)	166./917.	(5.3)	74.4/13202.	(0.6)
$p_T^{\tau_h} > 40$ GeV	72.1/38.5	(9.5)	87.2/70.2	(8.9)	80.2/72.2	(8.2)	71.7/67.5	(7.6)	32.4/479.	(1.5)
$\not{E}_T > 30$ GeV	53.0/19.0	(9.3)	69.3/54.6	(8.0)	63.4/53.8	(7.5)	58.0/58.6	(6.7)	26.3/38.6	(3.8)
$H_T^{\rm jet} < 50$ GeV	37.6/9.6	(8.7)	49.0/17.4	(8.9)	44.9/23.0	(7.6)	41.7/13.7	(8.5)	18.7/16.0	(4.0)
$H_T^{\rm lep} > 350$ GeV	30.3/4.0	(9.3)	34.5/8.4	(8.4)	31.4/10.9	(7.2)	24.2/3.8	(8.0)	10.7/8.2	(3.2)
$(m_Z)_{ee} \pm 10$ GeV	-	(-)	-	(-)	-	(-)	-	(-)	9.3/2.5	(4.2)

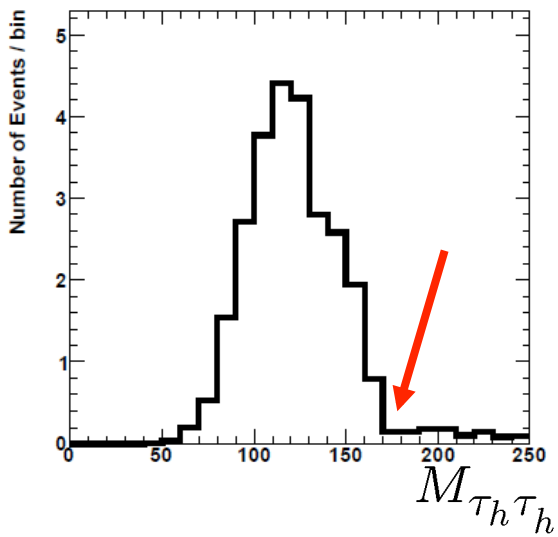
Lepton channels	$1\tau_h 1\mu 2e$		$1\tau_h 3e$		$1\mu 3e$		$4e$	
	s/b	(S)	s/b	(S)	s/b	(S)	s/b	(S)
Pre-selection	29.2/132.	(2.5)	8.7/120.	(0.8)	1.7/7.6	(0.6)	0.4/268.	(0.0)
$p_T^{\tau_h} > 40$ GeV	19.3/38.6	(2.9)	5.6/34.2	(0.9)	-	(-)	-	(-)
$\not{E}_T > 30$ GeV	15.5/22.1	(3.0)	4.6/19.2	(1.0)	1.2/3.4	(0.6)	0.3/2.6	(0.2)
$(m_Z)_{ee} \pm 10$ GeV	13.6/2.4	(5.8)	4.0/6.5	(1.4)	1.1/1.2	(0.9)	0.2/0.7	(0.2)

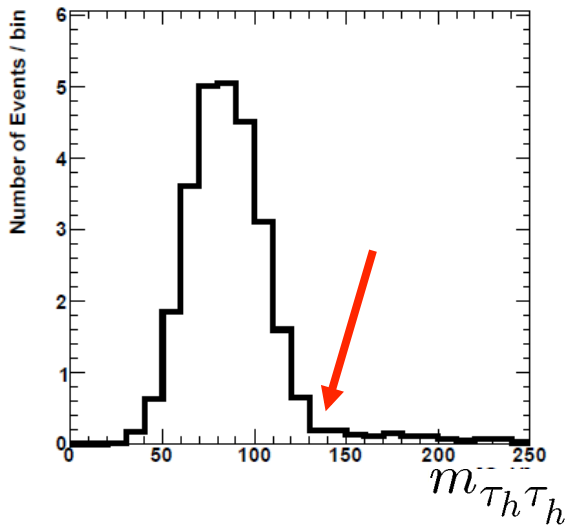


L=100 [fb^{-1}]

- **Remarks:**
  - **Higgs boson masses may be obtained by finding endpoints of $M_{\tau_h\tau_h}$ distributions.**

mH=130GeV & mA=170GeV





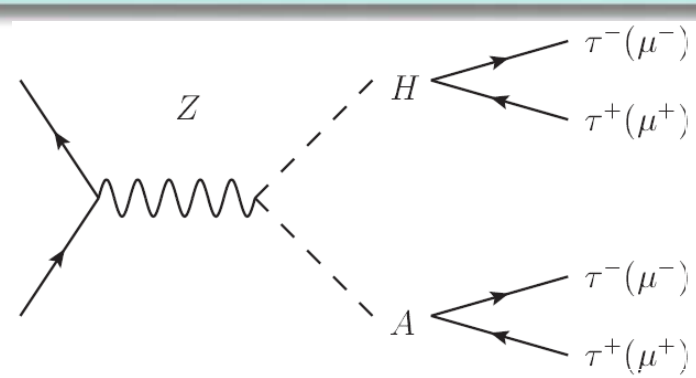
$M_{\tau_h\tau_h} > m_{\tau_h\tau_h}$

Pairing of tau-jets from the four can be chosen for the pair which has max. transverse momentum of tau-jet-pair, or which has smallest distance.

Does ILC have advantages?

Multi tau lepton signature @ ILC

◻ Advantages:



-Less BG events **mH=130GeV & mA=170GeV**

σ=30fb, ZZ(567"fb"), ttbar(580"fb"), WW(7700"fb") @ ILC500

[σ=50fb, VV(107pb), ttbar(492pb), DY(30nb) @ LHC14]

-Precise mass determination by using collinear approx.

$$\vec{0} = z_1^{-1}\,\vec{p_T}_{\tau_j 1} + z_2^{-1}\,\vec{p}_{\tau_j 2} + z_3^{-1}\,\vec{p}_{\tau_j 3} + z_4^{-1}\,\vec{p}_{\tau_j 4}$$
$$\sqrt{s} = z_1^{-1}\,E_{\tau_j 1} + z_2^{-1}\,E_{\tau_j 2} + z_3^{-1}\,E_{\tau_j 3} + z_4^{-1}\,E_{\tau_j 4}$$

4 unknown(z1-z4) are calculated by solving simultaneous 4 eqs.

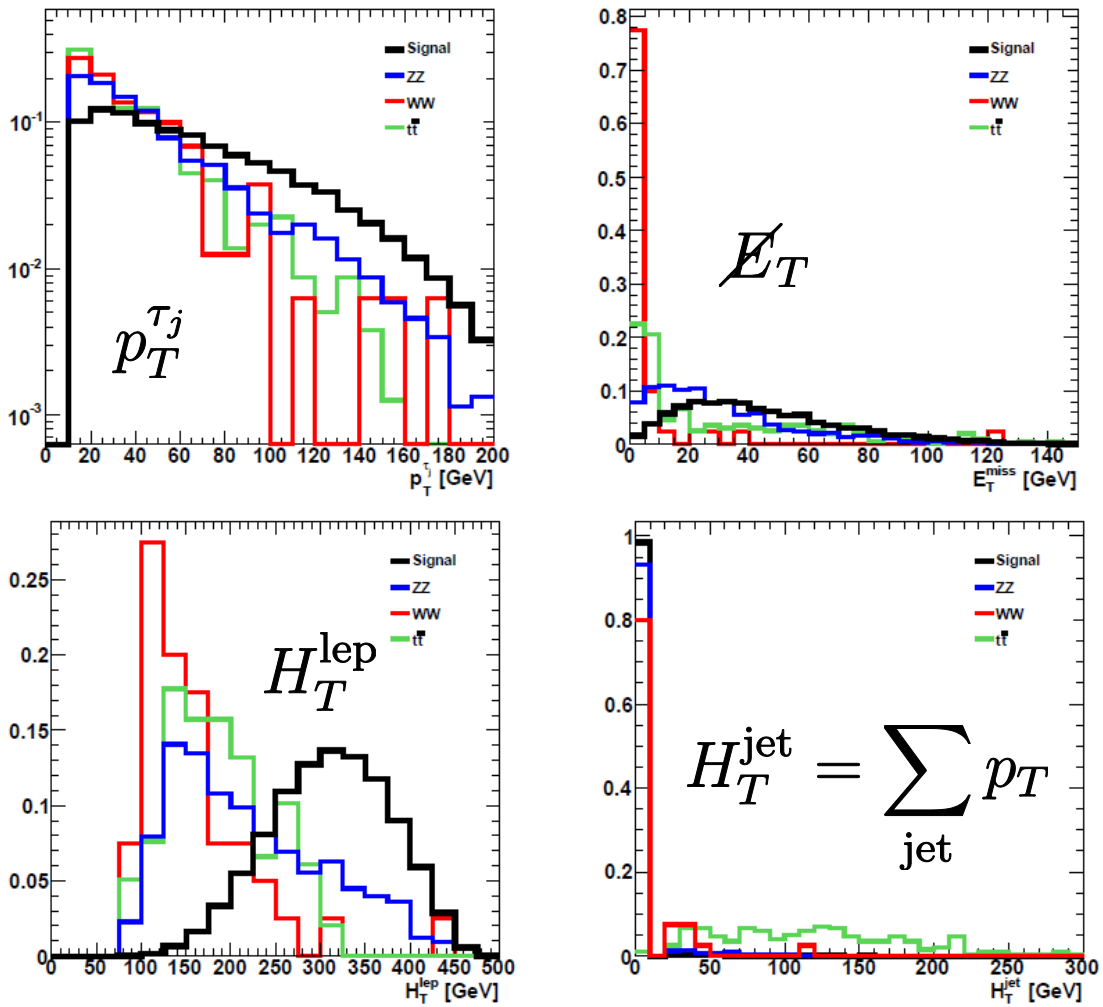
→ 4 τ mom. are fully reconstructed from taujet & missing mom.!!

No missing other than tau decays

$4\tau_h$ channel : τ_h τ_h τ_h τ_h @ILC500 (an example)

HA: 30fb for mH=130GeV & mA=170GeV
ZZ, ttbar, WW: 567fb,580fb, 7700fb @ ILC

Before pre-selection cuts!!
(Normalized by same # of evts)

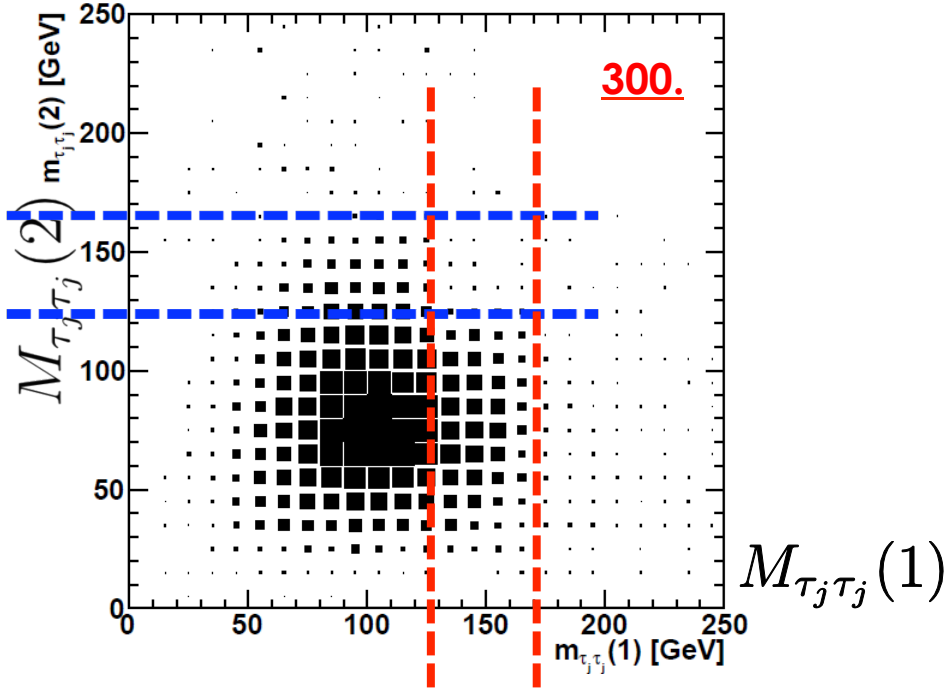


$4\tau_h$ channel : τ_h τ_h τ_h τ_h @ILC500 (an example)

$4\tau_h$ 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.

BG events are well reduced even at pre-selection level!!

- $M_{\tau_j\tau_j}$ @ILC500 (before collinear approx.)

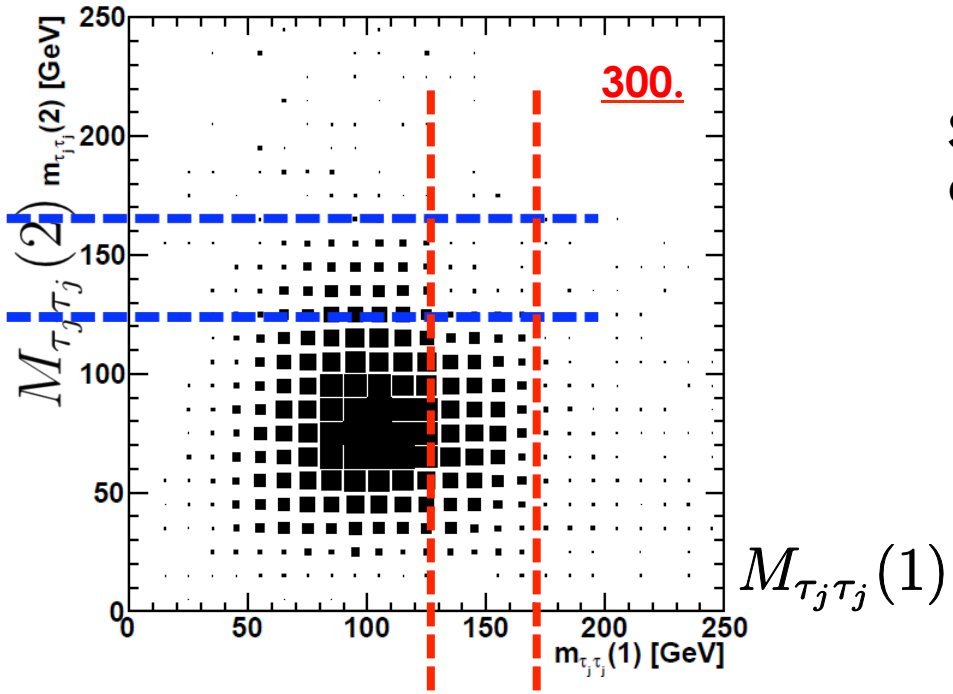


Endpoint analysis

$4\tau_h$ channel : τ_h τ_h τ_h τ_h @ILC500 (an example)

$4\tau_h$ 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.

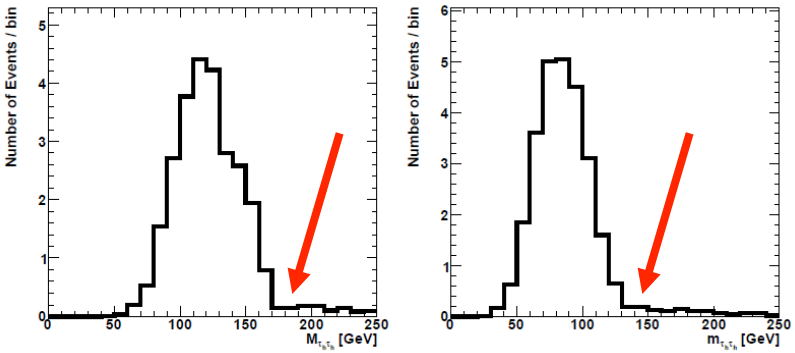
- $M_{\tau_j\tau_j}$ @ILC500 (before collinear approx.)



Endpoint analysis

Similarly to LHC14, masses can be determined by endpoint analysis.

$M_{\tau_j\tau_j}$ **@LHC14**

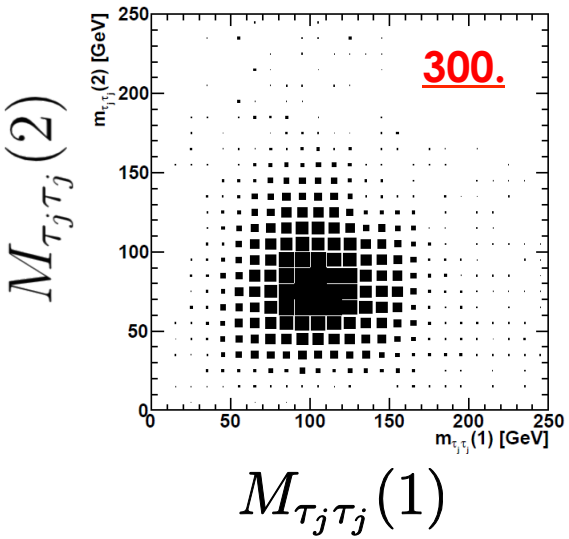


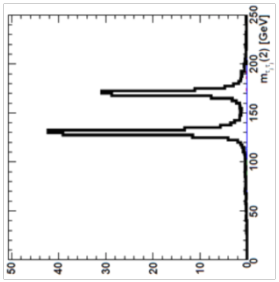
$M_{\tau_h\tau_h} > m_{\tau_h\tau_h}$

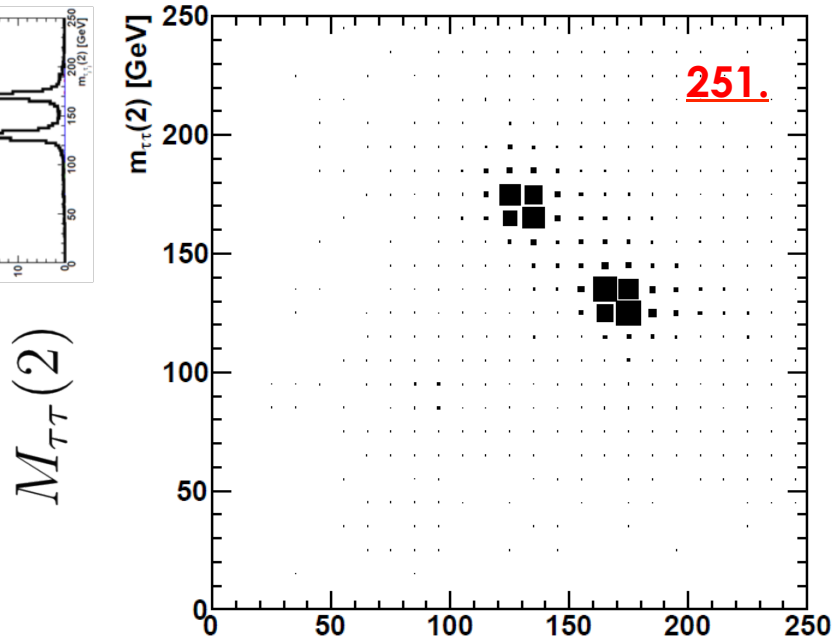
$4\tau_h$ channel : τ_h τ_h τ_h τ_h @ILC500 (an example)

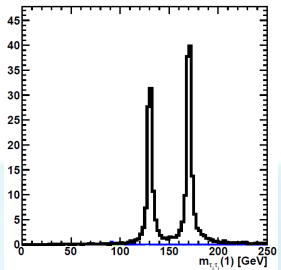
$4\tau_h$ event analysis	HA	VV	$t\bar{t}$	S (100 fb^{-1})
Pre-selection	300.	10.6	1.2	38.
$0 \leq z_{1-4} \leq 1$	251.	6.2	0.1	38.
$(m_Z)_{\tau\tau} \pm 20$ GeV	238.	1.8	0.	43.

- $M_{\tau_j\tau_j}$ → collinear approx.





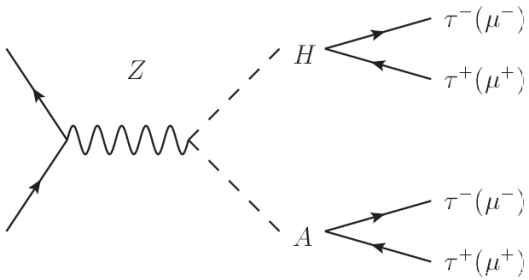


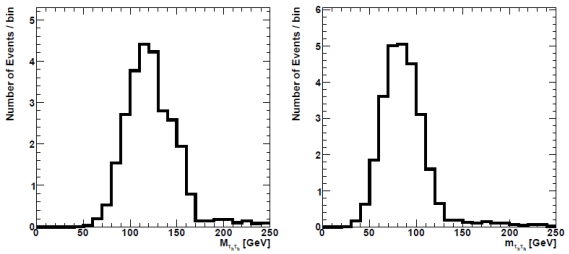


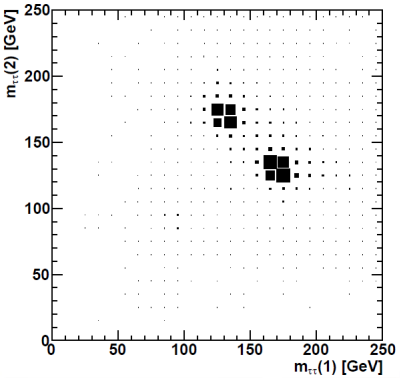
We can see ττ invariant mass distributions.
We can directly probe scalar pair productions.

Summary

- **Type-X (leptophilic) 2HDM is interesting.**
  - Light scalar bosons are allowed by experimental data.
  - Scalar bosons mainly decay into τ.
- **Multi tau lepton signatures at colliders**
  - DY production & H/A → ττ
  - **4τ signal @ LHC14 w/o collinear approx.**
    - Endpoint analysis for mass
  - **4τ signal @ ILC500 w/ collinear approx.**
    - Invariant Mass analysis
    - Directly probe pair productions







Back up

ρ-parameter

- **In the SM (top-bottom, Higgs-gauge loop)**

$$\Delta\rho_t = \frac{3G_F m_t^2}{8\sqrt{2}\pi^2}, \quad \Delta\rho_h = -\frac{3G_F m_Z^2 s_W^2}{8\sqrt{2}\pi^2}\left(\ln\frac{m_h^2}{m_W^2} - \frac{5}{6}\right)$$

- **In the 2HDM (in addition, Higgs-Higgs loop)**

$$\Delta\rho_\Phi = \frac{G_F}{8\sqrt{2}\pi^2}\left[F_\Delta(m_{H^\pm}^2, m_A^2) + s_{\beta-\alpha}^2 F_\Delta(m_{H^\pm}^2, m_H^2) + c_{\beta-\alpha}^2 F_\Delta(m_{H^\pm}^2, m_h^2)\right.$$
$$\left. + s_{\beta-\alpha}^2 F_\Delta(m_A^2, m_H^2) + c_{\beta-\alpha}^2 F_\Delta(m_A^2, m_h^2)\right]$$
$$F_\Delta(m_1^2, m_2^2) = \frac{m_1^2 + m_2^2}{2} - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2}\ln\frac{m_1^2}{m_2^2}$$

Typical solutions

1) $m_{H^\pm} \simeq m_A$
2) $m_{H^\pm} \simeq m_H$ with $\sin^2(\beta-\alpha) \simeq 1$
3) $m_{H^\pm} \simeq m_h$ with $\cos^2(\beta-\alpha) \simeq 1$

Direct search limit for scalar bosons

Higgs Bosons — H^0 and $H^{\pm}$, Searches for

The limits for H_1^0 and A_0 refer to the m_h^{max} benchmark the supersymmetric parameters.

H^0 Mass $m >$ 114.4 GeV, CL = 95%

H_1^0 in Supersymmetric Models ($m_{H_1^0} < m_{H_2^0}$)

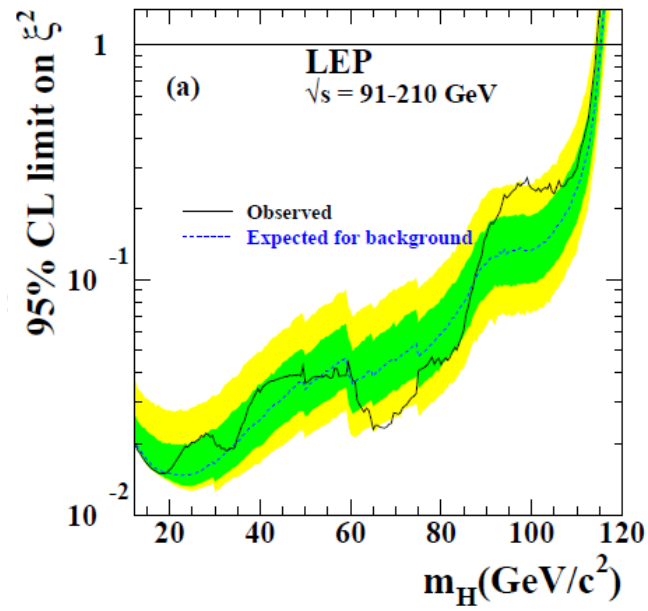
Mass $m >$ 92.8 GeV, CL = 95%

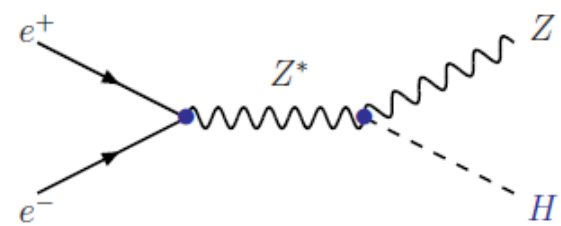
A^0 Pseudoscalar Higgs Boson in Supersymmetric Models

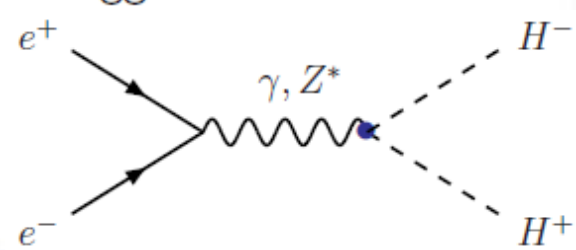
Mass $m >$ 93.4 GeV, CL = 95% $\tan\beta > 0.4$

$H^{\pm}$ Mass $m >$ 79.3 GeV, CL = 95%

See the Particle Listings for a Note giving details of Higgs Bosons.





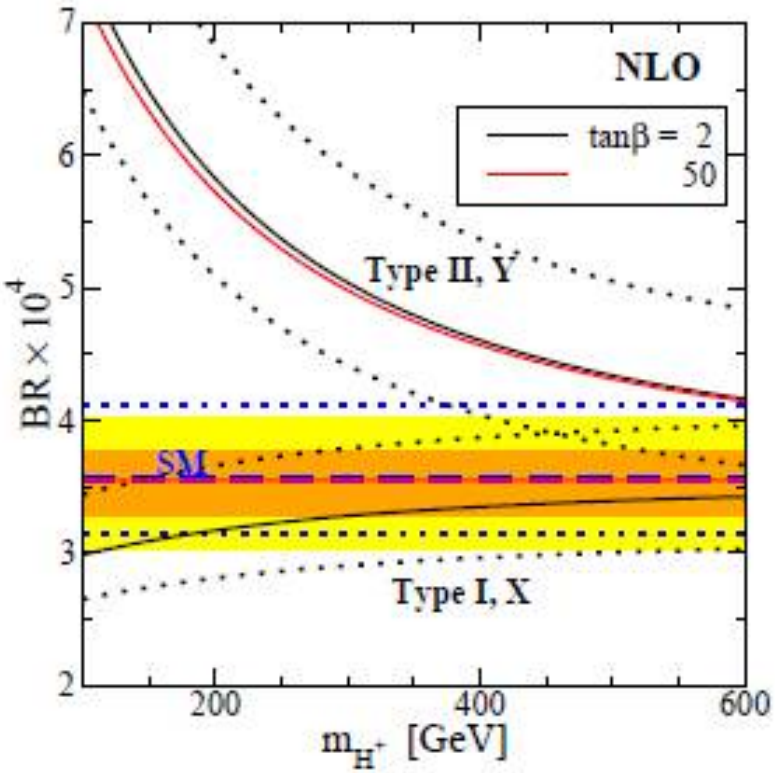


b → s γ

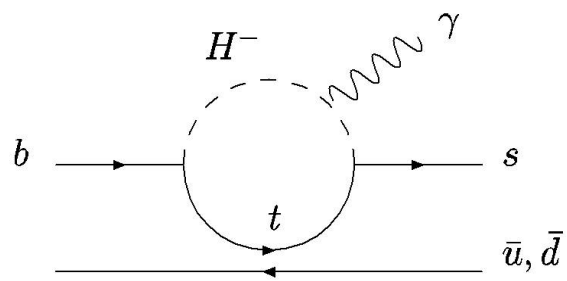
In addition to C7W (SM W boson loop),

Constant for wide range of tanb.

$$C_7^{H^\pm} = 2\sqrt{2}G_F\left\{\frac{1}{\tan^2\beta}F\left(\frac{m_t^2}{m_{H^\pm}^2}\right) + \frac{1}{\tan\beta}\tan\beta\, G\left(\frac{m_t^2}{m_{H^\pm}^2}\right)\right\}$$



Type-II



mH+ > 300GeV

Light H+ is disfavored for Type-II.

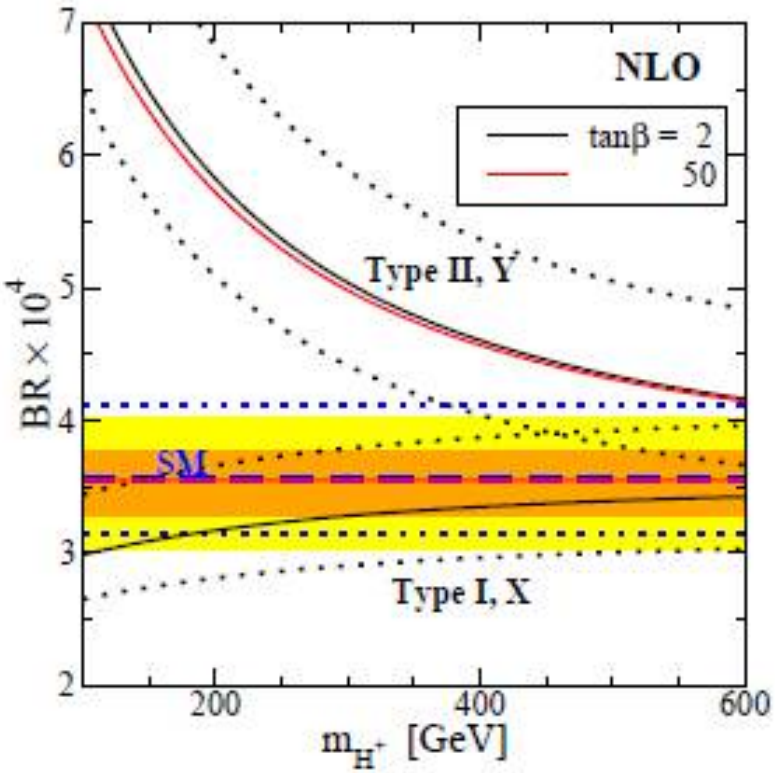
chargino−stop loop can cancel this contribution in MSSM

→ Light charged Higgs boson is still possible **for MSSM**.

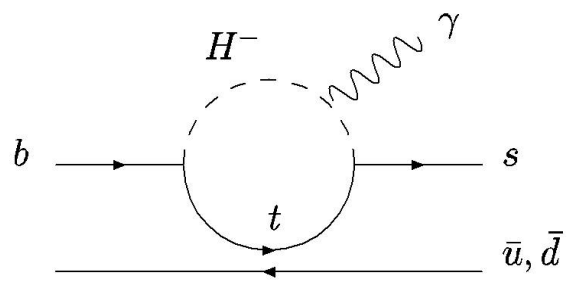
b → s γ

In addition to C7W (SM W boson loop), **small contrib. for tanb>2.**

$$C_7^{H^\pm} = 2\sqrt{2}G_F\left\{\frac{1}{\tan^2\beta}F\left(\frac{m_t^2}{m_{H^\pm}^2}\right) + \frac{1}{\tan\beta}\frac{1}{\tan\beta}G\left(\frac{m_t^2}{m_{H^\pm}^2}\right)\right\}$$



Type-X



Light charged Higgs is allowed for Type-X in tanb>2.

4 types of Yukawa int.

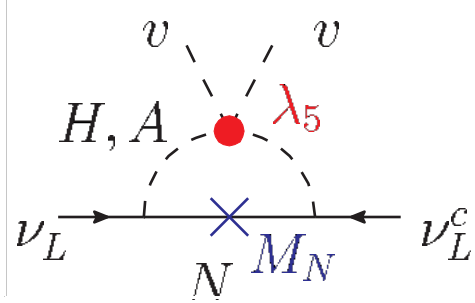
- 4 independent combinations of Z2 charges

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

- **Type-I: SM-like Higgs and an extra scalar**

Fermion masses are generated onlv from Φ2

(may relate for Ma model,…<Φ1>=0)



4 types of Yukawa int.

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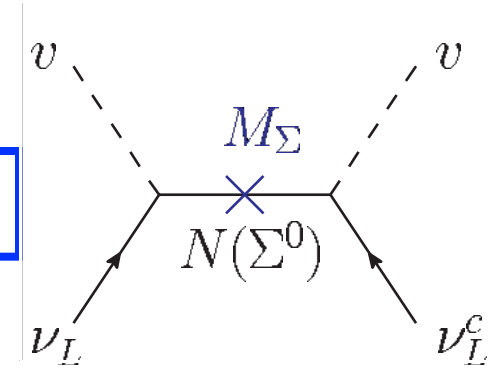
	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q, L
Type-I	+	-	-	-	-	+
Type-II	+	-	-	+	+	+
Type-X	+	-	-	-	+	+
Type-Y	+	-	-	+	-	+



- **Type-X: gauged type-III seesaw**

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

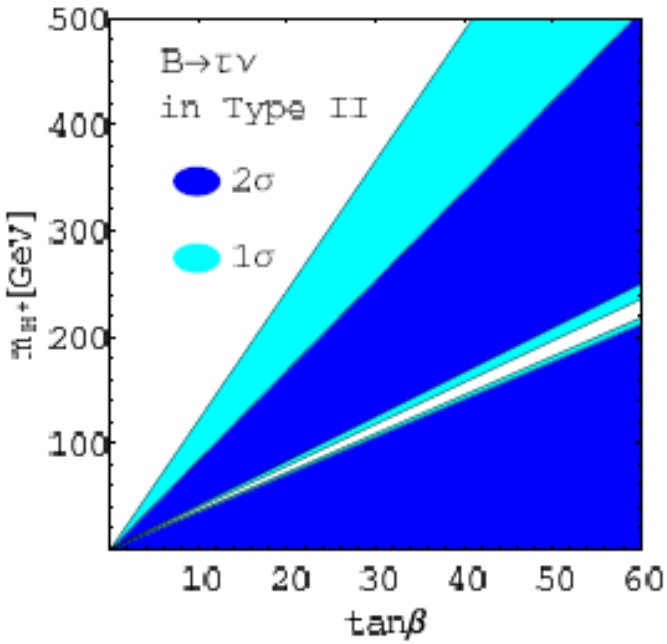
Higgs bosons distinguish quarks and leptons!!

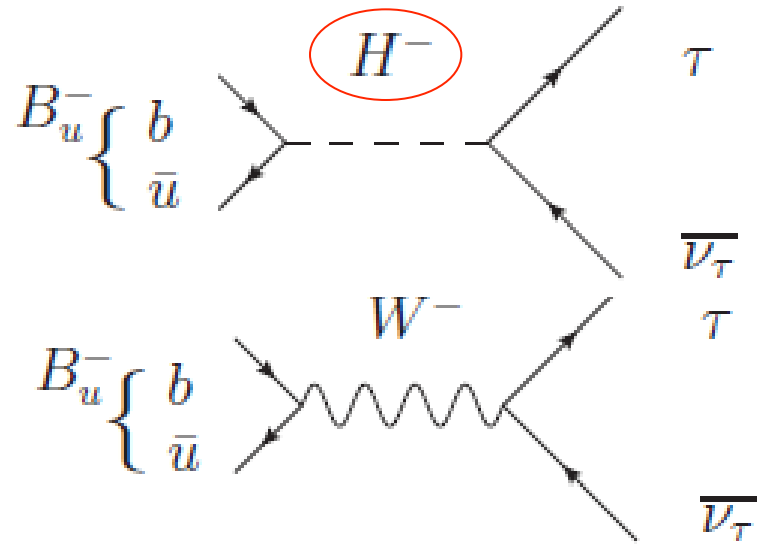
Extra Higgs can be leptophilic (tanβ>3)

$B \to \tau \nu$ in 2HDMs

Hou, PR D48, 234 (1993), Grossman, Ligeti, PLB332, 37 (1994)
Aoki, Kanemura, Tsumura, Yagyu, PRD80, 015017 (2009)

- In 2HDMs, charged Higgs boson contrib. can be important!





$$\frac{\mathcal{B}^{\rm 2HDM}}{\mathcal{B}^{\rm SM}} \approx \left| 1 - \frac{m_B^2}{m_{H^\pm}^2} \xi_d \xi_\ell \right|^2$$

	ξ^u	ξ^d	ξ^ℓ
Type-I	$1/\tan\beta$	$-1/\tan\beta$	$-1/\tan\beta$
Type-II	$1/\tan\beta$	$\tan\beta$	$\tan\beta$
Type-X	$1/\tan\beta$	$-1/\tan\beta$	$\tan\beta$
Type-Y	$1/\tan\beta$	$\tan\beta$	$-1/\tan\beta$

$\tan^2\beta$ enhancement !!
well known stringent constraint on SUSY(2HDM-II) charged Higgs

No constraint on 2HDM-X.

Other flavour constraints

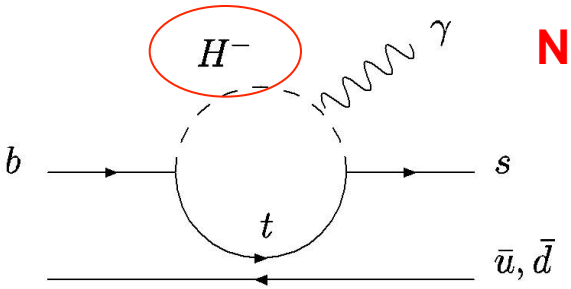
Barger, Hewett, Phillips, PRD41, 3421 (1990)
Grossman, NPB426, 355 (1994)

◻ b → s γ

almost tanβ indep. for 2HDM-II.

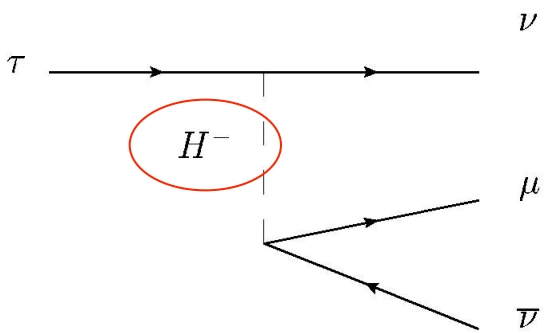
Type-II $$C_7^{H^\pm} = 2\sqrt{2}\left\{\left(\frac{1}{\tan\beta}\right)^2 F\left(\frac{m_t^2}{m_{H^\pm}^2}\right) + \left(\frac{1}{\tan\beta}\right)\tan\beta\, G\left(\frac{m_t^2}{m_{H^\pm}^2}\right)\right\}$$

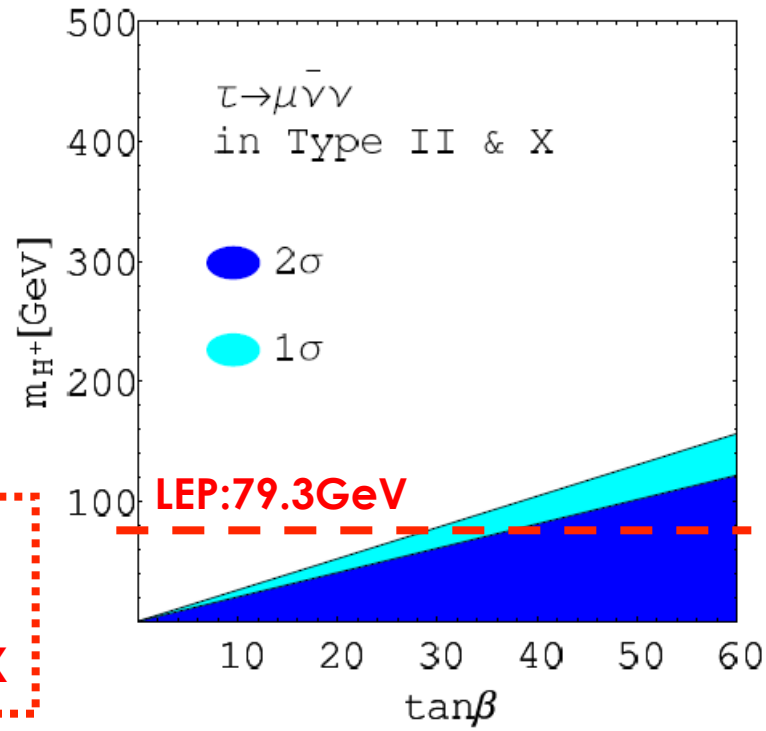
Type-X $$C_7^{H^\pm} = 2\sqrt{2}\left\{\left(\frac{1}{\tan\beta}\right)^2 F\left(\frac{m_t^2}{m_{H^\pm}^2}\right) + \left(\frac{1}{\tan\beta}\right)\left(\frac{1}{\tan\beta}\right) G\left(\frac{m_t^2}{m_{H^\pm}^2}\right)\right\}$$



No constraint on 2HDM-X.

◻ τ leptonic decay





Light charged Higgs (m_{H+} ~ 100GeV) is allowed for Type-X

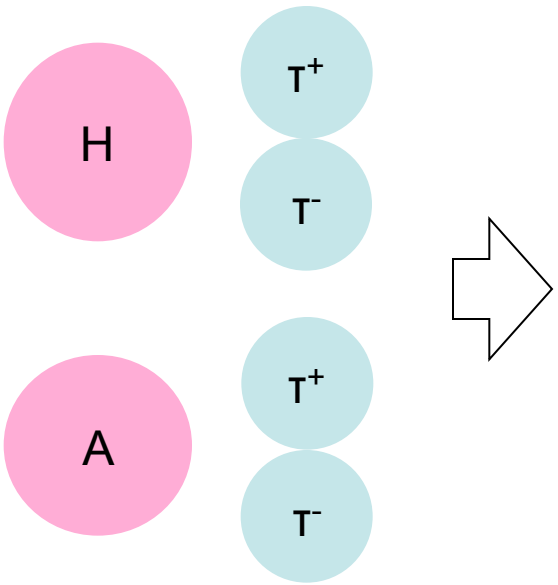
Aoki, Kanemura, Tsumura, Yagyu, PRD80, 015017 (2009)

4 τ lepton signature

$$pp \to Z^* \to HA$$

L = e μ

- H/A decay into tau-lepton pair by more than 99%.



$4\tau_h$	τ_h	τ_h	τ_h	τ_h	$\sim (65\%)^4 \sim 18\%$
$3\tau_h$ 1L	τ_h	τ_h	τ_h	L	$\sim 4\,(65\%)^3\,(35\%)$
$2\tau_h$ 2L	τ_h	τ_h	L	L	$\sim 6\,(65\%)^2\,(35\%)^2$
$1\tau_h$ 3L	τ_h	L	L	L	$\sim 4\,(65\%)\,(35\%)^3$
4L	L	L	L	L	$\sim (35\%)^4 \sim 1.5\%$

- **more tau-jets, the larger branching ratios**