Multi-tau-lepton signatures at the LHC in the two Higgs doublet model

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POwLHC @ KEK 16-18/2/2012

Outline:
- **Two-Higgs-doublet model**
- **Leptophilic Higgs boson**

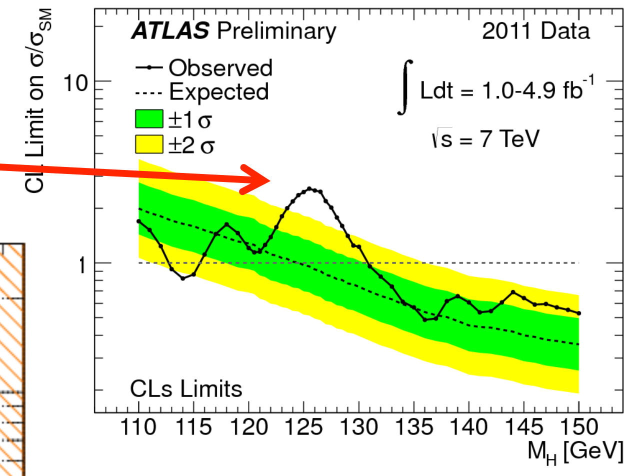
S. Kanemura, K. Tsumura and H. Yokoya, arXiv:1111.6089

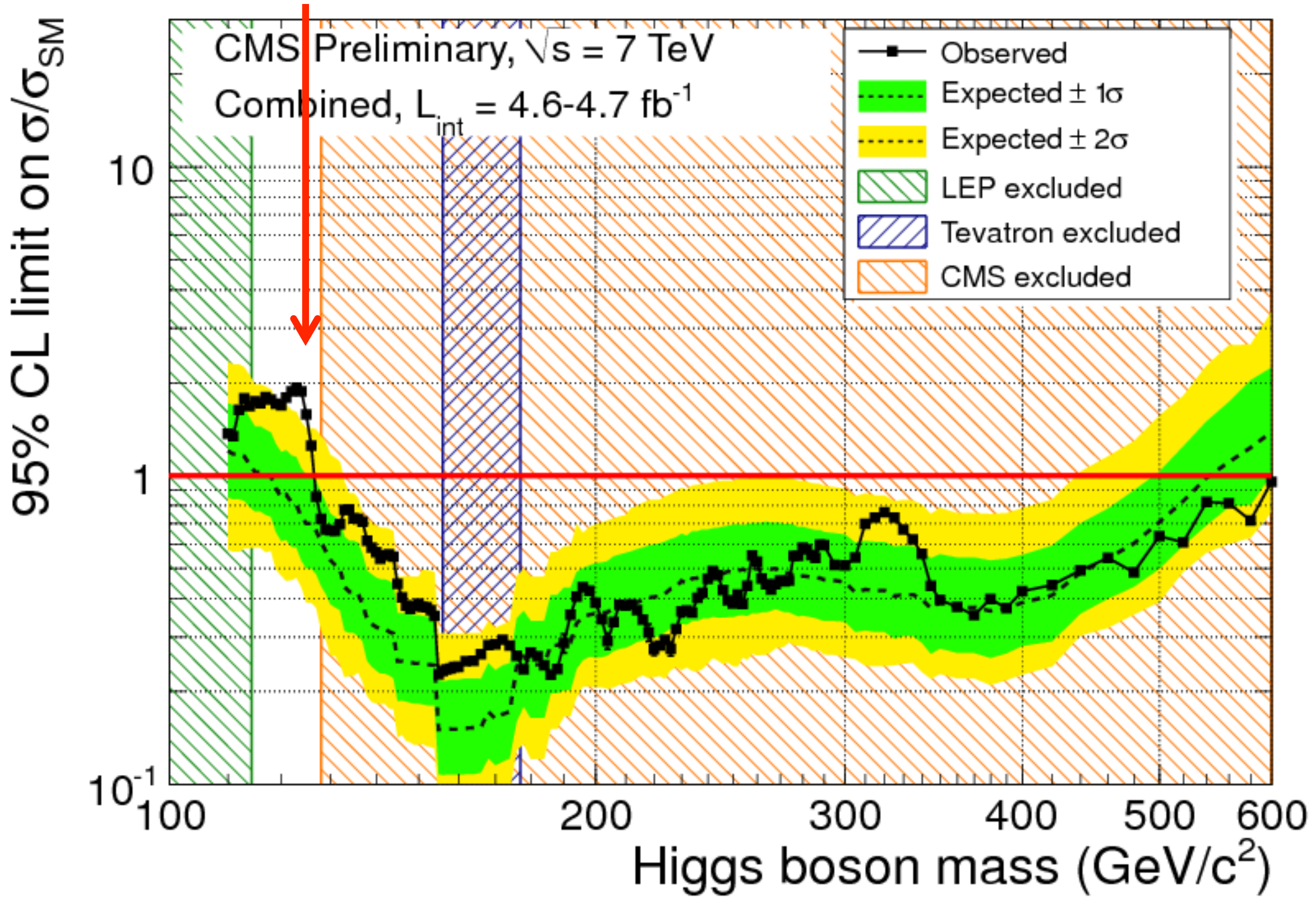
M. Aoki, S. Kanemura, K. Tsumura and K. Yagyu, Phys. Rev. D80 015017 (2009)

We have a hint of SM-like Higgs boson

- Results reported in Dec13
  - **Excess @ mh~125GeV ?**

ATLAS





CMS

Two-Higgs-doublet model (2HDM)

Models for tiny neutrino masses

- Zee model (radiative seesaw)

$$\mathcal{L} = +\overline{L} Y_{\ell 1} \ell_R H_1 + \overline{L} Y_{\ell 2} \ell_R H_2 + \mathrm{H.c.}$$

- Gauged Type-III seesaw

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

2HDM often appears in new physics BSM

2HDM in SUSY

SUSY requires 2HDM:

- Holomorohy of superpotential
- Mass generation for up- and down-type quarks
- Anomaly cancellation
- Gauge coupling unification

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

2HDM often appears in new physics BSM

2HDM is a low energy effective theory

Classify 2HDMs by Yukawa

□ General 2HDM (Type-III)

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

Yukawa int. is not simultaneously diagonalized with mass matrix.

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

□ Adding extra Z2 sym. to avoid FCNC

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

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

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**

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

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

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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**

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

Higgs bosons distinguish quarks and leptons!!

Extra Higgs can be leptophilic (tanβ>3)

2HDM (Notation)

- **Softly Z2 broken 2HDM potential** $\Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + i\, z_i) \end{pmatrix}$

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

- **5 physical Higgs bosons** (assume CP inv.)

m_3^2, λ_5 real

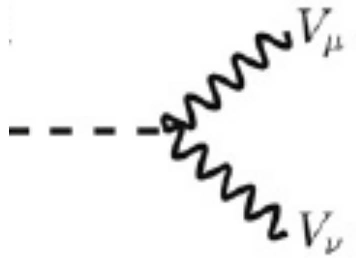
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \text{R}(\alpha) \begin{pmatrix} H \\ h \end{pmatrix}, \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \text{R}(\beta) \begin{pmatrix} z \\ A \end{pmatrix}, \begin{pmatrix} \omega_1^+ \\ \omega_2^+ \end{pmatrix} = \text{R}(\beta) \begin{pmatrix} \omega^+ \\ H^+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

- **Higgs boson masses in SM-like limit**

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

In the SM-like limit [sin(β-α)=1]

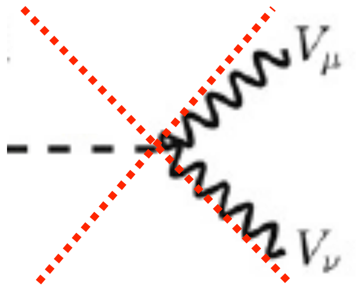
- "h" behaves as the SM Higgs boson



$$W_\mu^+ W_\nu^+ h : ig_W M_W \sin(\beta - \alpha) g_{\mu\nu}$$

- "H, A, H+" behave as scalar boson

$$W_\mu^+ W_\nu^- H : ig_W M_W \cos(\beta - \alpha) g_{\mu\nu}$$



Type-X Yukawa interaction

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

$\xi_f \times m_f/v$

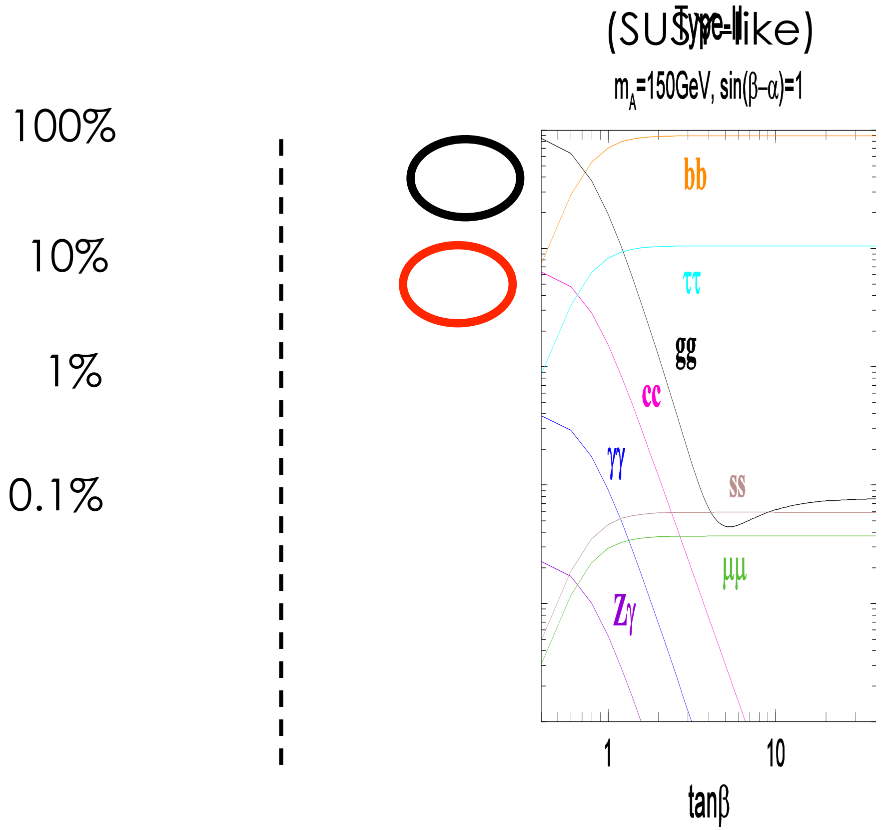
	ξ^u	ξ^d	ξ^ℓ	
Type-I	$1/\tan\beta$	$-1/\tan\beta$	$-1/\tan\beta$	SM-like
Type-II	$1/\tan\beta$	$\tan\beta$	$\tan\beta$	SUSY-like
Type-X	$1/\tan\beta$	$-1/\tan\beta$	$\tan\beta$	
Type-Y	$1/\tan\beta$	$\tan\beta$	$-1/\tan\beta$	

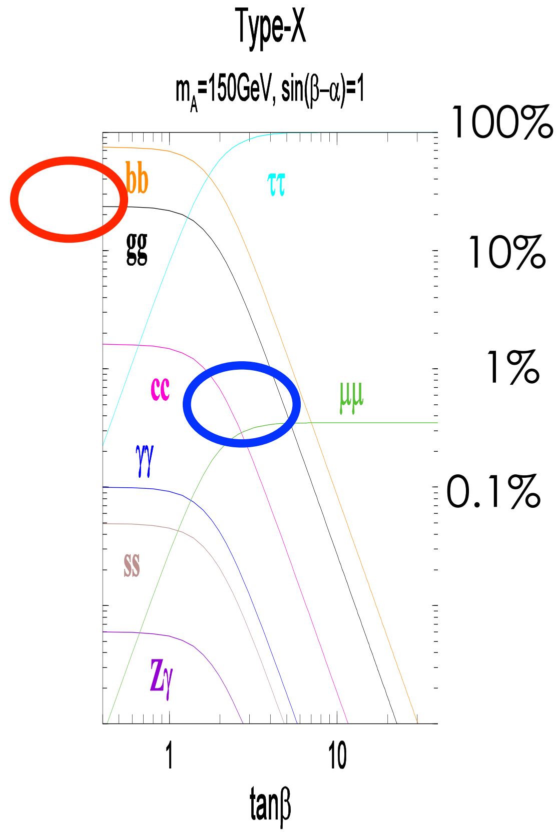
Type-X: Leptoplilic in tanβ>3

Higgs decays in 2HDMs

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

(SUSY-like)



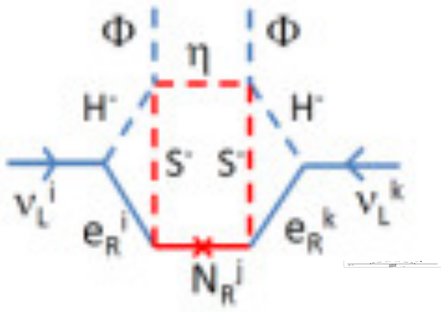


- 2HDM-X： Enhance leptonic Yukawa int. by tanβ.
  - More than 99% of H/A decay into ττ
  - Sizable μμ [$(m_\mu/m_\tau)^2$=1/300] mode

Why do we focus on Leptophilic Higgs boson?

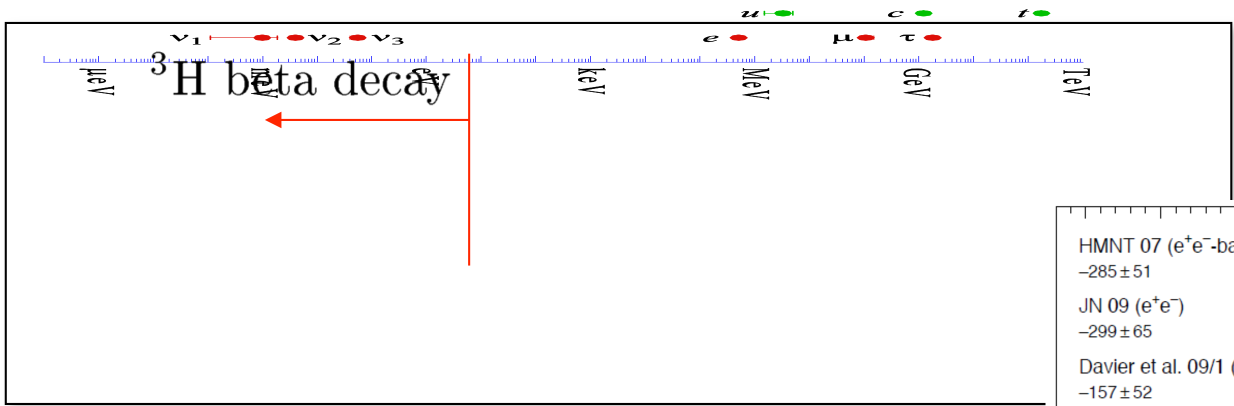
Leptophilic Higgs

□ Problems in Lepton sector?



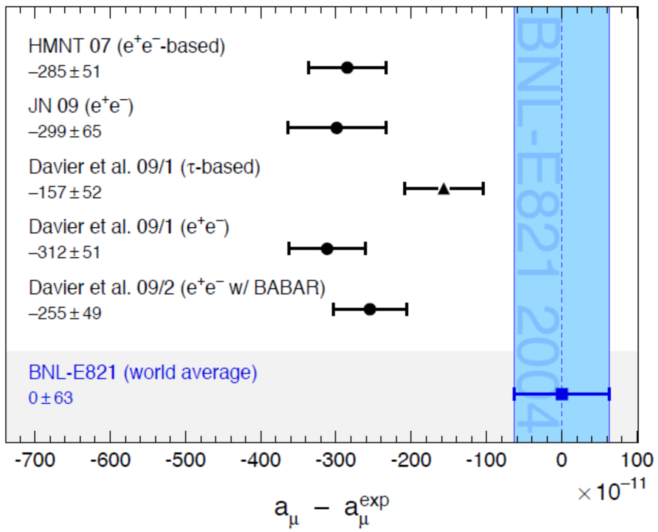
□ Tiny neutirno mass

3-loop neutrino mass, light H+,
by Aoki et al. PRL102:051805,2009



□ 3.2σ excess in Muon g-2

Light A **(CP odd Higgs)** with high tanβ
by Cao et al. PRD80:071701,2009

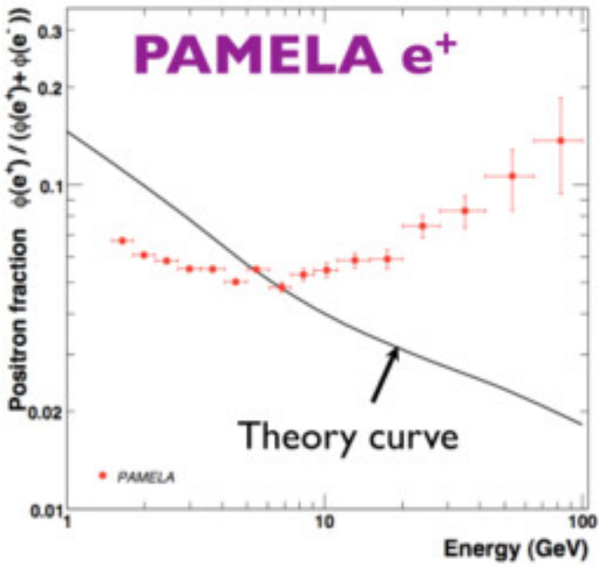


Leptophilic Higgs

- **Problems in Lepton sector?**
  - **Leptonic cosmic ray @ PAMELA, FERMI**

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

DM DM → $\Phi' \, \Phi' \rightarrow \tau\tau\tau\tau$



Experimental constraints

- **Direct search results**
- **Tau leptonic decays**

Direct search limit

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 ($m_{H_1^0} < m_{H_2^0}$)**

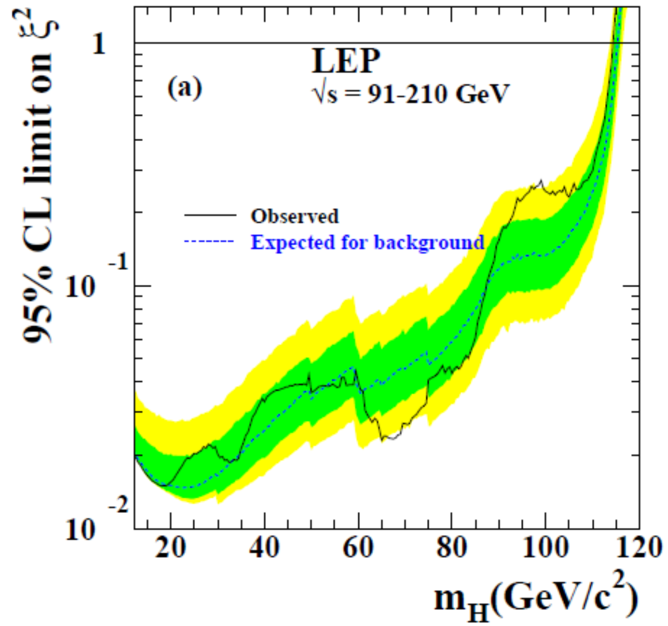
Mass $m >$ 92.8 GeV, CL = 95%

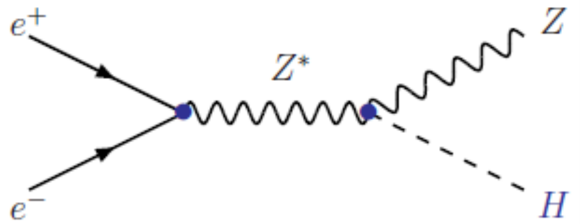
***A^0* Pseudoscalar Higgs Boson in Supersymmetric Models**

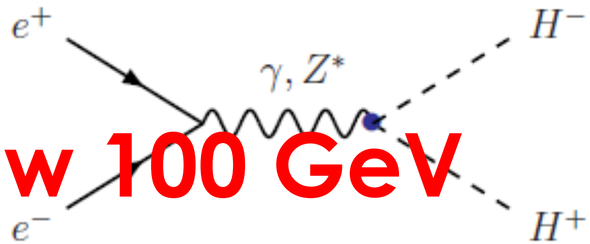
Mass $m >$ 93.4 GeV, CL = 95% $\tan\beta > 0.4$

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

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

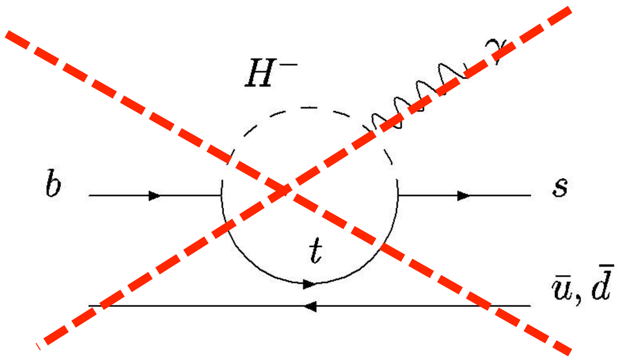


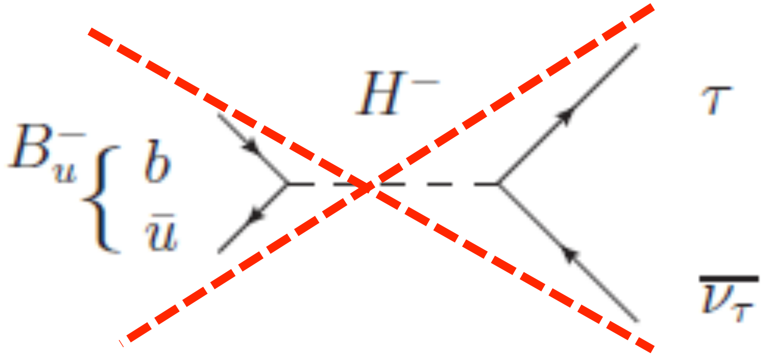




Direct search bounds are below 100 GeV

Small Yukawa coupling with quarks in Type-X.

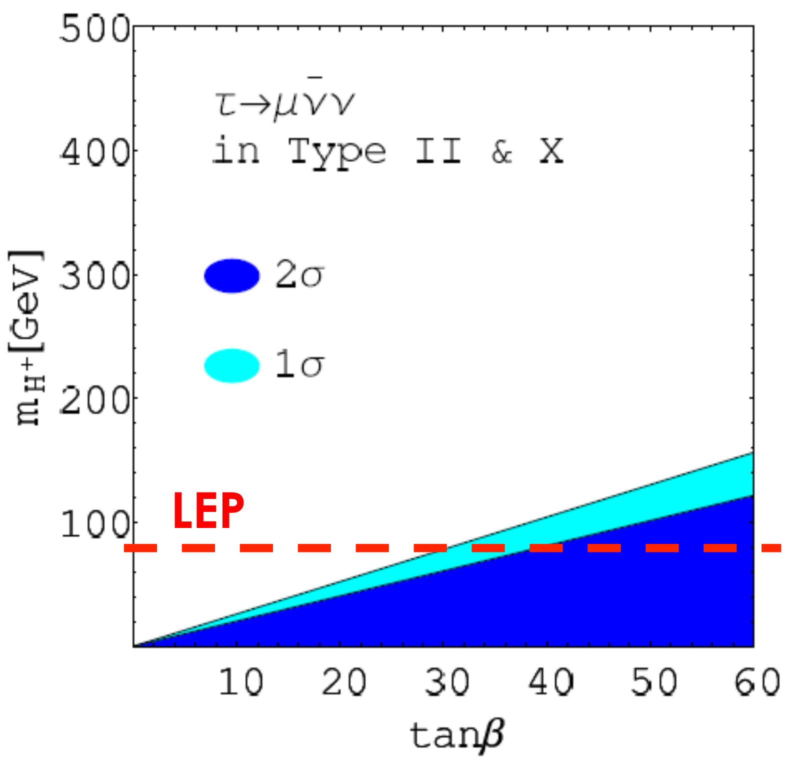


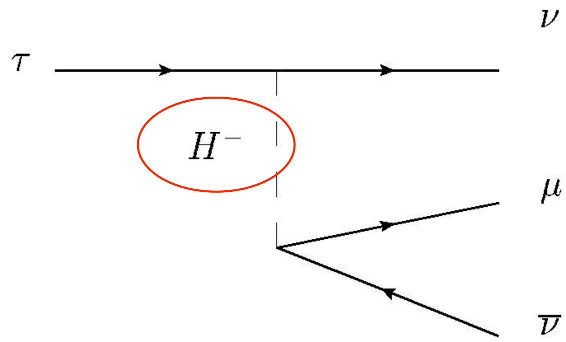


For large tanβ

Are there any purely leptonic constraint?

τ leptonic decay





Type-II, X

$$\frac{\mathcal{B}^{\text{2HDM}}}{\mathcal{B}^{\text{SM}}} = 1 - \frac{2m_\mu^2}{m_{H^\pm}^2} \tan^2\beta$$

Type-I, Y

$$\frac{\mathcal{B}^{\text{2HDM}}}{\mathcal{B}^{\text{SM}}} = 1 - \frac{2m_\mu^2}{m_{H^\pm}^2} \frac{1}{\tan^2\beta}$$

milder bounds for Type-II and -X

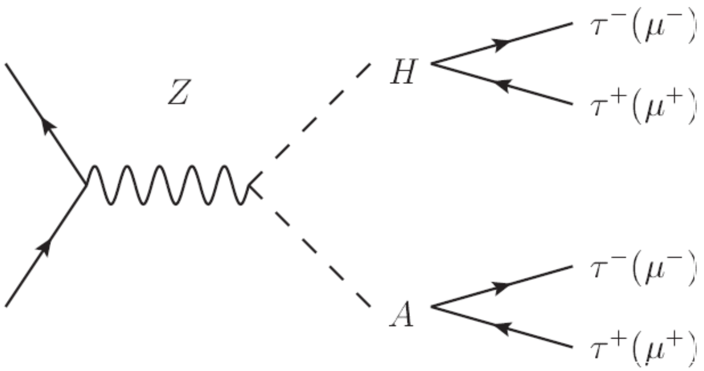
mH+ ~ 100GeV is allowed for Type-X

Leptophilic Higgs boson @ LHC

Leptophilic-2HDM @ LHC

Kanemura, Tsumura, Yokoya

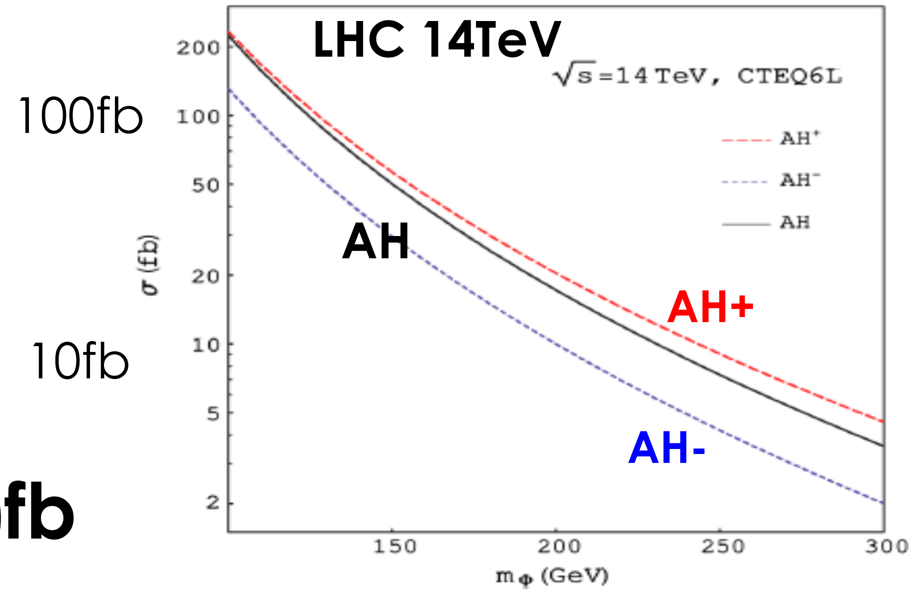
□ DY production with leptonic decay modes



Multi-tau signature

4τ: more than 99%

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



Cross sections are O(10)fb

Framework of Event analysis

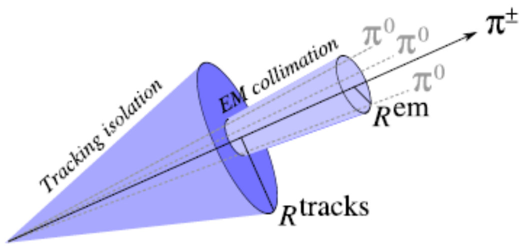
- Signal/BG(VV,ttbar,DY) are generated by PYTHIA and MG5

50fb for mH=130GeV & mA=170GeV/107pb, 492pb, 30nb

- jets (anti-kT alg. with R<0.4)

τj = taujet: $|\eta|$<2.5, pT>10GeV

Identification; 1 or 3 charged hadrons (1- & 3-prong)



narrow cone R<0.15 (95% of ET)

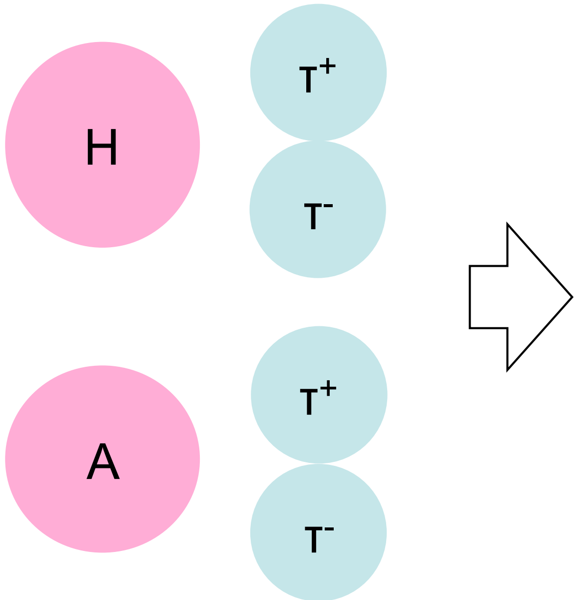
leptonic	1-prong	3-prong
$\tau \to \mu\nu\nu$: 17.36%	$\tau \to h^-\nu$: 11.61%	$\tau \to h^-h^+h^-(> 0h^0)\nu$: 14.56%
$\tau \to e\nu\nu$: 17.85%	$\tau \to h^-h^0\nu$: 25.1%	
	$\tau \to h^-(> 2h^0)\nu$: 10.85%	

4 tau 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**

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

$(0.65)^4 \sim 18\%$: **large number of events is expected**

- **perform selection cuts to enhance signal/background ratio**

High multiplicity of tau jet reduces BG.

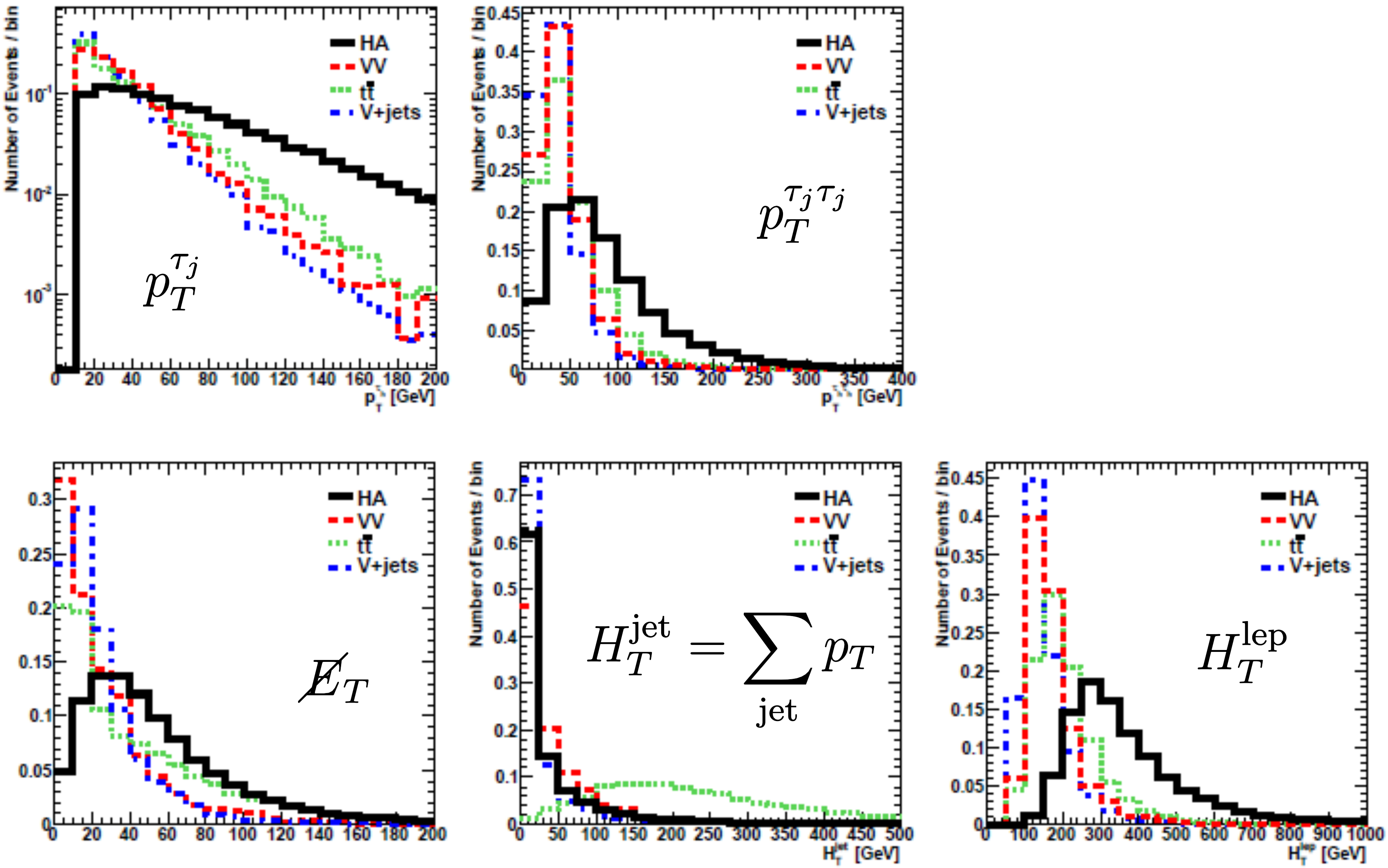
$4\tau_h$ event analysis	HA	$\phi^0 H^\pm$	VV	$t\bar{t}$	V+jets	s/b	S (100 fb^{-1})
Pre-selection	324.	52.8	147.	797.	5105.	0.1	4.7
$p_T^{\tau_h} > 40$ GeV	67.2	4.9	2.0	14.7	21.7	1.9	9.4
$\not{E}_T > 30$ GeV	48.6	4.4	1.1	7.6	10.4	2.8	9.3
$H_T^{\rm jet} < 50$ GeV	34.2	3.4	0.5	0.8	8.2	3.9	8.7
$H_T^{\rm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

High pT cut: VV

pT cut: DY

Htjet cut: ttbar

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



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- **Large significance** **with large s/b ratio for L = 100 [fb^{-1}].**

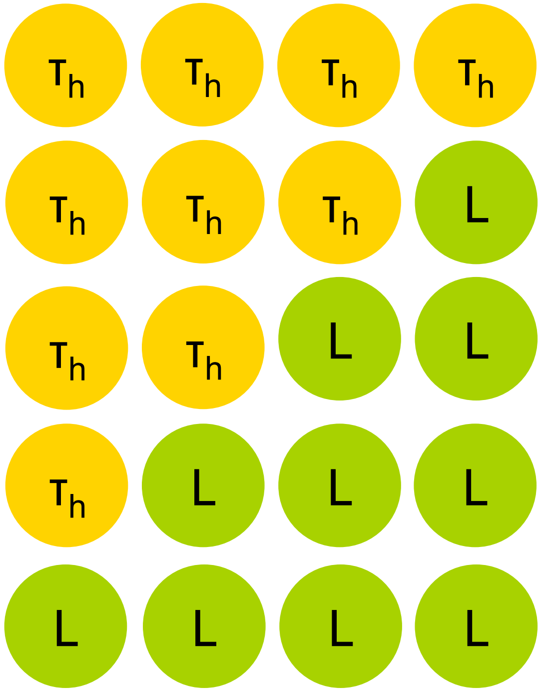
  (we only used one channel !!)

Almost BG free, excess can be found.

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

Lepton channels	$4\tau_h$ s/b	(S)	$3\tau_h 1\mu$ s/b	(S)	$3\tau_h 1e$ s/b	(S)	$2\tau_h 1\mu 1e$ s/b	(S)	$2\tau_h 2e$ 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	$1\tau_h 1\mu 2e$ s/b	(S)	$1\tau_h 3e$ s/b	(S)	$1\mu 3e$ s/b	(S)	$4e$ 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)



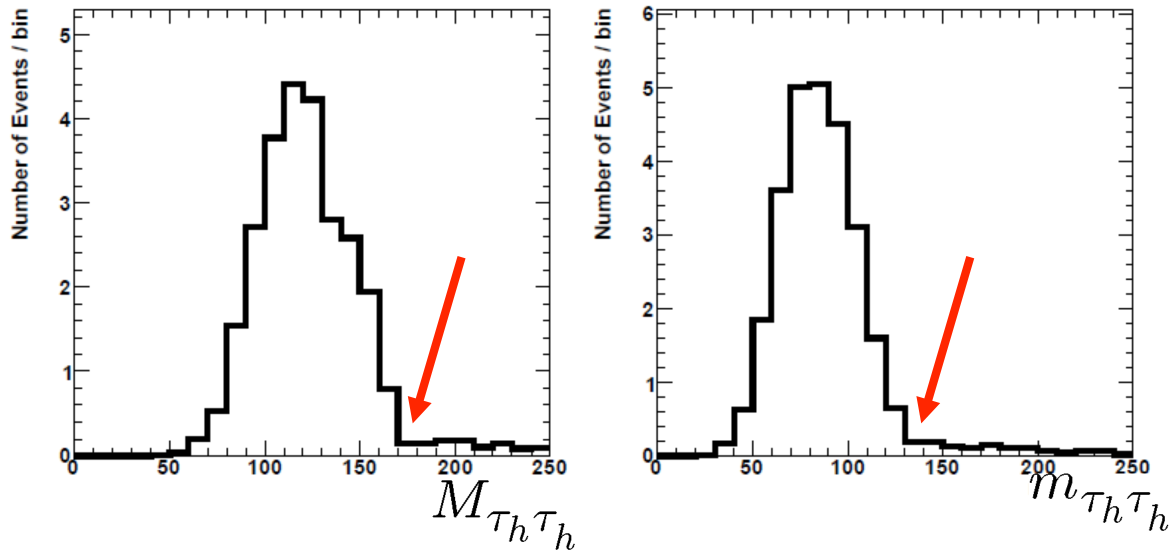
- **Many channels with Large significance**

Excess can be easily found.

Comments:

- Due to the many sources of missing momenta, mass reconstruction is difficult.
- Higgs boson masses may be obtained by finding endpoints of $M_{\tau_h\tau_h}$ distributions.

mH=130GeV & mA=170GeV

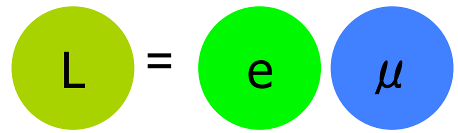


$M_{\tau_h\tau_h} > m_{\tau_h\tau_h}$

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.

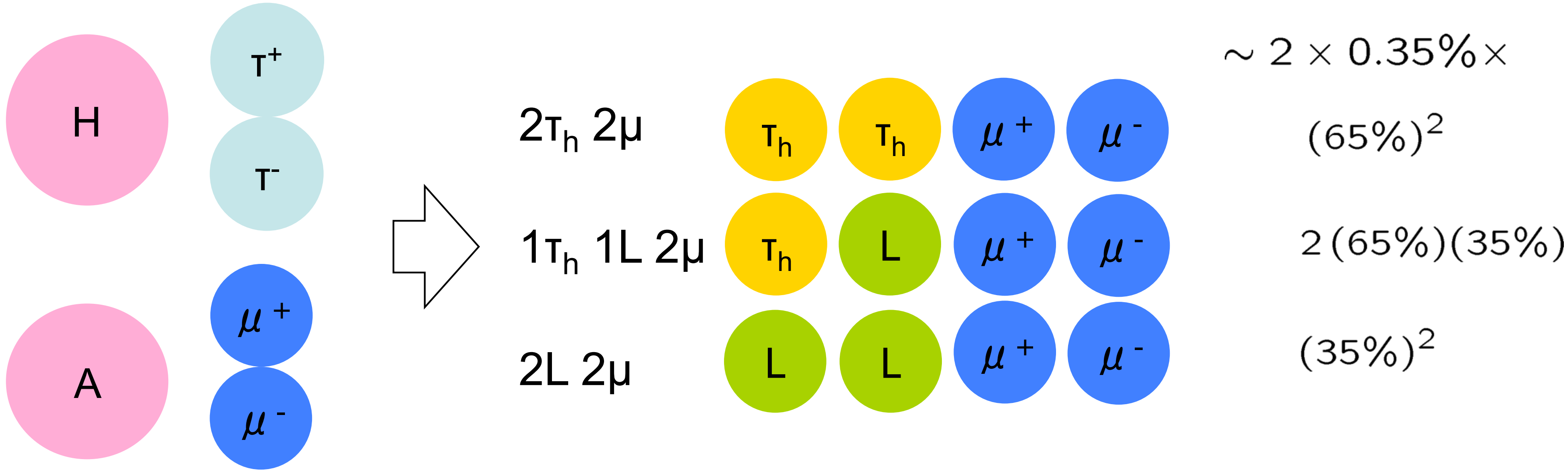
2 mu - 2 tau signature

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



occasionally, H/A decay into muons;

$$\mathcal{B}[H/A \to \mu\mu] \sim m_\mu^2/m_\tau^2 \sim 0.35\%$$

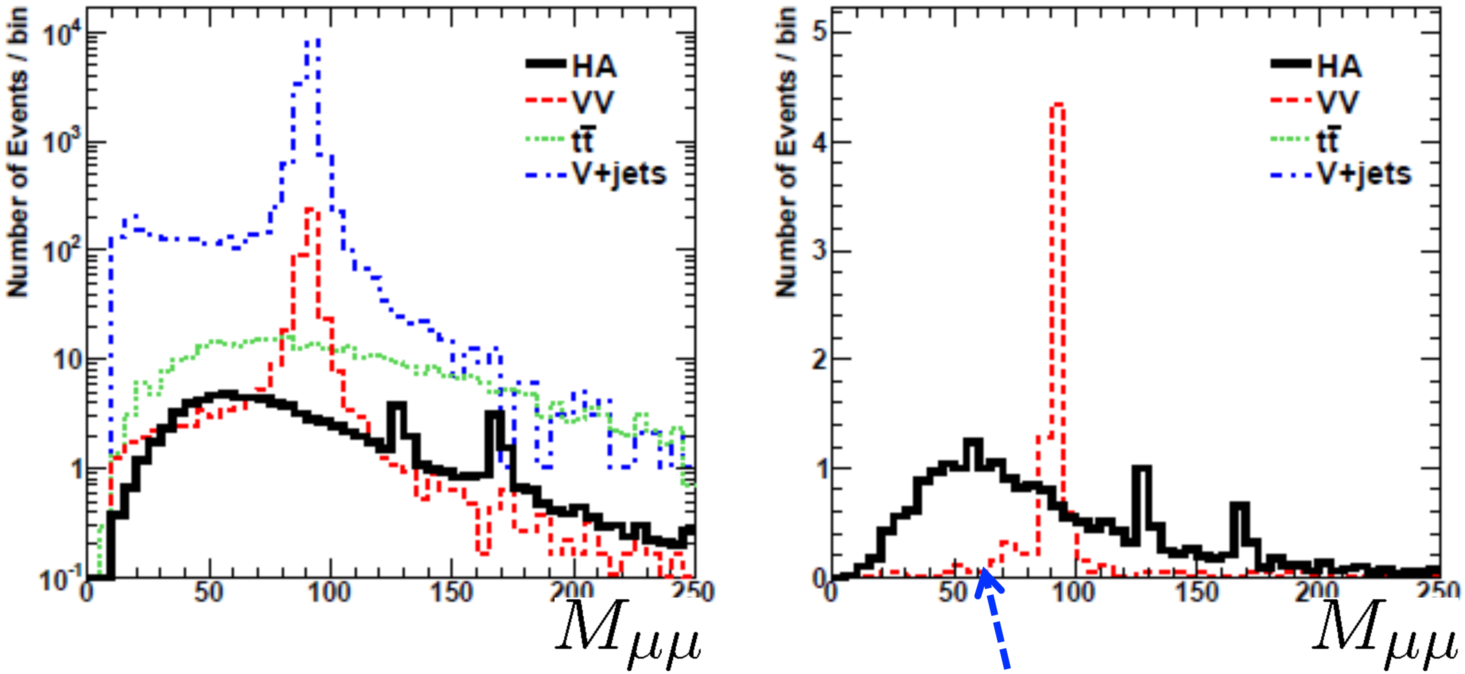


Small branching ratio, but clean signatures

of dimuon with sharp resonance peak.

$2\mu 2\tau_h$ channel : μ μ τ_h τ_h (an example)

- **Dimuon inv. mass dist.** $M_{\mu\mu}$



- **Sharp peaks (H,A→μμ) around M=130GeV,170GeV**

  Measurement of Masses, Direct probe of Pair production with collinear approx.

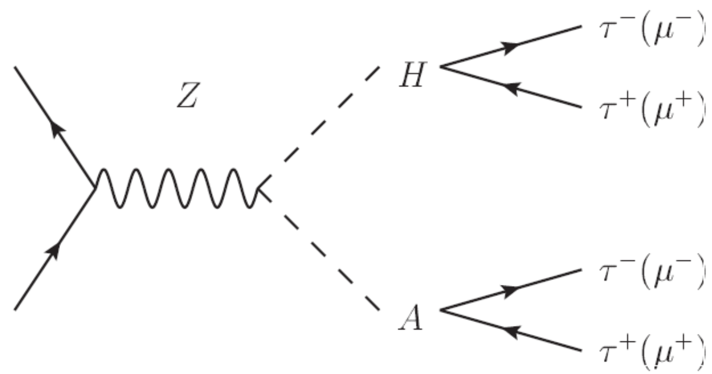
- **Broad dist. from muonic tau decay (4τ→2μ2τj)**

Summary

- **Leptophilic 2HDM is interesting.**
  - <u>Light scalar bosons</u> are allowed by experimental data.
  - **Scalar bosons mainly decay into <u>tau</u> (<u>mu</u>).**
- **Multi tau events can be clean signatures @ LHC**
  - Excess of 4 tau signature can be easily found.

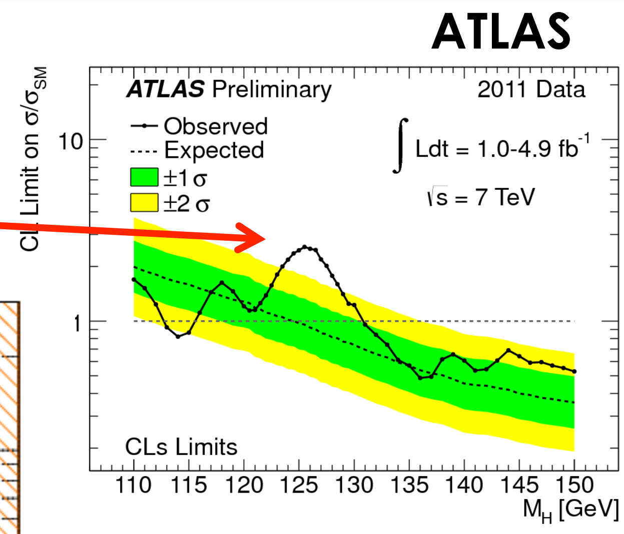
$4\tau_h$ channel : τ_h τ_h τ_h τ_h

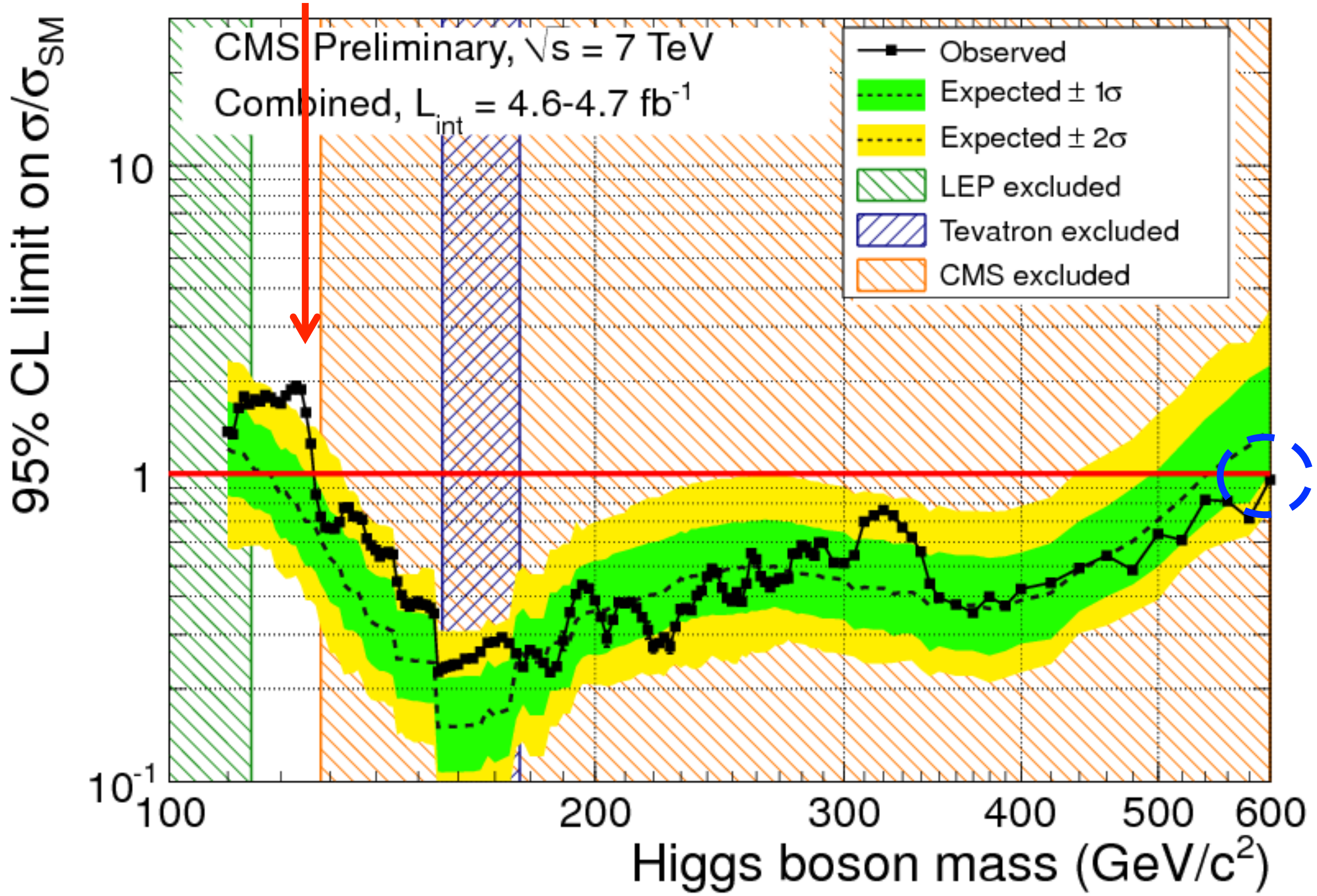
$2\mu 2\tau_h$ channel : μ μ τ_h τ_h



Allowed Higgs mass region

- Results reported in Dec13
  - **Excess @ mh~125GeV ?**





Mh > 600 GeV

CMS

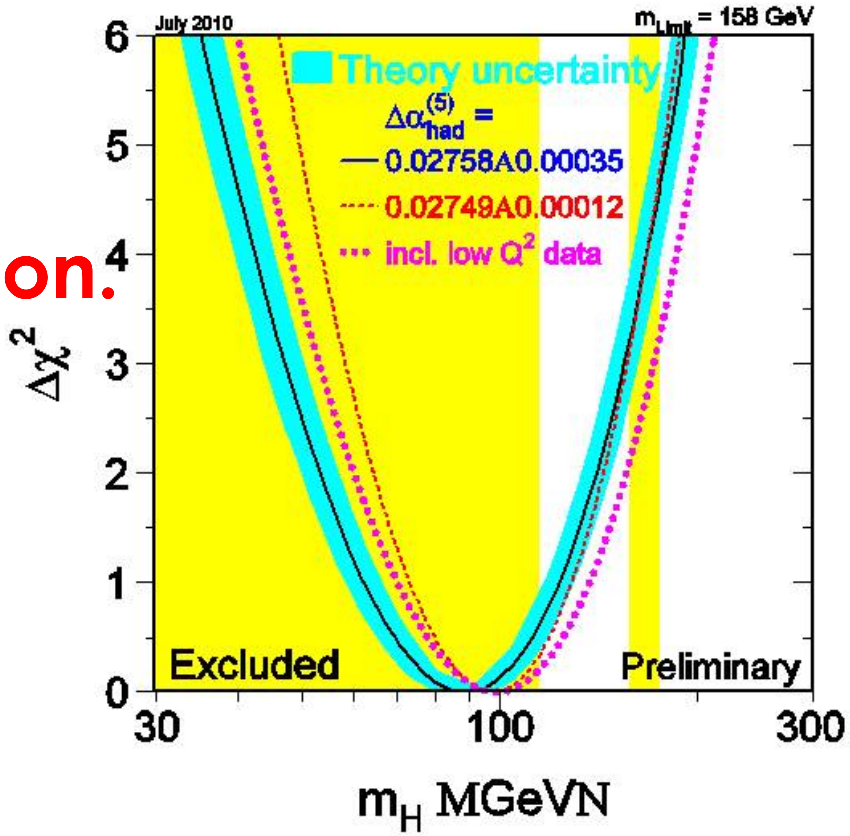
Official CERN Statement

- The main conclusion is that the Standard Model Higgs boson, if it exist, is most likely to have a mass constrained to the range 116-130 GeV by the ATLAS experiment, and 115-127 GeV by CMS. Tantalising hints have been seen by both experiments in this mass region, but these are not yet strong enough to claim a discovery.

EW precision data

- **Blue band plot** (A global fit of the Higgs boson mass)

This plot is the reason why
we believe a light Higgs boson.



$$\alpha_{\mathrm{EM}} T \equiv \Delta\rho = +\frac{N_c G_F (m_t - m_b)^2}{8\sqrt{2}\pi^2} - \frac{3 G_F m_Z^2 s_W^2}{8\sqrt{2}\pi}\left(\ln\frac{m_h^2}{m_W^2} - \frac{5}{6}\right)$$

EW precision data

- **ST-parameters**

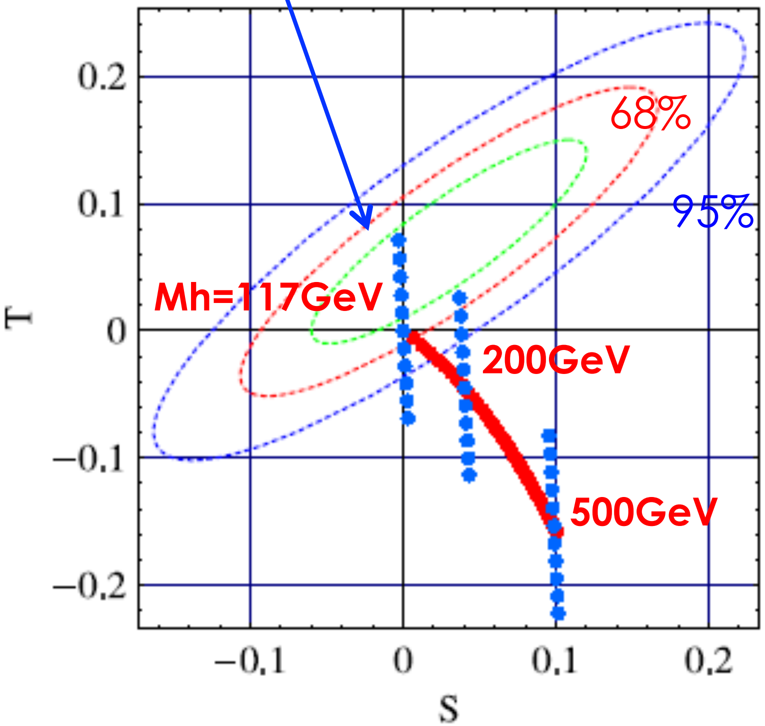
Count number of fermionic degrees
(sensitive to 4th-generation, technicolor)

$$S = 16\pi \left[\overline{\Pi}^{3Q'}_T(0) - \overline{\Pi}^{33'}_T(0) \right]$$

$$T = \frac{4\sqrt{2}G_F}{\alpha_{\mathrm{EM}}} \left[\overline{\Pi}^{33}_T(0) - \overline{\Pi}^{11}_T(0) \right]$$

Characterize custodial SU(2) breaking

mtop: 1GeV step



$$\alpha_{\mathrm{EM}} T \equiv \Delta\rho = + \frac{N_c G_F (m_t - m_b)^2}{8\sqrt{2}\pi^2} - \frac{3 G_F m_Z^2 s_W^2}{8\sqrt{2}\pi} \left(\ln \frac{m_h^2}{m_W^2} - \frac{5}{6} \right)$$

Log dependence on Higgs mass

$$S = 0.03 \pm 0.09,\ T = 0.07 \pm 0.08\ (\rho = 0.87)$$

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 only from Φ2

(may relate for Ma model,…<Φ1>=0)

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-Y: I have no idea related for NP.**

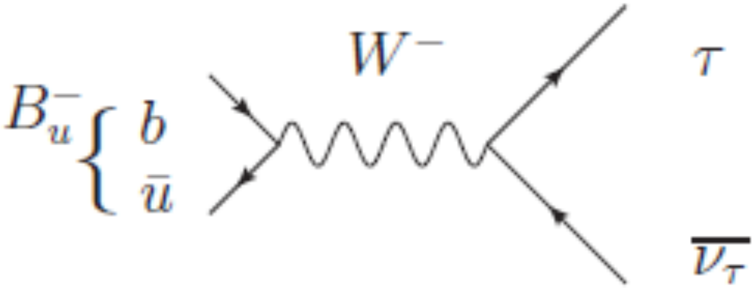
(actually stringently constrained by experimental data)

- **Type-III (general)**: Zee model

$$\mathcal{L} = +\overline{L}Y_{\ell 1}\ell_R H_1 + \overline{L}Y_{\ell 2}\ell_R H_2 + \text{H.c.}$$

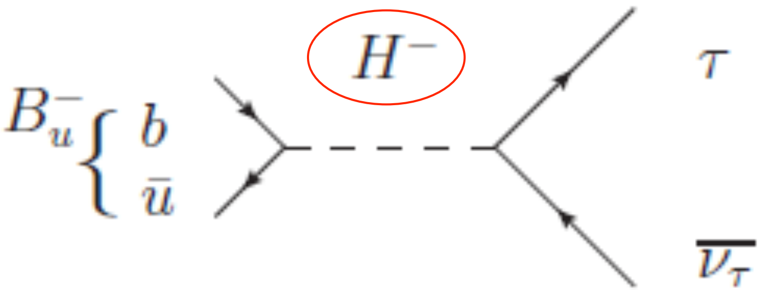
B → τ ν

- Only W boson contributes **B → τ ν** in the SM



$$\Gamma^{\mathrm{SM}} = \frac{G_F^2 |V_{ub}|^2 F_B^2 m_B m_\tau^2}{8\pi(1-m_B^2/m_W^2)^2}\left(1-\frac{m_\tau^2}{m_W^2}\right)^2$$

- In 2HDMs, **H+ contrib. can be important!**



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

	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	$1/\tan\beta$	$\tan\beta$	$-1/\tan\beta$

B → τ ν in 2HDMs

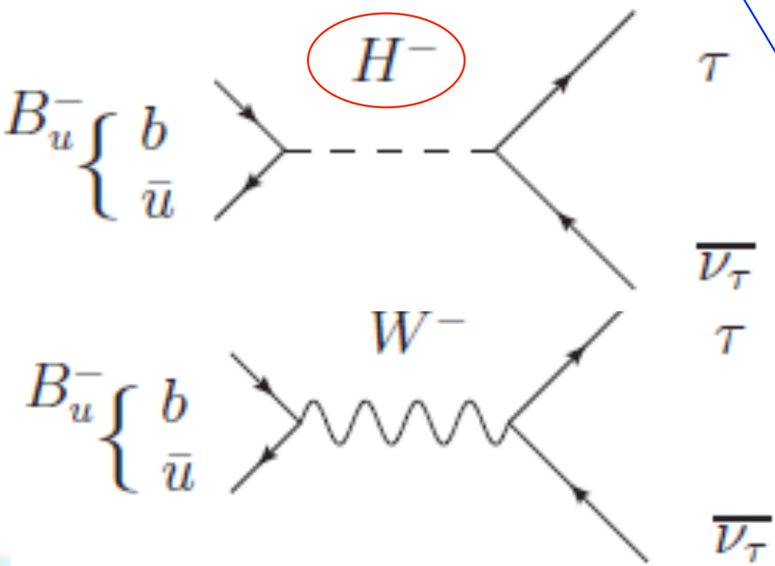
- Experimental limit:

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.4 \pm 0.4) \times 10^{-4}$$

Large deviations from the SM can be constrained.

In particular, Type-II 2HDM with large tanβ.

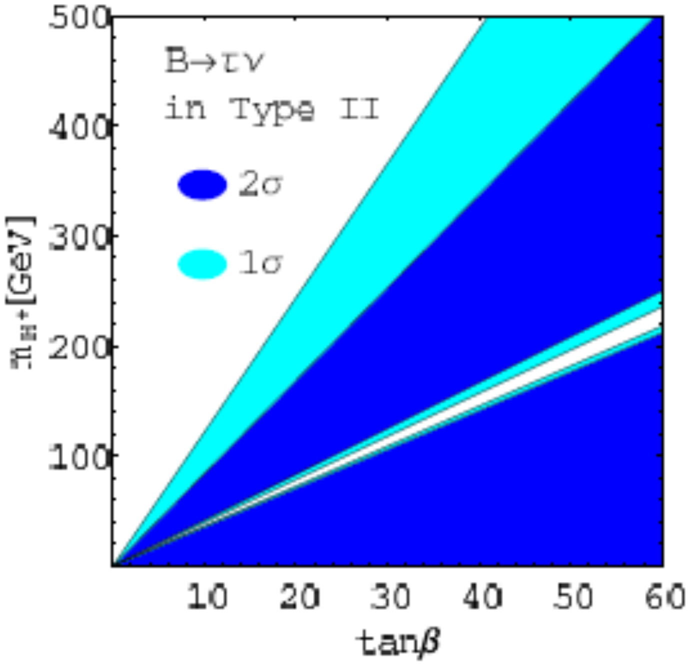
- In 2HDMs, **H+** contrib. can be important!



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

	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	$1/\tan\beta$	$\tan\beta$	$-1/\tan\beta$

B → τ ν in 2HDMs



Type-II

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

well known stringent constraint on SUSY charged Higgs

Type-X, Y

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

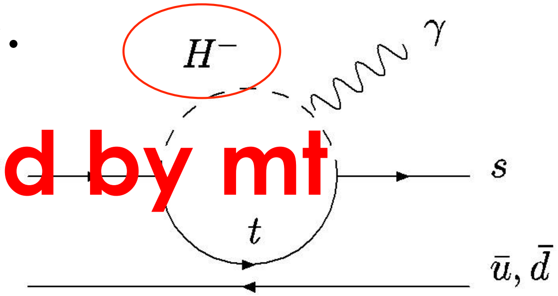
Type-I

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

This constraint is only applicable for 2HDM-II

One-loop: b → s γ

- b → s γ is one of important observable.



Although 1-loop, but enhanced by mt

In addition to C7W (SM W boson loop),

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

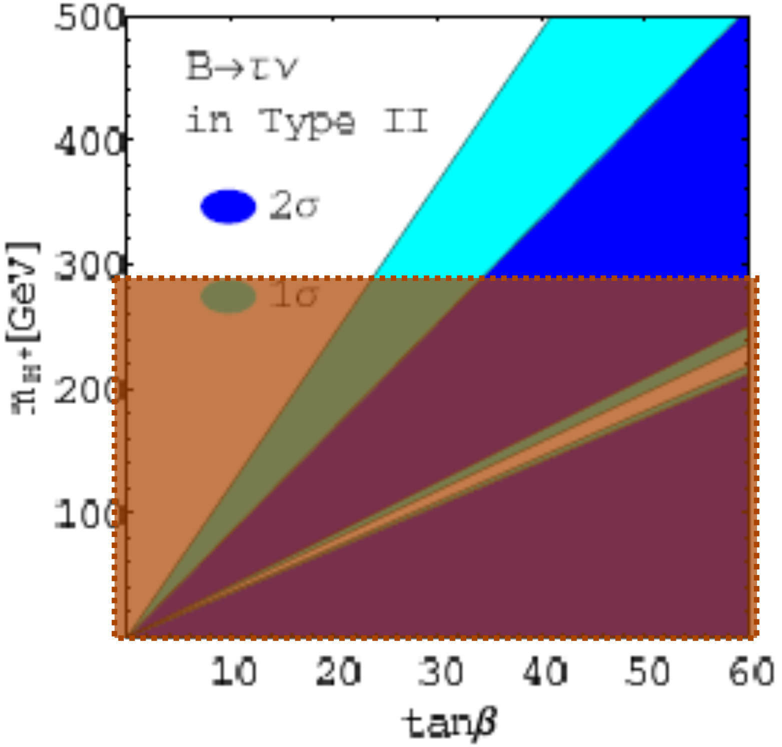
almost tanβ independent contrib.

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

	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	$1/\tan\beta$	$\tan\beta$	$-1/\tan\beta$

One-loop: b $\to$ s γ

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



almost tanb independent contrib.

Excluded by b $\to$ s γ

chargino–stop loop can cancel this contrib.
→ Light charged Higgs is still possible **in MSSM**.

This constraint is applicable for 2HDM-II & -Y

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

$2\mu 2\tau_h$ channel : μ μ τ_h τ_h (an example)

$6 \times (0.65)^2 \cdot (0.175)^2 \sim 7.8\%$ from $\tau\tau\tau\tau$

$0.7\% \times (0.65)^2 \sim 0.3\%$ from $\mu\mu\tau\tau$ → **dimuon peaks**

- **perform selection cuts to enhance signal/background ratio**

before cuts s/b < 10^{-2}, but ~ 3 after cuts

$2\mu 2\tau_h$ event analysis	HA	$\phi^0 H^\pm$	VV	$t\bar{t}$	V+jets	s/b	S (100 fb^{-1})
Pre-selection	91.0	7.7	441.	393.	15675.	10^{-2}	0.8
$p_T^{\tau_h} > 40$ GeV	41.1	1.7	37.7	33.4	548.	0.1	1.7
$\not{E}_T > 30$ GeV	33.1	1.6	14.7	29.9	5.1	0.7	4.5
$H_T^{\rm jet} < 50$ GeV	24.0	1.2	9.7	4.3	3.1	1.4	5.1
$H_T^{\rm lep} > 250$ GeV	21.6	1.1	8.6	3.1	1.0	1.7	5.1
$(m_Z)_{\mu\mu} \pm 10$ GeV	18.8	1.0	2.1	3.3	1.0	3.1	5.8

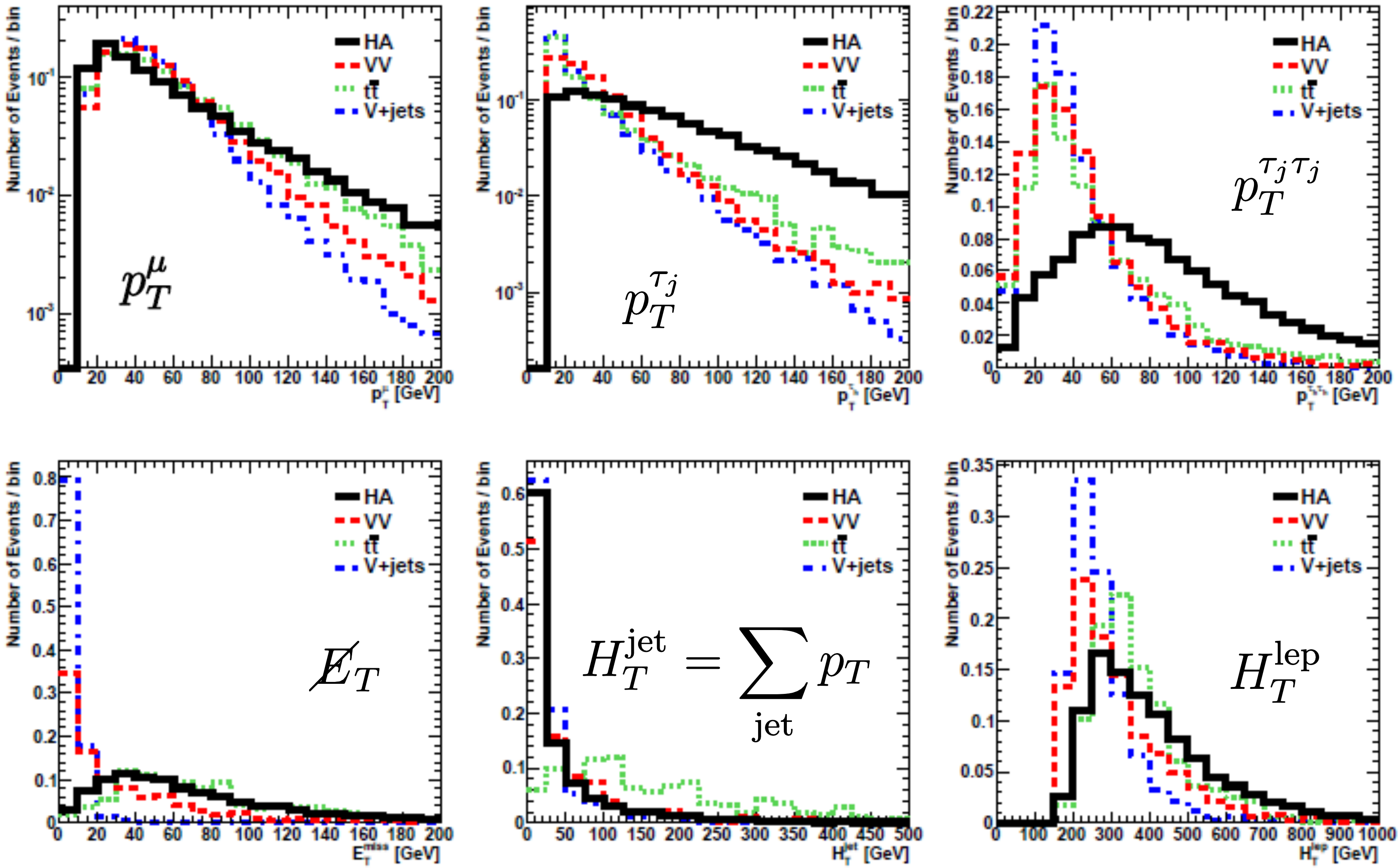
pT cut: DY

HTjet cut: ttbar

InvMass cut: VV

Numbers are for L=100 [fb^{-1}]

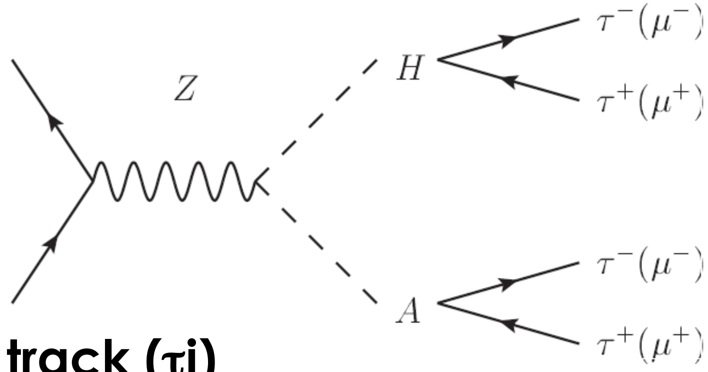
$2\mu 2\tau_h$ channel : μ μ τ_h τ_h (an example)



Event by event determination of HA pair

◻ τ–τ inv. Mass can be reconstructed !!

- ◻ Collinear approx.



$$\boxed{\vec{p}_\nu \simeq c\,\vec{p}_{\tau_j}}$$

ν from energetic τ decay is along with charged track (τj)

→ τ mom. can be determined from taujet and missing pT

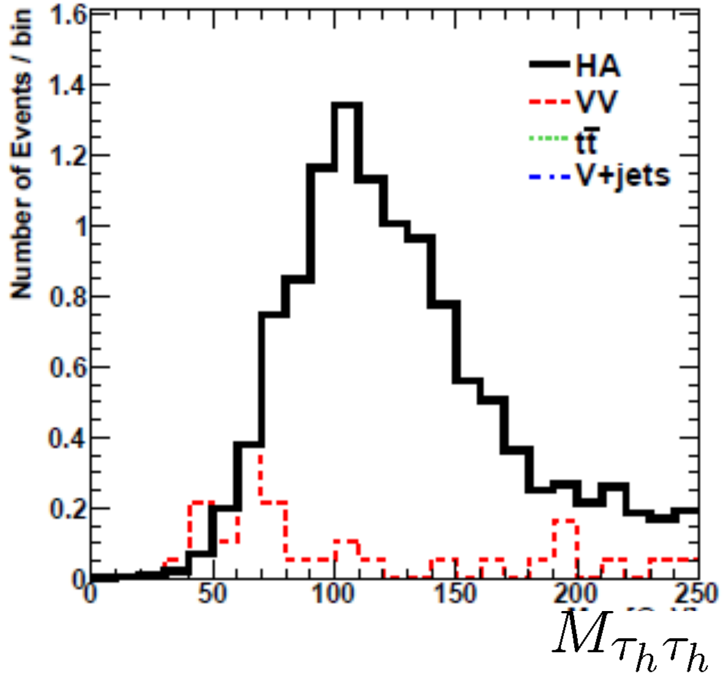
$$\boxed{\vec{p_T}^{\,\mathrm{miss}} \simeq c_1\,\vec{p_T}_{\tau_j 1} + c_2\,\vec{p_T}_{\tau_j 2}}$$

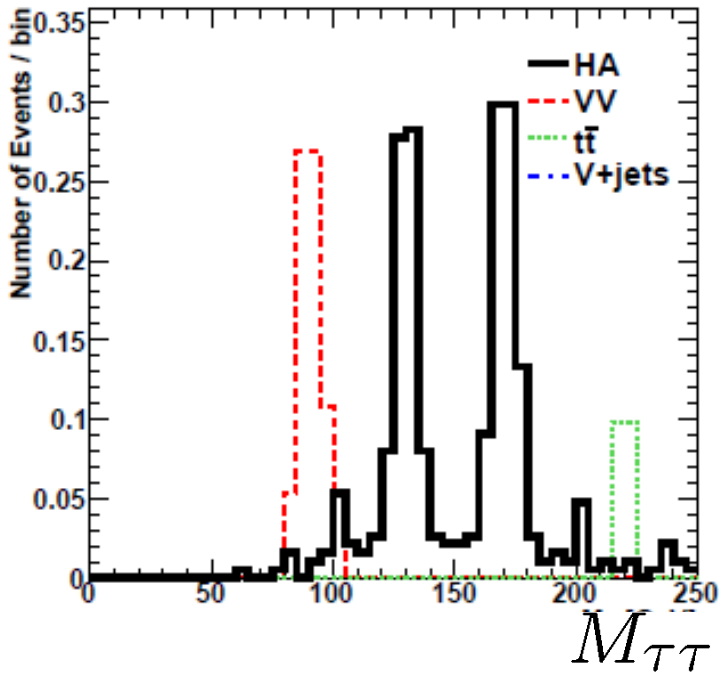
2 unknown (c1 & c2) are calculated by solving simultaneous 2 eqs.

$$\boxed{M_{\tau\tau} = \sqrt{(p_{\tau 1} + p_{\tau 2})^2} \simeq M_{\tau_j \tau_j} / \sqrt{z_1 z_2}}$$

$$\vec{p}_{\tau_j} \simeq z\,\vec{p}_\tau = \frac{1}{1+c}\vec{p}_\tau$$

Taujet inv. Mass and Tau inv. Mass





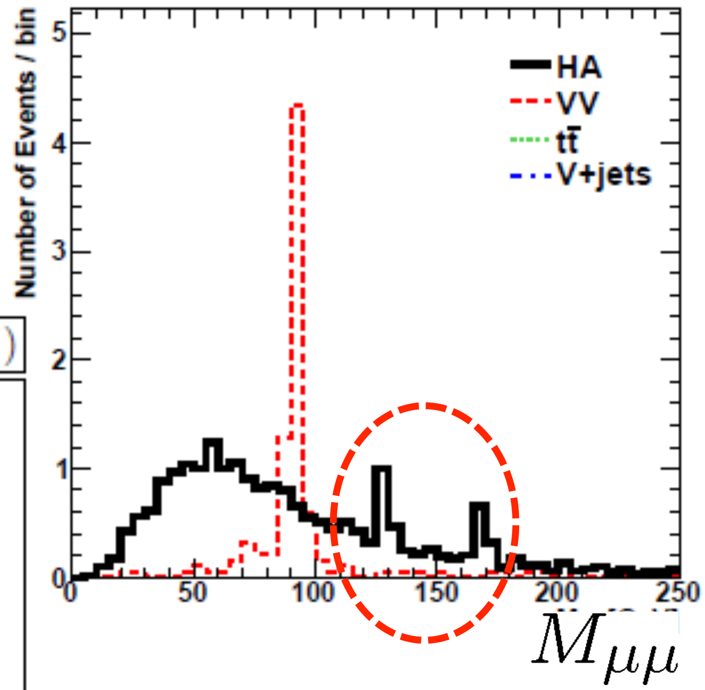
- Sharp peaks **(H,A→ττ)** around M=130GeV,170GeV

$$M_{\tau\tau} = \sqrt{(p_{\tau 1} + p_{\tau 2})^2} \simeq M_{\tau_j \tau_j} / \sqrt{z_1 z_2}$$

□Less # of events

under the collinear approx.

$2\mu 2\tau_h$ event analysis	HA	$\phi^0 H^\pm$	VV	$t\bar{t}$	V+jets	s/b	S (100 fb^{-1})
Pre-selection	91.0	7.7	441.	393.	15675.	10^{-2}	0.8
$p_T^{\tau_h} > 40$ GeV	41.1	1.7	37.7	33.4	548.	0.1	1.7
$\not{E}_T > 30$ GeV	33.1	1.6	14.7	29.9	5.1	0.7	4.5
$H_T^{\text{jet}} < 50$ GeV	24.0	1.2	9.7	4.3	3.1	1.4	5.1
$H_T^{\text{lep}} > 250$ GeV	21.6	1.1	8.6	3.7	1.0	1.7	5.1
$(m_Z)_{\mu\mu} \pm 10$ GeV	18.8	1.0	2.1	3.3	1.0	3.1	5.8
O.S. muons	13.2	0.6	2.0	3.3	1.0	2.2	4.4
$0 \le z_{1,2} \le 1.1$	2.9	0.1	1.0	0.6	0.	1.9	1.9
$(m_Z)_{\tau\tau} \pm 20$ GeV	2.7	0.1	0.2	0.6	0.	3.5	2.3



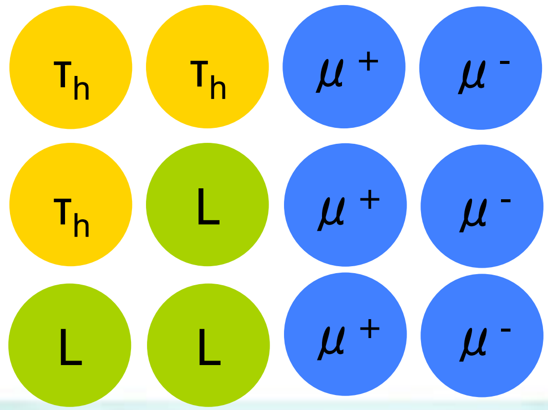
$$M_{\tau\tau} = \sqrt{(p_{\tau 1} + p_{\tau 2})^2} \simeq M_{\tau_j \tau_j} / \sqrt{z_1 z_2}$$

$$\vec{p}_{\tau_j} \simeq z\, \vec{p}_\tau = \frac{1}{1+c} \vec{p}_\tau$$

$2\mu2\tau_h$ channel : μ μ τ_h τ_h **(an example)**

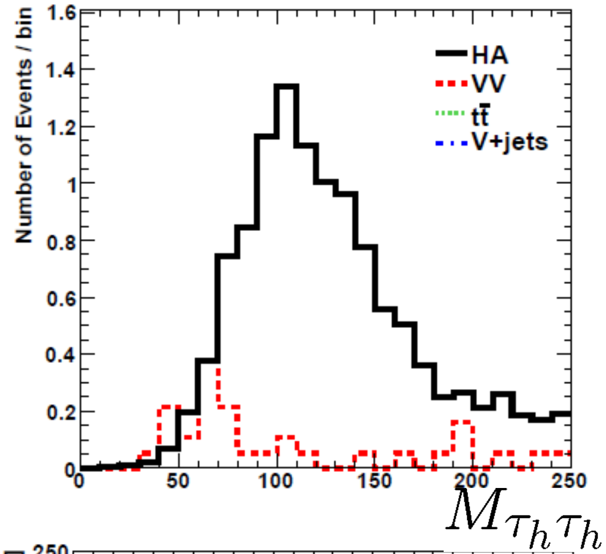
□ Several channels can be combined

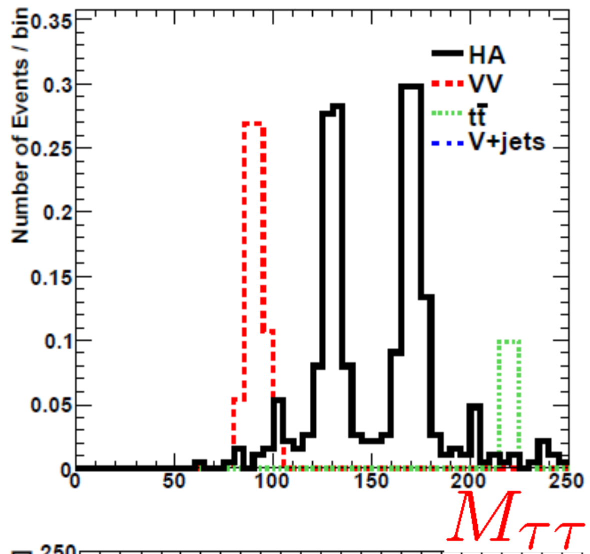
Lepton channels	$2\mu2\tau_h$ s/b	(S)	$2\mu1\tau_h1e$ s/b	(S)	$3\mu1\tau_h$ s/b	(S)	4μ s/b	(S)	$3\mu1e$ s/b	(S)	$2\mu2e$ s/b	(S)
Pre-selection	98.7/16507.	(0.8)	35.7/154.	(2.8)	14.3/162.	(1.1)	0.9/401.	(0.0)	2.6/8.9	(0.8)	3.3/647.	(0.1)
$p_T^{\tau_h} > 40$ GeV	42.8/618.	(1.7)	23.6/46.2	(3.2)	9.4/46.8	(1.3)	-	(-)	-	(-)	-	(-)
$\not{E}_T > 30$ GeV	34.7/ 59.7	(4.5)	19.2/25.3	(3.3)	7.7/27.5	(1.4)	0.7/4.2	(0.3)	2.0/5.8	(0.8)	2.5/5.7	(1.0)
$H_T^{\text{jet}} < 50$ GeV	25.2/17.1	(5.1)	-	(-)	-	(-)	-	(-)	-	(-)	-	(-)
$H_T^{\text{lep}} > 250$ GeV	22.7/13.3	(5.1)	15.7/18.4	(3.3)	6.5/20.2	(1.4)	0.6/2.1	(0.4)	1.5/2.8	(0.8)	1.7/3.0	(0.9)
$(m_Z)_{\mu\mu} \pm 10$ GeV	19.8/6.4	(5.8)	13.7/2.3	(5.9)	5.4/5.1	(2.1)	0.5/0.5	(0.6)	1.3/0.6	(1.3)	1.3/0.3	(1.6)
O.S. muons	13.8/6.3	(4.4)	9.5/2.0	(4.6)	-	(-)	-	(-)	-	(-)	0.9/0.3	(1.3)
$0 \le z_{1,2} \le 1.1$	3.0/1.6	(1.9)	3.0/1.0	(2.3)	2.0/1.3	(1.5)	0.4/0.2	(0.7)	0.7/0.3	(1.0)	0.4/0.2	(0.8)
$(m_Z)_{\tau\tau} \pm 20$ GeV	2.8/0.8	(2.3)	2.8/0.3	(3.0)	1.8/0.7	(1.7)	0.3/0.1	(0.8)	0.6/0.2	(1.0)	0.4/0.0	(-)

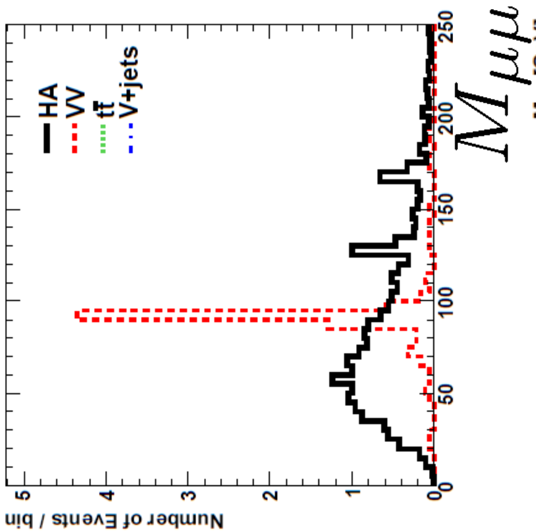


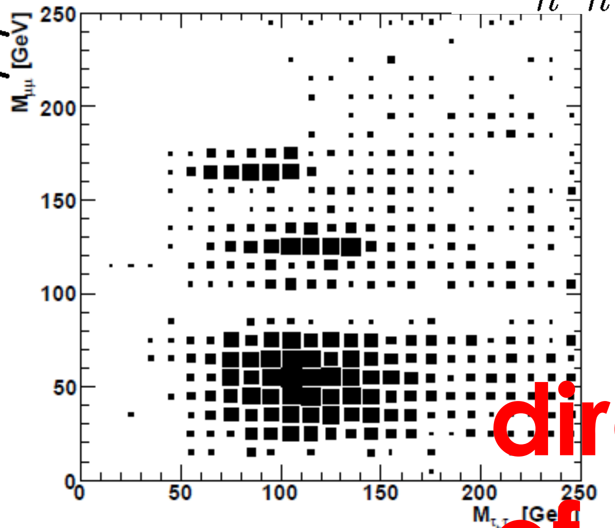
$2\mu2\tau_h$ channel : μ μ τ_h τ_h (an example)

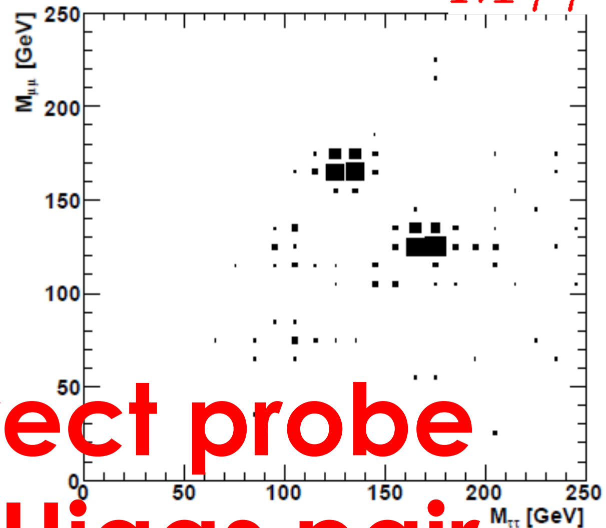
- 2D inv.-mass distributions of $M_{\mu\mu}$ vs. $M_{\tau\tau}$











direct probe of Higgs pair