Seminar @ NTHU
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Phenomenology of Higgs Triplet Model

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A. G. Akeroyd and CC, Phys. Rev. D 80, 113010 (2009) (0909.4419 [hep-ph]); and work in progress (0103.xxxx [hep-ph])

Outline

- Motivation
- Higgs Triplet Model (HTM) -- its particle contents, mass spectrum, and some features
- Properties of charged Higgs bosons ($H^{\pm\pm}$ and $H^{\pm}$)
- Production and signature of $H^{\pm\pm}$ at hadron colliders
- Large mixing between CP-even Higgs bosons
  (provided time allows)
- Summary

Motivation for Higgs Triplet Model

Physics Beyond SM

- Theoretical considerations call for new physics:
  - Naturalness (fine-tuning or hierarchy problem)
  - CP violation and 1st-order phase transition for Baryon Asymmetry of Universe (BAU)
  - Flavor problem and GUT's
- Experimental evidence *demands* physics beyond the SM:
  - Terrestrial: neutrino oscillation phenomena
  - Celestial: dark matter (DM) and dark energy (DE)

Massive Neutrino

- Observation of neutrino oscillations
  $\Rightarrow$ Massive neutrinos
  $\Rightarrow$ mismatch between flavor and mass eigenstates.
- Example of 2-flavor neutrino oscillation:

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_i(t) = \nu_i(0) e^{-iE_i t}$$

$$P_{\nu_e \to \nu_\mu} = \sin^2(2\theta) \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

where L is the distance traveled by the neutrino and E is its energy.

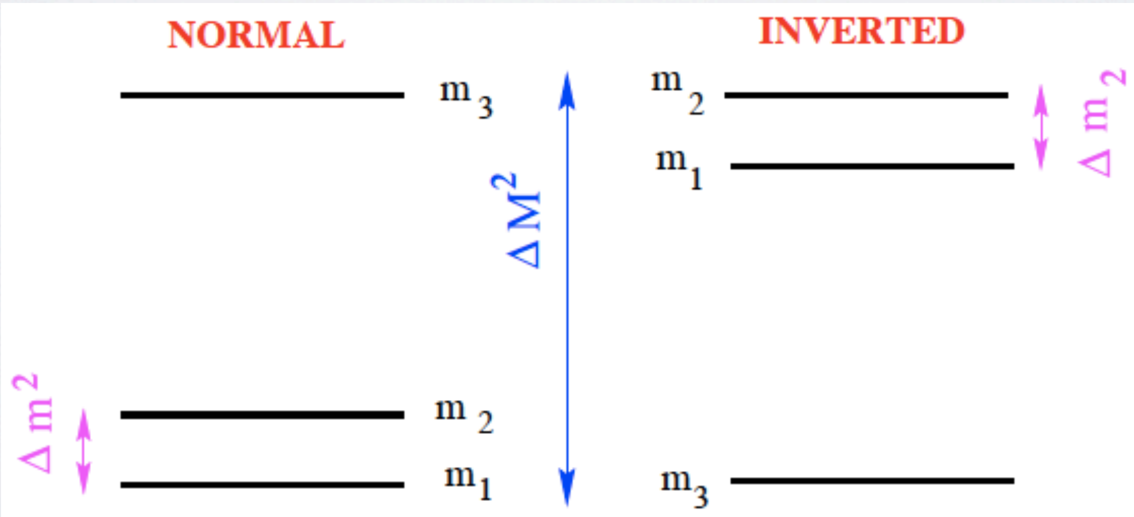
Neutrino Mass Data

Maltoni, Schwetz, Tortola, Valle 2004

- Current experiments for atmospheric and solar neutrinos give the following constraints:

$$\Delta m_{21}^2 \simeq 8 \times 10^{-5} \text{eV}^2 \ , \qquad |\Delta m_{31}^2| \simeq 2.5 \times 10^{-3} \text{eV}^2 \ ,$$
$$\sin^2 2\theta_{12} \simeq 0.8 \ , \qquad \sin^2 \theta_{23} = 0.5 \ , \qquad \sin^2 2\theta_{13} \simeq 0 \ ,$$

- Normal hierarchy (NH): $\Delta m_{31}^2 > 0 \Rightarrow m_3 > m_2 > m_1$.
- Inverted hierarchy (IH): $\Delta m_{31}^2 < 0 \Rightarrow m_2 > m_1 > m_3$.



ORIGIN OF MASSES

- Masses of most particles in SM are given through the VEV of the Higgs boson:
  - EW gauge bosons: Higgs mechanism
  - Quarks and charged leptons: Yukawa couplings with Higgs boson
- What is the mechanism responsible for neutrino masses?
  - Same as others ⇒ Yukawa couplings $\leq 10^{-9}$ ⇒ fine-tuning
  - Seesaw mechanism ⇒ beyond SM

Seesaw Mechanism

Minkowski 1977; Gell-Mann, Ramond, Slansky 1979;
Yanagida 1979; Glashow 1980; Mohapatra, Senjanovic 1980

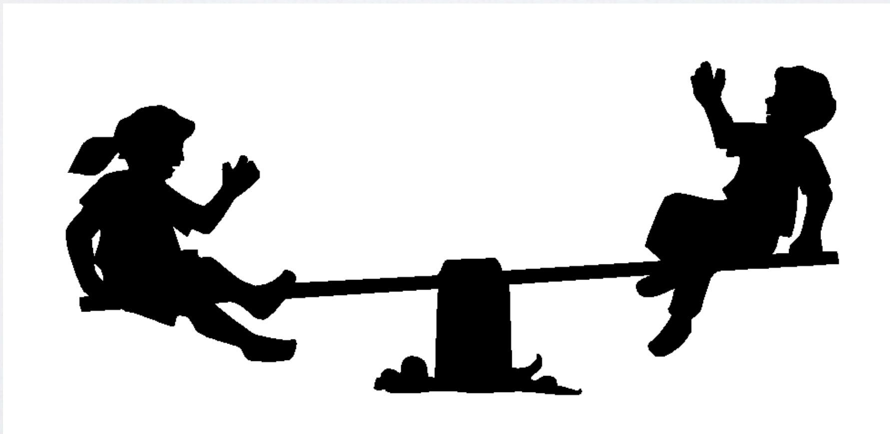
- Suppose neutrino mass matrix is in the form

$$\mathcal{L} \supset -\frac{1}{2} (\nu_L^c \quad \nu_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

for all generations.

- If $M_R \gg m_D$, the eigenmasses are

$$m_\nu \simeq -m_D M_R^{-1} m_D^T \qquad m_N \simeq M_R$$



Seesaw Models

- This provides a natural reason why the SM neutrinos are much lighter than their charged partners and of *Majorana* nature.

- We hope to achieve seesaw while:

➡ remaining the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$.

➡ adding at most one type of new particles to the spectrum.

Seesaw Model Type I

- Introduce a singlet RH neutrino ν_R: (1,1,0) for each generation:

$$\mathcal{L} \supset \bar{L}_L Y_D \tilde{\Phi} \nu_R + \frac{1}{2} \bar{\nu}_R^c M_R \nu_R + \text{h.c.}$$

$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \text{ with } m_D = Y_D \langle \tilde{\Phi} \rangle$$

- The Higgs field

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v_0 + h + i\eta) \end{pmatrix} , \qquad \tilde{\Phi} = i\sigma_2 \Phi^*$$

SEESAW MODEL II

Konetschny, Kummer 1977; Schechter, Valle 1980;
Cheng, Li 1980; Gelmini, Roncadelli 1981

- Introduce a triplet Higgs field Δ: (1,3,1) in 2×2 form:

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

with the $SU(2)_L \times U(1)_Y$ invariant potential

$$\begin{aligned} \mathcal{L} \supset\ & (D_\mu\Phi)^\dagger(D^\mu\Phi) - m^2(\Phi^\dagger\Phi) - \lambda(\Phi^\dagger\Phi)^2 \\ & + \mathrm{Tr}(D_\mu\Delta)^\dagger(D^\mu\Delta) - M_\Delta^2\,\mathrm{Tr}(\Delta^\dagger\Delta) - \frac{\mu}{\sqrt{2}}(\Phi^T i\sigma_2\Delta^\dagger\Phi) \\ & - \lambda_i(\text{quartic terms}) \\ & - h_{ij}\psi_{iL}^T C i\sigma_2 \Delta\psi_{jL} + \text{h.c.} \end{aligned}$$

- This is the so-called Higgs Triplet Model. The simplest version sets all λ_i's = 0, as considered by most people.

Higgs Triplet Model

HIGGS POTENTIAL OF HTM

- Require $m^2 < 0$ and $M_\Delta^2 > 0$:

$$\begin{aligned}\mathcal{L} \supset\ & (D_\mu\Phi)^\dagger(D^\mu\Phi) - m^2(\Phi^\dagger\Phi) - \lambda(\Phi^\dagger\Phi)^2 \\ & + \mathrm{Tr}(D_\mu\Delta)^\dagger(D^\mu\Delta) - M_\Delta^2\mathrm{Tr}(\Delta^\dagger\Delta) - \frac{\mu}{\sqrt{2}}(\Phi^T i\sigma_2\Delta^\dagger\Phi) \\ & - \lambda_1(\Phi^\dagger\Phi)\mathrm{Tr}\Delta^\dagger\Delta + \lambda_2(\mathrm{Tr}\Delta^\dagger\Delta)^2 \\ & + \lambda_3\mathrm{Tr}(\Delta^\dagger\Delta)^2 + \lambda_4\Phi^\dagger\Delta\Delta^\dagger\Phi \\ & - h_{ij}\psi_{iL}^T C i\sigma_2\Delta\psi_{jL} + \mathrm{h.c.}\end{aligned}$$

LNV

- Triplet VEV and Majorana neutrino mass matrix

$$\langle\delta^0\rangle = \frac{v_\Delta}{\sqrt{2}}\,, \qquad v_\Delta = \frac{\mu v_0^2}{\sqrt{2}M_\Delta^2}\,, \qquad M_\nu = \sqrt{2}hv_\Delta$$

NEUTRAL HIGGS MASSES

mixing between doublet and triplet

- CP-even states:

$$\mathcal{M}^2_{\text{even}} = \begin{pmatrix} \lambda v_0^2/2 & \left[(\lambda_1+\lambda_4)v_\Delta - \sqrt{2}\mu\right] v_0 \\ \left[(\lambda_1+\lambda_4)v_\Delta - \sqrt{2}\mu\right] v_0 & (\sqrt{2}\mu v_0^2 + 4(\lambda_2+\lambda_3)v_\Delta^3)/2v_\Delta \end{pmatrix}$$

where all 6 HTM parameters (5 couplings and 1 VEV) show up.
$\Rightarrow$ h^0 and H^0.

- CP-odd states:

$$\mathcal{M}^2_{\text{odd}} = \mu \begin{pmatrix} 2\sqrt{2}v_\Delta & -\sqrt{2}v_0 \\ -\sqrt{2}v_0 & v_0^2/(\sqrt{2}v_\Delta) \end{pmatrix}$$

where only the μ and v_Δ enter, independent of all λ_i's.
$\Rightarrow$ 1 Goldstone mode "eaten" by Z + 1 CP-odd A^0.

- H^0 and A^0 have almost the same mass.

Charged Higgs Masses

- Singly-charged states:

$$\mathcal{M}^2_{\pm} = \left(\mu - \frac{\lambda_4 v_\Delta}{2\sqrt{2}}\right)\begin{pmatrix} \sqrt{2}v_\Delta & -v_0 \\ -v_0 & v_0^2/(\sqrt{2}v_\Delta) \end{pmatrix}$$

where μ, λ_4 and v_Δ control the overall factor.
⇒ 1 Goldstone mode “eaten” by W + 1 singly-charged $H^\pm$.

- Doubly-charged state:

$$\mathcal{M}^2_{\pm\pm} = \frac{\mu v_0^2}{\sqrt{2}v_\Delta} - \frac{\lambda_4}{2}v_0^2 - \lambda_3 v_\Delta^2$$

depending on μ, λ_3, λ_4 and v_Δ .

Higgs Boson Spectrum

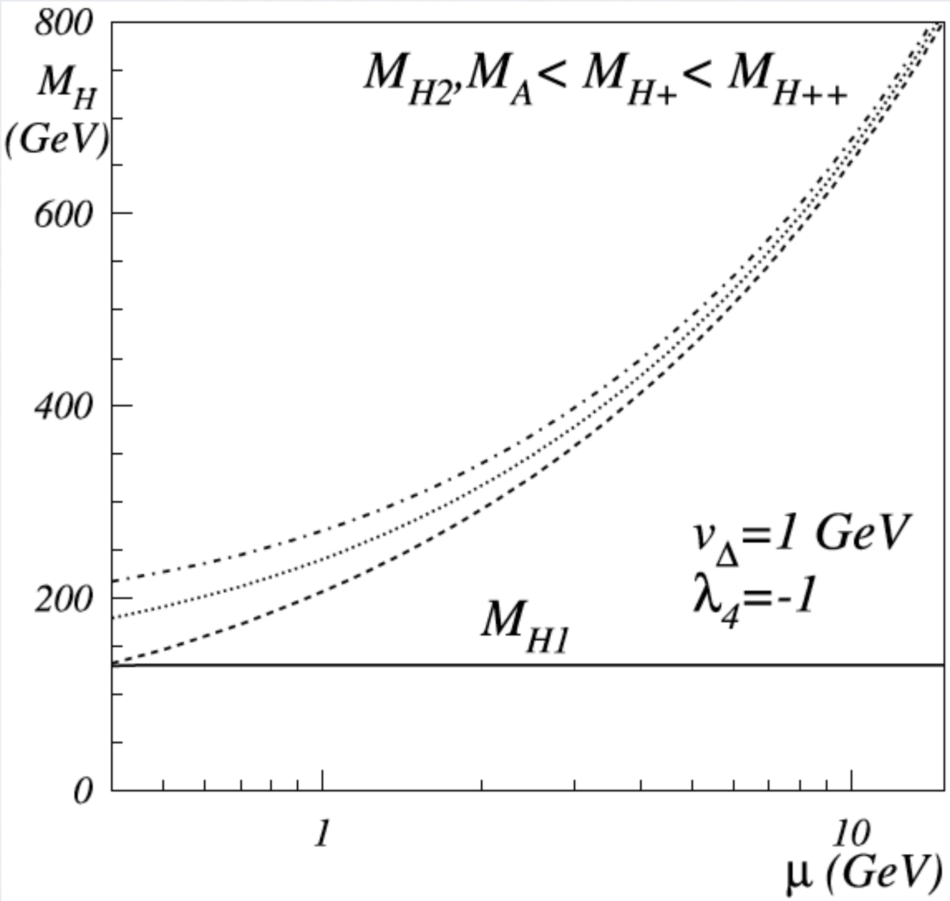
The HTM has *7* Higgs bosons: $H^{\pm\pm}$, $H^{\pm}$, H^0, A^0, and h^0.

- $H^{\pm\pm}$ is purely triplet $\delta^{\pm\pm}$, a very unique feature.
- $H^{\pm}$, H^0, A^0, and h^0 are mixtures of doublet ϕ and triplet δ.
- For $M_\Delta \gg v_0$, mixing angle ~ $v_\Delta/v < 0.01$ and
  $\Rightarrow$ h^0 plays the role of SM Higgs boson.
  $\Rightarrow$ $H^{\pm}$, H^0, and A^0 are dominantly triplet.
  $\Rightarrow$ $H^{\pm\pm}$, $H^{\pm}$, H^0, A^0 are close to degenerate ~ M_Δ.

- For $H^{\pm\pm}$, $H^{\pm}$ to be within LHC reach, $M_\Delta < 1$ TeV.
  $\Rightarrow$ large mixing possible between H^0 and h^0.

Higgs Boson Masses

- Higgs boson masses as a function of the μ parameter.
(v_Δ = 1 GeV, λ = 0.566, λ_1 = 0, $\lambda_{2,3}$ = 1, λ_4 = −1)



Neutrino Masses

- Triplet-lepton-lepton coupling:

$$h_{ij}\left[\sqrt{2}\bar{\ell}^c_{iL}\ell_{jL}\ \delta^{++} + (\bar{\ell}^c_{iL}\nu_{jL} + \bar{\ell}^c_{jL}\nu_{iL})\delta^{+} - \sqrt{2}\bar{\nu}^c_{iL}\nu_{jL}\delta^0\right] + \text{h.c.}$$

- Majorana mass matrix for neutrinos: $M^{\nu}_{ij} \propto v_{\Delta} h_{ij}$
- Relate to mass eigenstates:

$$h_{ij} = \frac{1}{\sqrt{2}v_{\Delta}} V_{\text{PMNS}}\ \text{diag}(m_1, m_2 e^{i\phi_1}, m_3 e^{i\phi_2}) V^T_{\text{PMNS}}$$

- Here the PMNS matrix $V_{\text{PMNS}} = V_{\ell}^{\dagger} V_{\nu}$.

Pontecorvo 1958; Maki, Nakagawa, Sakata 1962

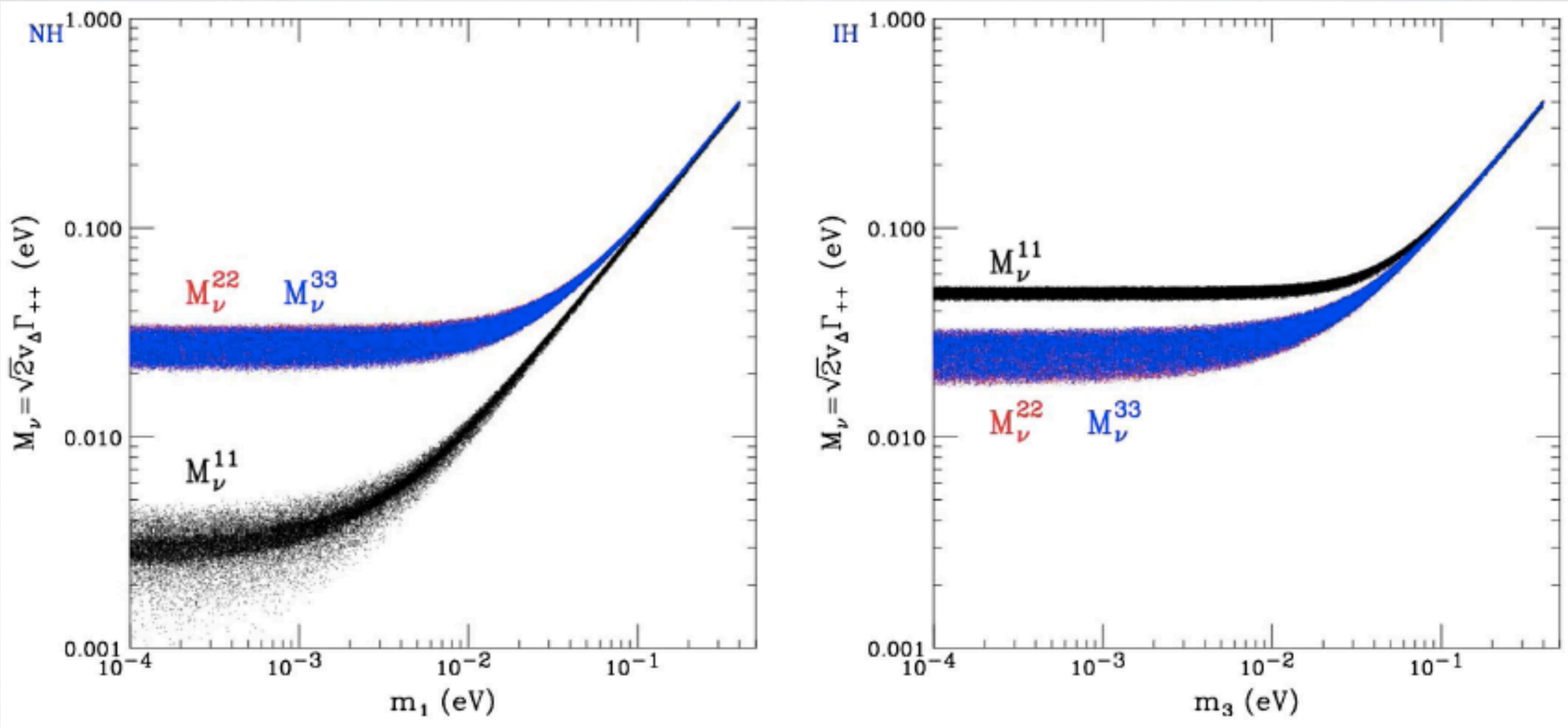
- h_{ij} are functions of nine parameters in the neutrino mass matrix (3 masses, 3 mixing angles, and 3 CPV phases).

Garayoa et.al. 2007; Akeroyd et. al. 2007; Kadastik et. al. 2007; Han et. al. 2008

Neutrino Mass Matrix

Perez et. al. 2008

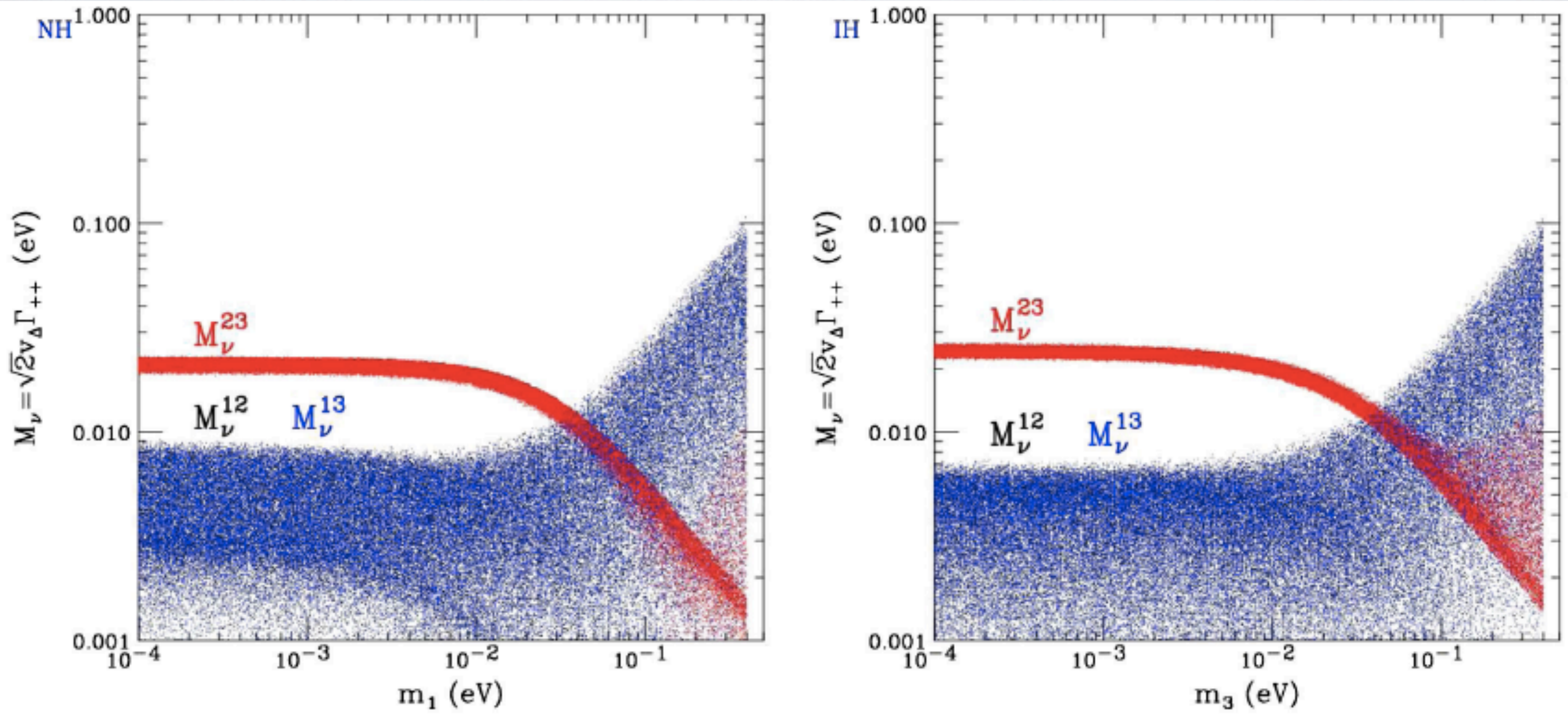
- Constraints on *diagonal* elements of M_ν versus the lightest neutrino mass, assuming zero Majorana phases:



Neutrino Mass Matrix

Perez et. al. 2008

- Constraints on *off-diagonal* elements of M_ν versus the lightest neutrino mass, assuming zero Majorana phases:



Constraints on v_Δ

- Based on realistic neutrino masses, perturbation is allowed for $v_\Delta \gtrsim 1$ eV.
- Non-zero Higgs triplet VEV leads to

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \neq 1$$

Current $\rho^{exp} \approx 1.0004^{+0.0008}_{-0.0004}$ requires that $v_\Delta \lesssim$ a few GeV.

PDG 2008; Abada et al 2007

- We first concentrate on the parameter space where v_Δ is around the eV scale, where $H^{\pm\pm}$ and $H^\pm$ dominantly decay into leptonic final states.

DECAYS OF H$^{\pm\pm}$ AND H$^{\pm}$

same-sign di-leptons
or di-bosons

- Decay rates of H$^{\pm\pm}$:

$$\Gamma(H^{\pm\pm} \to \ell_i^{\pm} \ell_j^{\pm}) \quad \propto \quad |h_{ij}|^2$$

$$\Gamma(H^{\pm\pm} \to W^{\pm} W^{\pm}) \quad \propto \quad v_{\Delta}^2$$

Chun, Lee, Park 2003

⇒ The former is larger than the latter when $v_{\Delta} < 10^{-4}$ GeV.

- Decay rates of H$^{\pm}$:

$$\Gamma(H^{\pm} \to \ell^{\pm} \nu) \quad \propto \quad M_{H^{\pm}} |h_{ij}|^2$$

$$\Gamma(H^{\pm} \to tb) \quad \propto \quad M_{H^{\pm}} |h_t|^2 \left(\frac{v_{\Delta}}{v}\right)^2$$

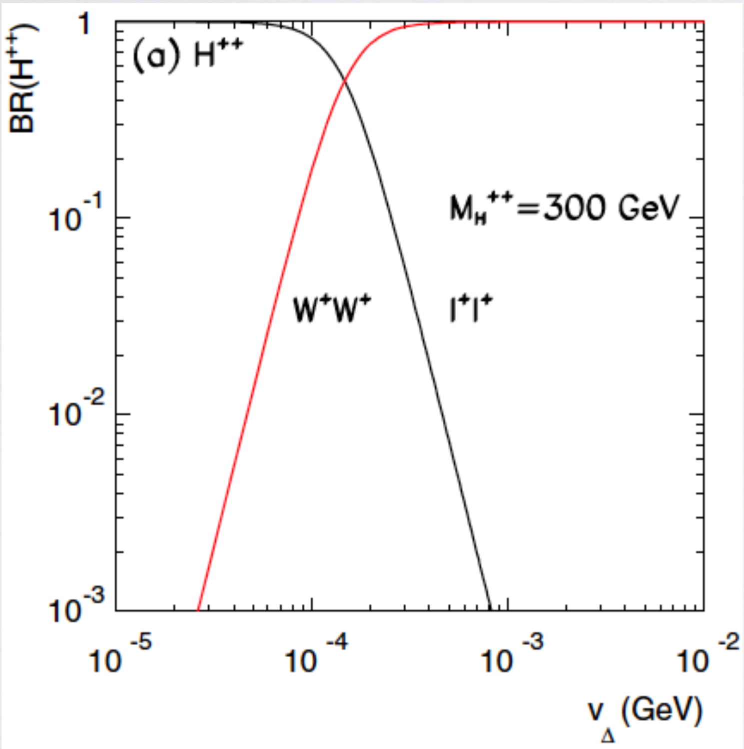
$$\Gamma(H^{\pm} \to W_T^{\pm} Z_T) \quad \propto \quad \frac{M_Z^2}{M_{H^{\pm}}} \left(\frac{v_{\Delta}}{v}\right)^2$$

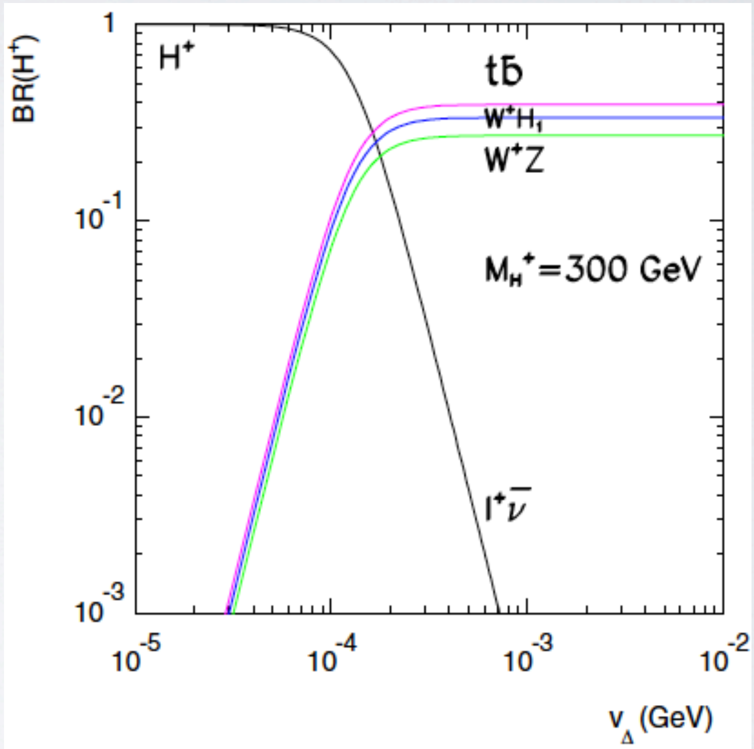
$$\Gamma(H^{\pm} \to W_L^{\pm} Z_L) \quad \propto \quad \frac{M_{H^{\pm}}^3 v_{\Delta}^2}{v^4}$$

⇒ The first is larger than the rest when $v_{\Delta} < 10^{-4}$ GeV too.

SIGNATURE MODES

- In the case of small v_Δ, both $H^{\pm\pm}$ and $H^{\pm}$ decay dominantly into leptonic final states, more desirable at hadron colliders.



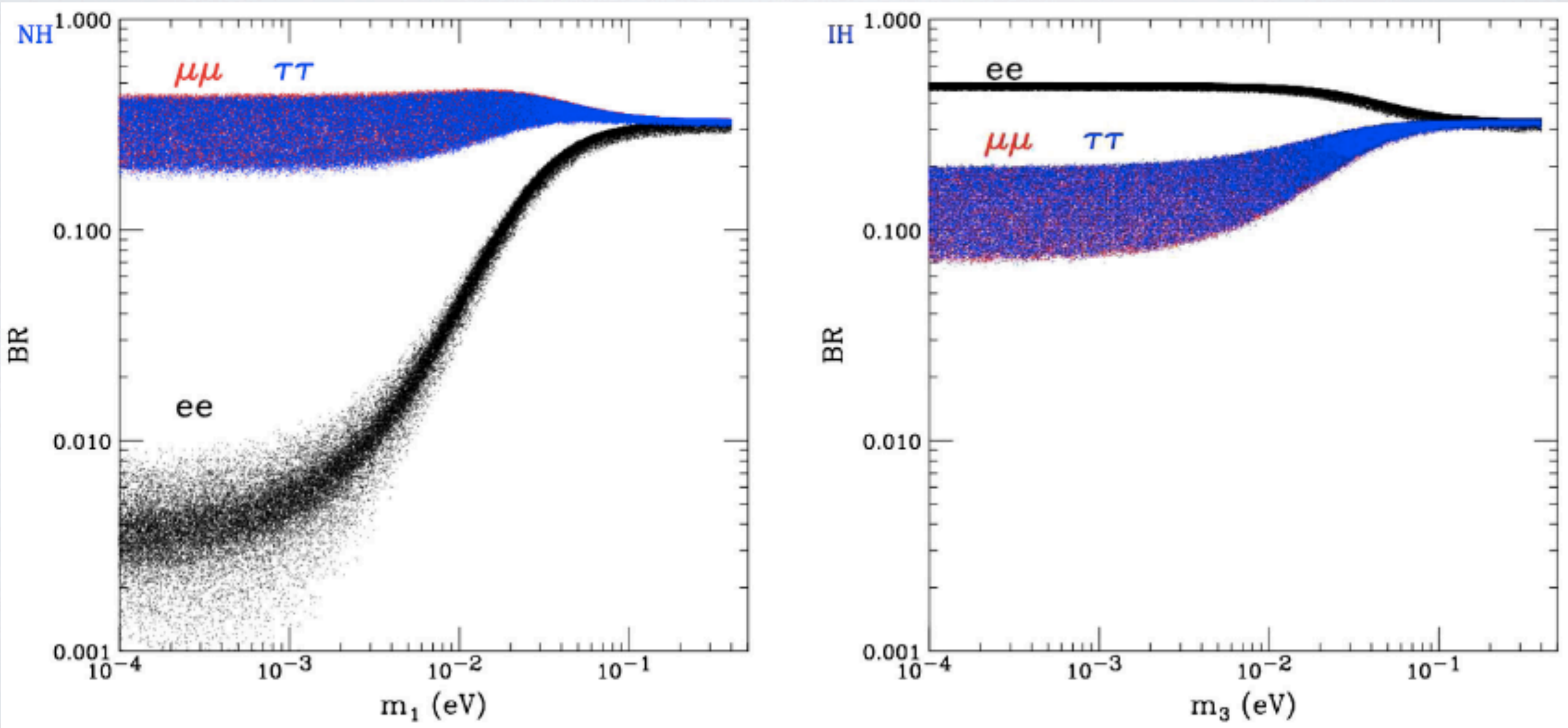


Perez et. al. 2008

LEPTONIC $H^{\pm\pm}$ DECAYS

Perez et. al. 2008

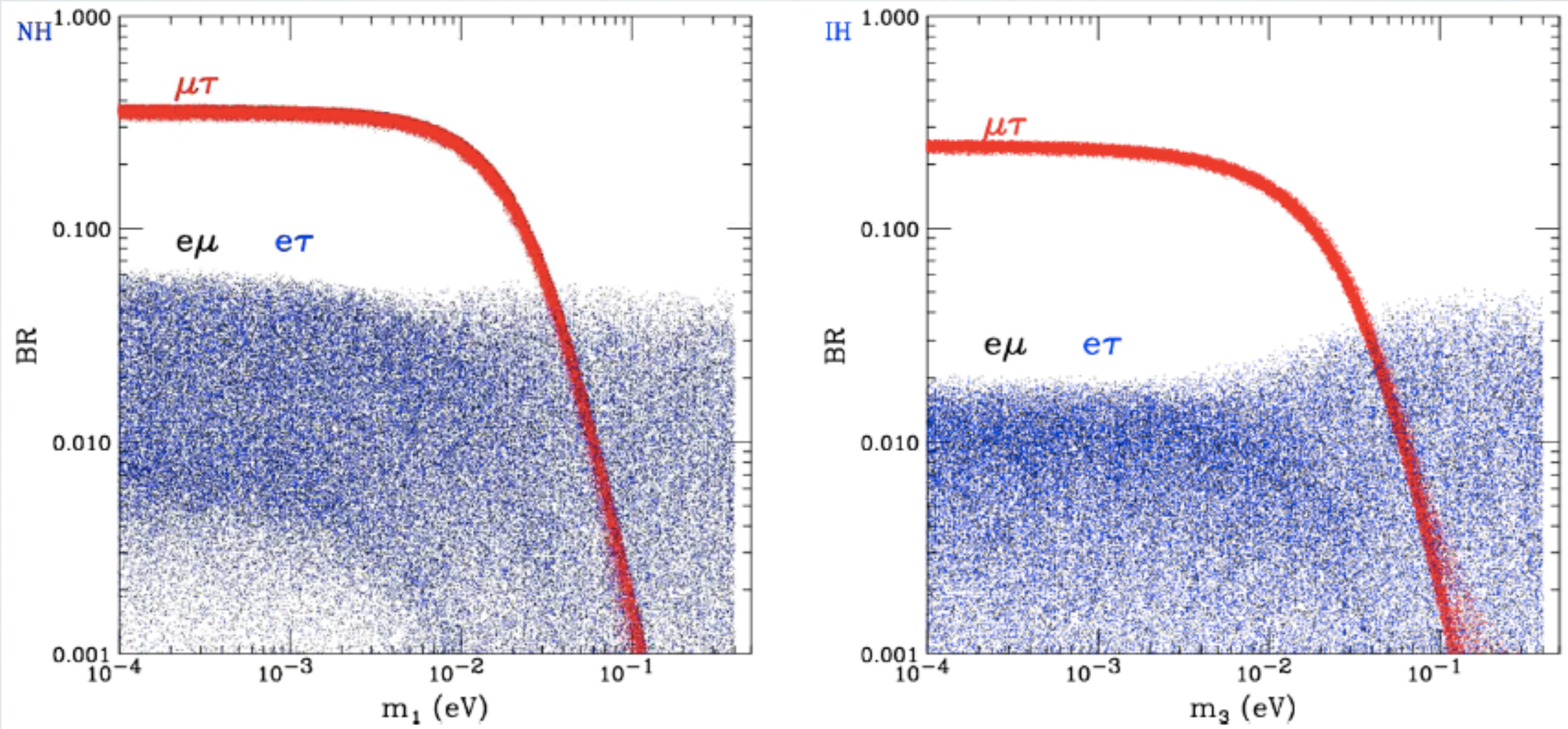
- Branching fractions of *flavor-diagonal* like-sign di-leptons versus the lightest neutrino mass, assuming zero Majorana phases:



LEPTONIC H±± DECAYS

Perez et. al. 2008

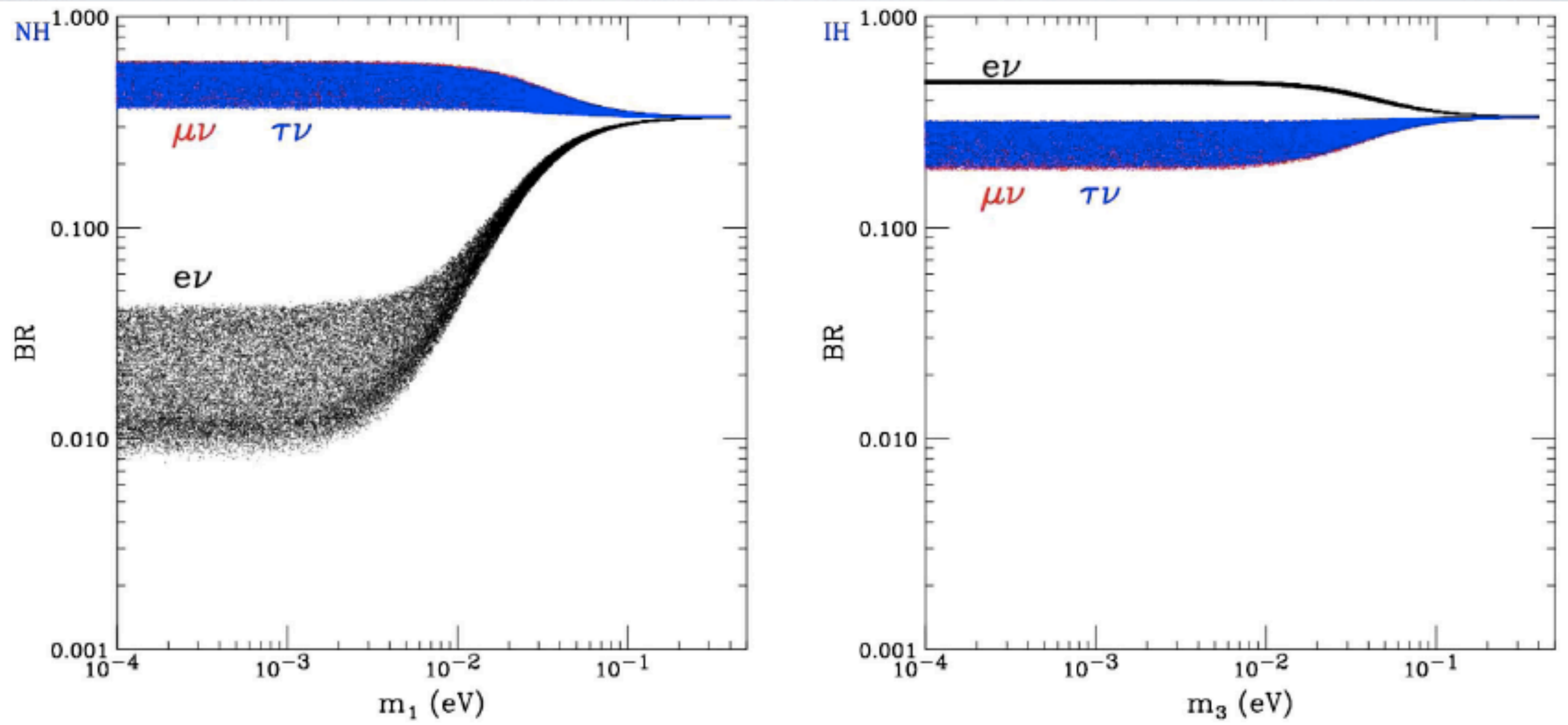
- Branching fractions of *flavor-off-diagonal* like-sign di-leptons versus the lightest neutrino mass, assuming zero Majorana phases:



LEPTONIC H± DECAYS

Perez et. al. 2008

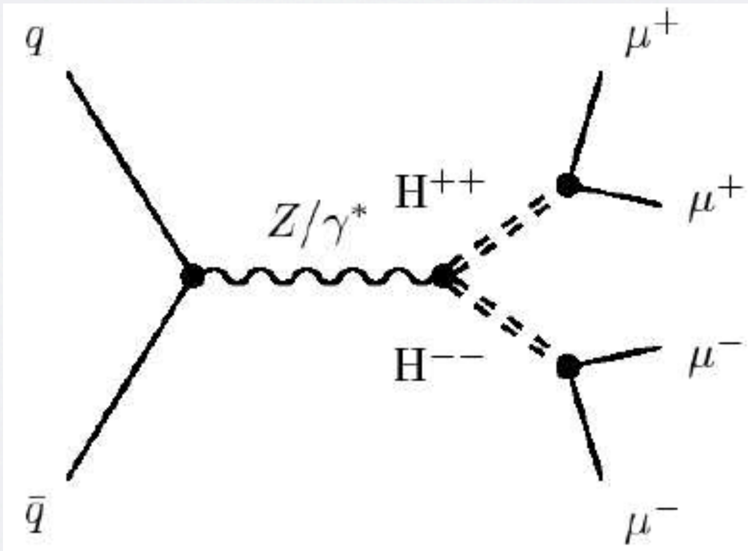
- Branching fractions of leptonic decays versus the lightest neutrino mass, results independent of Majorana phases:



Production of $H^{\pm\pm}$ at Hadron Colliders

Searches at Tevatron

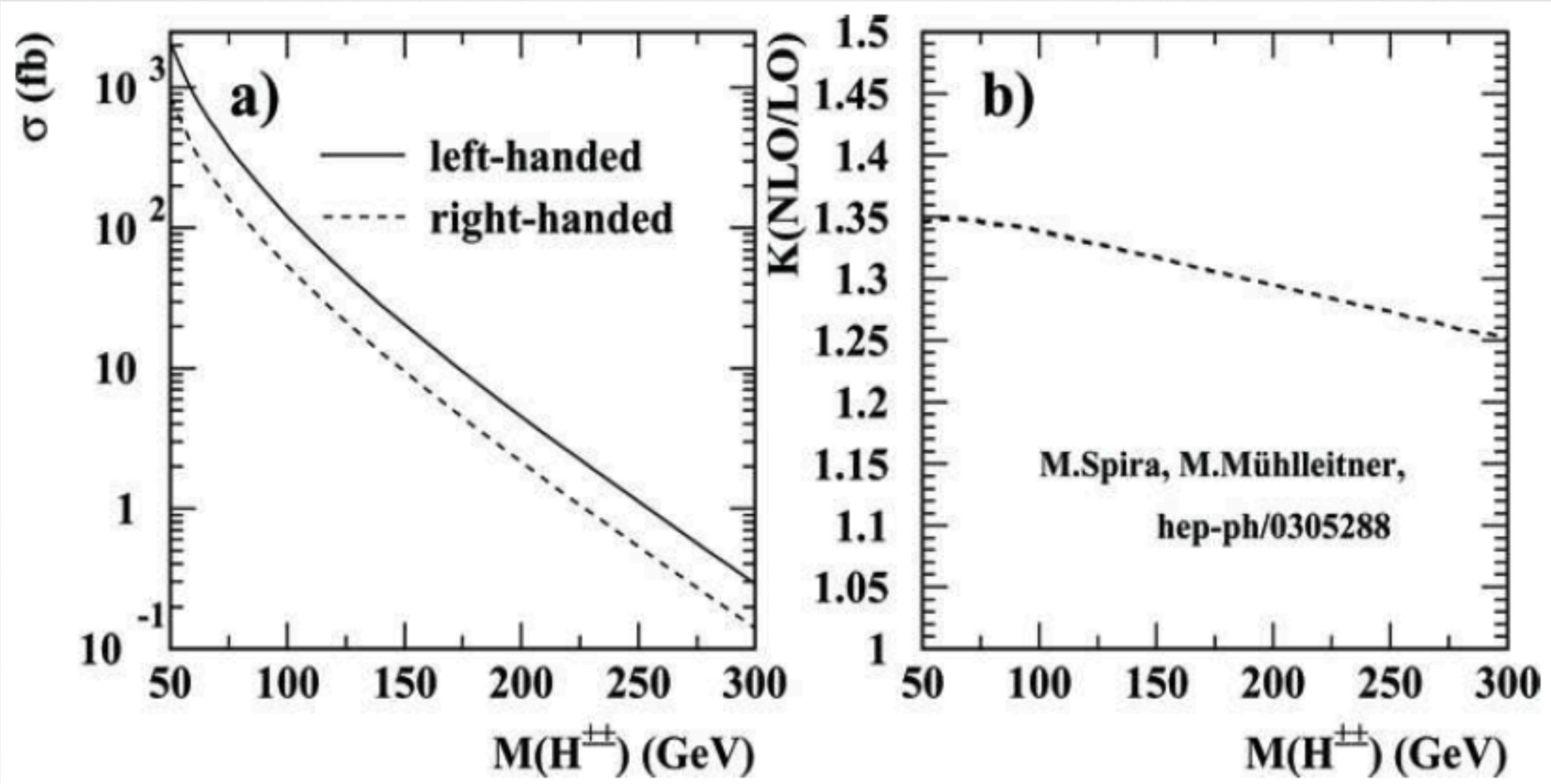
- Smoking gun of the model: production of doubly-charged Higgs boson that then decay into like-sign lepton pairs.
- CDF and D0 at Tevatron started first searches in 2003.
- In the searches, they have assumed
  - $q\bar{q} \to \gamma^*/Z \to H^{++}H^{--}$ is the only significant production channel
  - $H^{\pm\pm}$ decays into like-sign muon pairs at 100% rate.



PREDICTED CROSS SECTION

D0 Note 5458

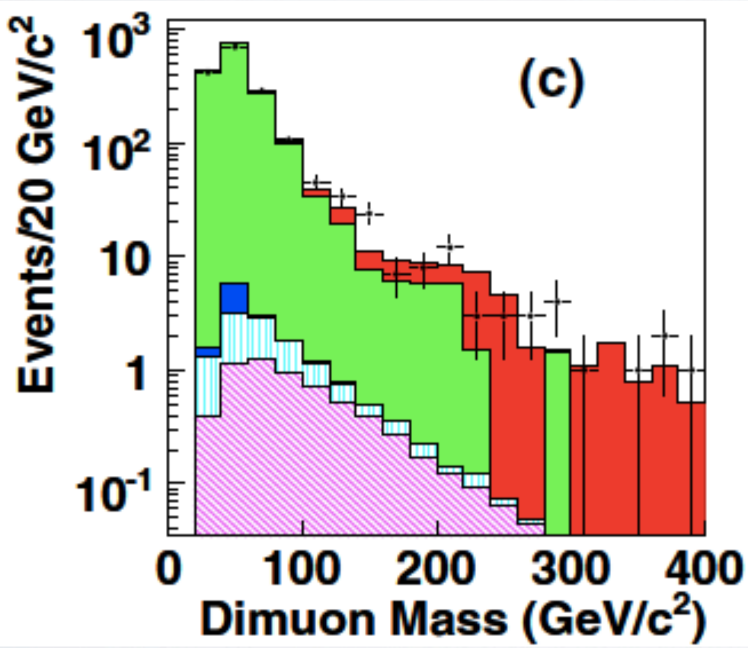
- Predicted cross section $\sigma_{H^{\pm\pm}H^{\mp\mp}}$ at Tevatron:



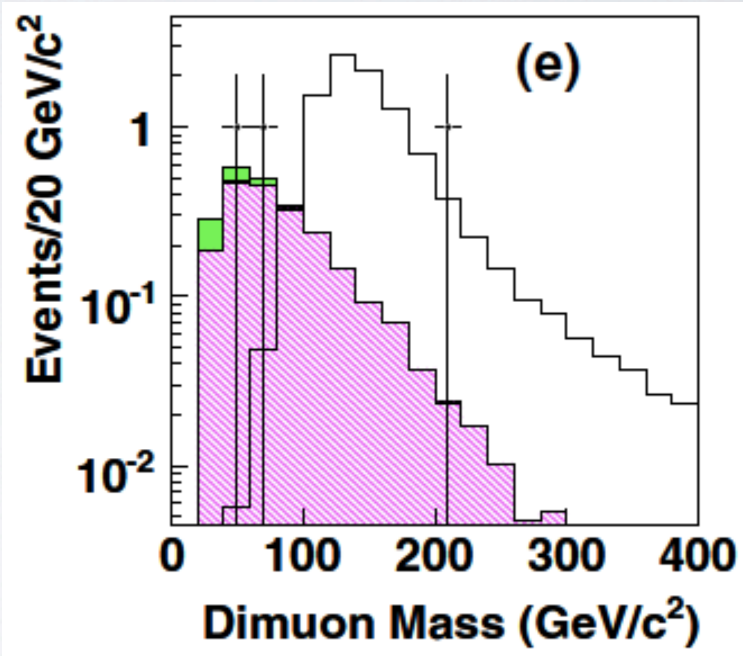
RESULTS

D0 2008

- Left panel: look for two same-sign $\mu^{\pm}\mu^{\pm}$.
- Right panel: look for two same-sign $\mu^{\pm}\mu^{\pm}$ and one $\mu^{\mp}$.



2.6σ excess at 150 GeV?



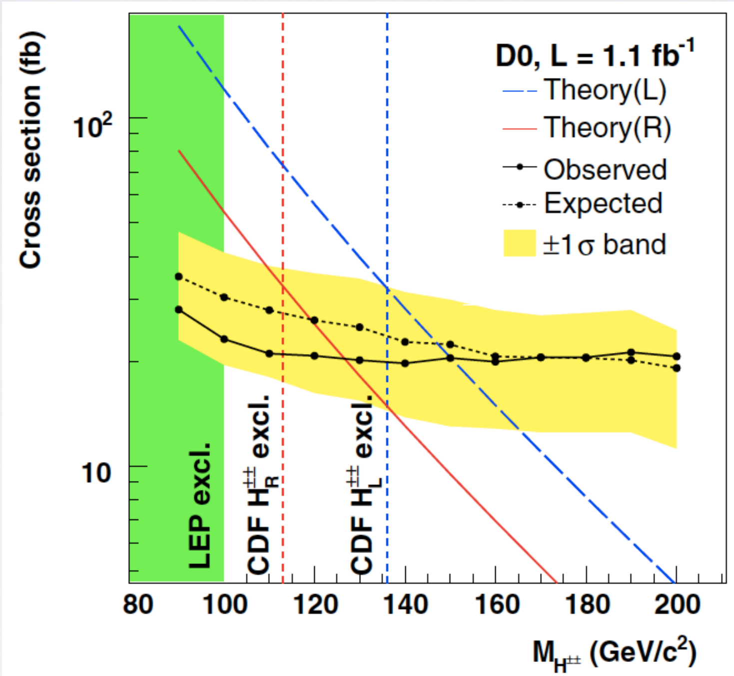
open histogram expected for $m_{H^{\pm\pm}}$ = 140 GeV

Lower Mass Limit

D0 2008

- D0 concludes that $m_{H^{\pm\pm}} \geq 150$ GeV, based on

$$p\bar{p} \rightarrow H^{++}(\rightarrow \mu^+\mu^+)H^{--}(\rightarrow \mu^-\mu^-)$$

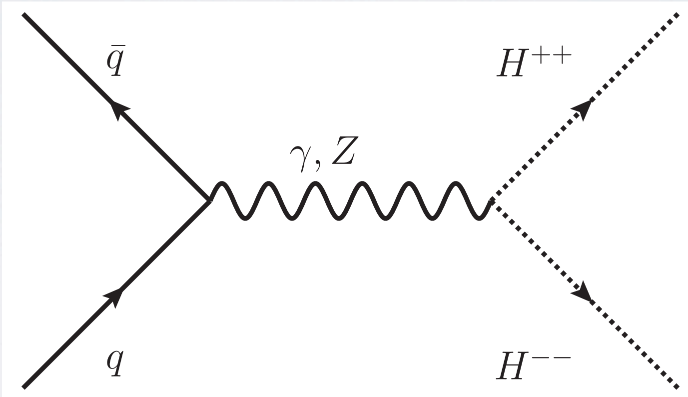


- However, they have overlooked one important mechanism and other channels...

Pair Production

- Interaction for pair production

$$\mathcal{L} \supset i\left[(\partial^\mu H^{--})H^{++}\right](gW_{3\mu} + g'B_\mu) + \text{h.c.}$$



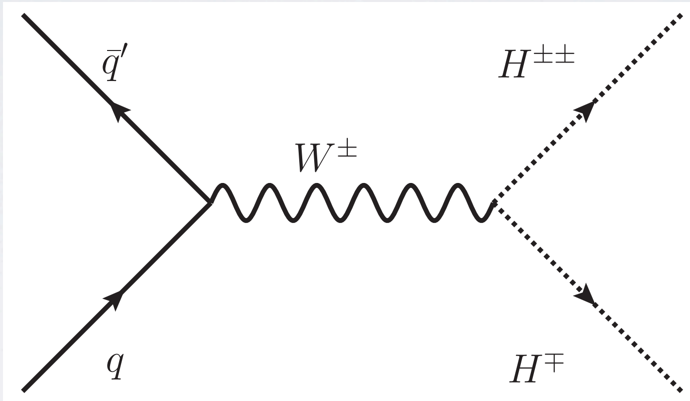
- The cross section $\sigma_{H^{\pm\pm}H^{\mp\mp}}$ is a simple function of $m_{H^{\pm\pm}}$ and has no dependence on h_{ij} .

Gunion 1989, Raidal 1996

Single Production

- Interaction for single production

$$\mathcal{L} \supset i\left[(\partial^{\mu}H^{+})H^{-} - (\partial^{\mu}H^{--})H^{+}\right]W_{\mu}^{+} + \text{h.c.}$$



- The cross section $\sigma_{H^{\pm\pm}H^{\mp}}$ is a simple function of $m_{H^{\pm\pm}}$ and $m_{H^{\pm}}$.

Dion et. al 1998, Gunion 1998

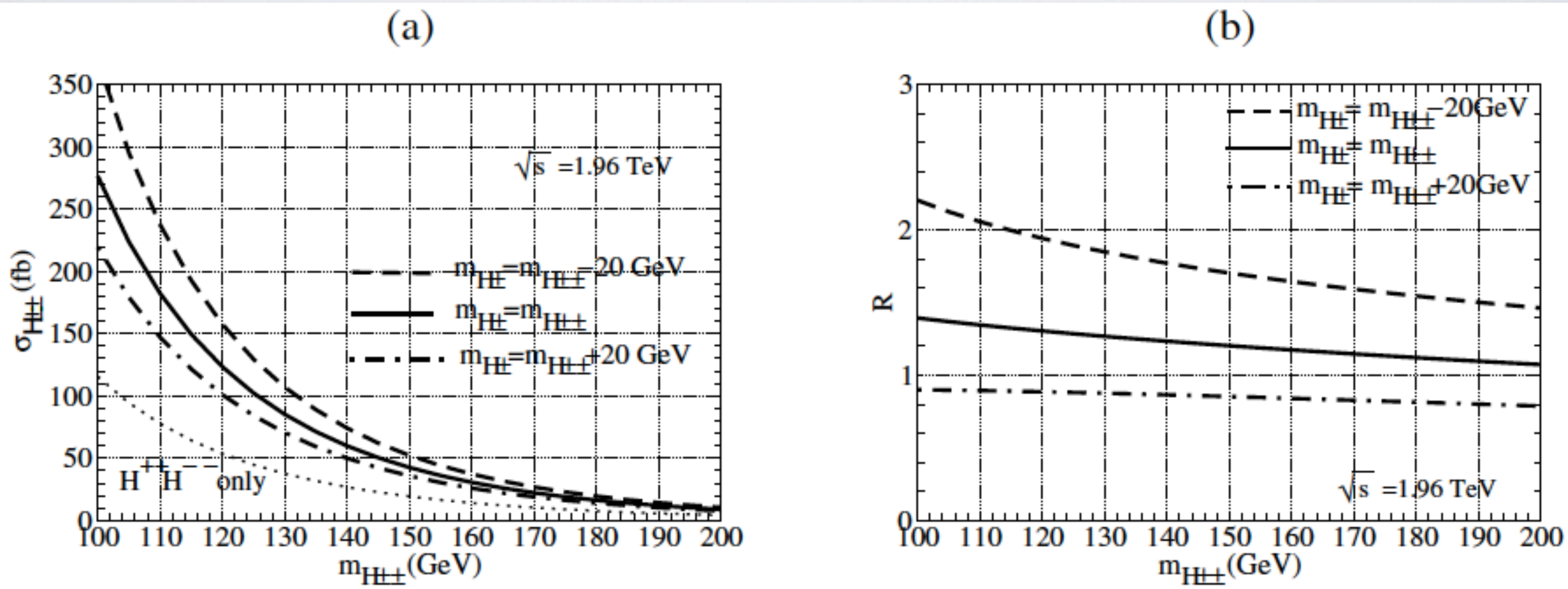
- If $m_{H^{\pm\pm}} \sim m_{H^{\pm}}$, then $\sigma_{H^{\pm\pm}H^{\mp}} \sim \sigma_{H^{++}H^{--}}$, equally important!
- Note a combinatorial factor of 2 comes in for single production.

Total Cross Section @ Tevatron

Akeroyd, Aoki 2005

- Consider

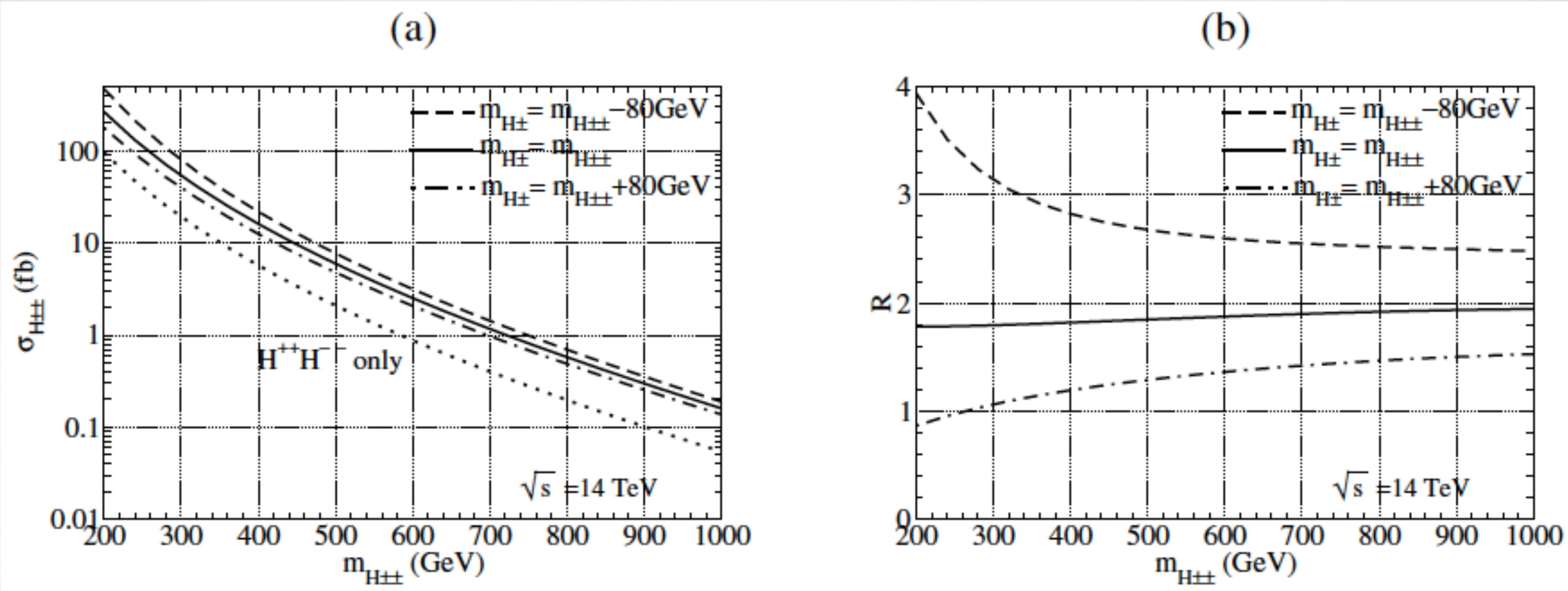
$$R \equiv \frac{\sigma(p\bar{p}, pp \to H^{++}H^{-}) + \sigma(p\bar{p}, pp \to H^{--}H^{+})}{\sigma(p\bar{p}, pp \to H^{++}H^{--})}$$



Total Cross Section @ LHC

Akeroyd, Aoki 2005

$$R \equiv \frac{\sigma(p\bar{p}, pp \to H^{++}H^{-}) + \sigma(p\bar{p}, pp \to H^{--}H^{+})}{\sigma(p\bar{p}, pp \to H^{++}H^{--})}$$



Multi-Lepton Channels

- Four-lepton final states are clear channels from pair production of doubly-charged Higgs boson.
- Three-lepton final states with two same-signs and the other opposite-sign have a higher production rate and should be sufficiently useful.
- Concentrate on light charged leptons, because τ is more difficult to identify as it often decays hadronically.
- D0 has only looked for $\mu^{\pm}\mu^{\pm}\mu^{\mp}$, whereas there are totally six light 3-lepton channels:

$$e^{\pm}e^{\pm}e^{\mp}, e^{\pm}e^{\pm}\mu^{\mp}, e^{\pm}\mu^{\pm}e^{\mp}, e^{\pm}\mu^{\pm}\mu^{\mp}, \mu^{\pm}\mu^{\pm}e^{\mp}, \text{ and } \mu^{\pm}\mu^{\pm}\mu^{\mp}$$

- Tevatron currently has 7 fb^{-1} and expects up to ~10 fb^{-1} at each detector before it shuts down.

Tri-Lepton Signature of HTM at Hadron Colliders

TRI-LEPTON CROSS SECTION

- Define reduced (normalized) cross section through

$$\sigma_{\ell\ell\ell} = \hat{\sigma}_{\ell\ell\ell} \times \sigma(pp \to H^{++}H^{--})$$

- Assume $m_{H^{\pm\pm}} = m_{H^{\pm}}$ to fix $\sigma(pp \to H^{\pm\pm}H^{\mp})$.
- Reduced cross sections of the six channels are (for LHC):

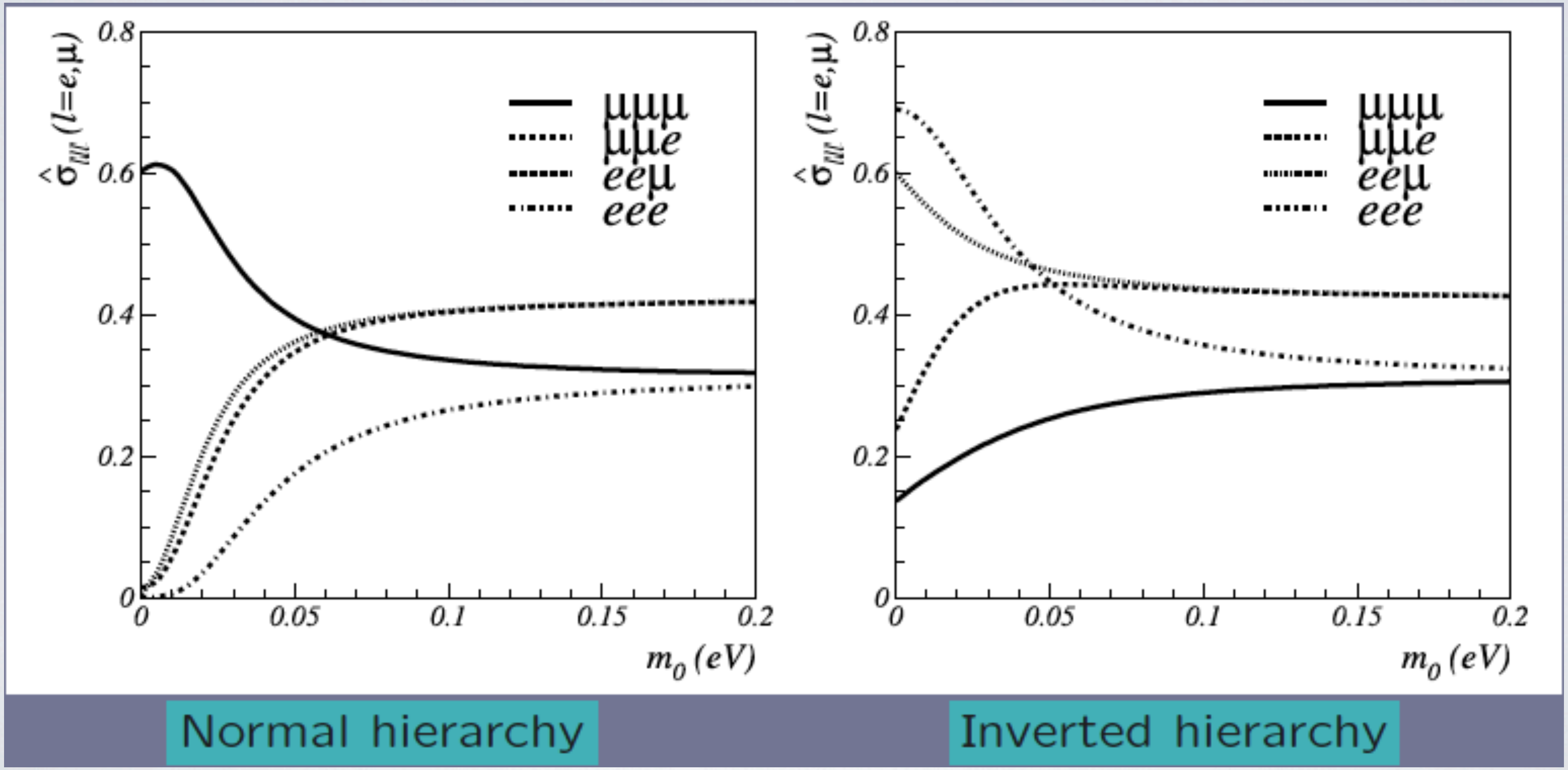
$$\begin{aligned}
\hat{\sigma}_{eee} &= \mathcal{B}_{ee}\left[\mathcal{B}_{ee} + 2(\mathcal{B}_{e\mu} + \mathcal{B}_{e\tau}) + 1.8\mathcal{B}_{e\nu}\right] \;, \\
\hat{\sigma}_{ee\mu} &= \mathcal{B}_{ee}\left[2(\mathcal{B}_{\mu\mu} + \mathcal{B}_{e\mu} + \mathcal{B}_{\mu\tau}) + 1.8\mathcal{B}_{\mu\nu}\right] \;, \\
\hat{\sigma}_{e\mu e} &= \mathcal{B}_{e\mu}\left[\mathcal{B}_{e\mu} + 2(\mathcal{B}_{ee} + \mathcal{B}_{e\tau}) + 1.8\mathcal{B}_{e\nu}\right] \;, \\
\hat{\sigma}_{e\mu\mu} &= \mathcal{B}_{e\mu}\left[\mathcal{B}_{e\mu} + 2(\mathcal{B}_{\mu\mu} + \mathcal{B}_{\mu\tau}) + 1.8\mathcal{B}_{\mu\nu}\right] \;, \\
\hat{\sigma}_{\mu\mu e} &= \mathcal{B}_{\mu\mu}\left[2(\mathcal{B}_{ee} + \mathcal{B}_{e\mu} + \mathcal{B}_{e\tau}) + 1.8\mathcal{B}_{e\nu}\right] \;, \\
\hat{\sigma}_{\mu\mu\mu} &= \mathcal{B}_{\mu\mu}\left[\mathcal{B}_{\mu\mu} + 2(\mathcal{B}_{e\mu} + \mathcal{B}_{\mu\tau}) + 1.8\mathcal{B}_{\mu\nu}\right]
\end{aligned}$$

first two of same sign and last one of opposite sign

additional contribution to these processes than CDF and D0 considerations, 1.2 for Tevatron

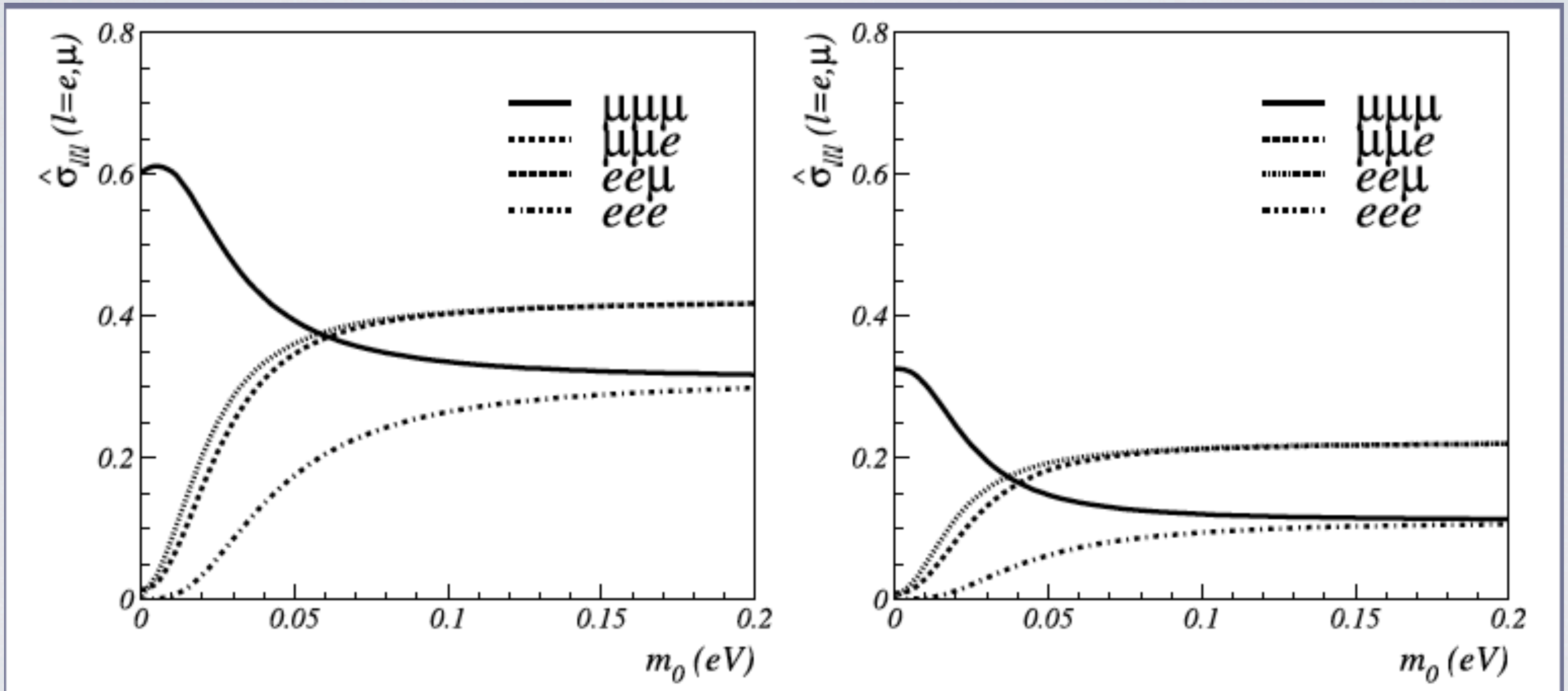
RESULTS

- Reduced cross section as a function of lightest neutrino mass at LHC, assuming zero Majorana phases:



Impact of Single Production

- With or without the single production at LHC, also , assuming zero Majorana phases:

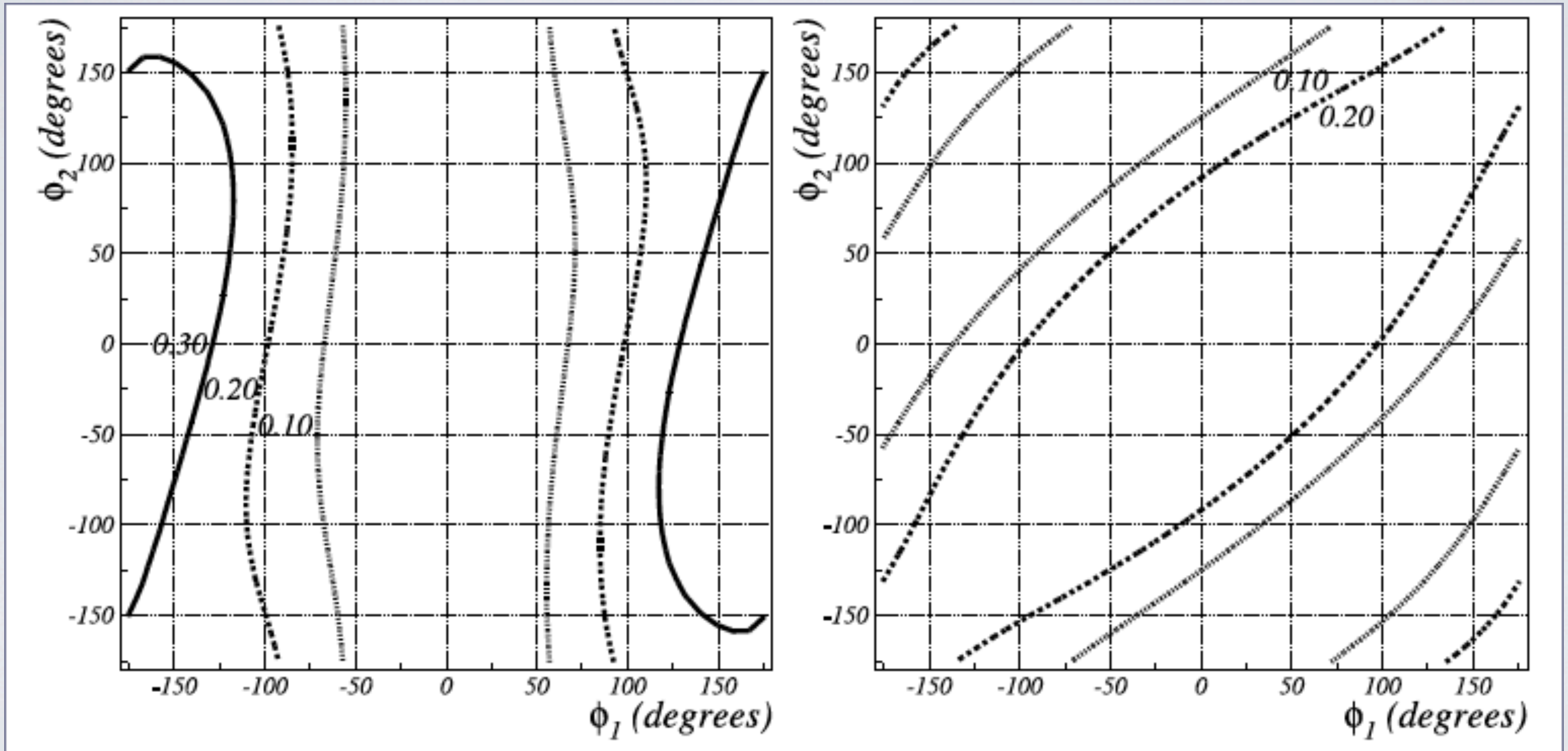


With $pp \to H^{\pm\pm}H^{\mp}$

Without $pp \to H^{\pm\pm}H^{\mp}$

Effects of Majorana Phases

- Reduced cross sections for $m_0 = 0.2$ eV.



$e^{\pm}\mu^{\pm}\mu^{\mp}$ $\mu^{\pm}\mu^{\pm}\mu^{\mp}$

Range of Reduced X-sec

- Approximate range of reduced cross section for NH at Tevatron, by varying both Majorana phases:

m_0	$e^\pm e^\pm e^\mp$	$e^\pm e^\pm \mu^\mp$	$e^\pm \mu^\pm e^\mp$	$e^\pm \mu^\pm \mu^\mp$	$\mu^\pm \mu^\pm e^\mp$	$\mu^\pm \mu^\pm \mu^\mp$
0.20 eV	0.10/0.24	0.10/0.57	0.0/0.35	0.0/0.38	0.0/0.36	0.0/0.25
0.10 eV	0.08/0.21	0.08/0.56	0.0/0.31	0.0/0.37	0.0/0.35	0.0/0.27
0.05 eV	0.06/0.18	0.07/0.49	0.0/0.20	0.0/0.33	0.0/0.31	0.02/0.31
0.01 eV	0.0/0.0	0.0/0.08	0.0/0.0	0.0/0.08	0.02/0.07	0.28/0.50
0 eV	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.01	0.0/0.01	0.37/0.50

- Any of these channels can be dominant; we should measure all of them.

NUMBER OF EVENTS

- Expected number of tri-lepton events being produced at hadron colliders for different masses of doubly-charged Higgs boson under certain integrated luminosities:

	$\mathcal{L}$ (fb^{-1})	$m_{H^{\pm\pm}}$	$\sigma_{\ell\ell\ell}$	$N_{\ell\ell\ell}$
Tevatron	10	150 GeV	$\sim$ 20 fb	$\sim$ 200
LHC	10	150 GeV	$\sim$ 200 fb	$\sim$ 2000
LHC	100	250 GeV	$\sim$ 30 fb	$\sim$ 3000

Large Mixing Scenario

Larger Triplet VEV

- When $v_\Delta \sim$ GeV, $H^{\pm\pm} \to W^\pm W^\pm$ and $H^\pm \to W^\pm Z$ become dominant, instead of leptonic ones.
- No search for such channels yet.
- LHC has less sensitivity in these modes than the leptonic modes.

- With other appropriate parameters, large mixing is possible for CP-even Higgs bosons ($\Rightarrow H_1$ and H_2).
- In this scenario, H_2 may be detected before the charged Higgs bosons.

SEARCH FOR H$_2$

- It is a usual practice to assume essentially no mixing between CP-even neutral doublet and triplet states.
$\Rightarrow$ almost impossible to detect H$_2$: very little couplings to weak gauge bosons and no couplings to SM fermions
$\Rightarrow$ suppressed production rate at hadron colliders
- Large mixing is possible if $\mathcal{M}_{11}^2 = \mathcal{M}_{22}^2$, irrespective to $\mathcal{M}_{12}^2$, as

$$\tan 2\theta = \frac{2\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2}$$

$$\mathcal{M}_{\rm even}^2 = \begin{pmatrix} \lambda v_0^2/2 & \left[(\lambda_1+\lambda_4)v_\Delta - \sqrt{2}\mu\right] v_0 \\ \left[(\lambda_1+\lambda_4)v_\Delta - \sqrt{2}\mu\right] v_0 & \left[\sqrt{2}\mu v_0^2 + 4(\lambda_2+\lambda_3)v_\Delta^3\right]/2v_\Delta \end{pmatrix}$$

STABILITY CONSTRAINT

- The parameters λ and λ_i are picked in order to produce $m_{H1} \approx 130$ GeV and to satisfy the stability condition for the Higgs potential:

$$\lambda_1 + \lambda_4 + 2\sqrt{\lambda(\lambda_2 + \lambda_3)} > 0$$

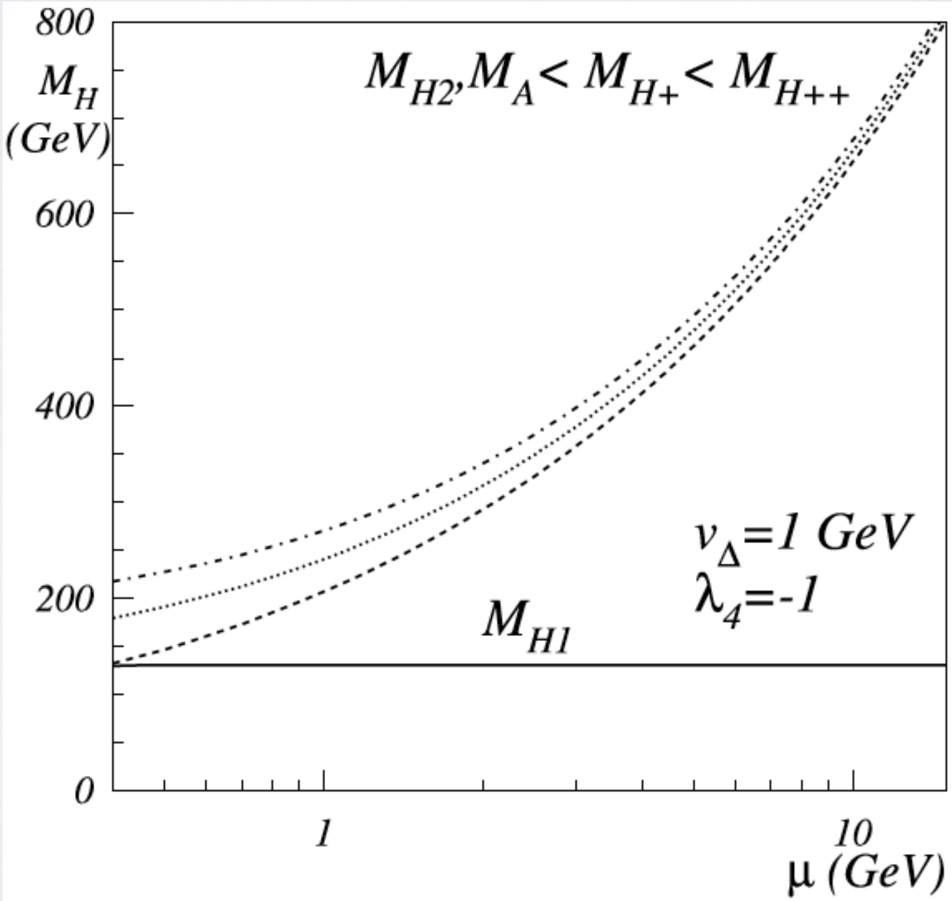
- One benchmark parameter choice is:

$$v_\Delta = 1 \text{ GeV}, \lambda = 0.566, \lambda_1 = 0, \lambda_{2,3} = 1, \lambda_4 = -1.$$

★ From now on, (h^0, H^0) and (H_1, H_2) are used interchangeably, with the latter referring to the case of large mixing in particular.

HIGGS BOSON MASSES AGAIN

- Higgs boson masses as a function of the μ parameter. (v_Δ = 1 GeV, λ = 0.566, λ_1 = 0, $\lambda_{2,3}$ = 1, λ_4 = –1)



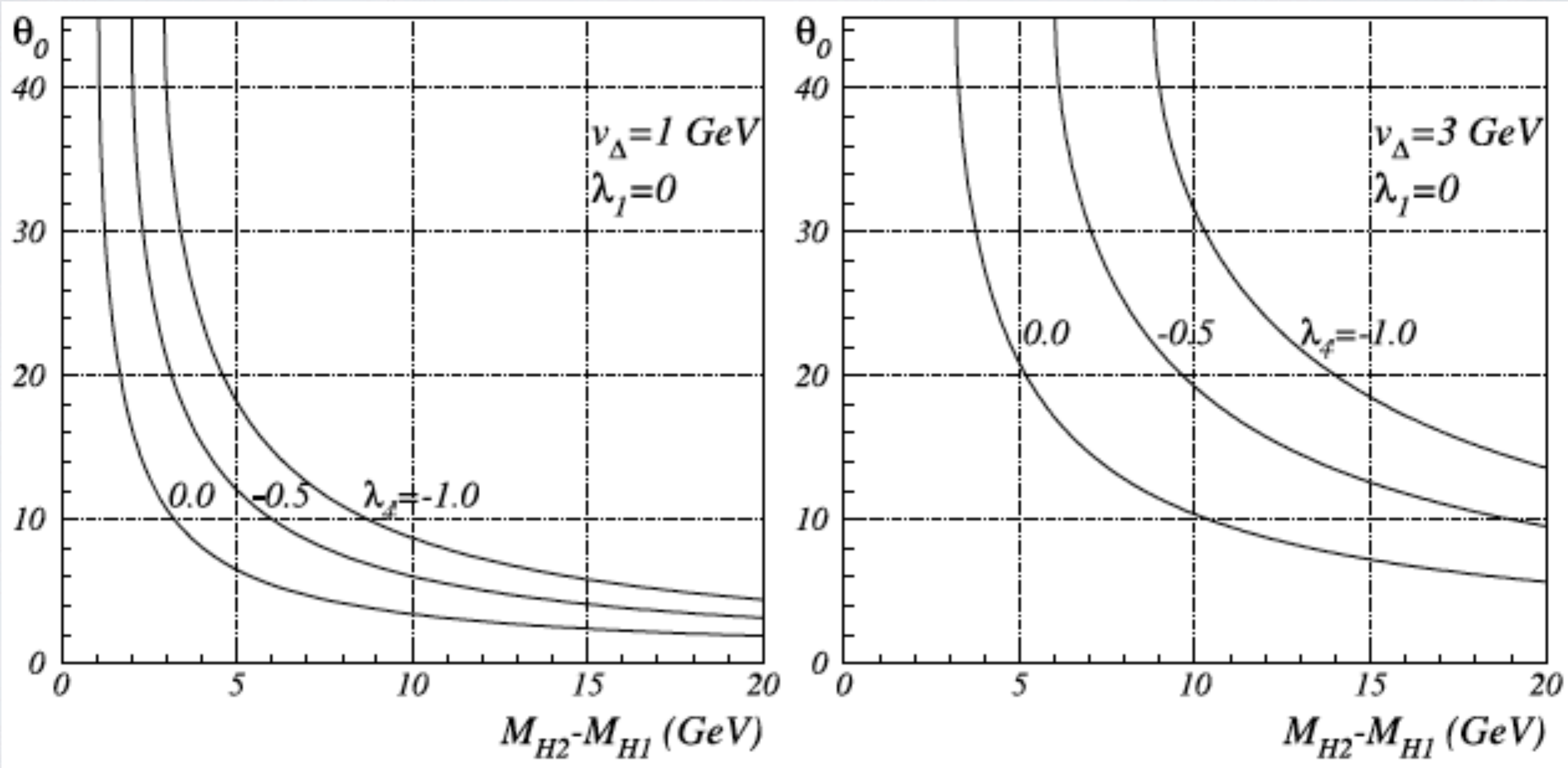
SEARCH CHANNELS

Akeroyd, CC in progress

- Assuming (*nearly*) *maximal* mixing, then each of H_1 and H_2 is ~50% SM Higgs boson-like, as far as couplings to fermions and weak gauge bosons are concerned.
- It is thus possible to produce H_1 and H_2 through the usual channels for SM Higgs boson:
  - Gluon-gluon fusion, followed by h^0 decay to leptons: $gg \to h^0$, $h^0 \to ZZ^* \to \ell\ell\ell\ell$
  - Weak-boson fusion, followed by h^0 decay to $\tau^+\tau^-$: $qq \to h^0 qq$, $h^0 \to \tau^+\tau^-$
  - Weak-boson fusion, followed by h^0 decay to W^+W^-: $qq \to h^0 qq$, $h^0 \to W^+W^-$
- Decay rates of both are suppressed from SM expectations.

Mixing Angle for $H_{1,2}$

- Mixing angle of CP-even Higgs bosons as a function of mass difference.



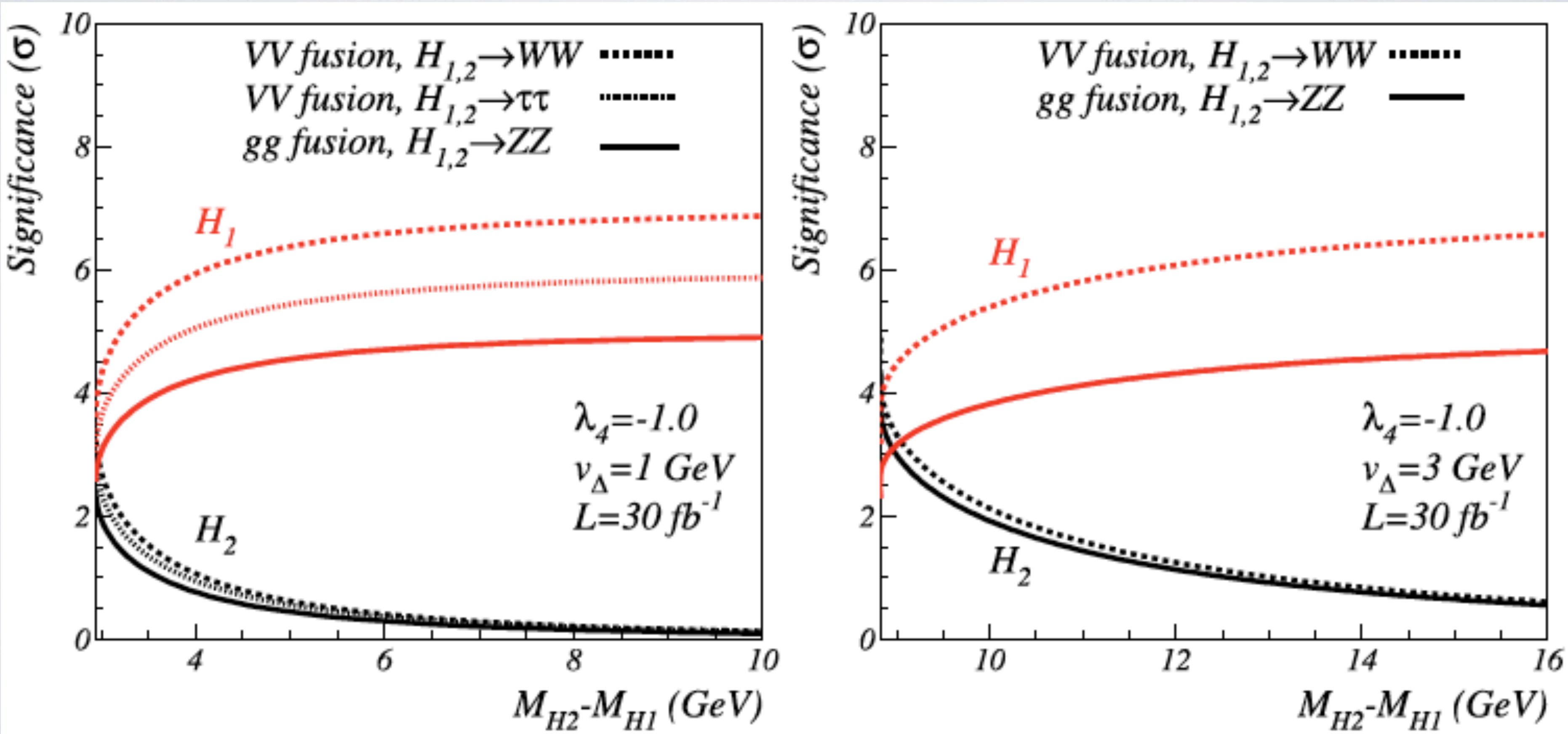
MASS RESOLUTION

- Simulations show that a precision of $\Delta m_H/m_H \sim 0.1\%$, O(0.1 GeV), for a SM Higgs boson can be reached via $H \to ZZ^* \to 4l^\pm$ using 300 fb^{-1} of data. Djouadi 2008

- It is thus conceivable that an O(GeV) precision can be achieved using a few tens fb^{-1} of data.
- Mixing could be *maximal* even when mass difference is as large as ~ O(10 GeV), in which case the two resonances should be resolvable.

Discovery Reach

- Statistical significance for different discovery channels at the LHC with 30 fb^{-1} of data.



SUMMARY

- HTM is motivated by neutrino masses and involves only a few model parameters in the Higgs sector, rendering the model relatively predictive.
- We point out the ignorance of an important production channel for doubly-charged Higgs boson by the experimentalists at Tevatron.
- We study the discovery reach of Tevatron and LHC for the doubly-charged Higgs boson, as one varies parameters in the neutrino sector.
- We examine the scenario of large mixing between CP-even Higgs bosons.

Thank You!