Probing Majorana Phases and Neutrino Mass Spectrum in the Higgs Triplet Model at the LHC

Andrew Akeroyd

National Cheng Kung University, Tainan, Taiwan

- TeV scale mechanisms ("testable") for neutrino mass generation
- Higgs Triplet Model
- Production of $H^{\pm\pm}$ at hadron colliders
- Precise measurements of $H^{\pm\pm} \to l^{\pm}l^{\pm}$ at the LHC
- Testing HTM at the LHC

A.A, Mayumi Aoki (ICRR, Kashiwa), Hiroaki Sugiyama (SISSA, Trieste), arXiv:0712.4019[he

IPMU Workshop on "Neutrino Mass", Kashiwa, 19 March 2008

TeV scale models of neutrino mass generation

Many models for neutrino mass generation!

Models with a specific signature at High Energy Colliders

(Tevatron/LHC) are phenomenologically appealing

One such model is:

Higgs Triplet Model (HTM) Schechter/Valle 80, Cheng/Li 80

Distinctive signature:

$H^{\pm\pm}$ with coupling to W, Z and leptons

Higgs Triplet Model (HTM)

SM Lagrangian with one $SU(2)_L$ $I = 1, Y = 2$ Higgs triplet

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

Higgs potential:

$$V = m^2(\Phi^\dagger\Phi) + \lambda_1(\Phi^\dagger\Phi)^2 + M^2\mathrm{Tr}(\Delta^\dagger\Delta)$$

$$+\lambda_i\ (\text{quartic terms})\ + \frac{1}{\sqrt{2}}\mu(\Phi^T i\tau_2\Delta^\dagger\Phi) + h.c$$

Triplet vacuum expectation value:

$$< \delta^0 >= v_L \sim \mu v^2/M^2 \quad (1\,eV < v_L < 8\,GeV)$$

Higgs boson spectrum

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

- $H^{\pm}, H^0, A^0, h^0$ are mixtures of doublet and triplet fields
- Mixing $\sim v_L/v$ and $v_L << v$
- h^0 plays role of *SM Higgs boson* (essentially $I = 1/2$ doublet)
- $H^{\pm\pm}$ *purely triplet* and $H^{\pm}, H^0, A^0$ *essentially triplet*
- $H^{\pm\pm}, H^{\pm}, H^0, A^0$ close to degenerate $\sim M$
- For $H^{\pm\pm}$ in range at LHC require $M < 1$ TeV.

Neutrino mass in Higgs Triplet Model (HTM)

No right-handed neutrino:

Neutrino mass from triplet-lepton-lepton coupling (h_{ij}):

$$h_{ij}\left[\sqrt{2}\,\bar{l}_i^c P_L l_j H^{++} + (\bar{l}_i^c P_L \nu_j + \bar{l}_j^c P_L \nu_i) H^{+} - \sqrt{2}\,\bar{\nu}_i^c P_L \nu_j H^0\right] + h.c$$

Light neutrinos receive a Majorana mass: $\mathcal{M}_\nu \sim v_L h_{ij}$

$$h_{ij} = \frac{1}{\sqrt{2} v_L} V_{\mathrm{MNS}}\, diag(m_1, m_2, m_3) V_{\mathrm{MNS}}^T$$

($V_{\mathrm{MNS}} = V_l^\dagger V_\nu$; take $V_l = I$ and $V_\nu = V_{\mathrm{MNS}}$)

Limits on h_{ij}

Presence of $H^{\pm\pm}$ would lead to lepton flavour violating decays

Many limits exist for h_{ij} (assuming $m_{H^{\pm\pm}} < 1$ TeV):

Cuypers/Davidson 98

- BR($\mu \to eee$) $< 10^{-12} \to h_{\mu e} h_{ee} < 10^{-7}$: 1988; no forthcoming experiment
- BR($\tau \to l_i l_j l_k$) $< 10^{-8} \to h_{\tau i} h_{jk} < 10^{-4}$ Limits from ongoing B factories
- BR($\mu \to e\gamma$) $< 10^{-11} \to \sum_i h_{\mu i} h_{ei} < 10^{-6}$ sensitivity to BR$> 10^{-13}$ from 2008

All constraints can be respected with suitably chosen h_{ij}

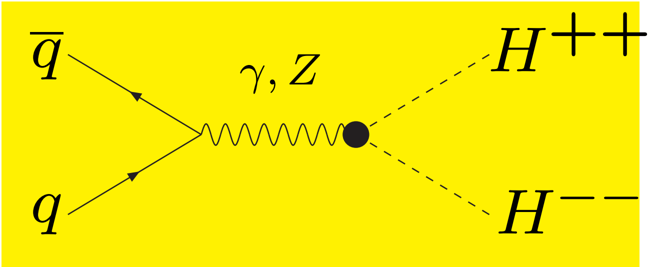
Absolute values not so important for $H^{\pm\pm}$ direct searches

Production of $H^{\pm\pm}$ at Hadron Colliders (Tevatron and LHC)

Production of $H^{\pm\pm}$ at Tevatron

First searches at a Hadron collider in 2003 CDF,D0

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

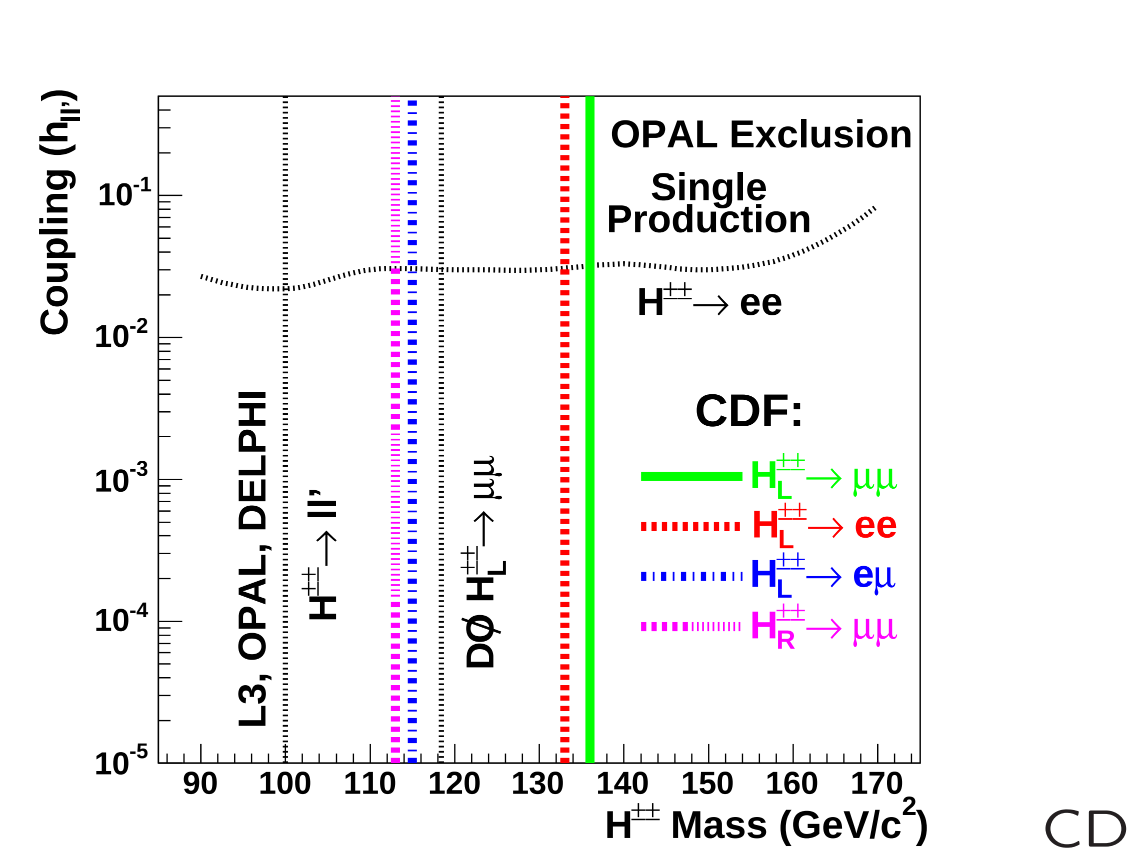


- $\sigma_{H^{++}H^{--}}$ is a simple function of $m_{H^{\pm\pm}}$
- $\sigma_{H^{++}H^{--}}$ has no dependence on h_{ij}

Search strategy

- $H^{\pm\pm}$ decays via h_{ij} to *same charge* $ee, \mu\mu, \tau\tau, e\mu, e\tau, \mu\tau$
- 4 leptons from pair produced $H^{++}H^{--}$
- For $e^{\pm}e^{\pm}$,$e^{\pm}\mu^{\pm}$,$\mu^{\pm}\mu^{\pm}$, sufficient to search for two leptons of high momentum and same charge
- Background almost negligible ($\approx$ 1 event)
- Mass limits presented for BR($H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}$) = 100% in a given channel

Comparison of $H^{\pm\pm}$ searches



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Strongest mass limits for any Higgs boson!

Branching ratio for $H^{\pm\pm} \to l^{\pm}l^{\pm}$ and testing HTM at LHC

Akeroyd,Aoki,Sugiyama, arXiv:0712.4019[hep-ph]

Light $H^{\pm\pm}$ at LHC

Simulations by Azuelos et al 05, Hebbeker et al 06, Hektor et al 07, Han et al 07

- Discovery for $m_{H^{\pm\pm}} < 400$ GeV with 1 fb^{-1}
- Precise measurements of BR$(H^{\pm\pm} \to l^{\pm}l^{\pm})$ possible for $l = e, \mu$
- Sensitivity to BR$(H^{\pm\pm} \to l^{\pm}l^{\pm}) \sim 1\%$ for $l = e, \mu$

Large Event Numbers for $H^{\pm\pm}$:

$m_{H^{\pm\pm}}$ (GeV)	N_{4l} (30 fb^{-1})	N_{4l} (300 fb^{-1})
200	1500	15000
300	300	3000
400	90	900

Branching ratios of $H^{\pm\pm} \to l^{\pm}l^{\pm}$

$\text{BR}(H^{\pm\pm} \to l_i^{\pm} l_j^{\pm})$ depends on relative values of h_{ij}

$$\Gamma(H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}) \sim \frac{m_{H^{\pm\pm}}}{8\pi} |h_{ij}|^2$$

In HTM h_{ij} is directly related to neutrino mass matrix

$$h_{ij} = \frac{1}{\sqrt{2} v_L} V_{\text{MNS}} diag(m_1, m_2, m_3) V_{\text{MNS}}^T$$

Prediction for $\text{BR}(H^{\pm\pm} \to l_i^{\pm} l_j^{\pm})$ determined by: Chun,Lee,Park 03

- Neutrino mass hierarchy (normal, inverted)
- Neutrino oscillation parameters (masses, mixing angles)

Explicit expressions for h_{ij}

All h_{ij} are functions of nine parameters:

$$h_{ee} = \frac{1}{\sqrt{2}v_\Delta}(m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\varphi_1} + m_3 s_{13}^2 e^{-2i\delta} e^{i\varphi_2})$$

Five parameters are experimentally constrained:

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\text{eV}^2\,, \quad |\Delta m_{31}^2| \equiv |m_3^2 - m_1^2| \simeq 2.7 \times 10^{-3}\text{eV}^2\,,$$
$$\sin^2 2\theta_{12} \simeq 0.86\,, \qquad \sin^2 2\theta_{23} \simeq 1\,, \qquad \sin^2 2\theta_{13} \lesssim 0.13\,.$$

Main uncertainty in h_{ij} comes from:

- Absolute mass of lightest neutrino: $0 < m_0 < 1eV$
- Majorana phases $0 < \phi_1, \phi_2 < 2\pi$

These three parameters are unconstrained by neutrino oscillation data

Testing the HTM at LHC via precise measurements of BR($H^{\pm\pm} \to l^{\pm} l^{\pm}$)

There are several models of neutrino mass generation with possibly light $H^{\pm\pm} \to l^{\pm} l^{\pm}$:

• Left-Right Symmetric Model: $I = 1, Y = 2$ triplet

Neutrino mass via seesaw mechanism, h_{ij} arbitrary

• Zee-Babu Model $I = 0, Y = 4$ singlet

Radiative neutrino mass; some correlation of h_{ij} with neutrino mass matrix

$\to$ HTM predicts distinctive regions for BR($H^{\pm\pm} \to l^{\pm} l^{\pm}$) which can be tested at LHC for $m_{H^{\pm\pm}} < 400$ GeV

Dependence of BR($H^{\pm\pm} \to l^{\pm}l^{\pm}$) on m_0,ϕ_1,ϕ_2

- Neglect Majorana phases, $\phi_1 = \phi_2 = 0$:

BR($H^{\pm\pm} \to l^{\pm}l^{\pm}$) essentially determined by absolute neutrino mass m_0

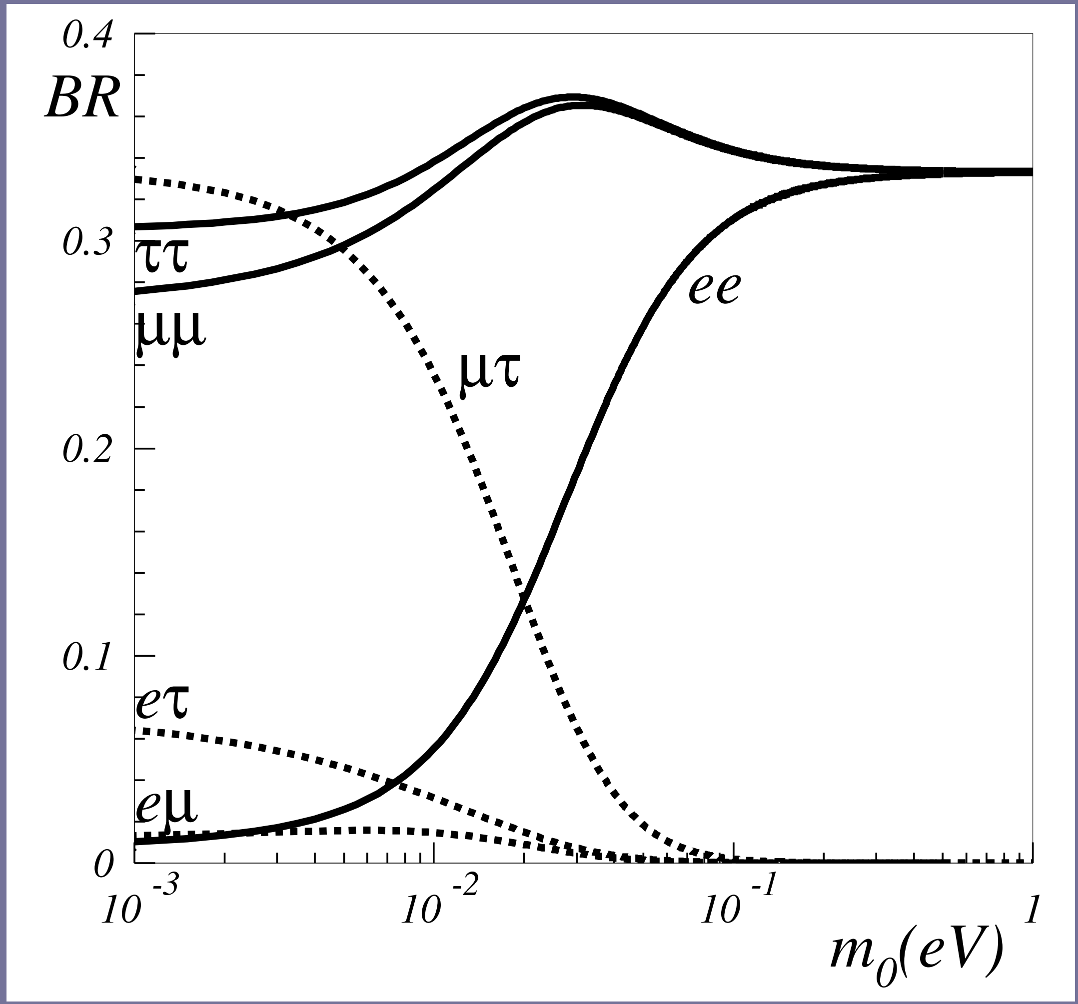
- Include Majorana phases, $\phi_1 \neq 0, \phi_2 \neq 0$:

Allowed regions for BR($H^{\pm\pm} \to l^{\pm}l^{\pm}$) considerably larger but still smaller than case of arbitrary h_{ij}

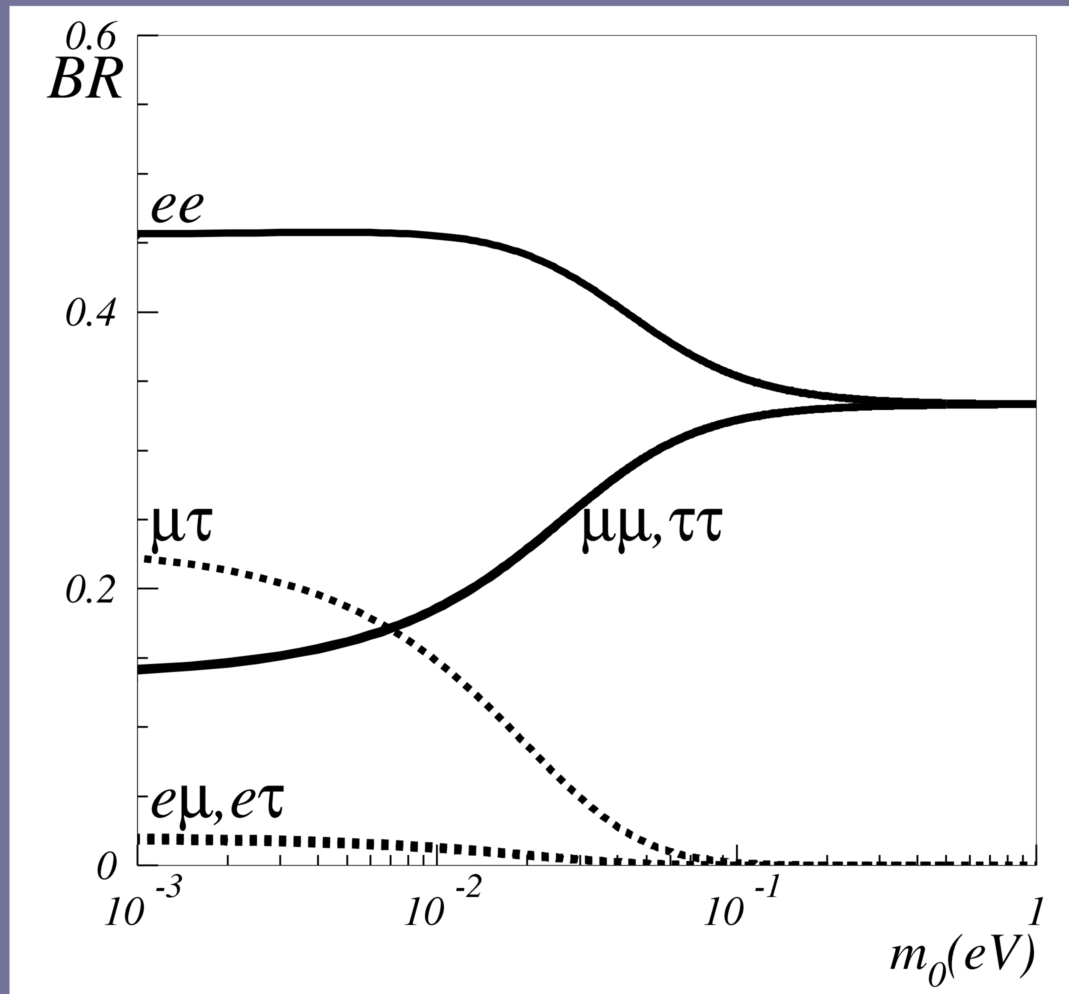
$\rightarrow$ we quantify the prediction for BR($H^{\pm\pm} \to l^{\pm}l^{\pm}$) in the HTM

(see also Garayoa et al,arXiv:0712.1453[hep-ph] and Kadastik et al, 0712.3912[hep-ph]

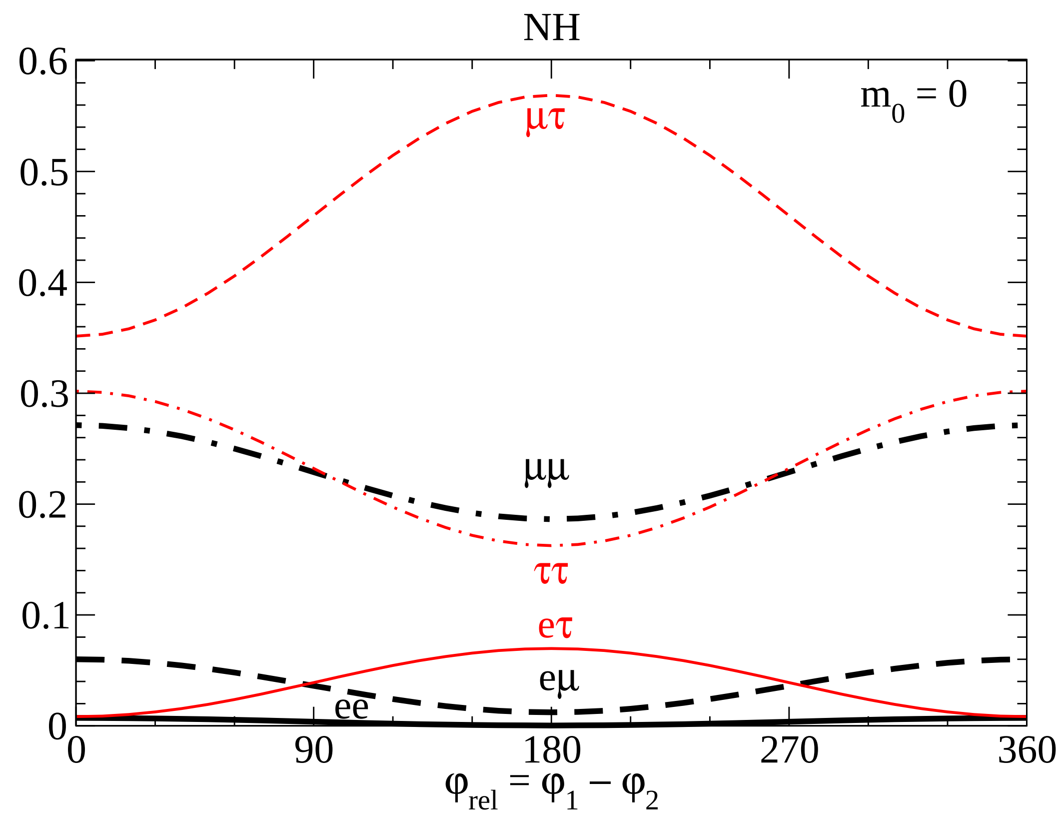
BR($H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}$) against lightest neutrino mass (m_0): normal hierarchy



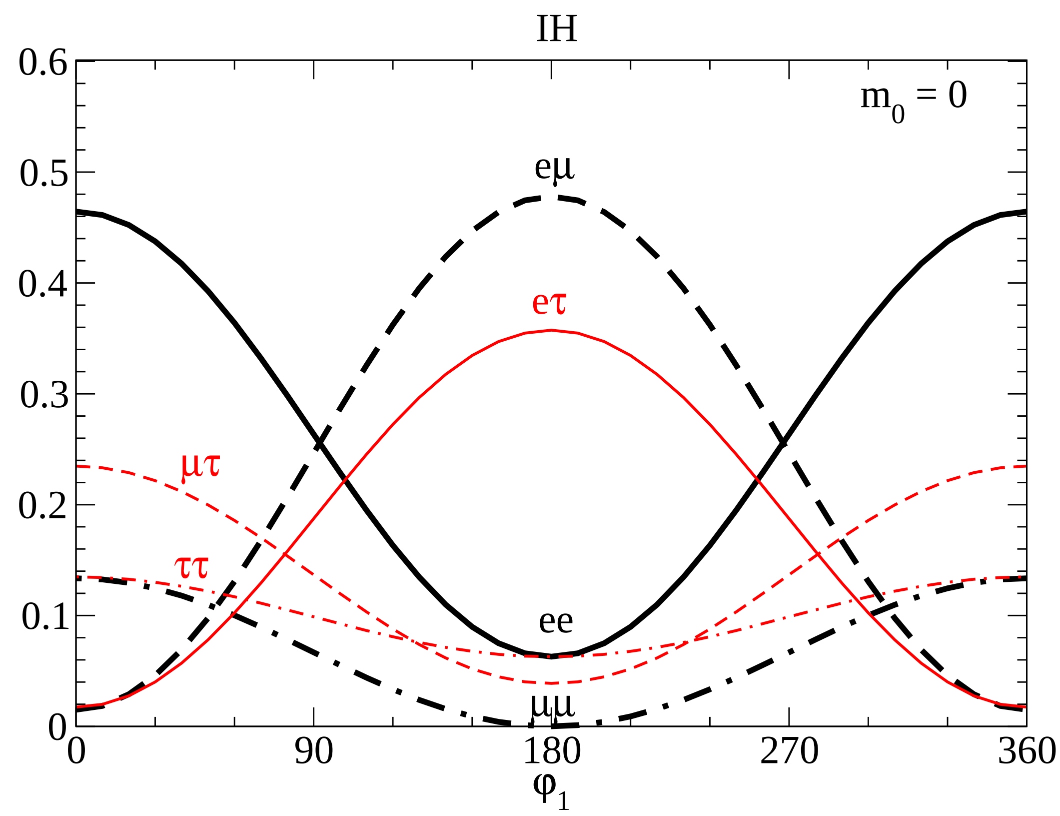
BR($H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}$) against lightest neutrino mass (m_0): inverted hierarchy



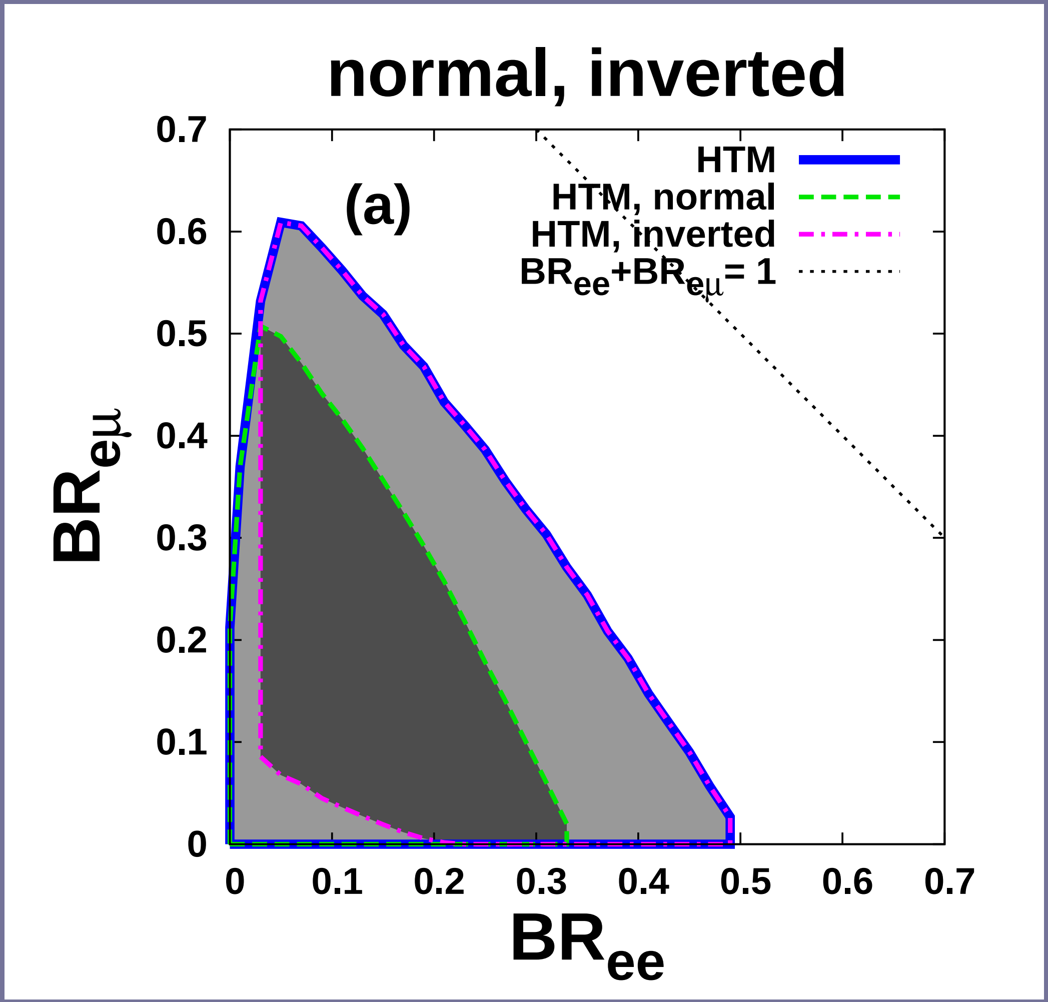
BR($H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}$) against Majorana phase and $m_0 = 0$: normal hierarchy



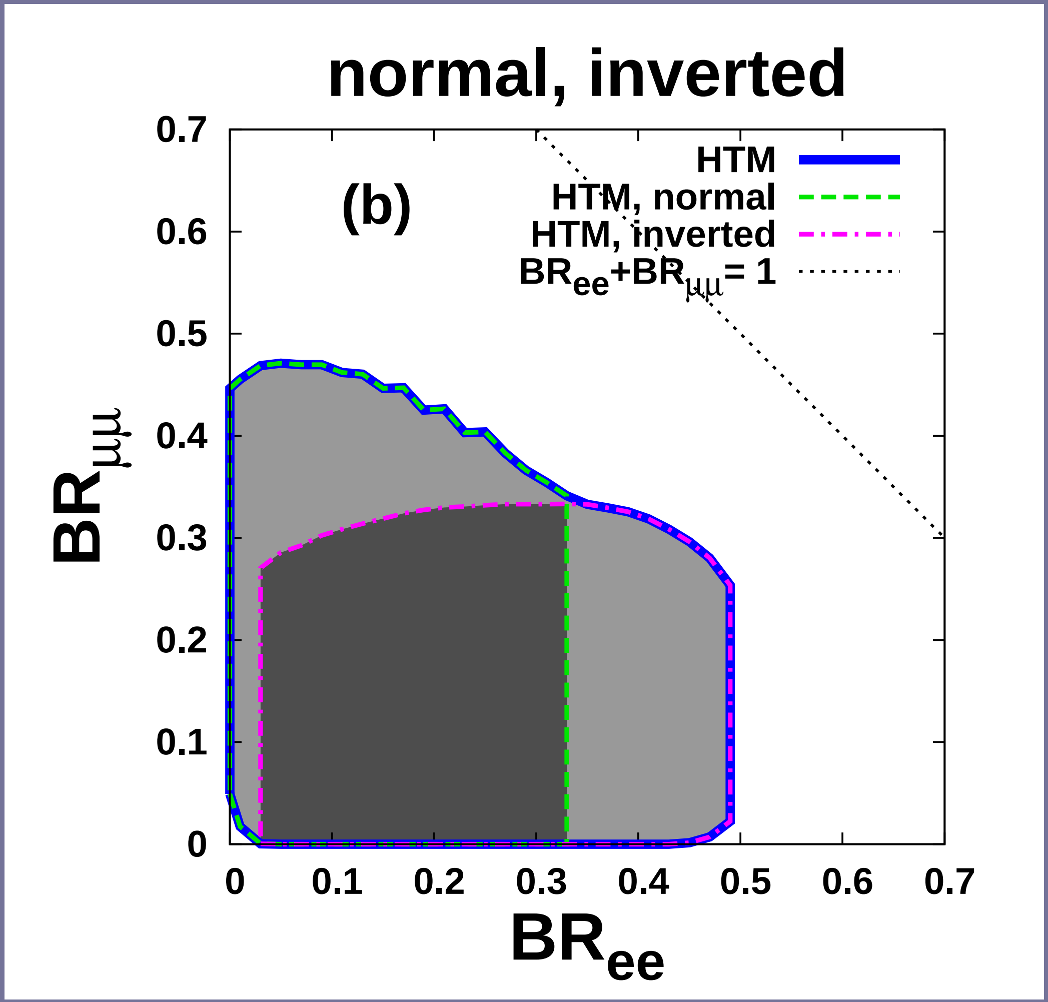
BR($H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}$) against Majorana phase and $m_0 = 0$: inverted hierarchy



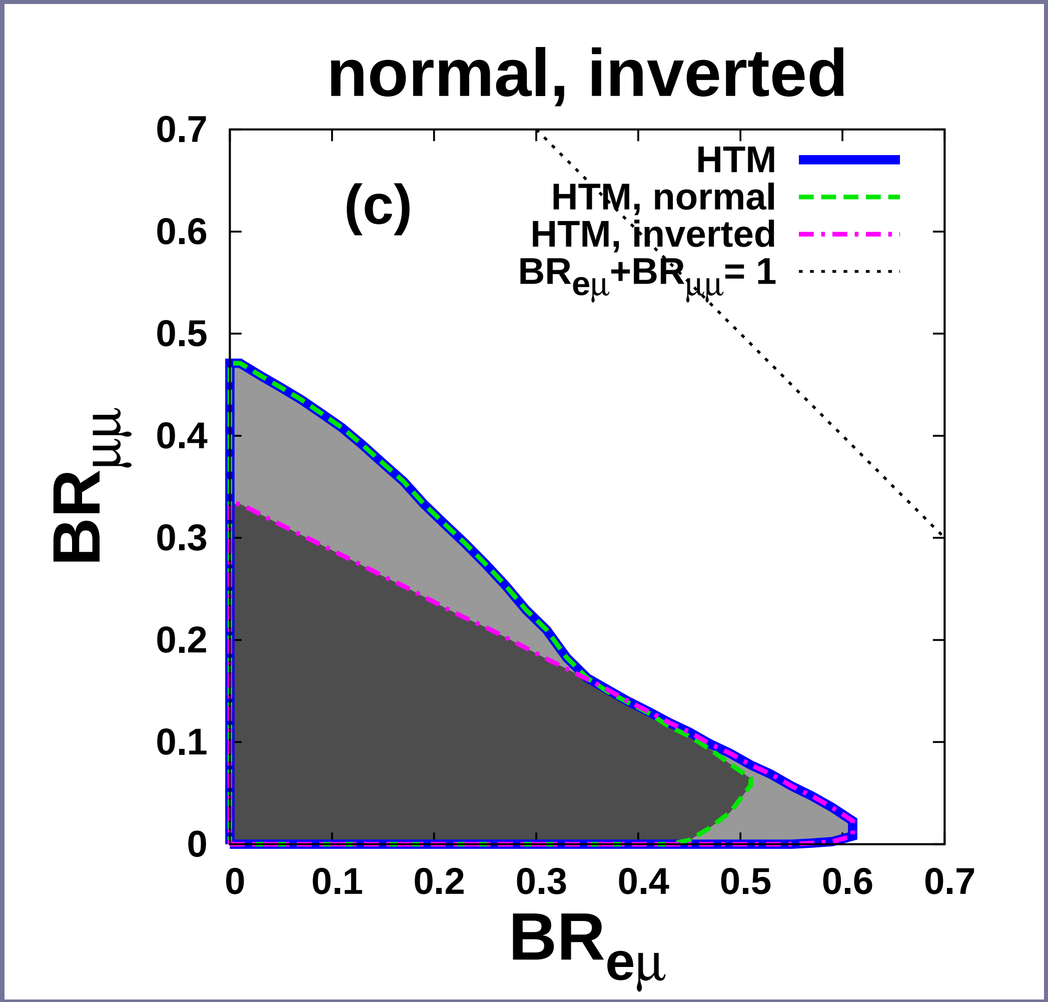
HTM prediction in the plane [BR($H^{\pm\pm} \to e^{\pm}e^{\pm}$),BR($H^{\pm\pm} \to e^{\pm}\mu^{\pm}$)]



HTM prediction in the plane [BR($H^{\pm\pm} \to e^{\pm}e^{\pm}$),BR($H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$)]

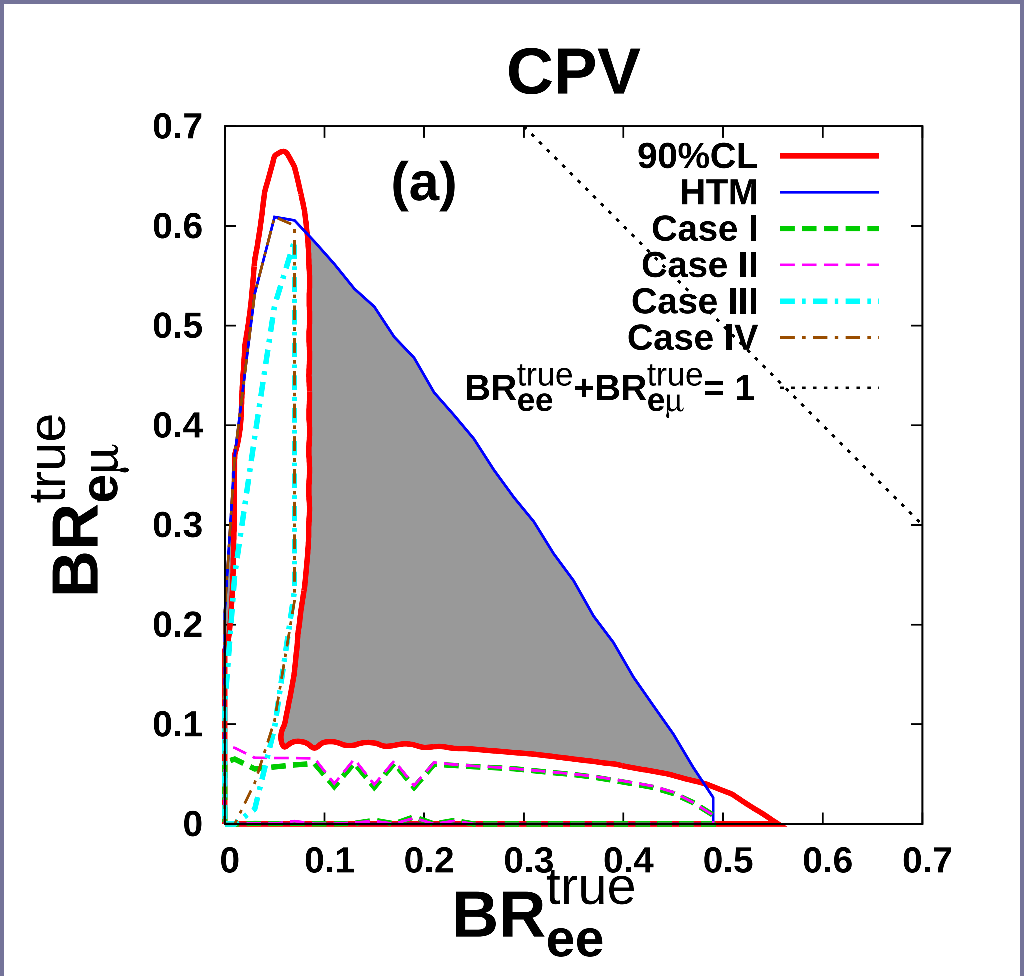


HTM prediction in the plane [BR($H^{\pm\pm} \to e^{\pm}\mu^{\pm}$),BR($H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$)]



HTM prediction in the plane [BR($H^{\pm\pm} \to e^{\pm}e^{\pm}$),BR($H^{\pm\pm} \to e^{\pm}\mu^{\pm}$)]

with/without CP violation from Majorana phases



Conclusions

- Higgs Triplet Model generates neutrino mass $h_{ij}v_T$
- $H^{\pm\pm} \to l^{\pm}l^{\pm}$ is a distinctive signal with BRs determined by h_{ij}
- LHC can produce thousands of $H^{\pm\pm} \to l^{\pm}l^{\pm}$ events

if $M_{H^{\pm\pm}} < 400$ GeV
- HTM predicts specific regions for BR$(H^{\pm\pm} \to l^{\pm}l^{\pm})$

which can be tested at LHC
- Majorana phases/neutrino mass determine the allowed

regions of BR$(H^{\pm\pm} \to l^{\pm}l^{\pm})$
- Collider information on such parameters

Other production mechanisms/decay channels for $H^{\pm\pm}$

Several production mechanisms: Barenboim et al 96,Maalampi et al 02

- $qq \to W^{\pm *} \to H^{\pm\pm} W^{\mp}$, $qq \to q' q' W^{\pm *} W^{\pm *} \to q' q' H^{\pm\pm}$
- $W W H^{\pm\pm} \sim v_L$; appreciable rates only for $v_L > 1$ GeV

Several decay channels:

- $H^{\pm\pm} \to W^{\pm} W^{\pm}$; small for $v_L < 0.1$ MeV
- $H^{\pm\pm} \to H^{\pm} W^{\pm *}$; not open for $m_{H^{\pm}} \geq m_{H^{\pm\pm}}$

Hereafter we assume the sole decay channel is $H^{\pm\pm} \to l^{\pm} l^{\pm}$

Tevatron search for $p\bar{p} \to H^{++}H^{--}$, $H^{\pm\pm} \to e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$