Higgs Bosons Phenomenology in the Higgs Triplet Model

Andrew Akeroyd

National Cheng Kung University, Tainan, Taiwan

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

A.A, Mayumi Aoki (Kashiwa, ICRR), Phys.Rev.D72,035011 (2005)

A.A, Mayumi Aoki, Hiroaki Sugiyama (SISSA), arXiv:0712.4019[hep-ph]

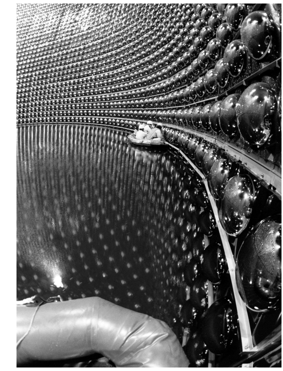
Seminar at National Tsing Hua Univ, Hsinchu, 17 April 2008

Large Hadron Collider

- LHC (CERN) due to commence operation in summer 2008
- Proton-Proton collisions at $\sqrt{s} = 14$ TeV
- Highest energy collider ever built
- ATLAS and CMS optimized for Higgs boson search
- New Physics discovery potential up to TeV scale

Neutrino Mass and Mixing

Strong evidence for neutrino masses and mixings from both terrestrial and celestial sources



$$V_{\text{MNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Mixing angles are being probed by oscillation experiments:

i) *Atmospheric angle* almost maximal: $\sin^2 2\theta_{23} \sim 1$

ii) *Solar angle* close to maximal: $\sin^2 2\theta_{12} \sim 0.8$

iii) *Reactor angle* not measured: $\sin^2 2\theta_{13} < 0.16$

θ_{23} and θ_{12} much larger than mixing angles in the quark sector

Neutrino Mass

Oscillation experiments only sensitive to neutrino mass differences:

i) $\Delta M^2_{atm} \sim 10^{-3} eV^2$ $(= M)$

ii) $\Delta M^2_{sol} \sim 10^{-5} eV^2$ $(= m)$

Other experiments constrain the *absolute* neutrino mass

- Neutrinoless double beta decay, Cosmological observations..
- Tritium beta decay $(H^3 \to He^3 + e^- + \overline{\nu}_e)$: $m_{\nu_e} < 2.2$ eV

Much lighter than charged fermion masses ($m_e = 0.5$ MeV)

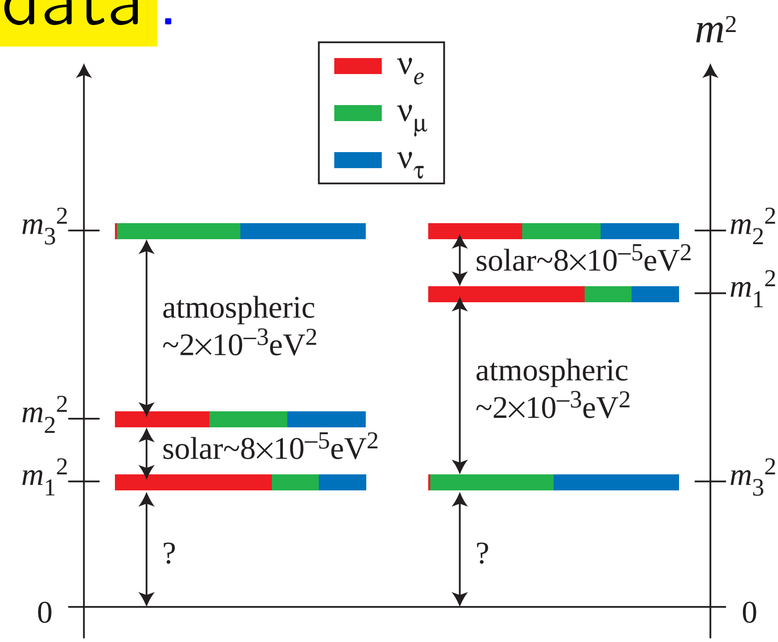
Neutrino mass hierarchies

Three possibilities to satisfy oscillation data:

1) *Hierarchical* $\sim (0, m, M)$.

2) *Inverted hierarchical* $\sim (M, M+m, 0)$

3) *Quasi-degenerate* $\sim (M, M, M)$



Future measurements of Neutrino parameters

Present and Future neutrino experiments

(e.g. MINOS, OPERA, T2K, DoubleChooz, Daya Bay

Neutrino Factory...)

i) Measure Δm^2, θ_{12}, θ_{23} with higher precision

ii) Possible first measurement of θ_{13}, CP Phase

Mechanism of mass and mixing?

Models which can be probed at the Tevatron/LHC

are of *immediate phenomenological interest*

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:

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

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

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 (ϕ) and triplet (δ) 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 $H^{\pm\pm}$, $H^{\pm}$ in range at LHC require $M < 1$ TeV.

Neutrino mass in Higgs Triplet Model (HTM)

No additonal (heavy) neutrinos: $\mathcal{L} = h_{ij}\psi^T_{iL}Ci\tau_2\Delta\psi_{jL} + h.c$

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

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

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

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

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

Decay channels for $H^{\pm\pm}$ and $H^{\pm}$

Decays of $H^{\pm\pm}$:

- $\Gamma(H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}) \sim h_{ij}^2$; $\Gamma(\mathrm{H}^{\pm\pm} \to W^{\pm}W^{\pm}) \sim v_L^2$
- $h_{ij} v_L = m_\nu$

$\Gamma(H^{\pm\pm} \to l^{\pm} l^{\pm}) > \Gamma(H^{\pm\pm} \to W^{\pm}W^{\pm})$ for $v_L < 10^{-4}$ GeV

- $H^{\pm\pm} \to H^{\pm}W^{*}$ suppressed if $m_{H^{\pm\pm}} \sim m_{H^{\pm}}$

Tevatron searches have only been performed for $H^{\pm\pm} \to l^{\pm} l^{\pm}$

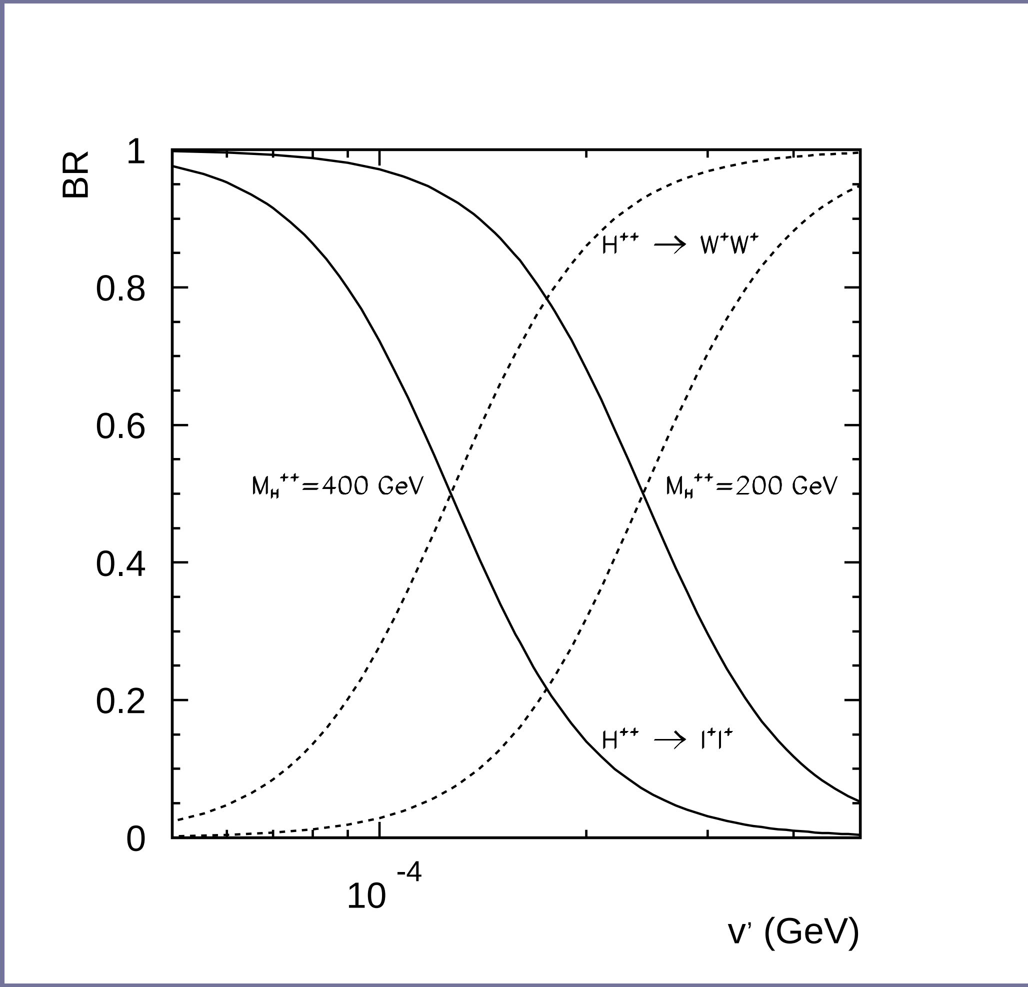
Decays of $H^{\pm}$:

- $\Gamma(\mathrm{H}^{\pm} \to l^{\pm}\nu) > \Gamma(H^{\pm} \to W^{\pm}Z, tb)$ for $v_L < 10^{-4}$ GeV

No Tevatron searches yet

BR($H^{\pm\pm} \to W^{\pm}W^{\pm}$) and BR($H^{\pm\pm} \to l_i^{\pm}l_j^{\pm}$) against triplet vev)

Han 07



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

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

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

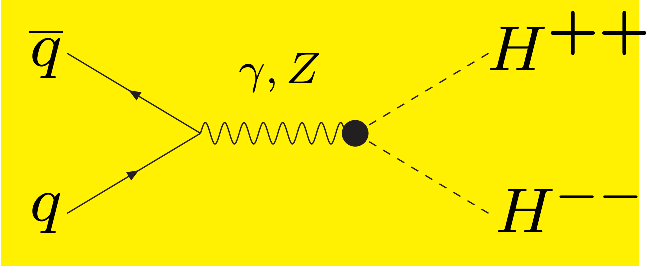
Absolute values not so important for $H^{\pm\pm}$ direct searches

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

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

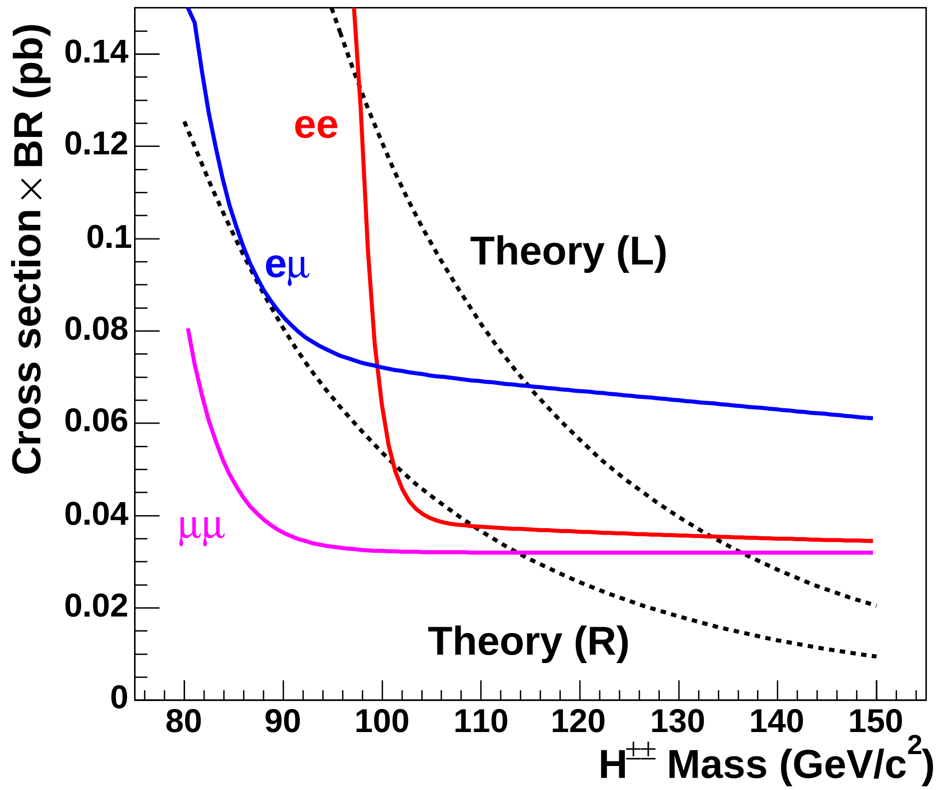


- $\sigma_{H^{++}H^{--}}$ is a simple function of $m_{H^{\pm\pm}}$ Raidal et al 96
- $\sigma_{H^{++}H^{--}}$ has no dependence on h_{ij}

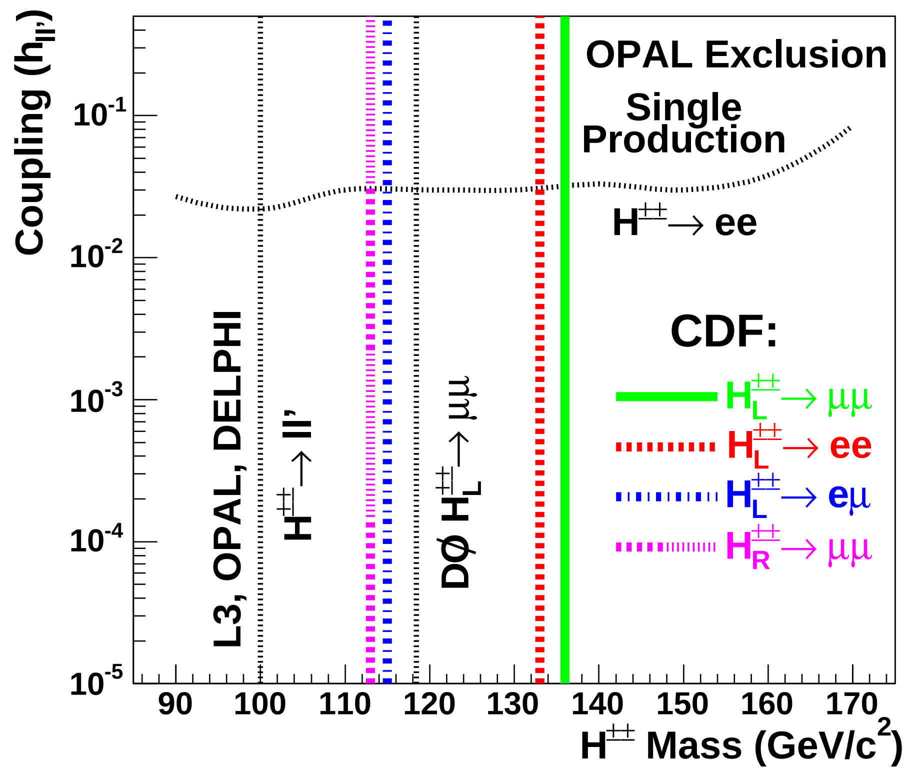
Search strategy

- $H^{\pm\pm}$ 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 2 or 3 leptons of high momentum with two being of same charge
- Background almost negligible ($\approx$ 1 event)
- Mass limits presented for BR($H^{\pm\pm} \rightarrow l_i^{\pm} l_j^{\pm}$) = 100% in a given channel

Tevatron search (2003) for $p\overline{p} \to H^{++}H^{--}$, $H^{\pm\pm} \to e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$



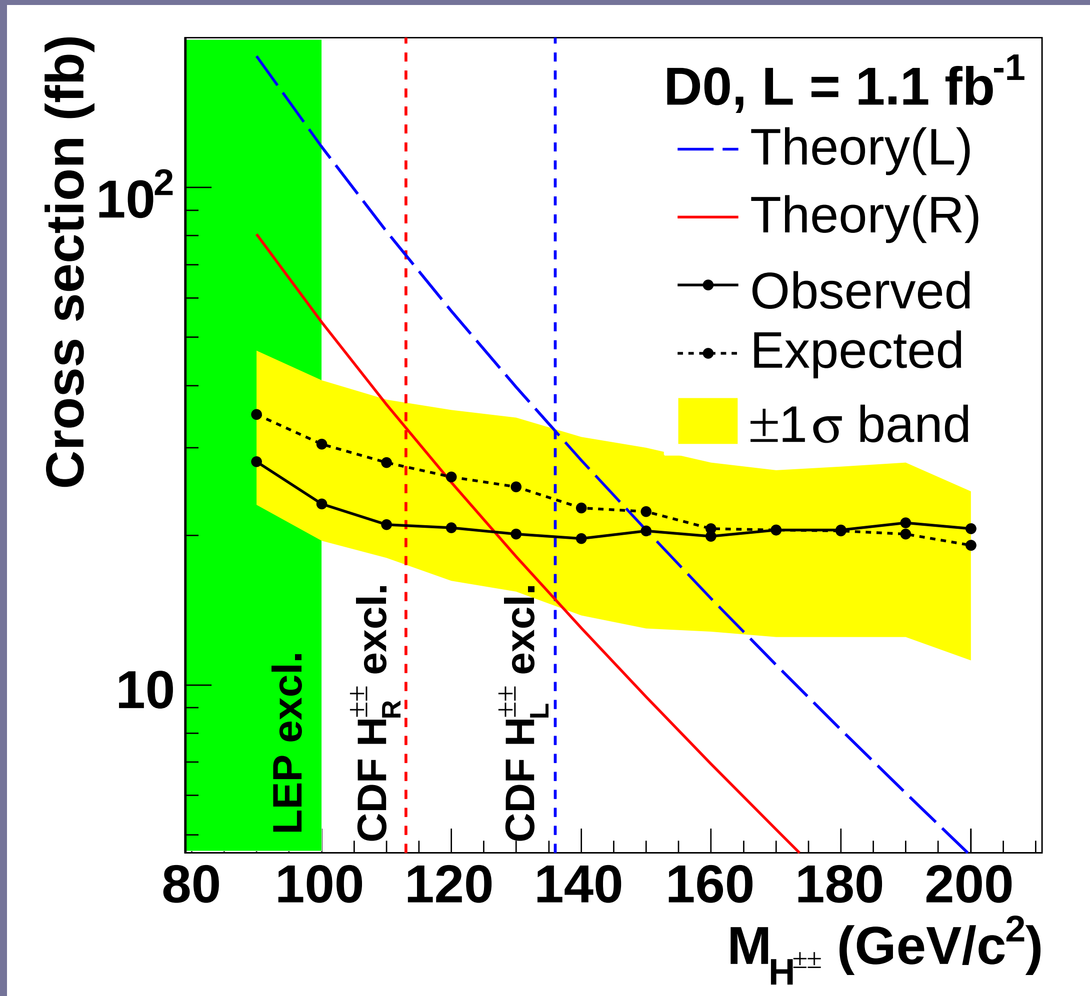
Comparison of $H^{\pm\pm}$ searches



CD

Strongest mass limits for any Higgs boson!

Tevatron search (2007) for $p\bar{p} \to H^{++}H^{--}$, $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$



Current status of Tevatron searches

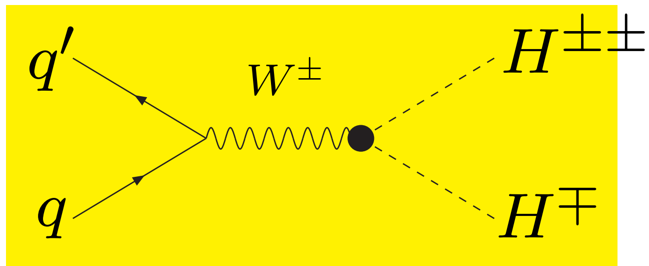
	ee	$e\mu$	$\mu\mu$	$e\tau$	$\mu\tau$	$\tau\tau$
2l	$>$ 133 GeV	$>$ 113 GeV	$>$ 136 GeV	x	x	x
3l			$>$ 150 GeV	$>$ 114 GeV	$>$ 112 GeV	
4l				$>$ 114 GeV	$>$ 112 GeV	

- $>$ 150 GeV limit uses 1.1 fb^{-1}
- Other limits use 0.24 fb^{-1} or 0.35 fb^{-1}
- Run II has accumulated $\sim$ 3 fb^{-1}
- Expect up to 8 fb^{-1} by 2009
- Sensitivity to $m_{H^{\pm\pm}} \sim$ 250 GeV in $ee, e\mu, \mu\mu$ channels

Single $H^{\pm\pm}$ production via $qq' \to H^{\pm\pm}H^{\mp}$

Additional production mechanism for $H^{\pm\pm}$

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



- $\sigma_{H^{\pm\pm}H^{\mp}}$ is a function of $m_{H^{\pm\pm}}$ and $m_{H^{\pm}}$ Dion et al 98, Gunion 98
- Similar magnitude to $\sigma(p\overline{p} \to H^{++}H^{--})$ for $m_{H^{\pm\pm}} \sim m_{H^{\pm}}$

Impact of $qq' \to H^{\pm\pm}H^{\mp}$

Current searches are already sensitive to $qq' \to H^{\pm\pm}H^{\mp}$!

- $2l$ search: sensitive to $H^{\pm\pm}H^{\mp}$ irrespective of $H^{\pm}$ decay
- $3l$ search: sensitive to $H^{\pm\pm}H^{\mp}$ if $H^{\pm} \to l^{\pm}\nu$

$\to$ Define inclusive single $H^{\pm\pm}$ cross-section for $2l$ search:

$$\sigma_{H^{\pm\pm}} = \sigma(p\overline{p} \to H^{++}H^{--}) + 2\sigma(p\overline{p} \to H^{\pm\pm}H^{\mp})$$

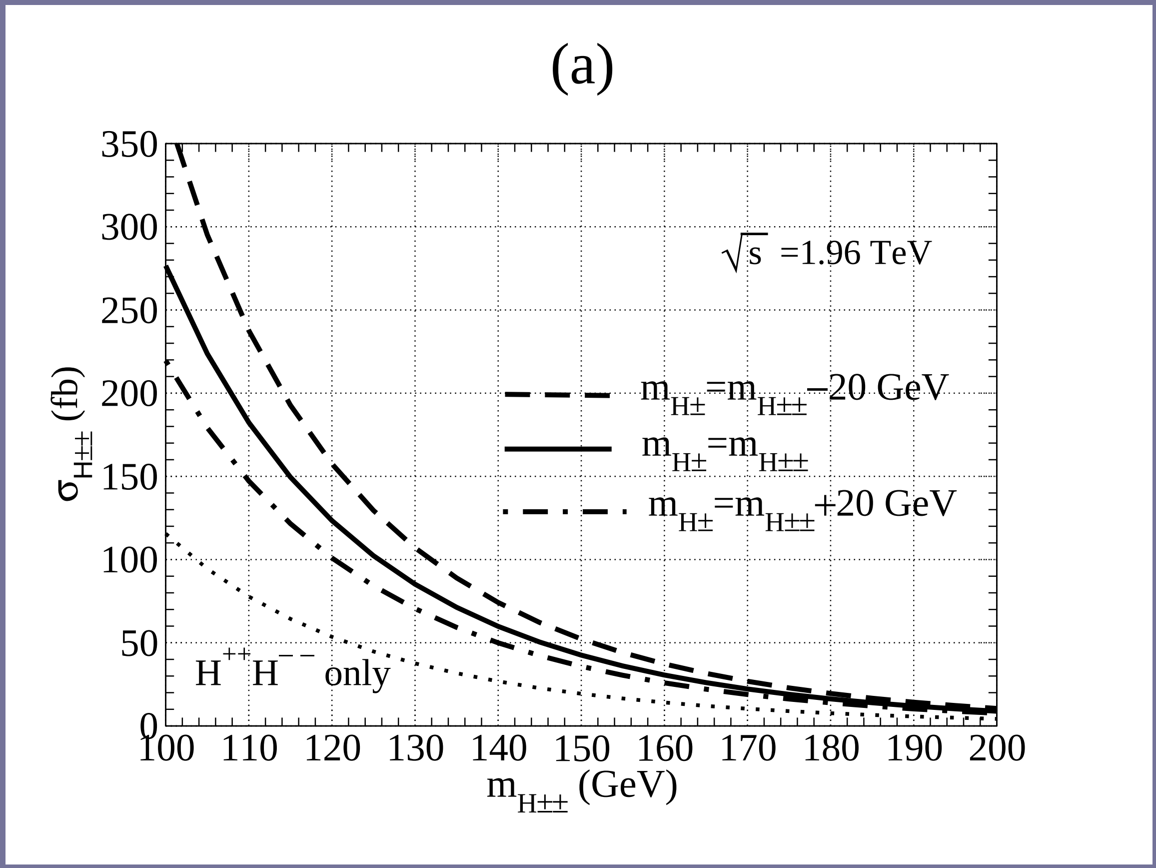
Increases search potential of Tevatron in $ee, e\mu, \mu\mu$ channels

Akeroyd,Aoki 05

Inclusive single $H^{\pm\pm}$ production at Tevatron

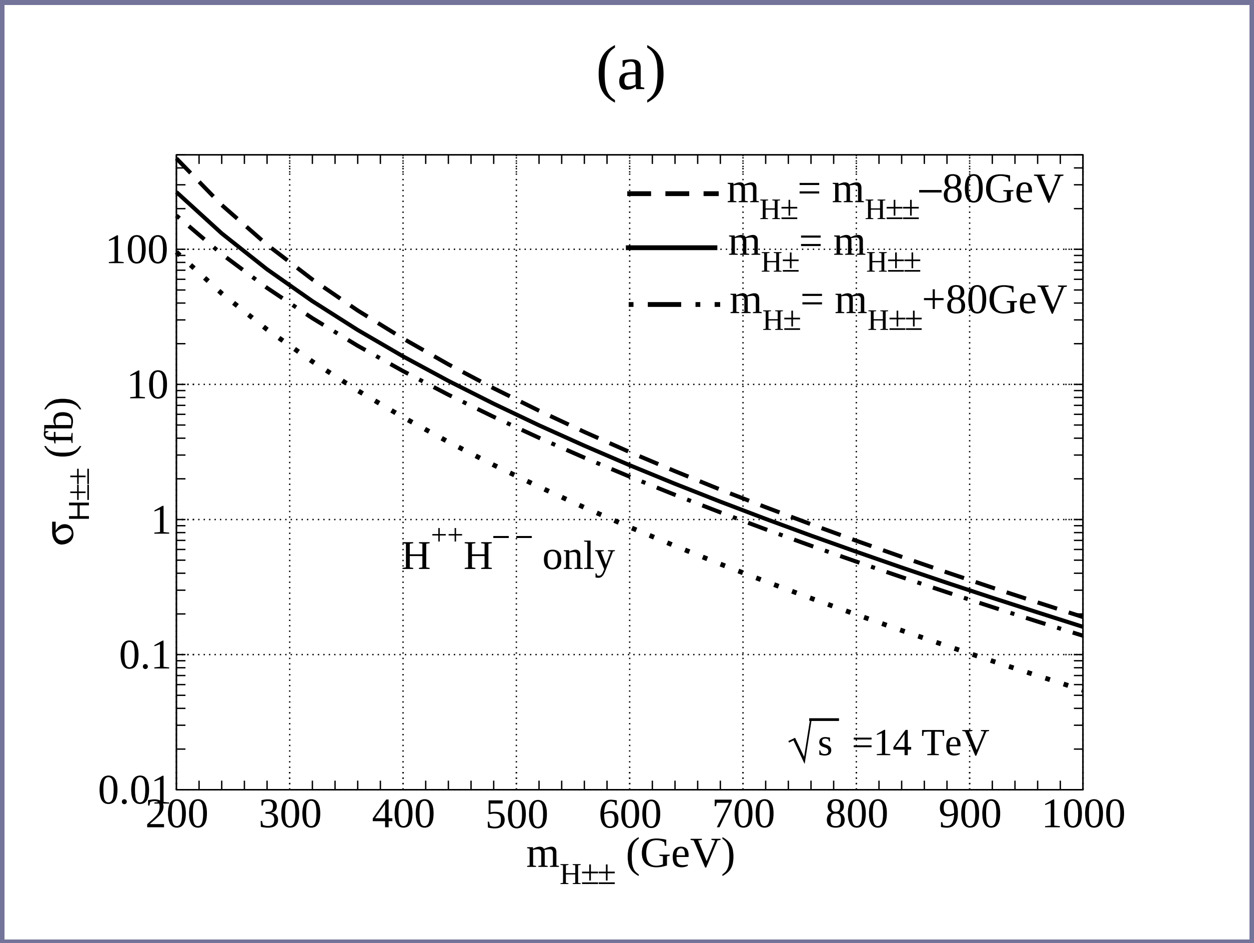
Akeroyd,Aoki 05

$$\sigma_{H^{\pm\pm}} = \sigma(p\overline{p} \to H^{++}H^{--}) + 2\sigma(p\overline{p} \to H^{++}H^{-})$$



Inclusive single $H^{\pm\pm}$ production at LHC

Akeroyd,Aoki 05



Summary for $qq' \to H^{\pm\pm}H^{\mp}$

- Cross-section can be as large as $q\overline{q} \to H^{++}H^{--}$
- Can enhance $H^{\pm\pm}$ discovery potential in $2l, 3l$ channels
- (Best?) Production process for $H^{\pm}$ of HTM at hadron colliders
- Not yet simulated (but see Han et al arXiv:0803.3450)

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})	N_{2l} (300 fb^{-1})
200	1500	15000	42000
300	300	3000	8400
400	90	900	2500

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

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

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

Prediction for 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:

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

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 see also Chen et al 06

Radiative neutrino mass, h_{ij} partially correlated 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

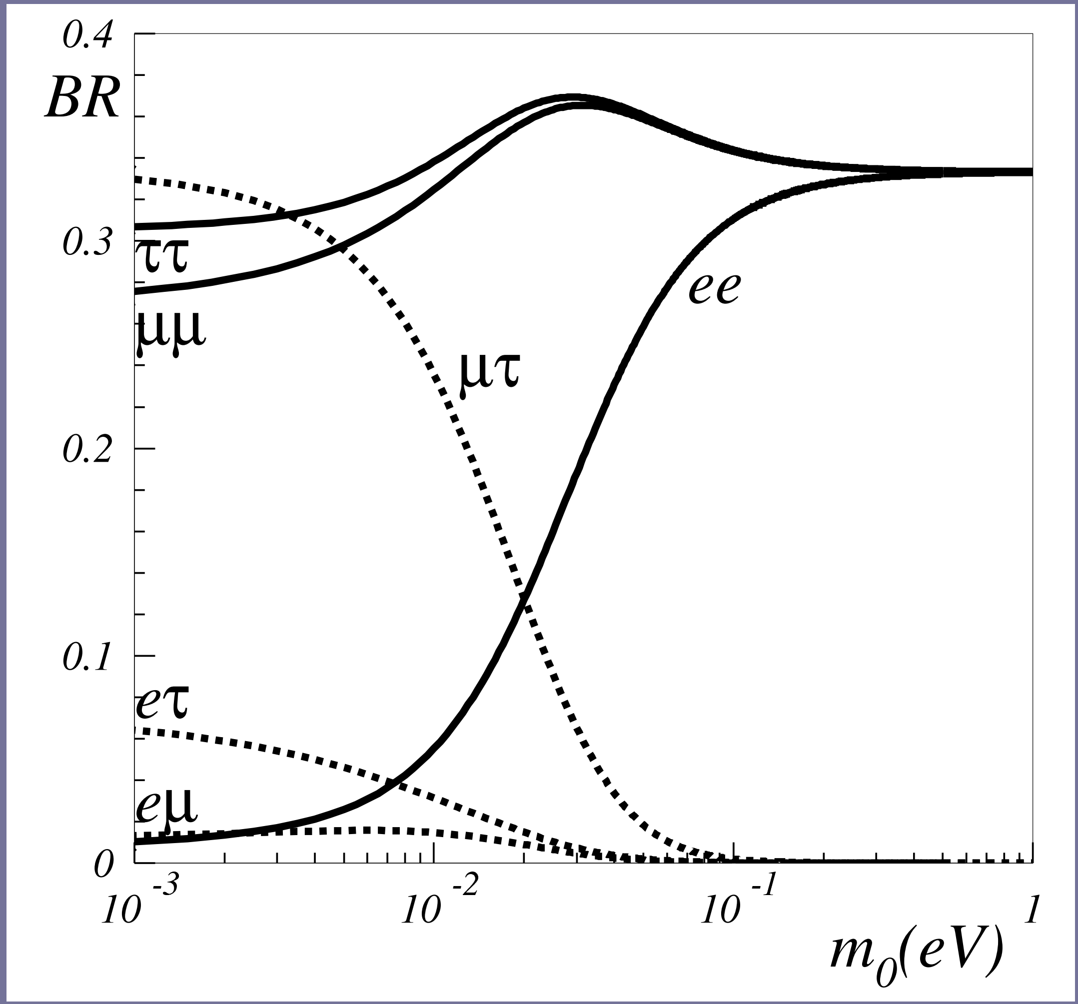
- Include Majorana phases, $\phi_1 \neq 0, \phi_2 \neq 0$:

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

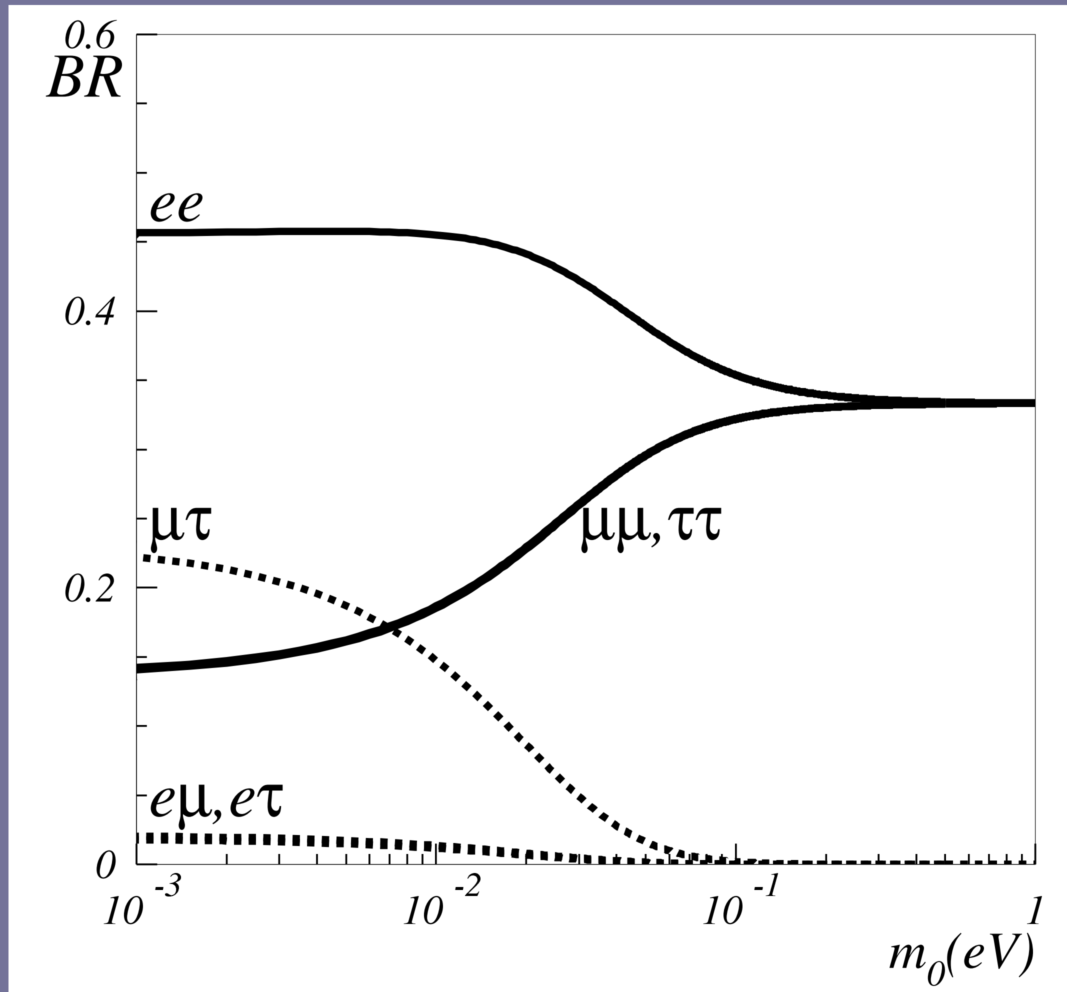
$\to$ we quantify the prediction for BR($H^{\pm\pm} \to l^{\pm}l^{\pm}$) in the HTM

(see also Garayoa et al,arXiv:0712.1453;Kadastik et al, 0712.3912;Han et al,0803.3450

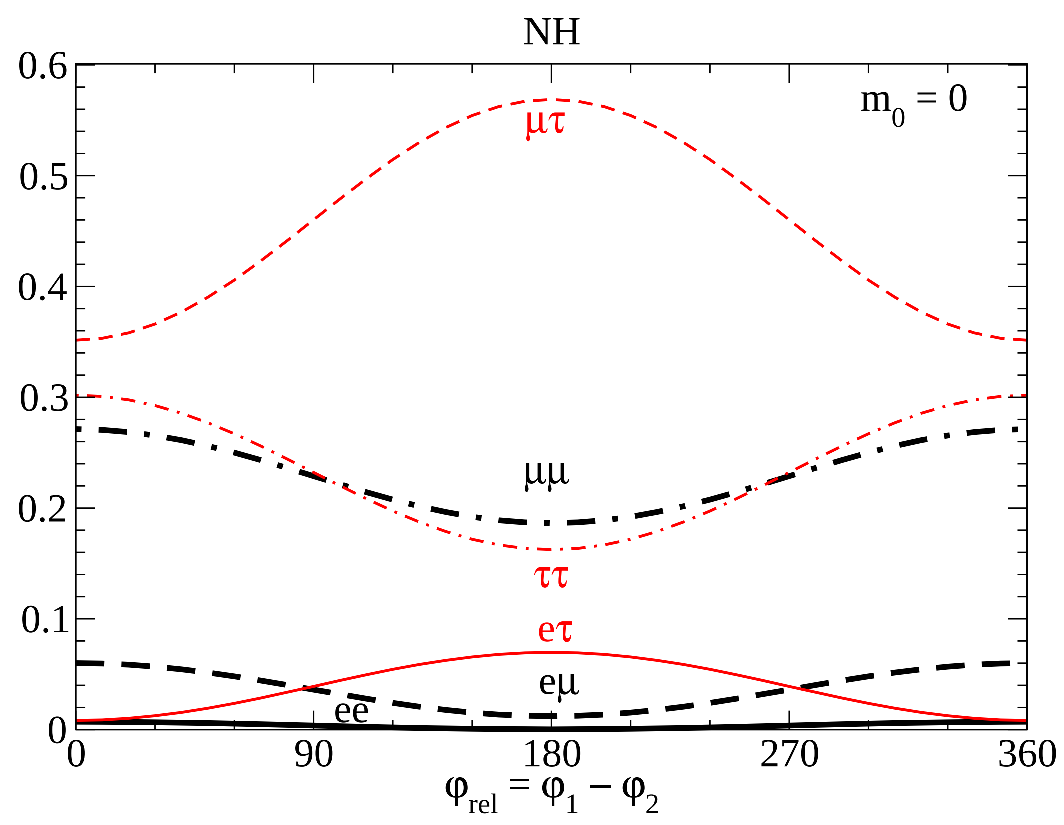
BR($H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}$) against lightest neutrino mass (m_0): normal hierarchy



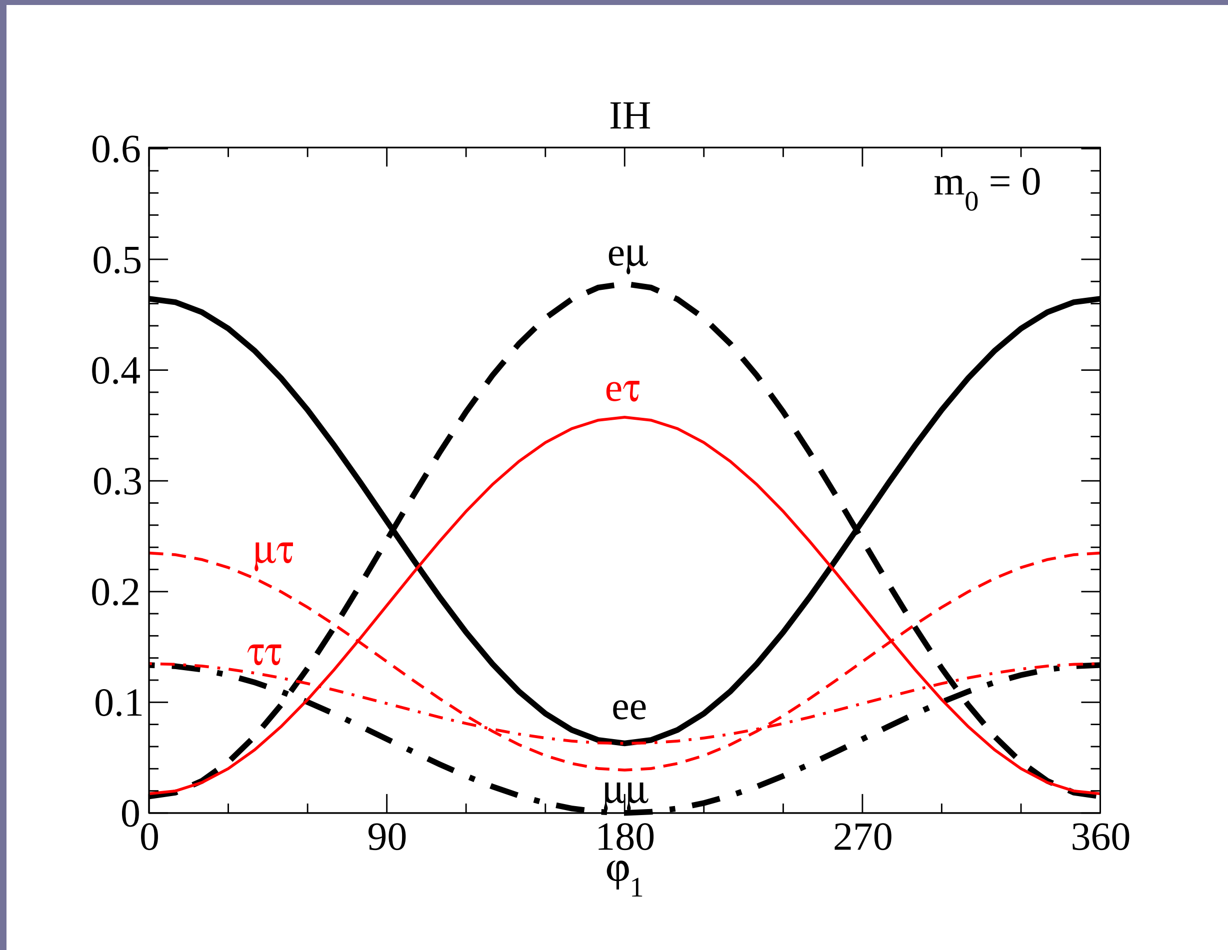
BR($H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}$) against lightest neutrino mass (m_0): inverted hierarchy



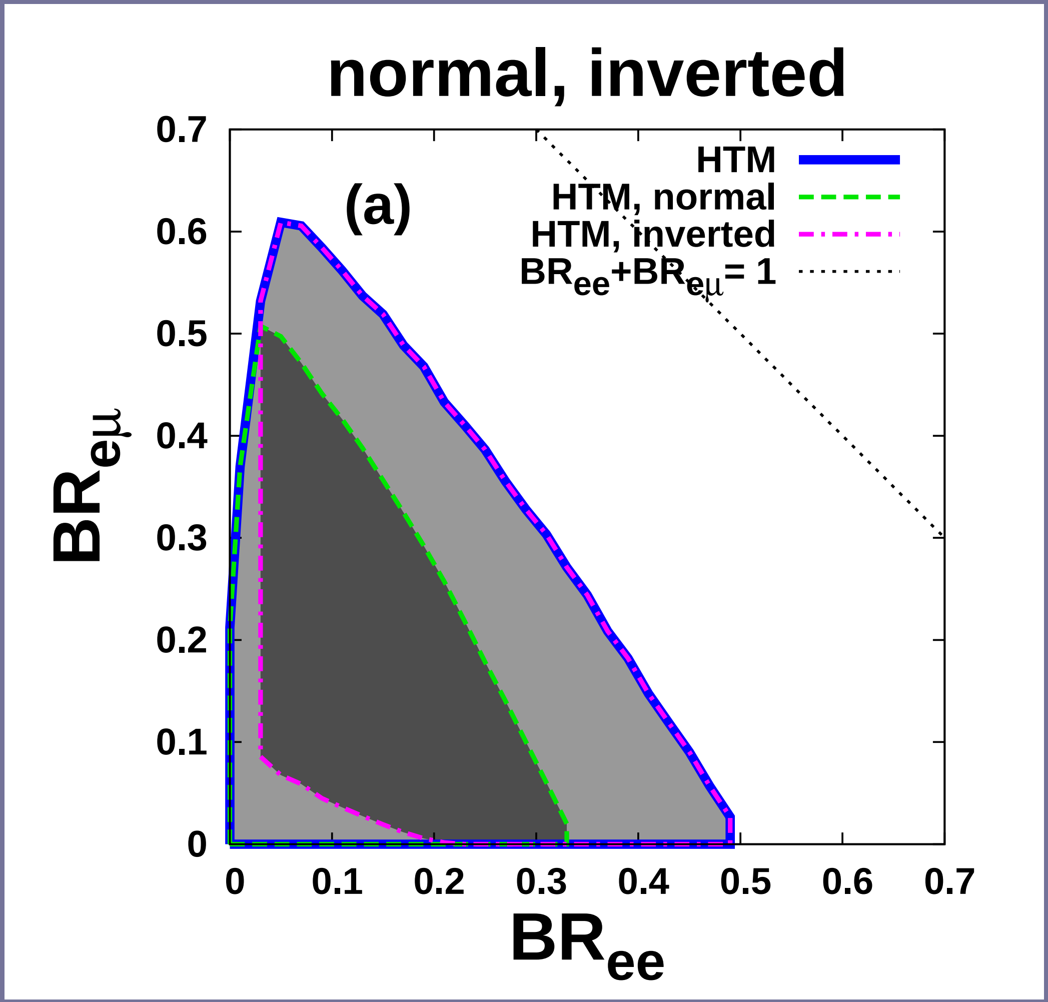
BR($H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}$) against Majorana phase and $m_0 = 0$: normal hierarchy



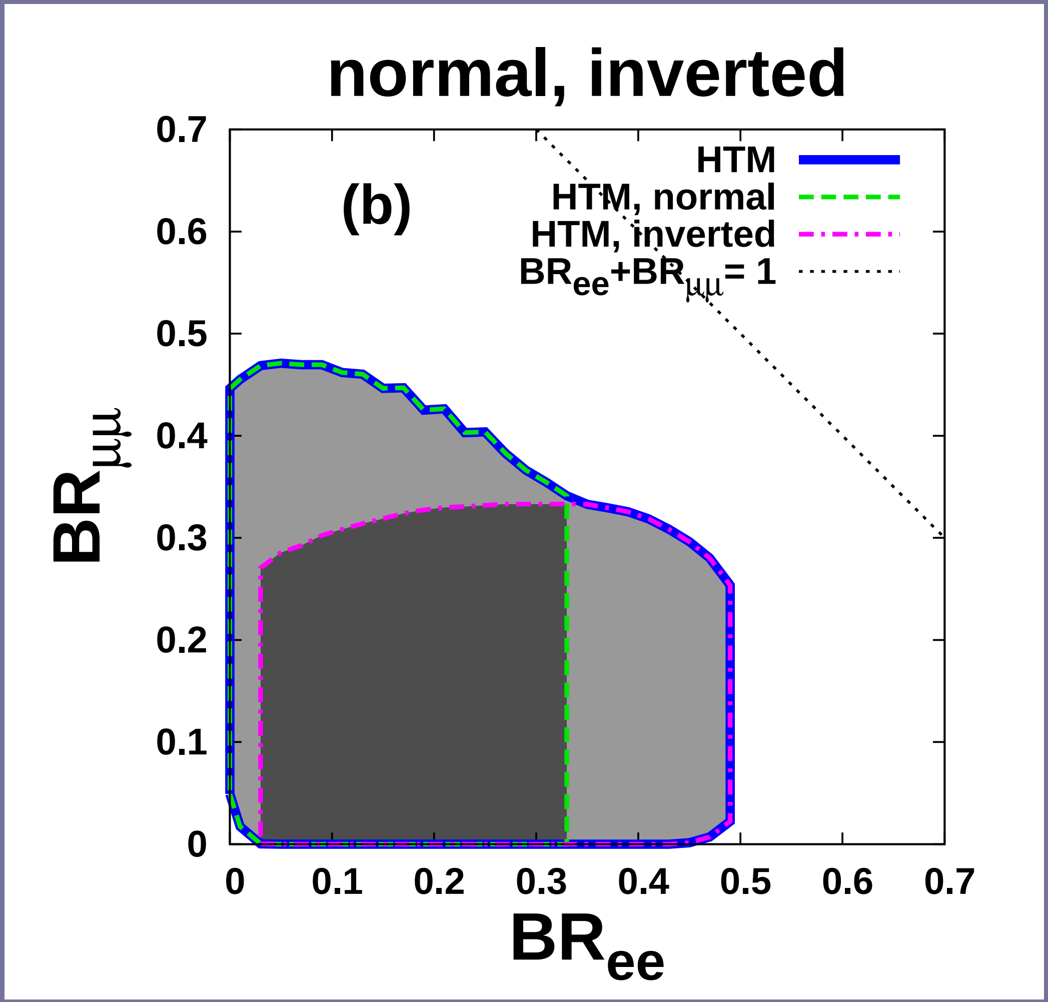
BR($H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}$) against Majorana phase and $m_0 = 0$: inverted hierarchy



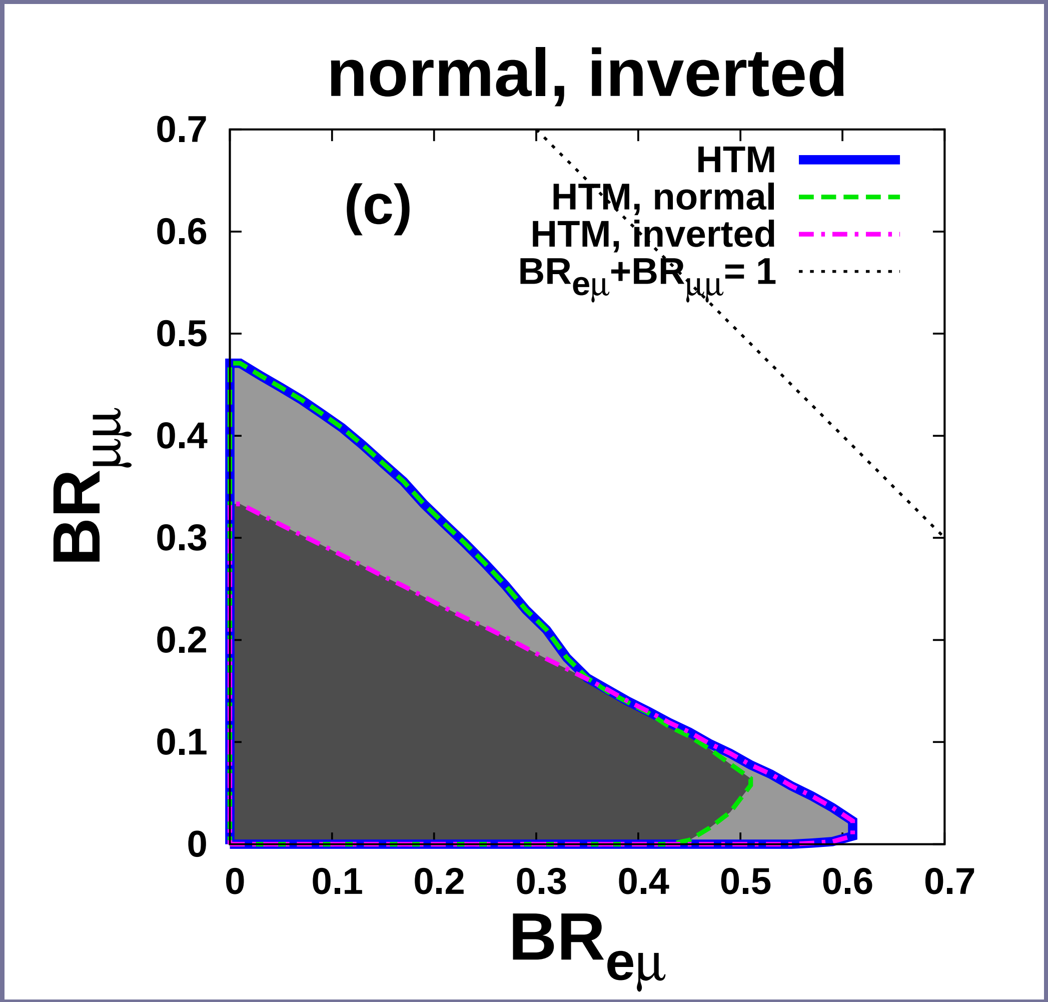
HTM prediction in the plane [BR($H^{\pm\pm} \to e^{\pm}e^{\pm}$),BR($H^{\pm\pm} \to e^{\pm}\mu^{\pm}$)]



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

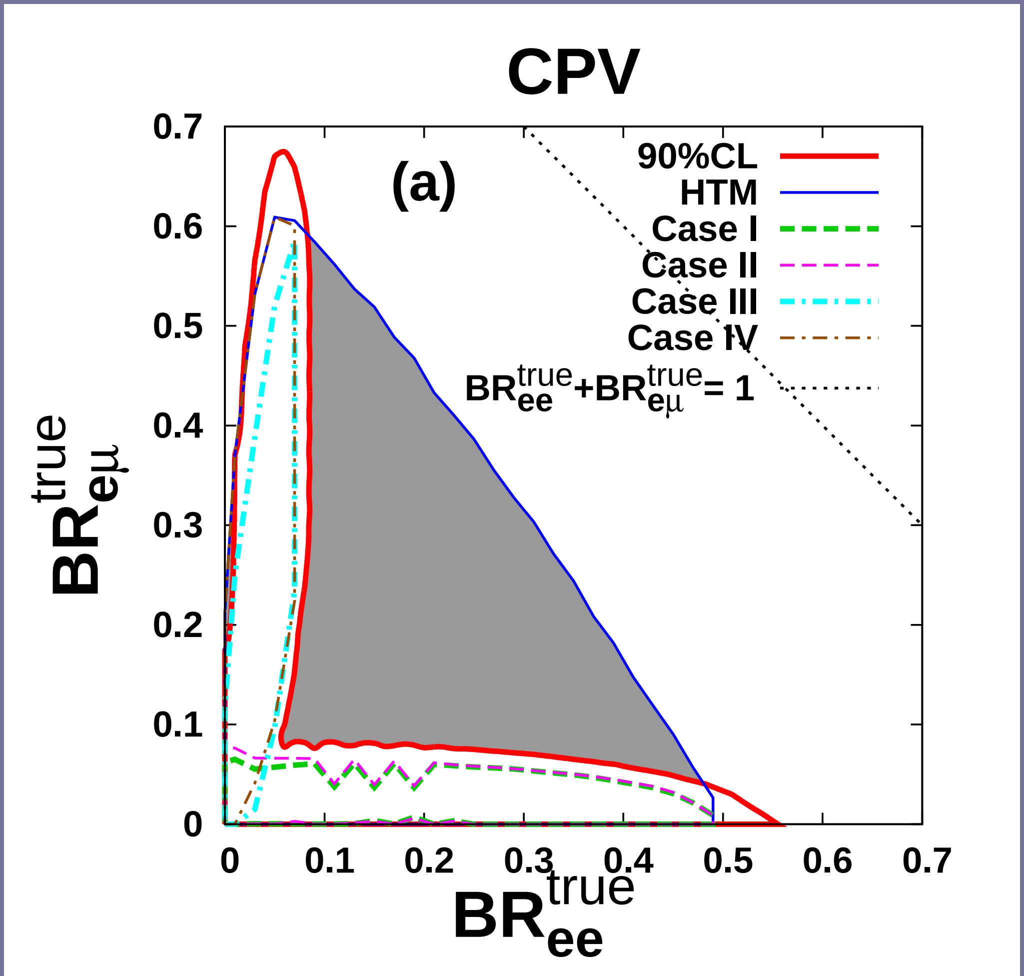


HTM prediction in the plane [BR($H^{\pm\pm} \to e^{\pm}\mu^{\pm}$),BR($H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$)]



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



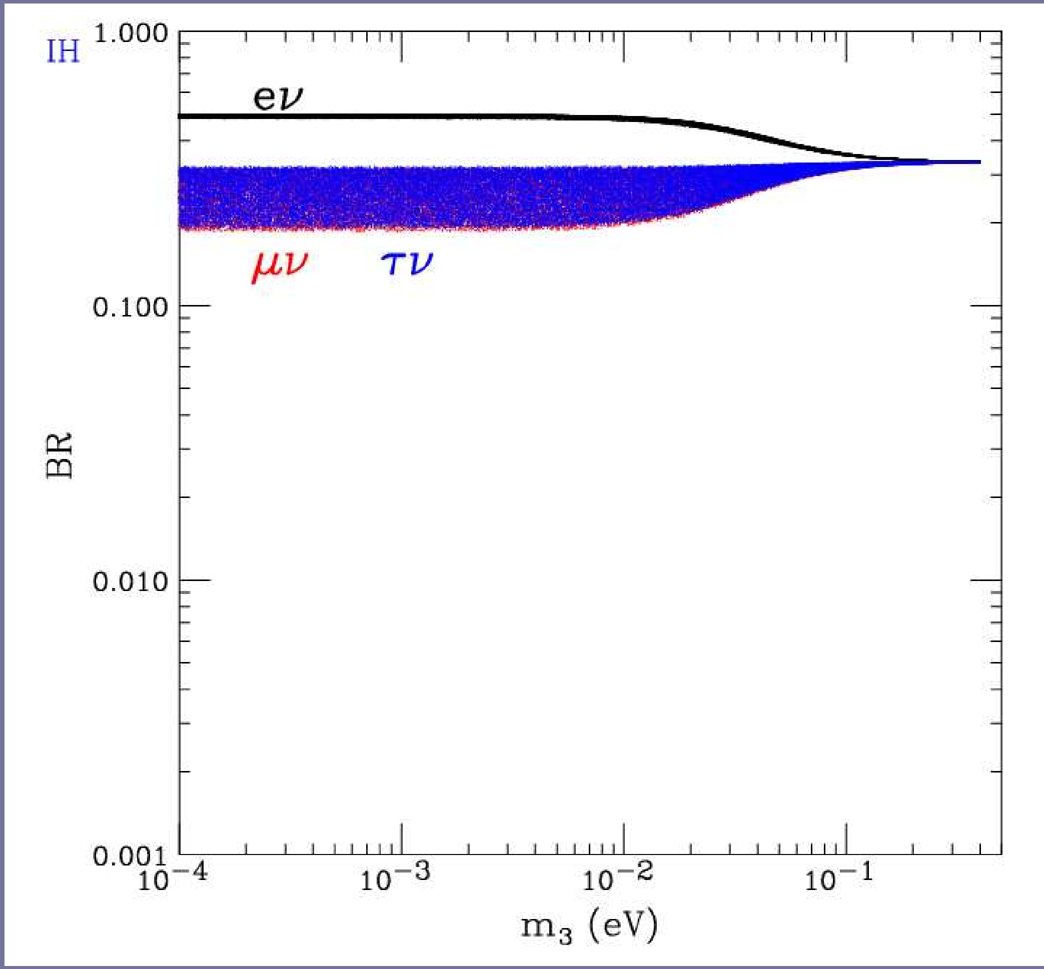
Prediction for BR($H^{\pm} \to l^{\pm}\nu$)

$H^{\pm}$ phenomenology important for testing HTM:

Han et al 0803.3450[hep-ph]

- $\Gamma(H^{\pm} \to l^{\pm}\nu_i) \sim m_{diag} V^T_{PMNS}$
- BR($H^{\pm} \to l^{\pm}\nu$) $= \sum_i BR(H^{\pm} \to l^{\pm}\nu_i)$
- BR($H^{\pm} \to l^{\pm}\nu$) has no dependence on Majorana phases
- Robust prediction as function of lightest neutrino mass
- Increases importance of $pp \to H^{\pm\pm}H^{\mp}$ in HTM

HTM prediction for $H^{\pm} \to l^{\pm}\nu$: Inverted Hierarchy Han 08



Conclusions

- Higgs Triplet Model generates neutrino mass $h_{ij}v_L$
- $H^{\pm\pm} \to l^{\pm}l^{\pm}$ 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

- Strong prediction for BR$(H^{\pm} \to l^{\pm}\nu)$
- $H^{\pm}$ best produced via $pp \to W \to H^{\pm\pm}H^{\mp}$
- Simulations of $pp \to W \to H^{\pm\pm}H^{\mp}$ well-motivated