Leptonic signatures of Doubly Charged Higgs Bosons at Hardon Colliders

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Andrew G. Akeroyd, Cheng-Wei Chiang, Naveen Gaur, JHEP 1011, 005 (2010) ; arXiv:1009.2780[hep-ph].

Some of the slides have been borrowed from Andrew's talk at Southampton

- ***Higgs Triplet Model (HTM)***
- ***Leptonic decay of doubly charged Higgs***
- ***Doubly charged Higgs production at Hadronic colliders***
- ***Current searches of doubly charged Higgs at hadronic colliders (Tevatron).***
- ***Search prospects at LHC (14 TeV)***

Charged Higgs Bosons (scalars)

The Standard Model Higgs Boson is a spinless neutral particle with a vacuum expectation value (vev)

Still undiscovered : If exists, how many Higgs bosons ??

We can classify Higgs bosons by their electric charge

- Neutral : $h^0(\mathrm{SM}), \quad H^0, \; A^0 \; (\mathrm{2HDM, MSSM})$
- Singly Charged : $H^\pm \; (\mathrm{2HDM, MSSM})$
- Doubly Charged : $H^{\pm\pm}$

Order of priority : neutral > singly charged > doubly charged

Models with Doubly Charged Higgs Bosons

Motivation --> neutrino mass generation

Scalar triplets (isospin I = 1) and scalar singlets (I=0)

- Higgs Triplet Model : I=1, Y=2 (tree-level mass for neutrino)
- LR symmetric model : I=1, Y=2 (tree level mass of neutrino)
- Zee-Babu model : I=0, Y=4 (radiative mass of neutrino)

We will focus on Higgs Triplet Model

Large Hadron Collider

- LHC is colliding protons at $\sqrt{s} = 7 \text{ TeV}$
- From 2013(?) it will operate at $\sqrt{s} = 14 \text{ TeV}$
- Highest energy collider ever built
- Search of Higgs bosons is of high (highest?) priority
- Fermilab Tevatron ($\sqrt{s} = 1.96 \text{ TeV}$) is still working and may collect upto 16 fb^-1.
- Great time to study phenomenology of Higgs boson

HiggsTriplet 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 invariant under $SU(2)_L \otimes U(1)_Y$: $m^2 < 0,\ M_\Delta^2 > 0$

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

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

Triplet vacuum expectation value: $\boxed{< \delta^0 >= v_\Delta \sim \mu v^2/M_\Delta^2}$

($v_\Delta < 5$ GeV to keep $\rho = (M_Z^2 \cos^2\theta_W)/M_W^2 \sim 1$)

Higgs Boson Spectrum

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

- $H^{\pm\pm}$ is *purely triplet*: $H^{\pm\pm} \equiv \delta^{\pm\pm}$
- $H^{\pm}, H^0, A^0, h^0$ are mixtures of doublet (ϕ) and triplet (δ) fields
- Mixing $\sim v_\Delta/v$ and small ($v_\Delta/v < 0.03$)
- h^0 plays role of *SM Higgs boson* (essentially $I = 1/2$ doublet)
- $H^{\pm}, H^0, A^0$ are *dominantly* composed of triplet fields
- Masses of $H^{\pm\pm}, H^{\pm}, H^0, A^0$ close to degenerate $\sim M_\Delta$
- For $H^{\pm\pm}$, $H^{\pm}$ in range at LHC require $\boxed{M_\Delta < 1 \text{ TeV}}$

Neutrino mass in HTM

No additional (heavy) neutrinos: $\mathcal{L} = h_{ij}\psi_{iL}^T C i\tau_2 \Delta \psi_{jL} + h.c$

$\psi_{iL}^T = (\nu_i, \ell_i);\ i = e, \mu, \tau$

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

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

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

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

(m_i=neutrino masses; $V_{\mathrm{PMNS}} = V_\ell^\dagger V_\nu$; take $V_\ell = I$ and $V_\nu = V_{\mathrm{PMNS}}$)

Decay modes of $H^{\pm\pm}$ and $H^{\pm}$

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

- $\Gamma(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim |h_{ij}|^2$; $\Gamma(H^{\pm\pm} \to W^{\pm}W^{\pm}) \sim v_{\Delta}^2$
- In HTM: $h_{ij} v_{\Delta} \sim \mathcal{M}_{ij}^{\nu}$

$\Gamma(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) > \Gamma(H^{\pm\pm} \to W^{\pm}W^{\pm})$ for $v_{\Delta} < 10^{-4}$ 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 $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$

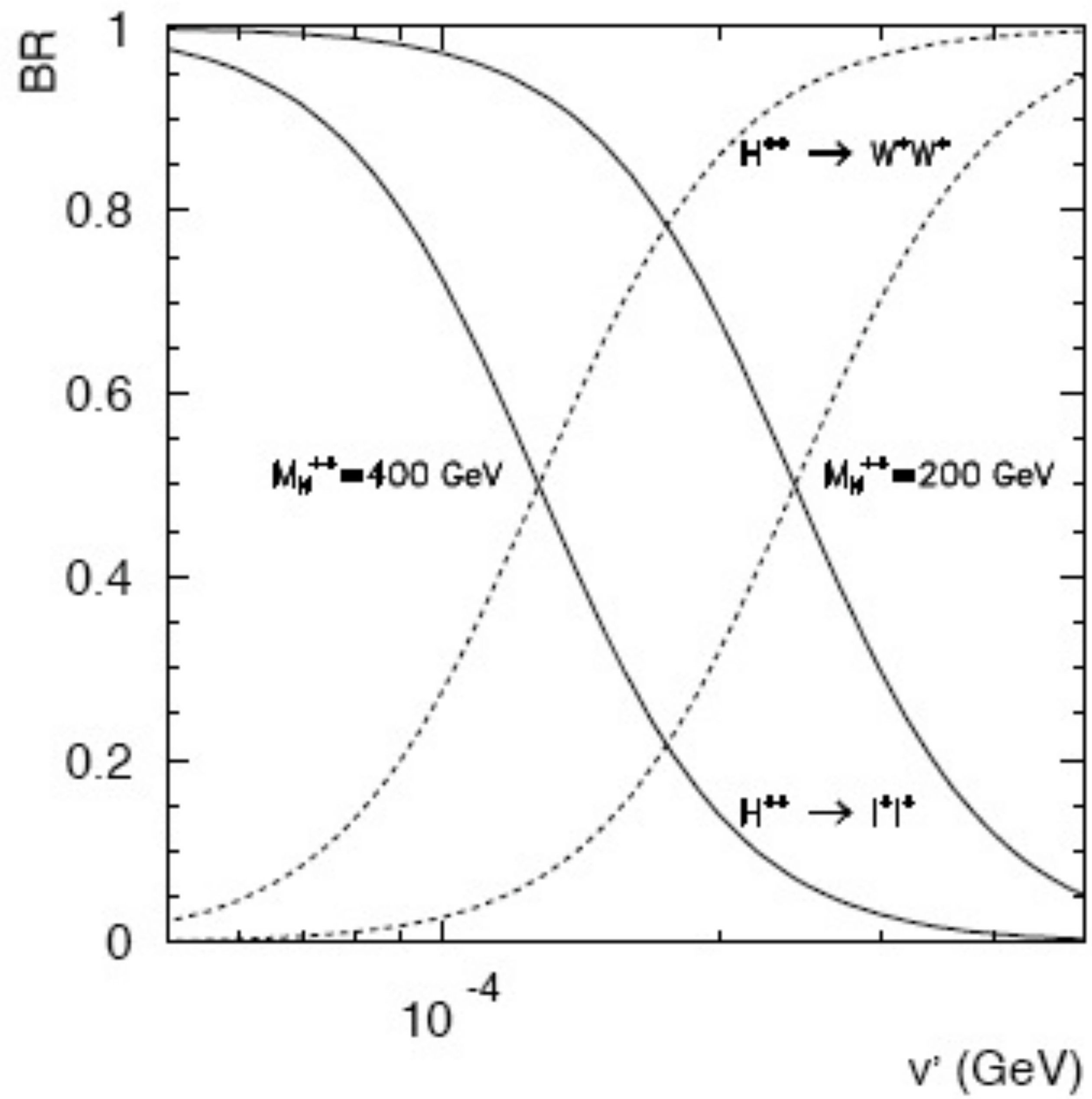
Decays of $H^{\pm}$:

- $\Gamma(H^{\pm} \to \ell_i^{\pm}\nu) > \Gamma(H^{\pm} \to W^{\pm}Z, tb)$ for $v_{\Delta} < 10^{-4}$ GeV

If $h_{ij} > h_{electron}$ then $v_{\Delta} < 10^{-4}$ GeV

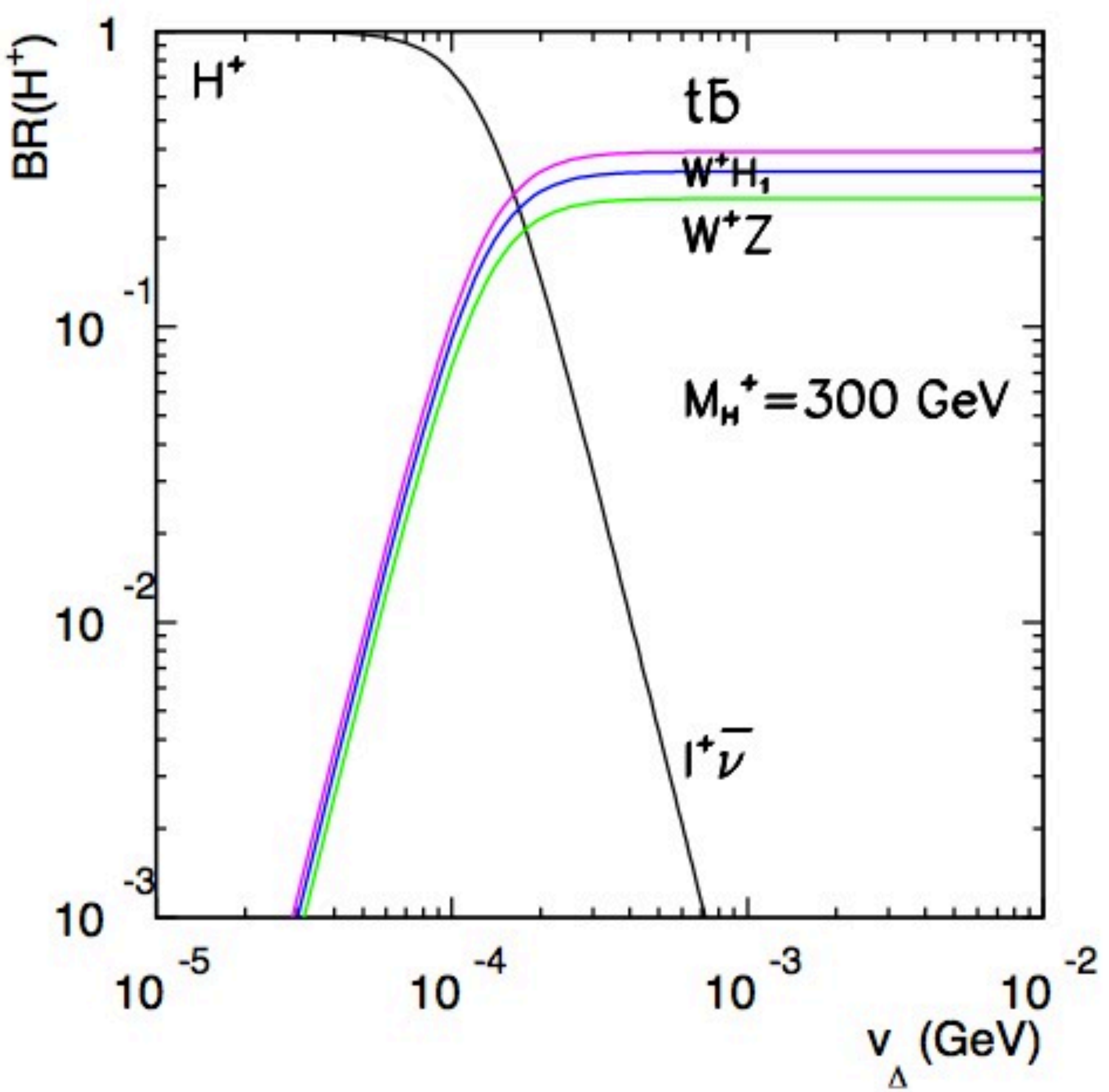
$\to$ leptonic decays $H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$ and $H^{\pm} \to \ell_i^{\pm}\nu$ dominate

BR of $H^{\pm\pm}$ as a function of triplet vev



T.Han, B. Mukhopadhyaya, Z. Si & K.Wang, arXiv:0706.0441 [hep-ph]

BR of $H^{\pm}$ as a function of triplet vev



P. Perez, T.Han, G. Huang, T. Li & K.Wang, arXiv:0805.3536 [hep-ph]

Branching Ratios of $BR(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm})$

BR$(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm})$ determined by h_{ij}

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

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

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

$\boxed{\text{Prediction for BR}(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm})}$ determined by:

- Neutrino mass matrix parameters (masses, angles, phases)
- Neutrino mass hierarchy: normal $(m_3 > m_2 > m_1)$ or inverted

Limits on h_{ij}

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

$$m_{H^{\pm\pm}} < 1\ TeV$$

- $BR(\mu \rightarrow eee) < 10^{-12} \rightarrow |h_{\mu e} h_{ee}| < 10^{-7}$ — 1988; no future experiment
- $BR(\tau \rightarrow \ell_i \ell_j \ell_k) < 10^{-8} \rightarrow |h_{\tau i} h_{jk}| < 10^{-4}$ — From B-factories
- $BR(\mu \rightarrow e\gamma) < 10^{-11} \rightarrow \sum_i |h_{\mu i} h_{ei}| < 10^{-6}$ — $MEG \ \sim 10^{-13}$

All constraints can be respected with $|h_{ij}| < 10^{-2}$ or 10^{-3}

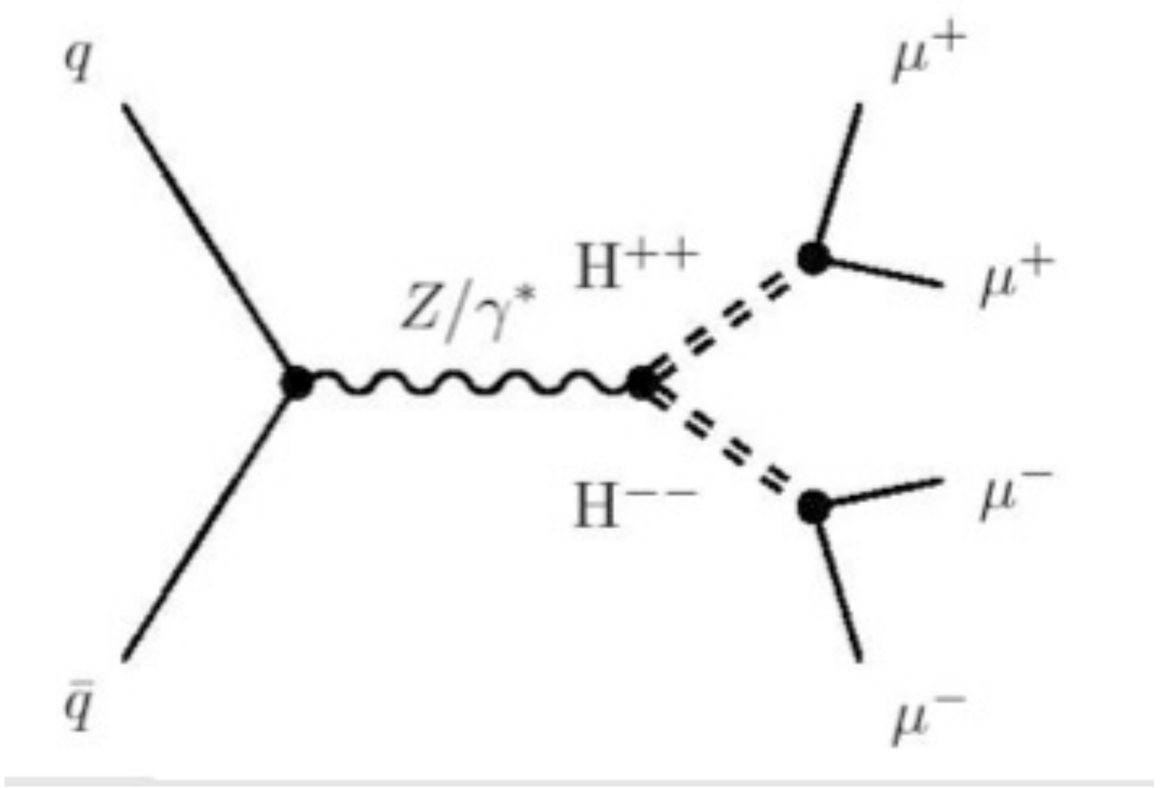
Production of $H^{\pm\pm}$ at Hadron Colliders (Tevatron and LHC)

$H^{\pm\pm}$ Production at hadronic colliders

(First searches at Hadronic collider in 2003 CDF, D0)

Interaction vertex

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



- 4 leptons from pair produced $H^{\pm\pm}$
- Assumed $BR(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) = 100\%$

Present Tevatron search strategy

- $H^{\pm\pm}$ decays via h_{ij} to *same charge* $ee, \mu\mu, \tau\tau, e\mu, e\tau, \mu\tau$
- Four leptons $(\ell^+\ell^+\ell^-\ell^-)$ from pair production of $H^{++}H^{--}$
- For $H^{\pm\pm} \to e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm$, sufficient to search for

three leptons of high momentum with two leptons having the same charge

$\rightarrow \boxed{\text{Six distinct signatures}}$

$e^\pm e^\pm e^\mp$, $e^\pm e^\pm \mu^\mp$, $e^\pm \mu^\pm e^\mp$, $e^\pm \mu^\pm \mu^\mp$, $\mu^\pm \mu^\pm e^\mp$ and $\mu^\pm \mu^\pm \mu^\mp$

- Only $\mu^\pm \mu^\pm \mu^\mp$ has been searched for (1.1 fb^{-1} of data)
- Tevatron currently has 7 fb^{-1}, and expects $9 \rightarrow 12$ fb^{-1}

D0, PRL, 101,071803 (2008)

In the standard model (SM) of electroweak interactions, elementary fermions and bosons acquire mass via a weak isospin scalar doublet. This mechanism results in the existence of an additional particle, the Higgs boson, which has not yet been observed. Extensions of the Higgs sector involving higher isospin multiplets predict the existence of doubly-charged Higgs bosons which can be relatively light and hence accessible at current experimental facilities. Doubly-charged Higgs bosons appear in many scenarios such as left-right symmetric models [1], Higgs triplet models [2], and Little Higgs models [3]. At the Fermilab Tevatron Collider, the two main production mechanisms are pair production via $p\bar{p} \to Z/\gamma^* X \to H^{++}H^{--}X$ and single production via WW fusion, $p\bar{p} \to W^{\pm}W^{\pm}X \to H^{\pm\pm}X$. However, higher isospin Higgs multiplets are generally severely constrained by $\rho \equiv m_W^2/(\cos\theta_W m_Z)^2 = 1$ at tree level. The existing phenomenological and theoretical constraints are easily satisfied when the $W^{\pm}W^{\pm} \to H^{\pm\pm}$ coupling is vanishing [4]. If the H^{++} coupling to W boson pairs is suppressed, the dominant final states are expected to be like-sign lepton pairs. Left-handed ($H_L^{\pm\pm}$) and right-handed ($H_R^{\pm\pm}$) states are distinguished by their coupling to left-handed and right-handed leptons, respectively. The pair production cross section for left-handed doubly-charged Higgs bosons for $100 \le M(H^{\pm\pm}) \le 200$ GeV/c^2 is about a factor two larger than that for the right-handed states due to different couplings to the intermediate Z boson [5]. Previous searches for $H^{\pm\pm}$ have been performed by the LEP collaborations [6] in e^+e^- collisions and by the D0 [7] and CDF [8] collaborations at the Tevatron $p\bar{p}$ collider. This Letter presents the results of a direct search for $p\bar{p} \to H^{++}H^{--}X$ with $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$ by the D0 collaboration with improved sensitivity.

In the previous D0 analysis [7], two like-sign muons were required in the final state. In this analysis, we require a third muon, which increases the sensitivity by decreasing backgrounds. We follow five steps to select events. In the first step (S1), events are required to have at least two muons. Each muon must have a transverse momentum $p_T > 15$ GeV/c and $|\eta| < 2.0$. Muons are selected using patterns of hits in the wire chambers and scintillators in the muon system. Each muon must be matched to a track in the central tracker with at least five hits in the CFT layers and at least two hits in the SMT layers. Muons from cosmic rays are removed by using a timing information on the hits in the scintillator layers.

In the second step (S2), isolation criteria based on the calorimeter and tracking information are applied to remove the background from multijet production with muons originating from in-flight decay of pions or kaons, or from semi-leptonic decays of B or D mesons. The sum of the transverse energies of the calorimeter cells in an annulus of radius $0.1 < \mathcal{R} < 0.4$, where $\mathcal{R} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and ϕ is the azimuthal angle, around the muon direction is required to be less than 2.5 GeV. A similar condition is defined for the scalar sum of the p_T of all tracks, excluding the muon in a cone of radius $\mathcal{R} = 0.5$ centered around the muon, which must be less than 2.5 GeV/c.

Selection S3 reduces the remaining $Z \to \mu^+\mu^-$ and multijet backgrounds. The azimuthal angle $\Delta\phi$ between at least one pair of muons is required to be less than 2.5 radians, since the two muons from Z boson decays are mostly back-to-back. This requirement also rejects a fraction of the multijet background with nearly back-to-back muons.

Current strategy is :

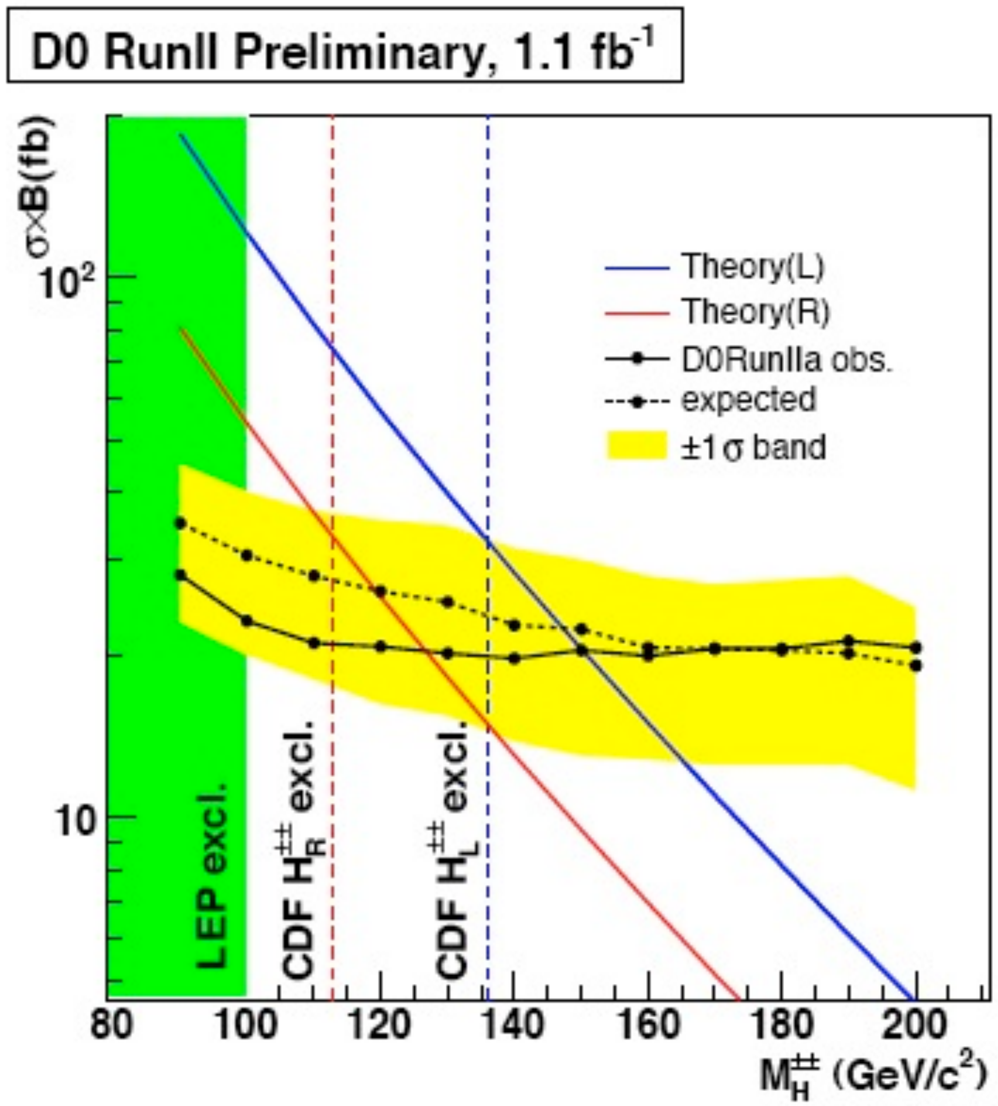
- **2 same sign leptons**
- **3 leptons with 2 of same sign**

D0 Note 5458-CONF (2007)

signal : $\mu^{\pm}\mu^{\mp}\mu^{\pm}$

Selection	Preselection S1	Isolation S2	$\Delta\phi < 2.5$ S3	Like sign S4	Third muon S5
Signal (140 GeV)	20.7	18.7	16.4	11.8	10.2
$Z \to \mu\mu$	69236	58325	4942	9.2	0.5±0.4
QCD	5244	423	40.5	14.2	0.5±0.2
$Z \to \tau\tau$	328	269	20.0	< 0.01	< 0.01
$t\bar{t}$	38	20	14	0.03	< 0.01
WW	40	34	20	< 0.01	< 0.01
WZ	19	16	11	3.0	1.6±0.03
ZZ	11	9	5	0.6	0.5±0.01
Total background	74917±123	59096±111	5052±33	27±1.7	3.1±0.5
Data	74086	59347	4623	35	3
$S/\sqrt{S+B}$	0.08	0.08	0.23	1.89	2.79

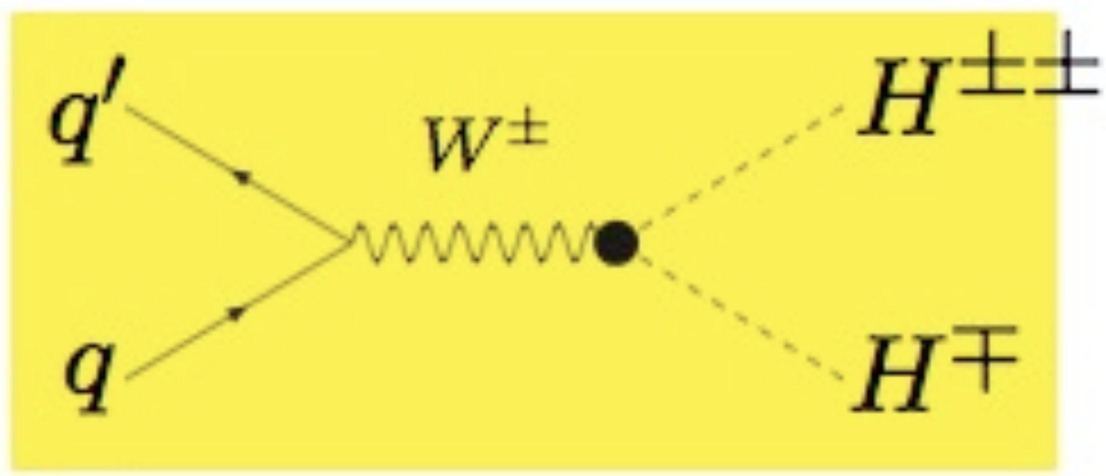
D0 Note 5458-CONF (2007)



$$m_{H^{\pm\pm}} > 150\ GeV, \quad BR(H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}) = 100\%$$

Single production of doubly charged Higgs

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



A. G. Akeroyd, M. Aoki, 2005

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

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

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

- $\ell^{\pm}\ell^{\pm}\ell^{\mp}$ search is sensitive to $H^{\pm\pm}H^{\mp}$ for $H^{\pm} \to \ell^{\pm}\nu$

$\to$ Define inclusive cross section for $\ell^{\pm}\ell^{\pm}\ell^{\mp}$ search:

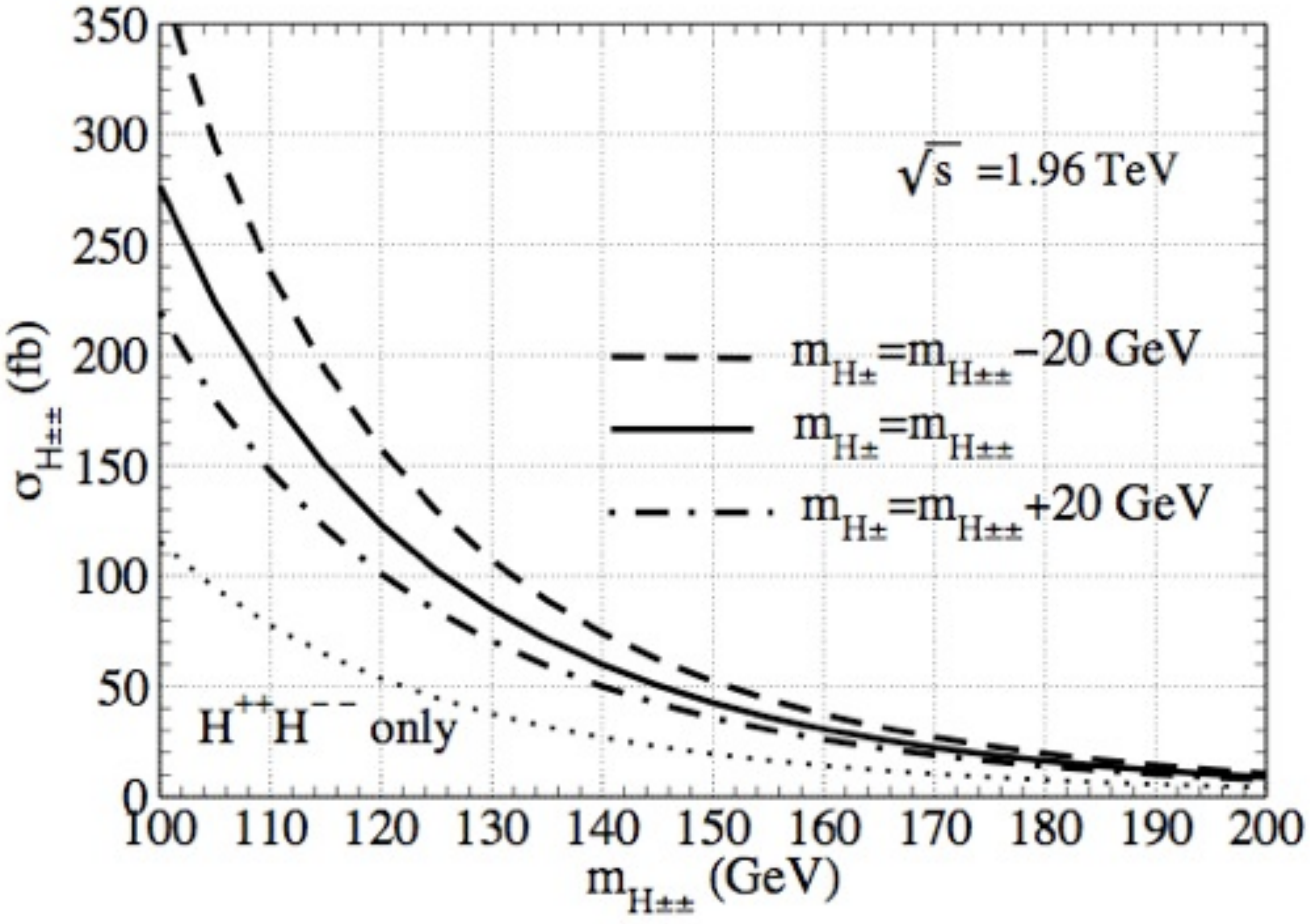
$$\sigma_{H^{\pm\pm}} = \sigma(p\bar{p} \to H^{++}H^{--}) + 2\sigma(p\bar{p} \to H^{++}H^{-})$$

AGA, Aoki 05

- Enables larger values of $m_{H^{\pm\pm}}$ to be probed in $\ell^{\pm}\ell^{\pm}\ell^{\mp}$ channels
- Not yet included in searches at the Tevatron

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

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



Could strengthen the mass limit of Doubly Charged Higgs

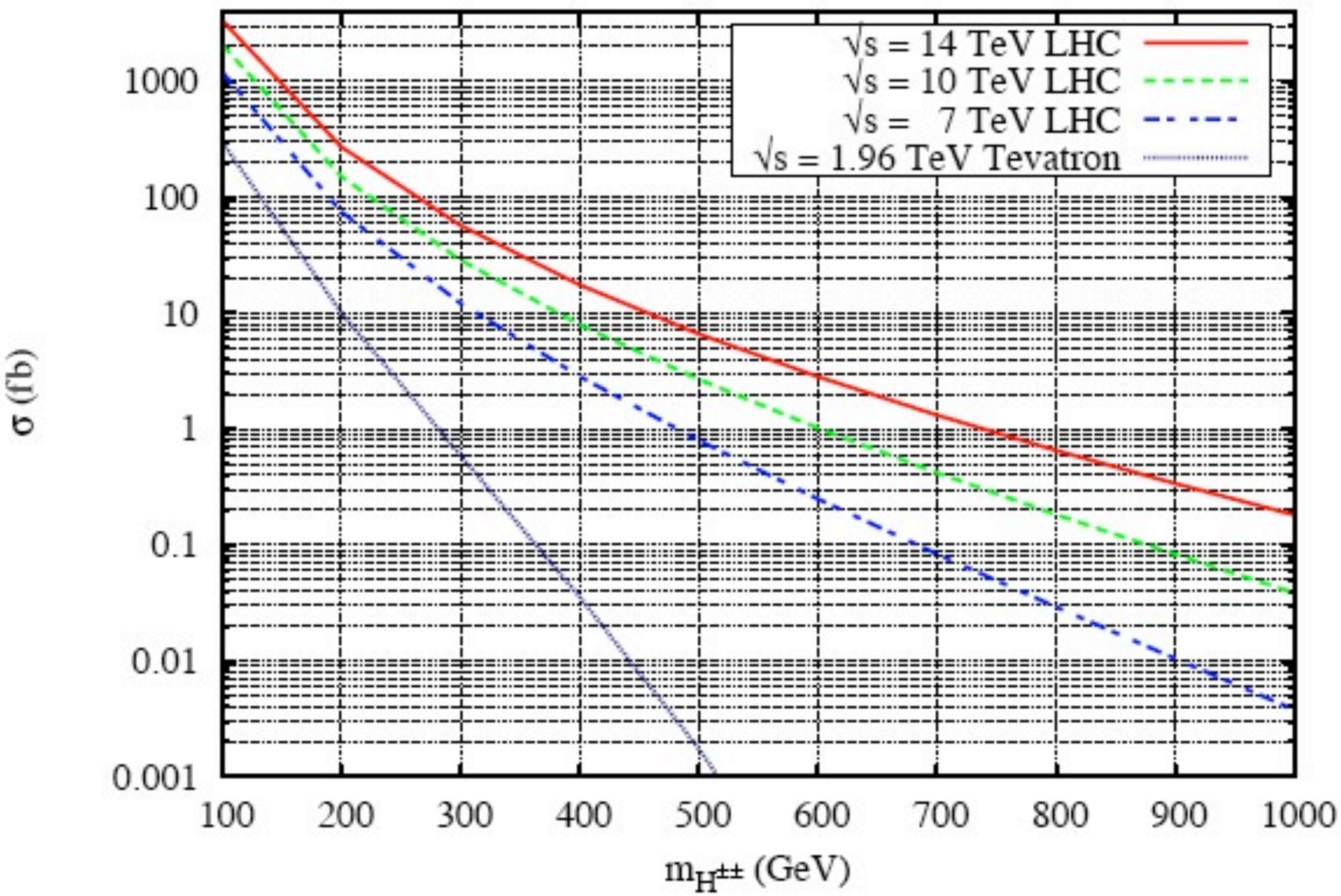
A. G. Akeroyd, M. Aoki, 2005

Summary of $q\bar{q}' \to H^{\pm\pm}H^{\mp}$

- $\sigma(q\bar{q}' \to H^{\pm\pm}H^{\mp})$ can be as large as $\sigma(q\bar{q} \to H^{++}H^{--})$
- Enhances the discovery potential for $H^{\pm\pm}$ in 3ℓ search channels, and strengthens the lower limit on $m_{H^{\pm\pm}}$
- Now receiving attention as a main production mechanism for $H^{\pm\pm}$
- Recently simulated at LHC Han et al 08, Del Aguila et al 08
- Not included in Pythia (frequently used by experimentalists)
- Convince Tevatron to include it in next search for $H^{\pm\pm}$?

Inclusive production at LHC

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



K-factors : LHC = 1.25, Tevatron = 1.3

Current status at LHC

4 lepton signature : only $H^{++}H^{--}$ contributes

- CMS (2007) : 4 muons
- ATLAS (2005) : 4 lepton (lepton = e,mu)

Tevatron search strategy is of looking for >= 3l

3ℓ ($\ell^{\pm}\ell^{\pm}\ell^{\mp}$) signature: both $H^{++}H^{--}$ and $H^{\pm\pm}H^{\mp}$ contribute

Del Aguila (2008) : exactly 3 lepton (additional lepton vetoed) hence lose contributions from pair production

AGA, Chiang, Gaur (2010) : >= 3 lepton (similar to Tevatron)

Framework

Signal process

1) Used Calchep to incorporate the vertex.
2) Partonic events were generated using calchep and interfaced to Pythia
3) Used ATLFAST
4) Analysis was done in ROOT

$m_{H^{\pm\pm}}$ (GeV)	200	300	400	500	600	700	800
Events generated	300 K	150 K	100 K	100 K	80 K	80 K	60 K

Table 1: Number of signal events generated where K stands for 10^3. These events are then scaled to the luminosity of $\mathcal{L} = 10\ \text{fb}^{-1}$.

Backgrounds :

1) Wbb, Zbb, Wtt, Ztt, WWW were generated using Calchep and interfaced with Pythia
2) ZZ, WZ, tt were generated using Pythia
3) Used ATLFAST

Process	ZZ	WZ	WWW	$t\bar{t}$	Z bb	W bb	Ztt	Wtt
Decay modes	all	all	all	SL	SL	SL	SL	SL
Events	1.5 M	1.5 M	300 K	90 M	1.2 M	900 K	150 K	800 K

Table 2: Number of background events generated where K stands for 10^3 and M stands for 10^6. The second row corresponds to the decay modes considered, and SL indicates "semi-leptonic." These events are then scaled to the luminosity of $\mathcal{L} = 10\ \text{fb}^{-1}$.

Process	WZ	ZZ	$t\bar{t}$	Zbb	Ztt	Wbb	$H^{\pm\pm}H^{\mp\mp}, H^{\pm\pm}H^{\mp}$
K-factors	1.5	1.35	1.67	2.4	1.35	2.57	1.25

Table 3: *K-factors for the background and signal processes at LHC*

Cuts

Primary Cuts:

- There are exactly four leptons with two for each charge sign ($\ell^+\ell^+\ell^-\ell^-$) in each event./ >= 3l, two of same sign
- Each of the leptons has $|p_T^\ell| > 5$ GeV and pseudorapidity in the range $|\eta| < 2.5$.
- Amongst the four leptons, at least two of the leptons have $|p_T^\ell| > 30$ GeV. This cut reduces the backgrounds where the leptons originate from the semileptonic b decays as they tend to be less energetic.
- Opposite-sign dilepton invariant mass cut: $m_{\ell^+\ell^-} > 20$ GeV. This is done in order to suppress the backgrounds where the opposite-sign lepton pair comes from a photon.

Secondary Cuts:

(a) The Z window cut. The invariant mass of opposite-sign dileptons is required to be sufficiently far from the Z mass: $|m_{\ell^\pm\ell^\mp} - M_Z| > 10$ GeV. This removes events where the leptons come from the Z decay.

(b) The H_T cut. One can also use the total transverse energy (H_T) as a parameter to distinguish signals from backgrounds. The total transverse energy is defined as

$$H_T = \sum_{\ell, \not{E}_T} |\vec{p}_T| \, . \tag{4.1}$$

Comparison of 4 lepton and >= 3 lepton

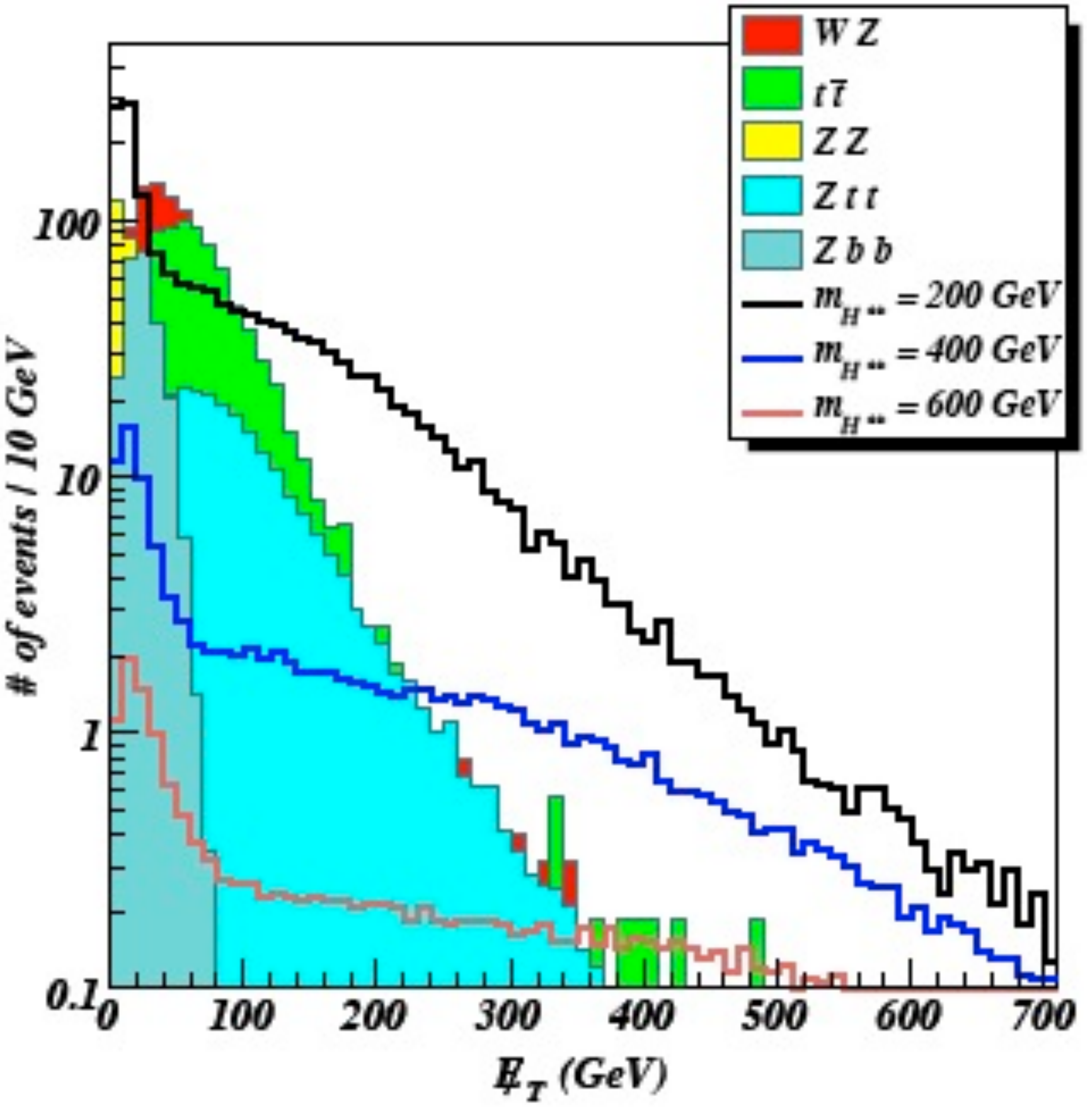
Exactly 4 lepton :

	Backgrounds						Signal ($M_{H^{\pm\pm}}$)	
Cut	WZ	ZZ	$t\bar{t}$	Zbb	Ztt	Wtt	200 GeV	600 GeV
Pre-selection	0.2	130.5	1.3	0.2	122.6	0.1	400.1	4.2
$\|m_{\ell^+\ell^-} - m_Z\| > 10$ GeV	0.1	2.1	0.3	0	2.1	0.1	330.6	4.1
$H_T > 300$ GeV	0	0.4	0	0	1.2	0	327.9	4.1
$H_T > 500$ GeV	0	0.1	0	0	0.3	0	222.9	4.1
$\mathcal{S}$							48.7	3.7

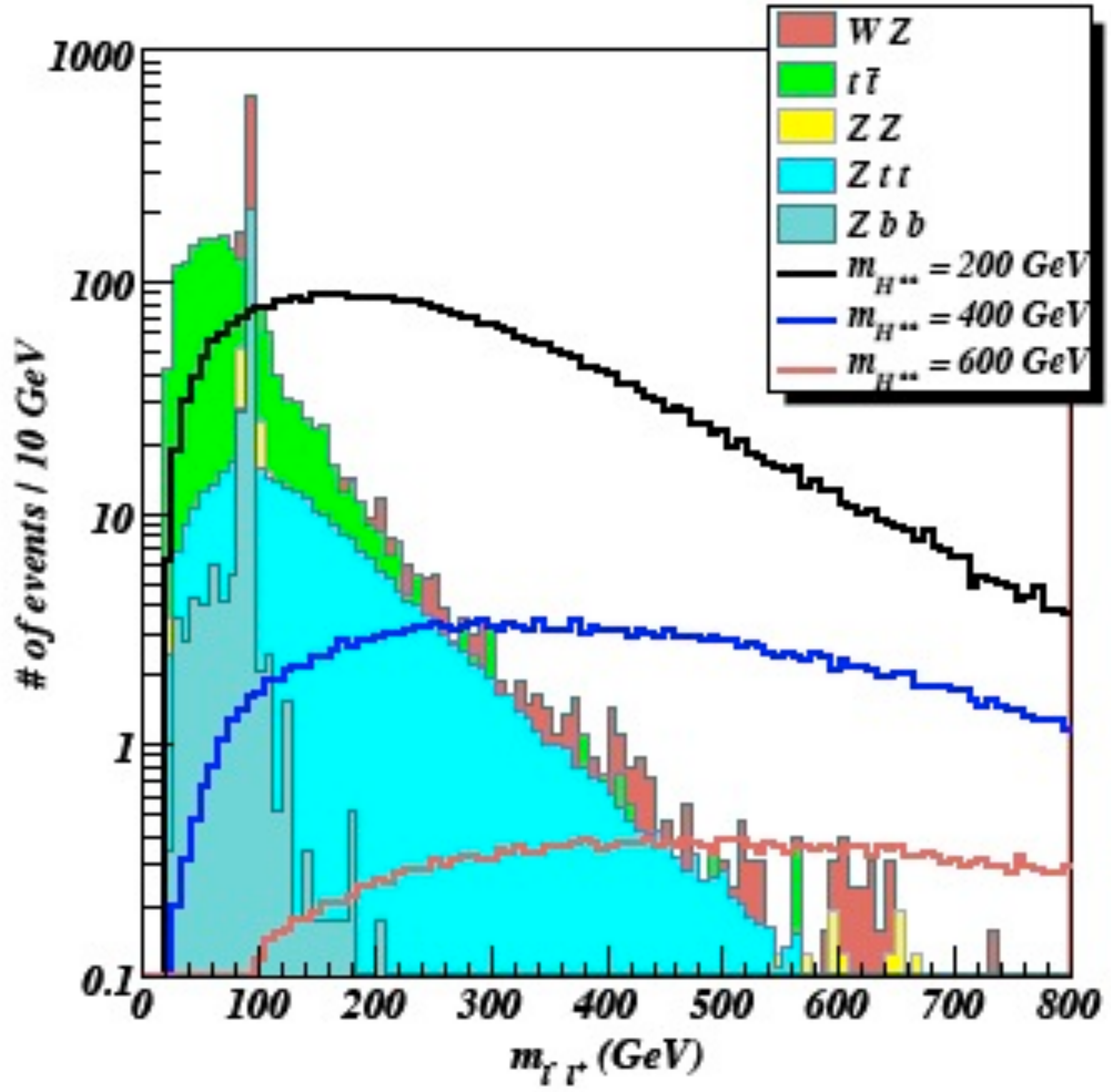
>= 3 lepton :

	Backgrounds							Signal ($M_{H^{\pm\pm}}$)	
Cuts $\Downarrow$	WZ	WWW	ZZ	$t\bar{t}$	Zbb	Ztt	Wtt	200	600
Pre-selection	591.7	3.5	203.6	159.9	57.7	212.5	9.7	1570.4	17.6
$\|m_{\ell^+\ell^-} - m_Z\| > 10$ GeV	50.9	2.7	12.1	113.2	0.9	33.4	7.4	1397.8	17.3
$H_T > 300$ GeV	7.5	1.1	1.6	8.9	0	17	3.4	1351.1	17.3
$H_T > 500$ GeV	1.7	0.3	0.4	0.9	0	3.2	0.6	796.2	17.3
$\mathcal{S}$								77.4	5

Missing transverse energy

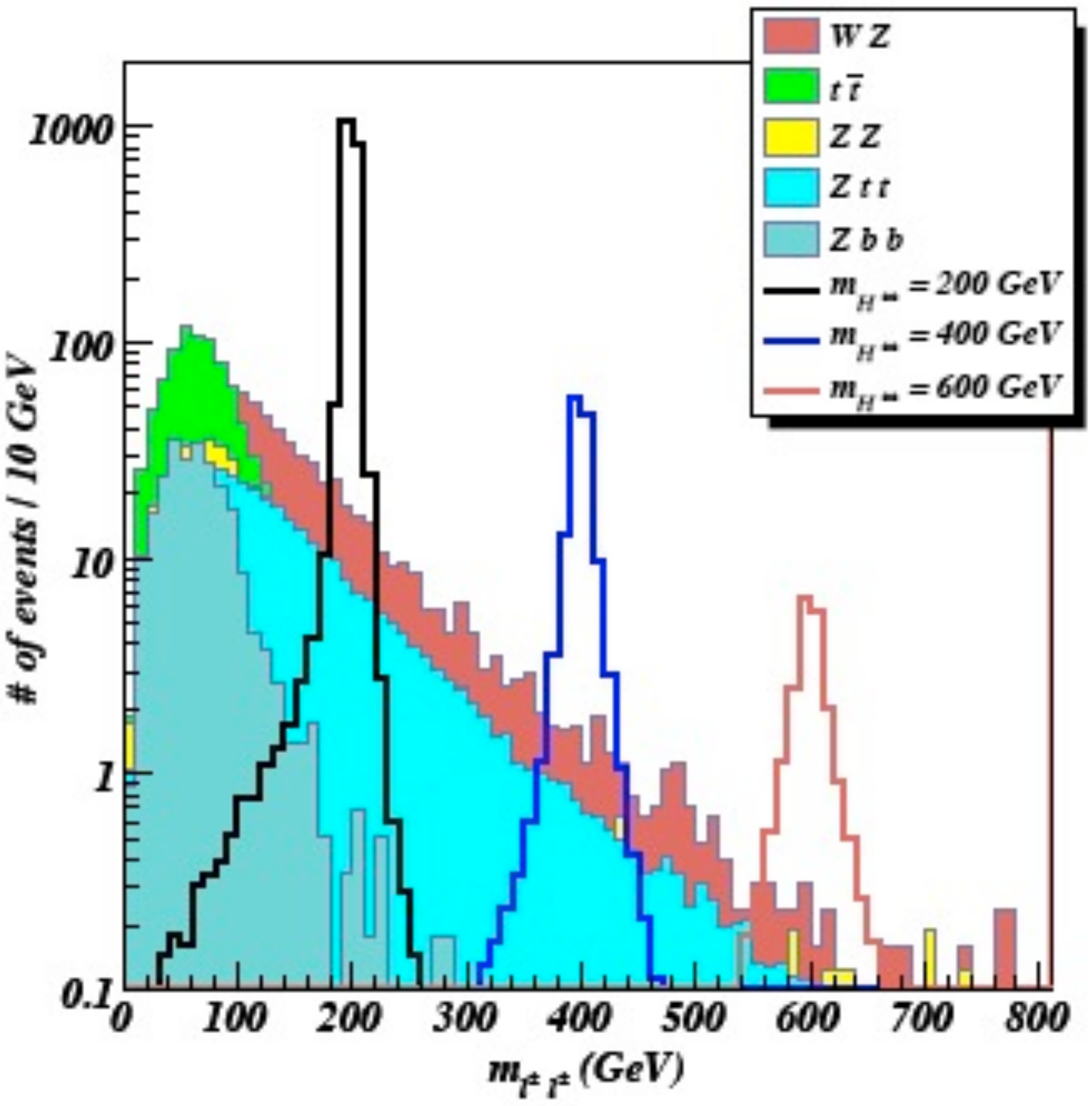


Opposite sign dilepton invariant mass

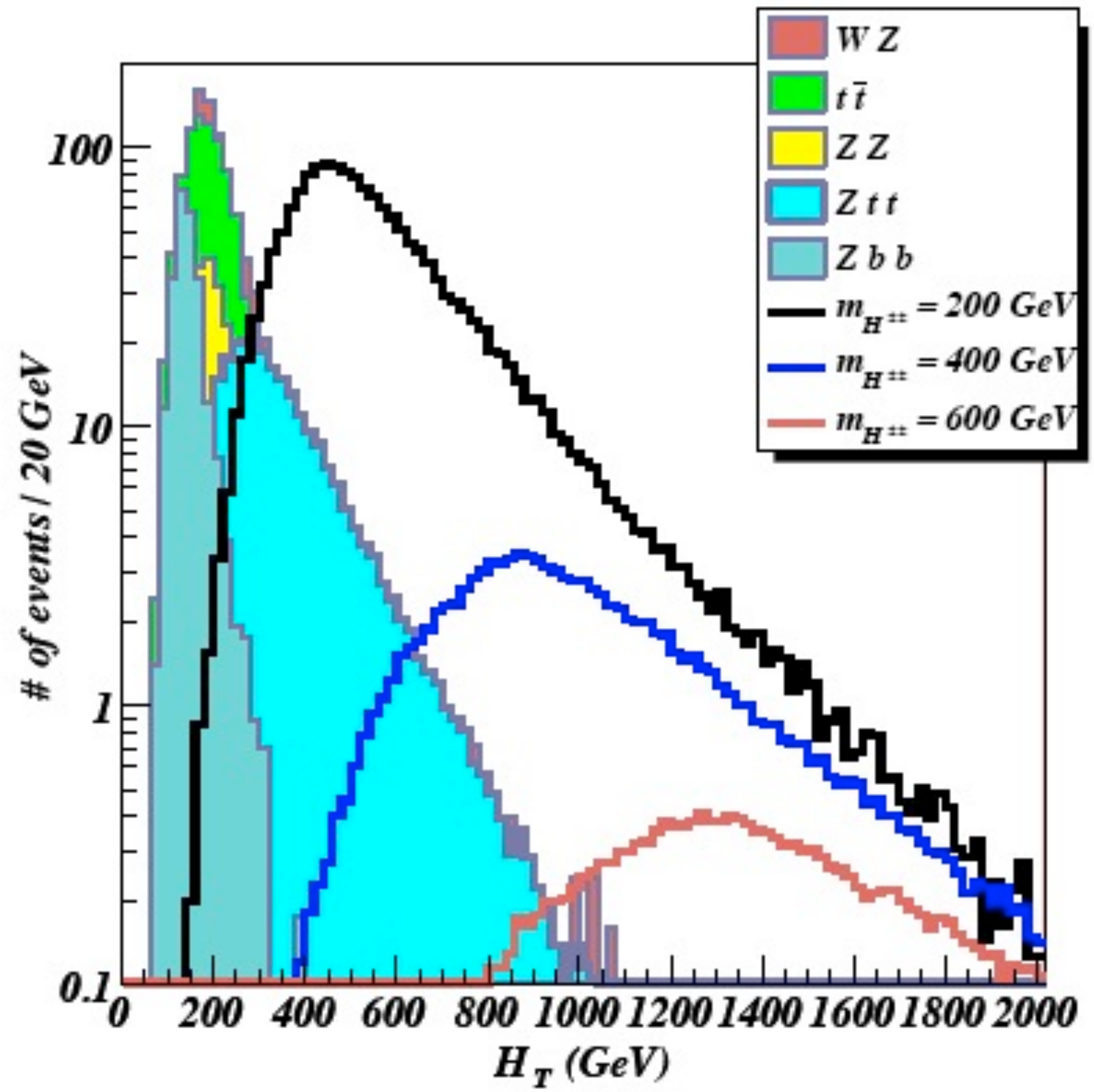


could be used to distinguish = 4l and >= 3l signatures

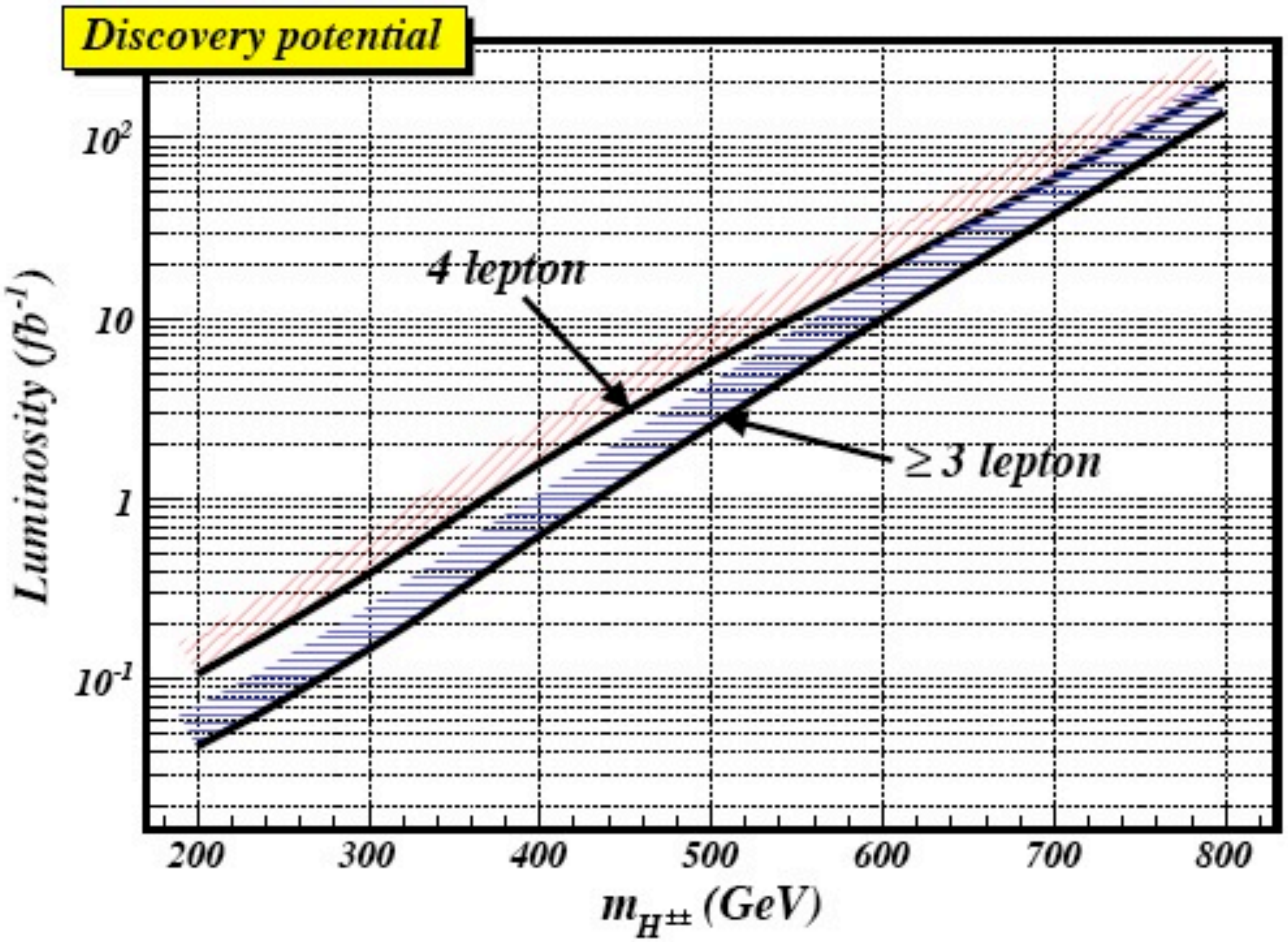
Same sign dilepton invariant mass



Total transverse energy



Comparison of exact 4 lepton and >= 3 lepton



Requests for Experimentalists :

- **Tevatron:** Include the process $p\bar{p} \to H^{\pm\pm}H^{\mp}$ in the analysis when searching for the $\geq 3\ell$ signature.
- **LHC:** Search for the $\geq 3\ell$ signature to increase the LHC discovery reach of the doubly charged Higgs boson.