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Collider Studies of Higgs Triplet Model

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JHEP **11**, 005 (2010) (1009.2780 [hep-ph])

Outline

- Motivation of Higgs Triplet Model (HTM)
- Properties of charged Higgs bosons ($H^{\pm\pm}$ and $H^{\pm}$)
- Production and signature of $H^{\pm\pm}$ at hadron colliders
- Summary

Physics Beyond SM

- Theoretical considerations suggest new physics:
  - Naturalness (fine-tuning or hierarchy problem)
  - Cosmological constant problem
  - Origin of CP violation and 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)

Neutrino Mass Data

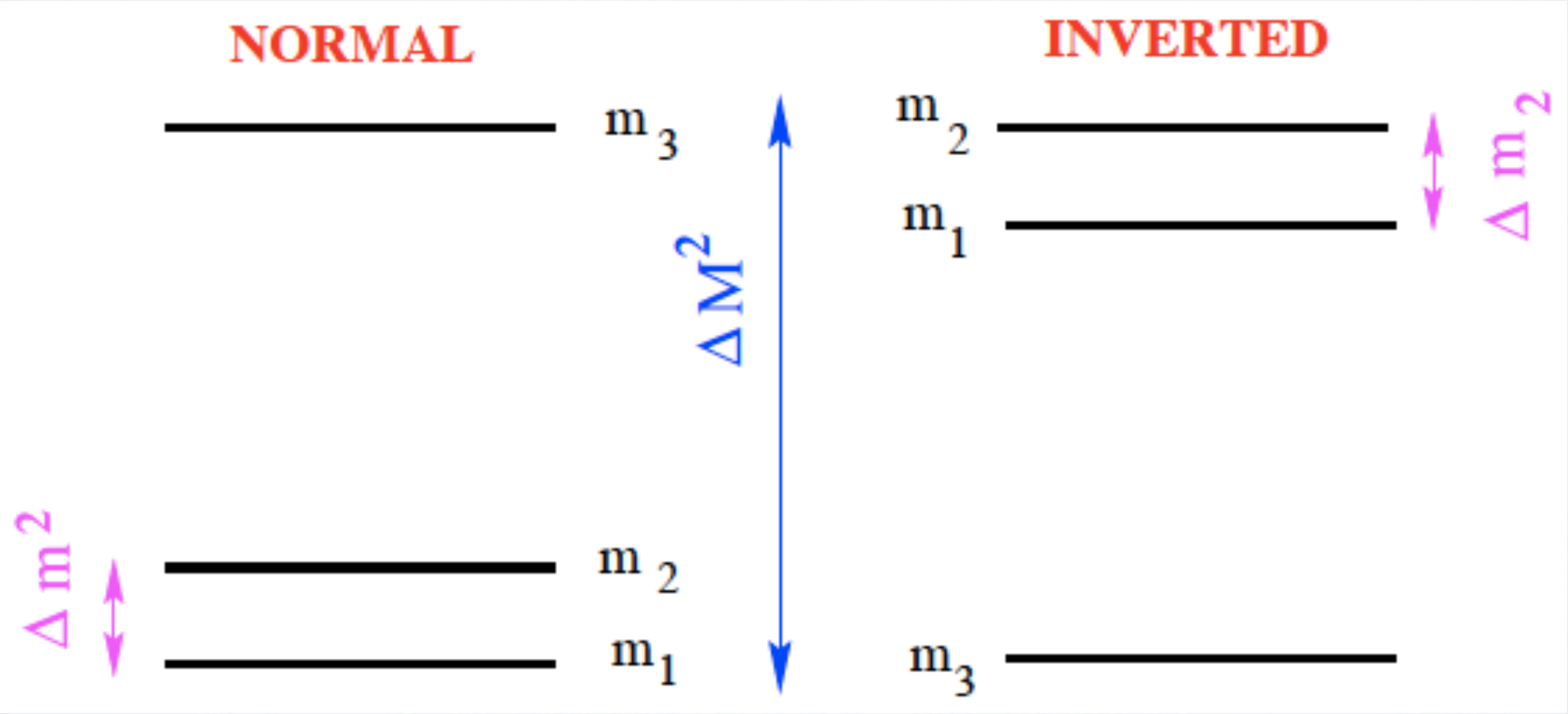
- Cosmic and astronomical observations: $\Sigma\, m_\nu \leq 1$ eV. Seljak 2004
- Solar and atmospheric neutrino experiments give:

$$\Delta m^2_{21} \simeq 8 \times 10^{-5} \mathrm{eV}^2 \ , \qquad |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3} \mathrm{eV}^2 \ ,$$

$$\sin^2 2\theta_{12} \simeq 0.8 \ , \qquad \sin^2 \theta_{23} = 0.5 \ , \qquad \sin^2 2\theta_{13} \simeq 0 \ ,$$

Maltoni, Schwetz, Tortola, Valle 2004

- 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 $\Rightarrow$ Yukawa couplings $\leq 10^{-11}$ $\Rightarrow$ fine-tuning
  - Explore possibilities beyond SM

SEESAW MECHANISM

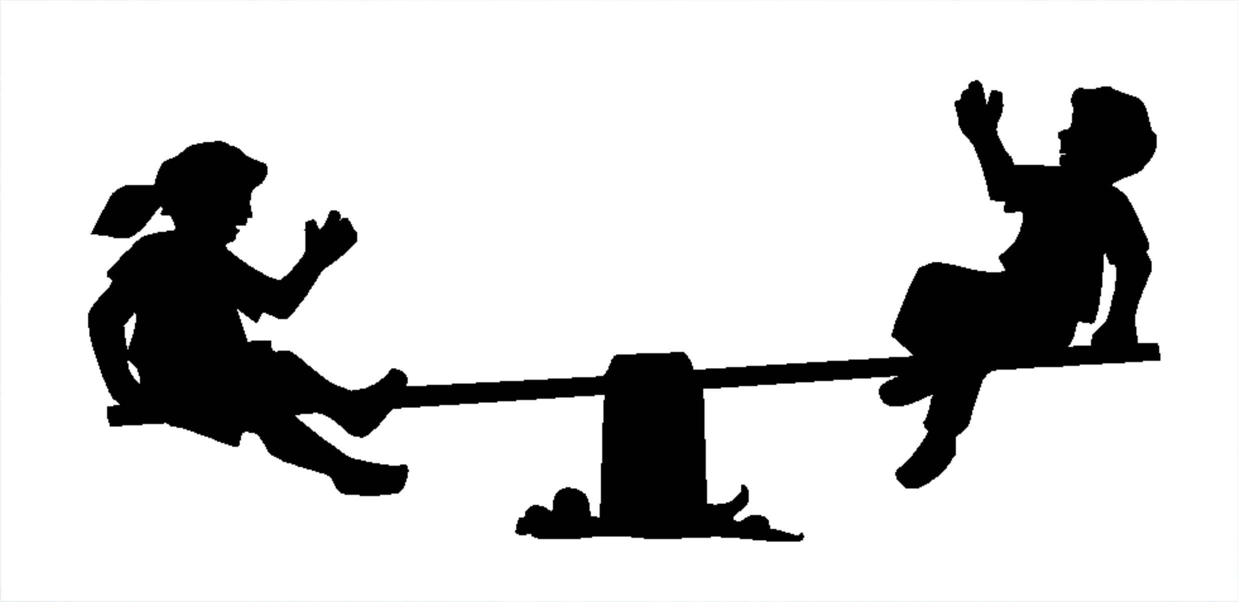
Minkowski 1977; Gell-Mann, Ramond, Slansky 1979;
Yanagida 1979; Glashow 1980; Mohapatra, Senjanovic 1980

- SM neutrinos can be naturally much lighter than their charged partners and of *Majorana* nature.

- Achieve seesaw while:

➡ keeping 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.



“The ‘most natural’ new physics: A lonely Higgs boson is NOT enough!”

-- Han’s talk

Seesaw Type II (aka HTM)

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

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

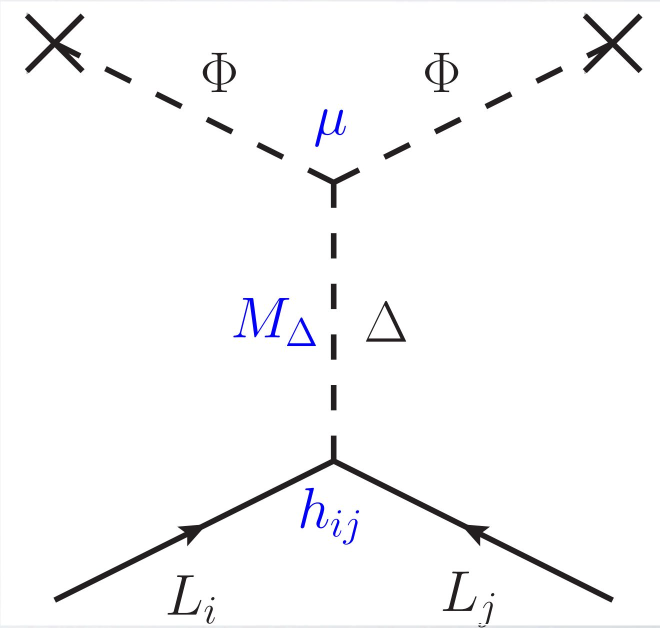
$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

with gauge invariant potential ($m^2 < 0$, $M_\Delta^2 > 0$ and $\mu > 0$):

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

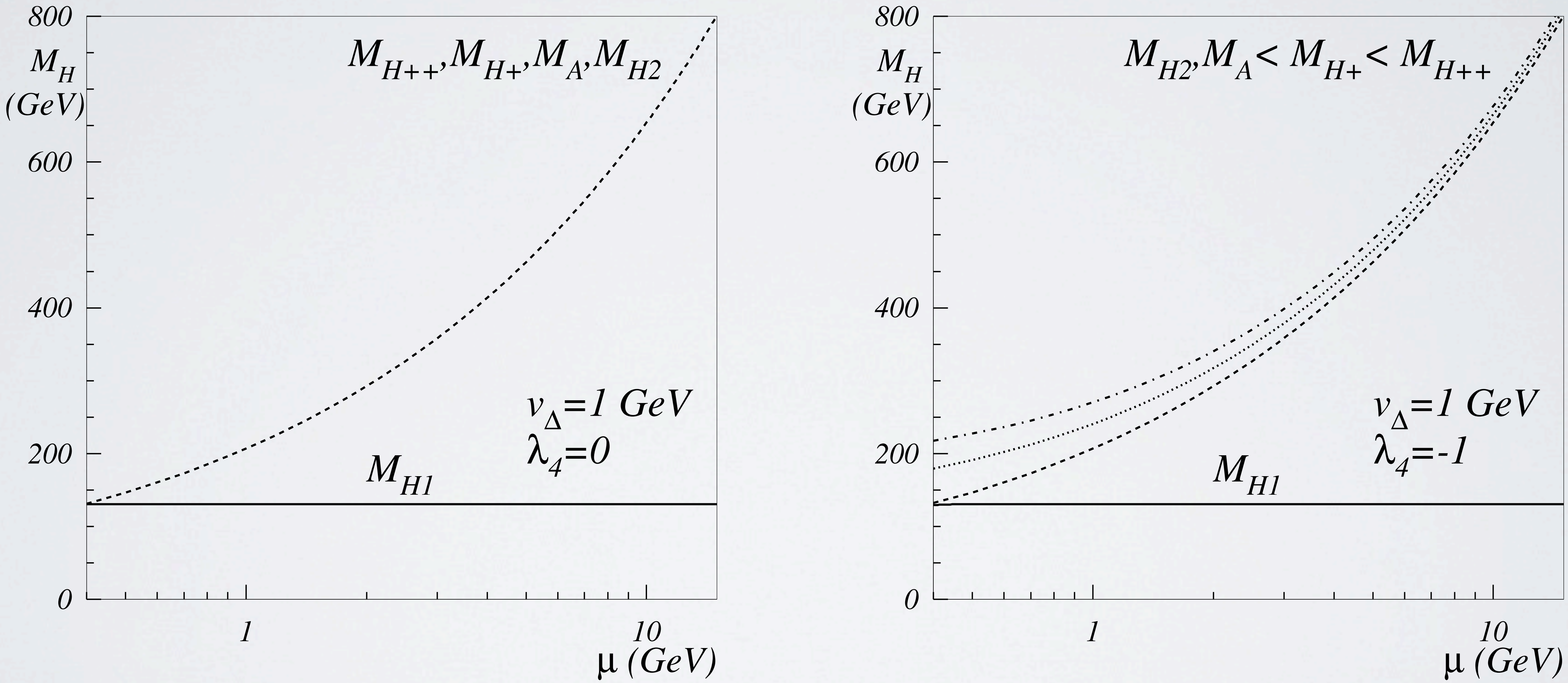
- Triplet VEV and Majorana neutrino mass

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



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.



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

CONSTRAINTS ON v_Δ

- Based on realistic neutrino masses, perturbation is allowed for $v_\Delta \geq 1$ eV.

- Non-zero Higgs triplet VEV leads to

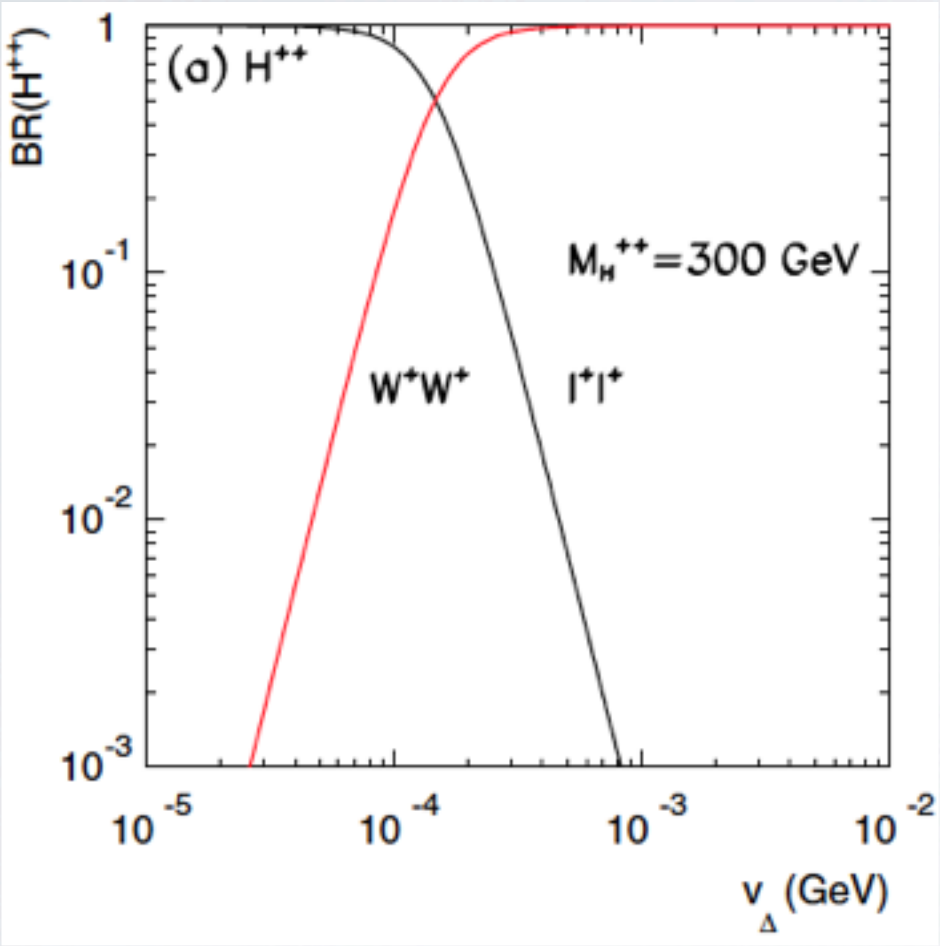
$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} \neq 1$$

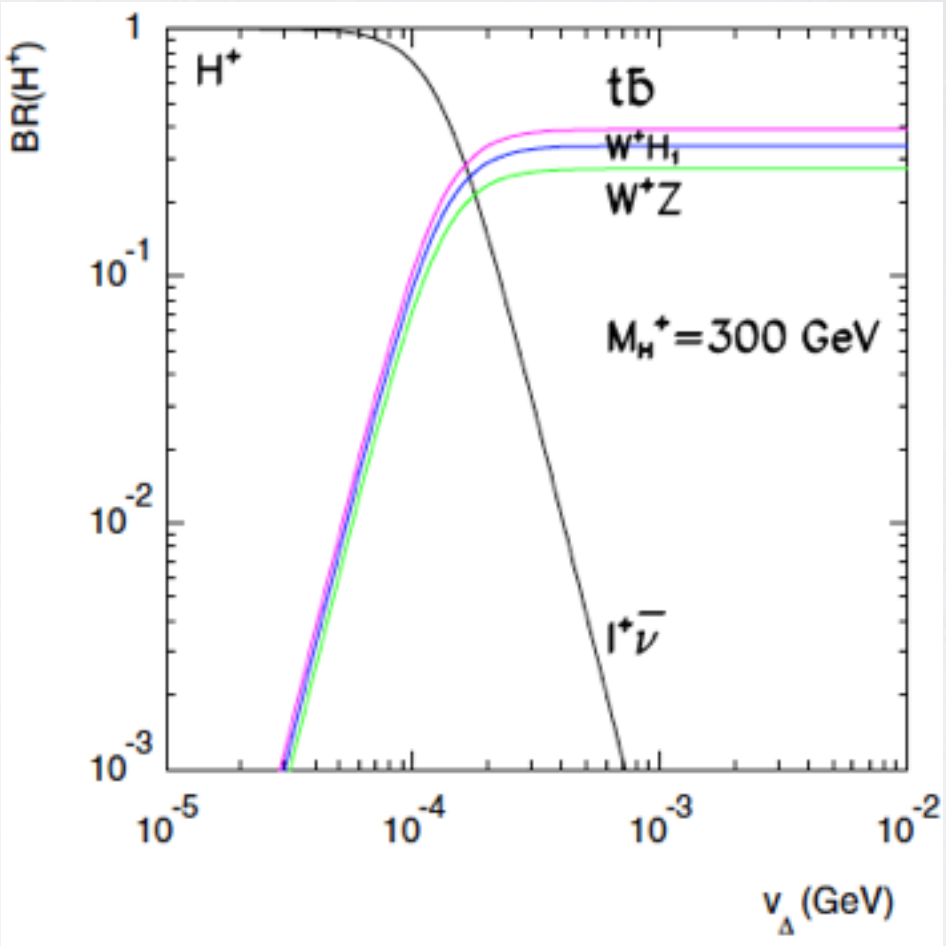
  Current $\varrho^{exp} \approx 1.0004^{+0.0008}_{-0.0004}$ requires that $v_\Delta \leq$ a few GeV.

PDG 2008;
Abada et al 2007

DECAY MODES

- Both $H^{\pm\pm}$ and $H^{\pm}$ can decay dominantly into *leptonic* final states -- more desirable at hadron colliders.





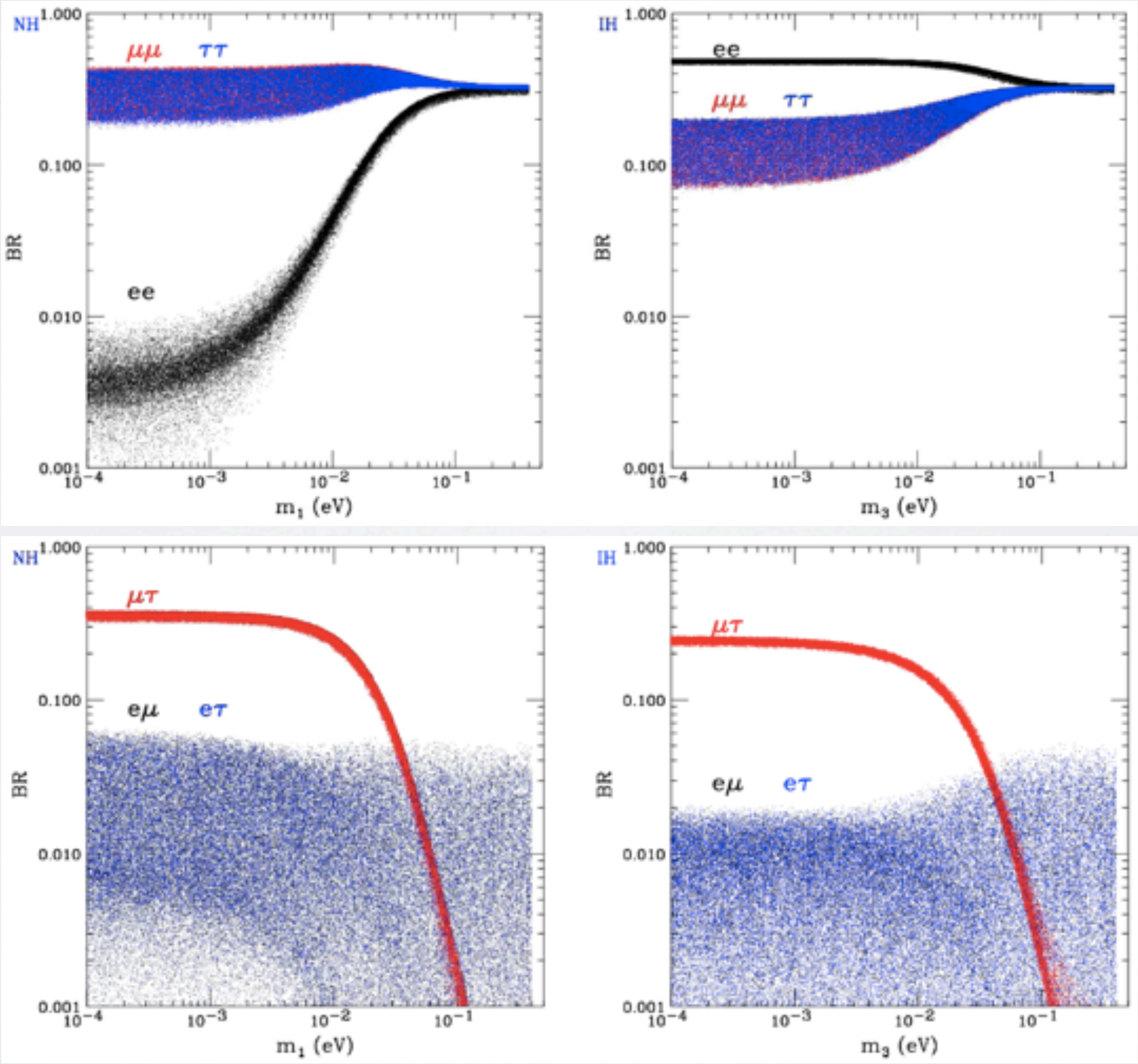
Perez et. al. 2008

- Concentrate on small v_Δ scheme ($< 10^{-4}$ GeV) and assume $M_{H^{\pm\pm}} = M_{H^{\pm}}$ for simplicity.

Leptonic $H^{\pm\pm}$ Decays

- BF's of leptonic modes versus lightest neutrino mass, assuming zero Majorana phases:

Perez et. al. 2008

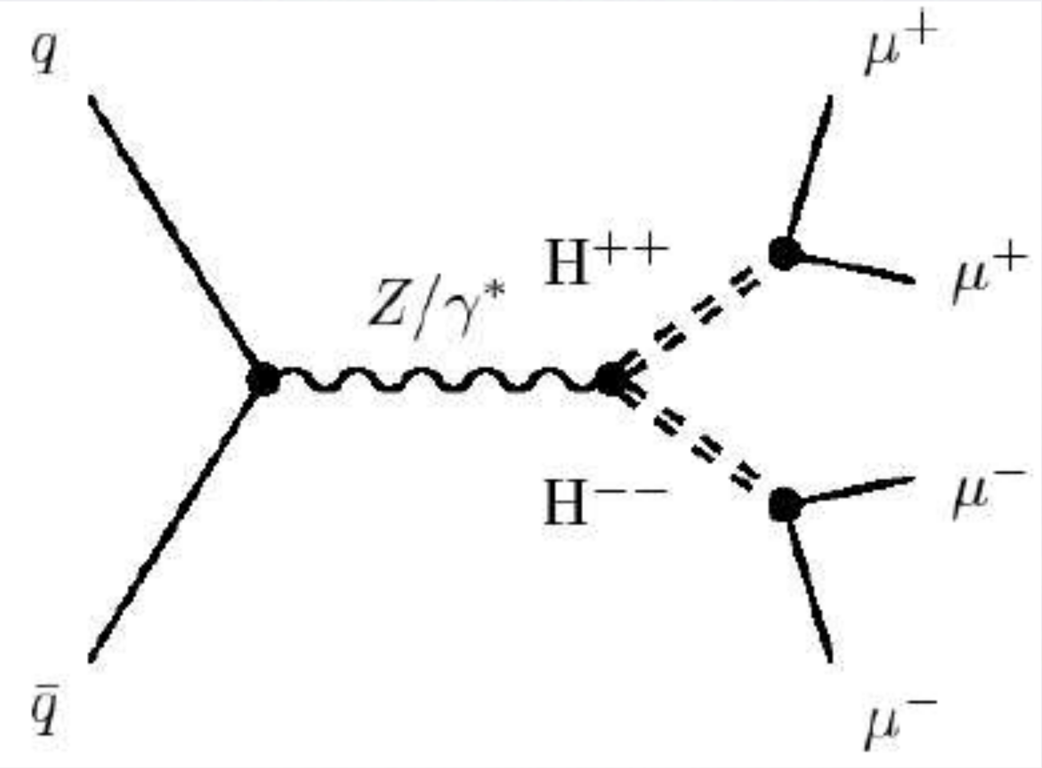


flavor conserving

flavor changing

SEARCHES AT TEVATRON

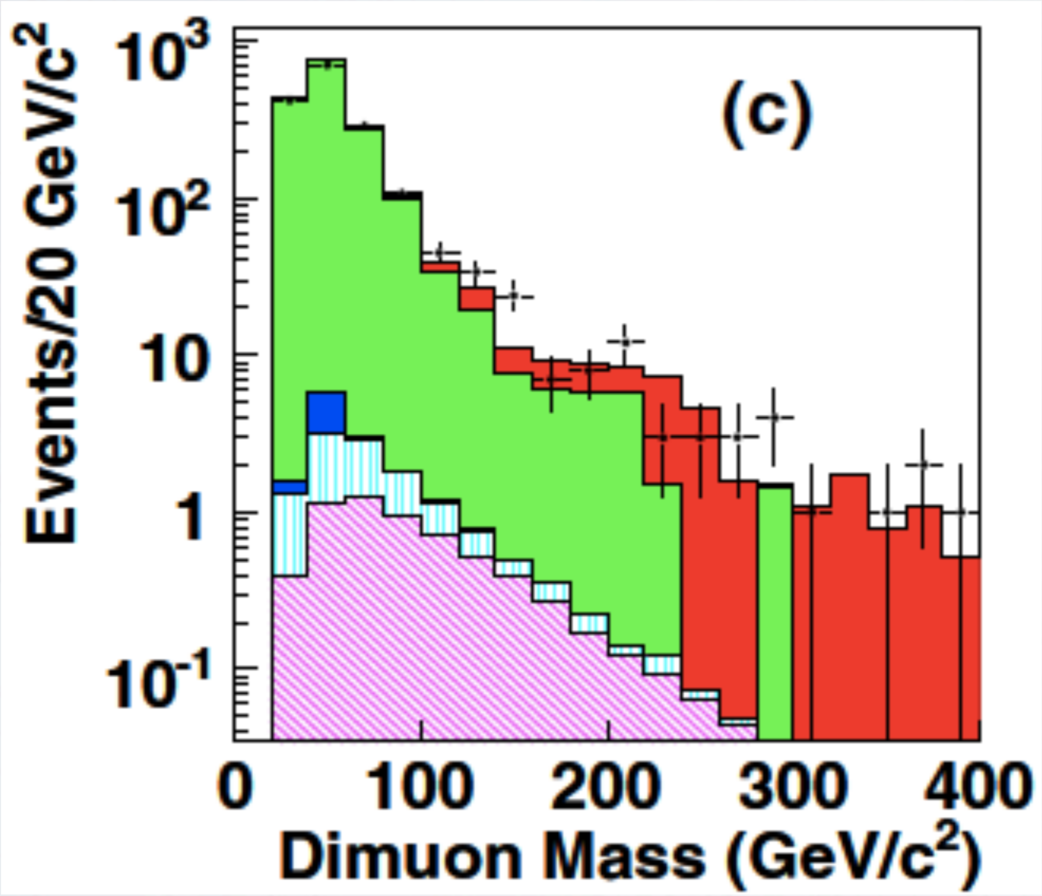
- Smoking gun of the model: production of doubly-charged Higgs boson that then decays into like-sign lepton pairs.
- CDF and D0 at Tevatron started first searches in 2003.
- The searches have assumed
  - $q\bar{q} \to \gamma^*/Z \to H^{++}H^{--}$ is the only significant production channel
  - $H^{\pm\pm}$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



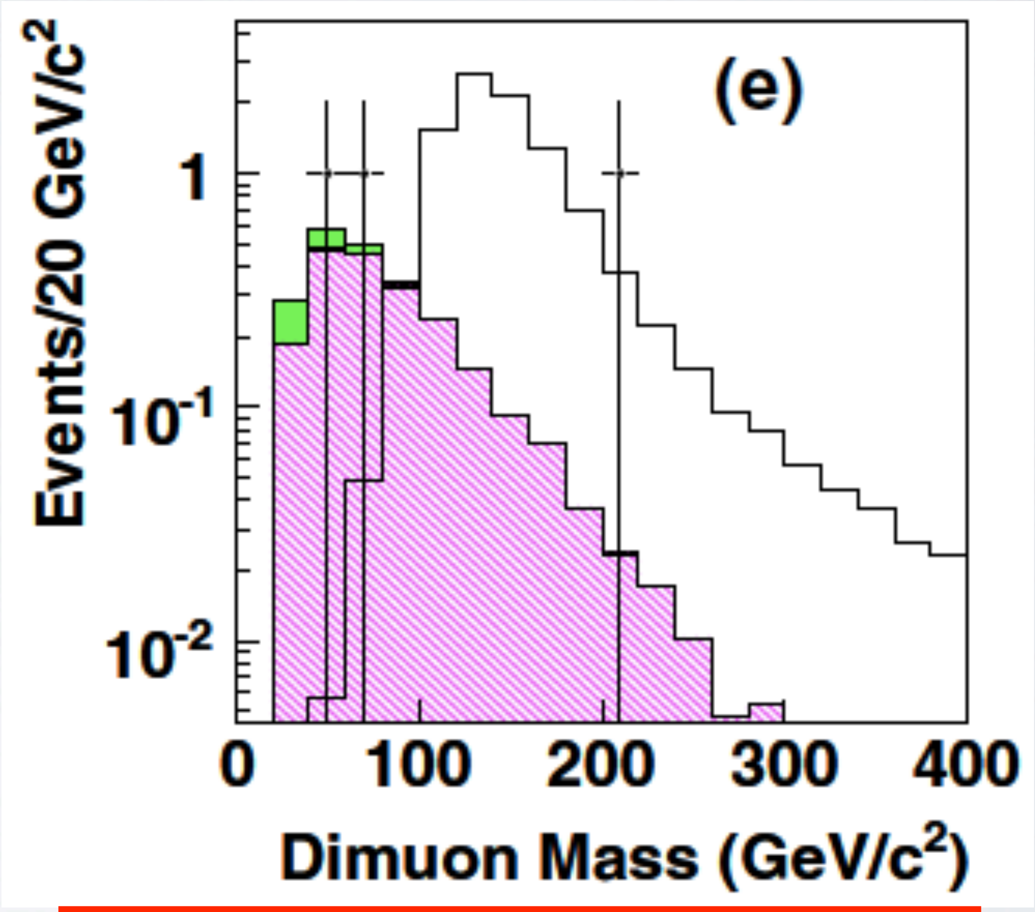
RESULTS

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?



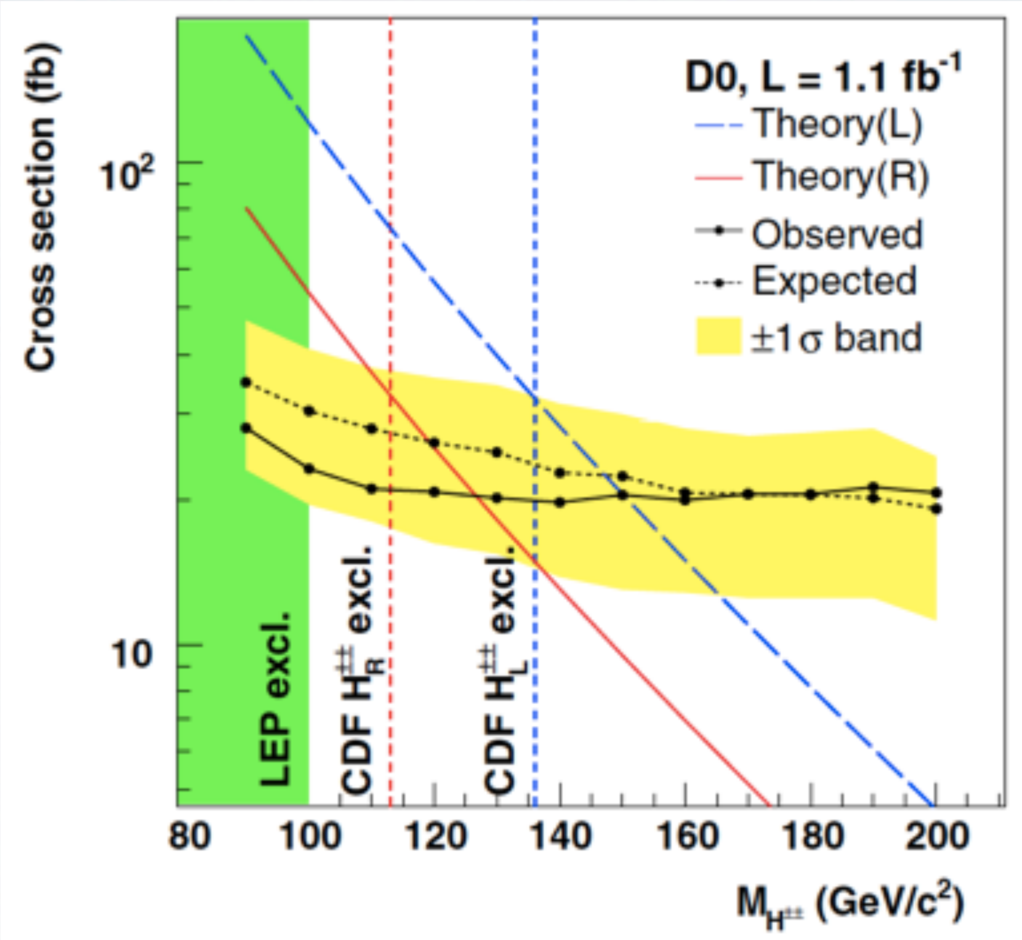
open histogram expected for $m_{H^{\pm\pm}}$ = 140 GeV

Lower Mass Limit

D0 2008

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

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

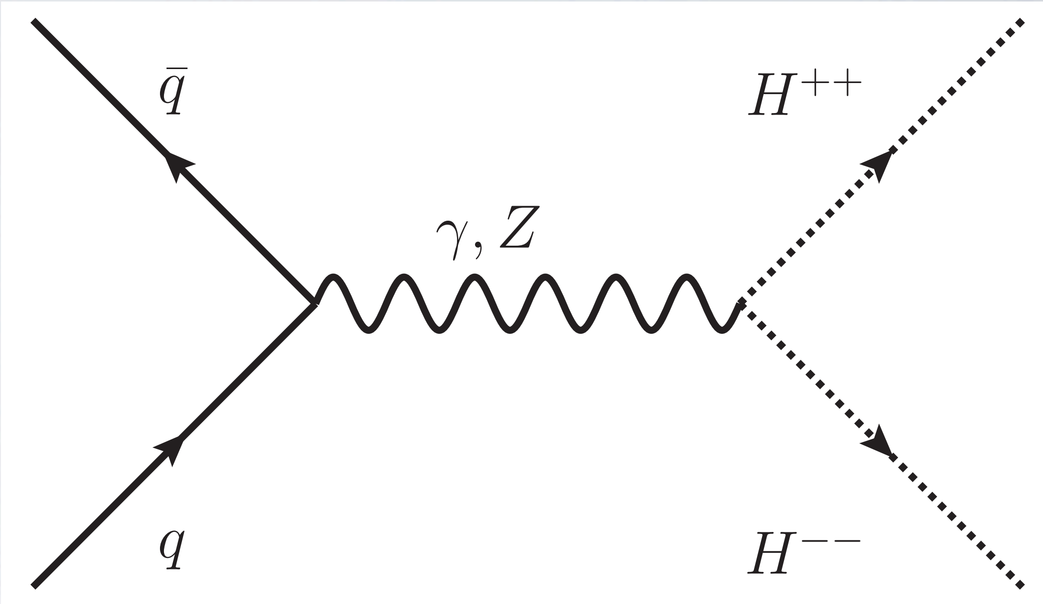


- However, they have overlooked:
(A) one important mechanism, and (B) other final states.

$H^{\pm\pm}$ Production

- $\sigma_{H^{\pm\pm}H^{\mp\mp}}$ is a function of $m_{H^{\pm\pm}}$ and independent of h_{ij} .

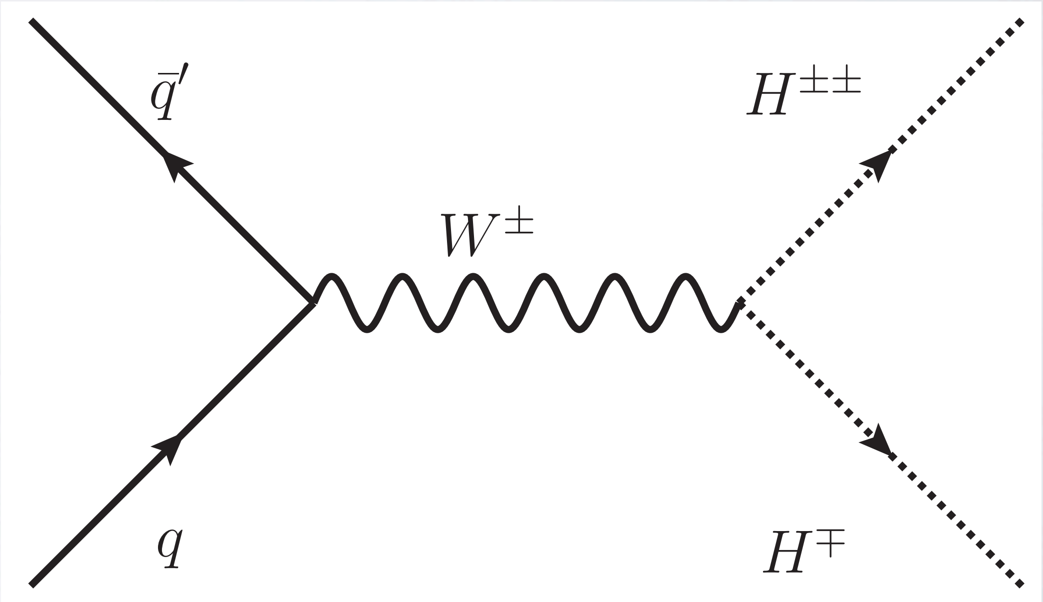
Barger et al 1982; Gunion et al 1989; Huitu et al 1997



$$(\partial^\mu H^{--})H^{++}\,(gW_{3\mu} + g' B_\mu) + \text{h.c.}$$

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

Gunion 1998, Dion et. al 1999

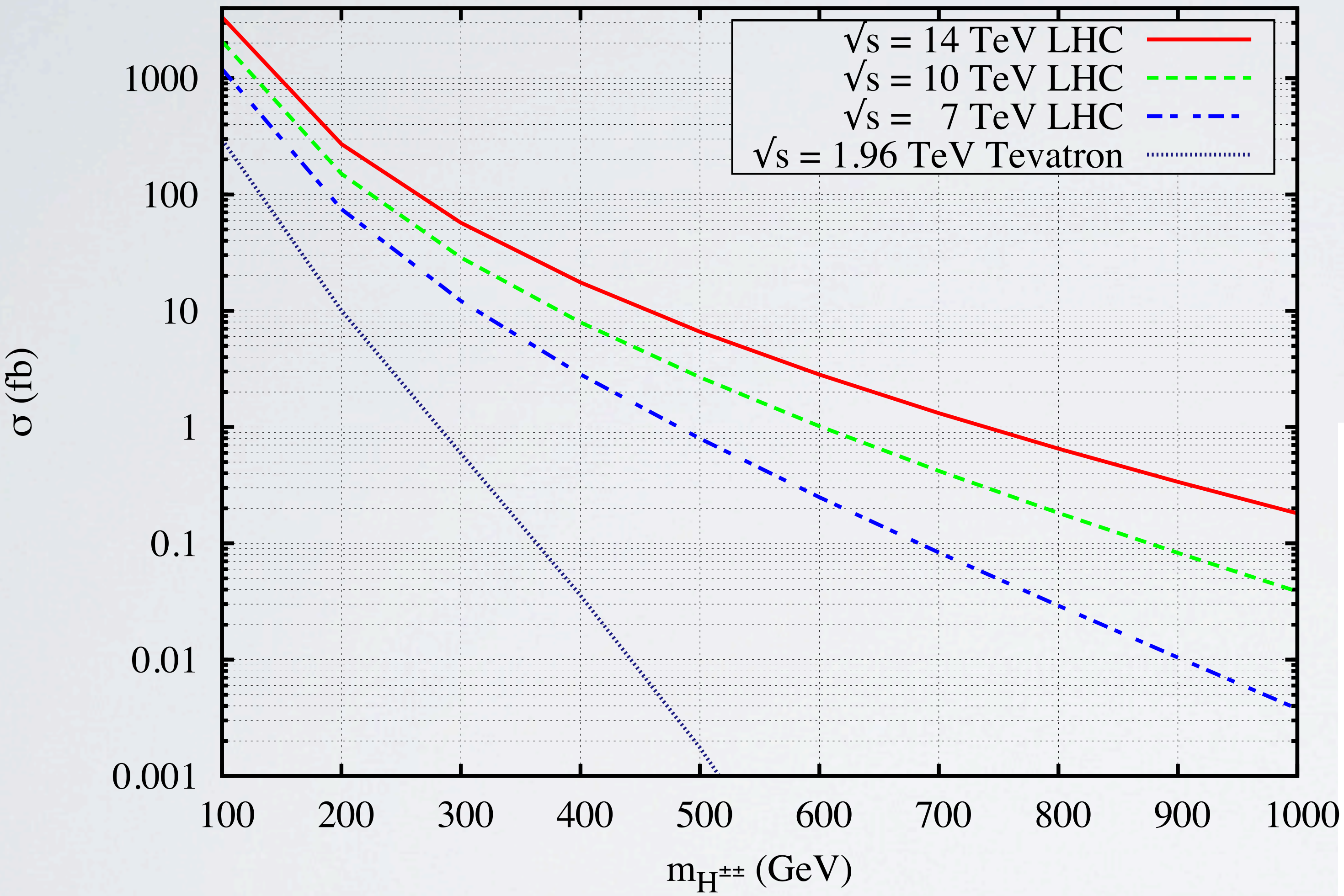


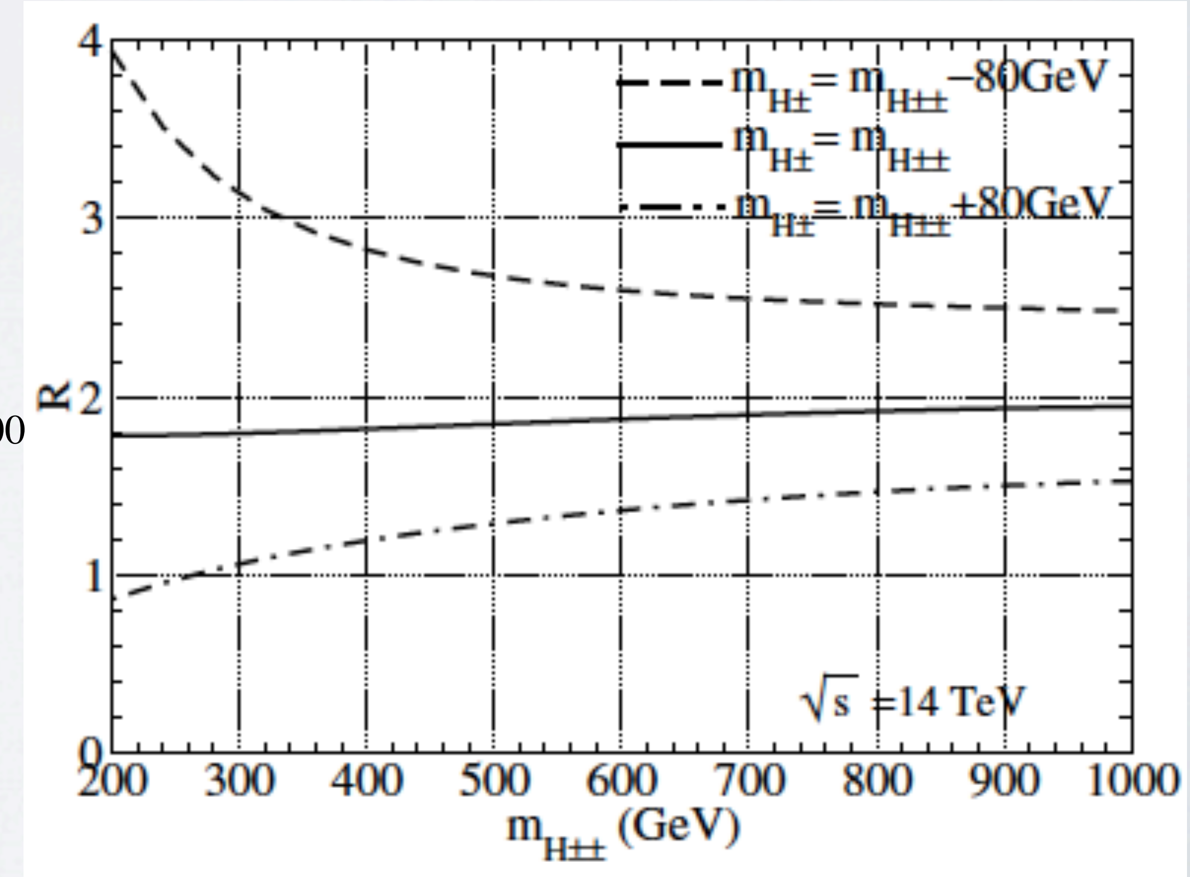
- If $m_{H^{\pm\pm}} \sim m_{H^{\pm}}$, then $\sigma_{H^{\pm\pm}H^{\mp}}$ and $\sigma_{H^{++}H^{--}}$ are about same order of magnitude
$\Rightarrow$ equally important!

$$ig\left[(\partial^\mu H^{++})H^{-} - (\partial^\mu H^{--})H^{+}\right] W^{+}_{\mu} + \text{h.c.}$$

Total Cross Section

- $M_{H^{\pm\pm}} = M_{H^\pm}$ and K = 1.25 (LHC) or 1.3 (Tevatron)





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

Akeroyd, Aoki 2005

Multi-Lepton Channels

- 4-lepton final states are clear channels from pair production of doubly-charged Higgs boson.
- 3-lepton final states with two same-signs and the other opposite-sign have a higher production rate and are best for discovery.

del Aguila, Aguilar-Saavedra 2009

- Consider only light charged leptons (ℓ =e,μ), 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:

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

Tri-Lepton Cross Section

- Define reduced (normalized) cross section through

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

- Reduced cross sections of the six channels are (for LHC):

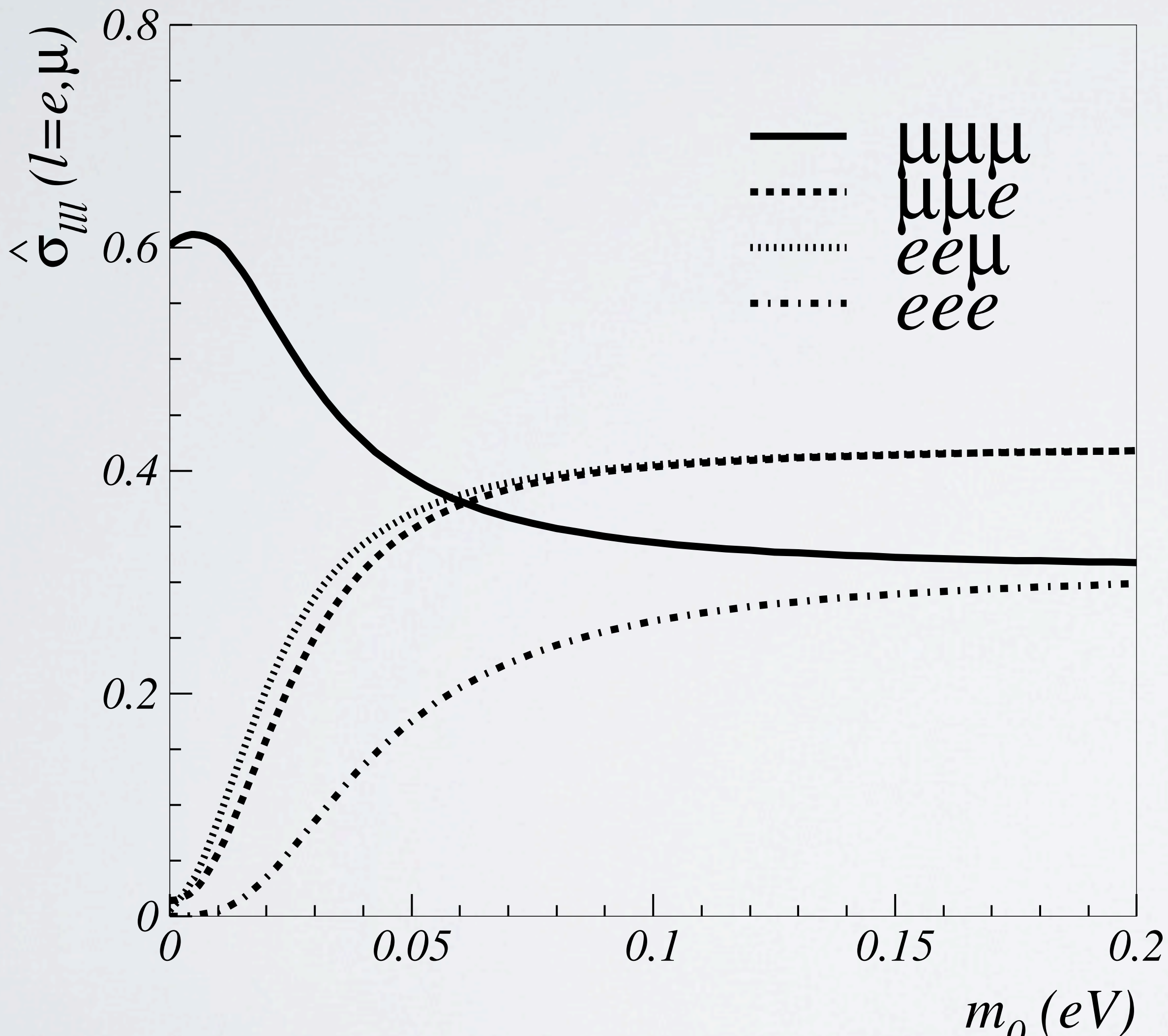
$$\begin{aligned}
\hat{\sigma}_{eee} &= \mathcal{B}_{ee}\left[\mathcal{B}_{ee} + 2(\mathcal{B}_{e\mu} + \mathcal{B}_{e\tau}) + 1.8\mathcal{B}_{e\nu}\right] \;, \\
\hat{\sigma}_{ee\mu} &= \mathcal{B}_{ee}\left[2(\mathcal{B}_{\mu\mu} + \mathcal{B}_{e\mu} + \mathcal{B}_{\mu\tau}) + 1.8\mathcal{B}_{\mu\nu}\right]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

first two of same sign and last one of opposite sign

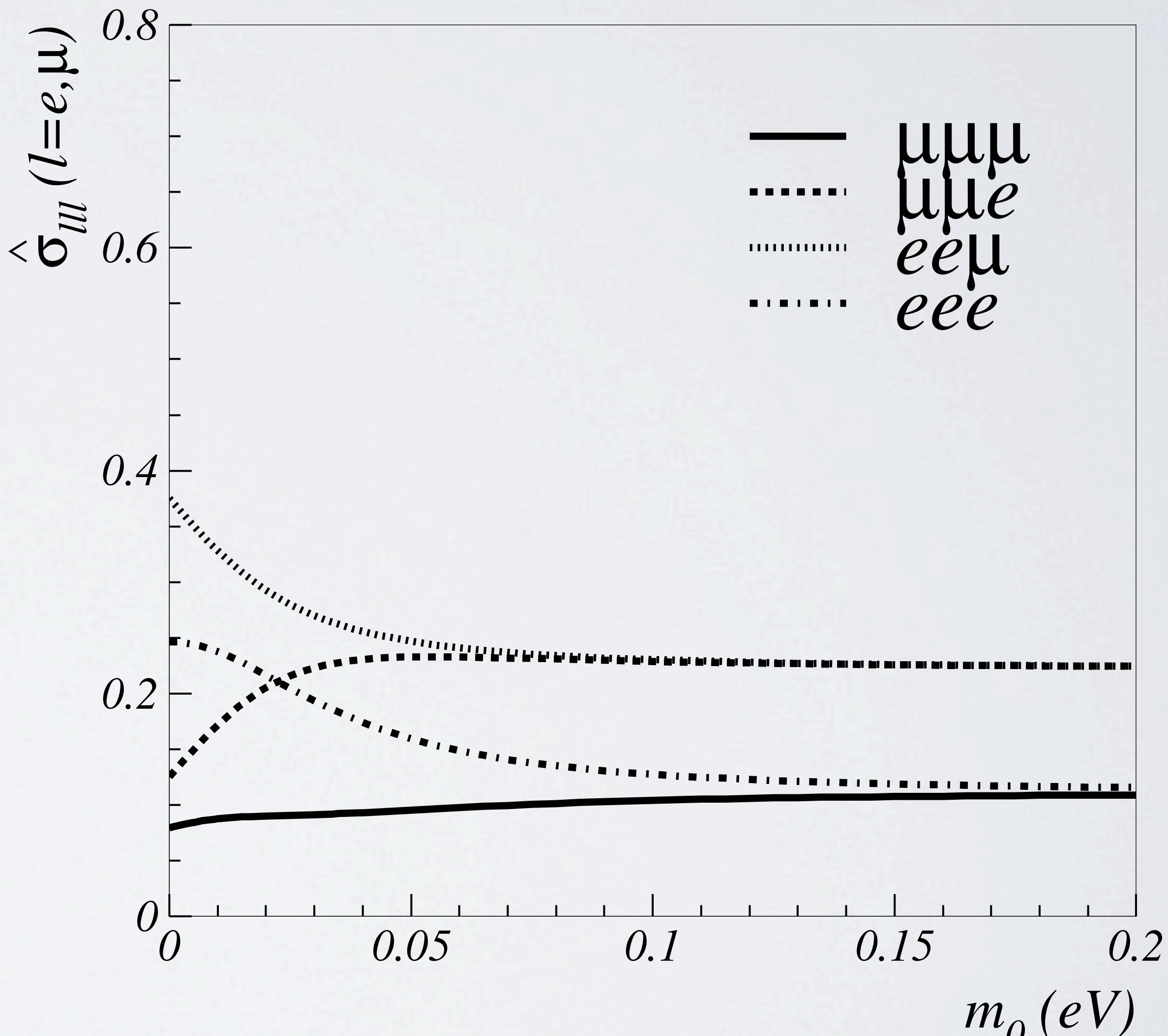
additional contribution to these processes than CDF and D0 considerations, 1.2 for Tevatron

Impact of Single Production

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



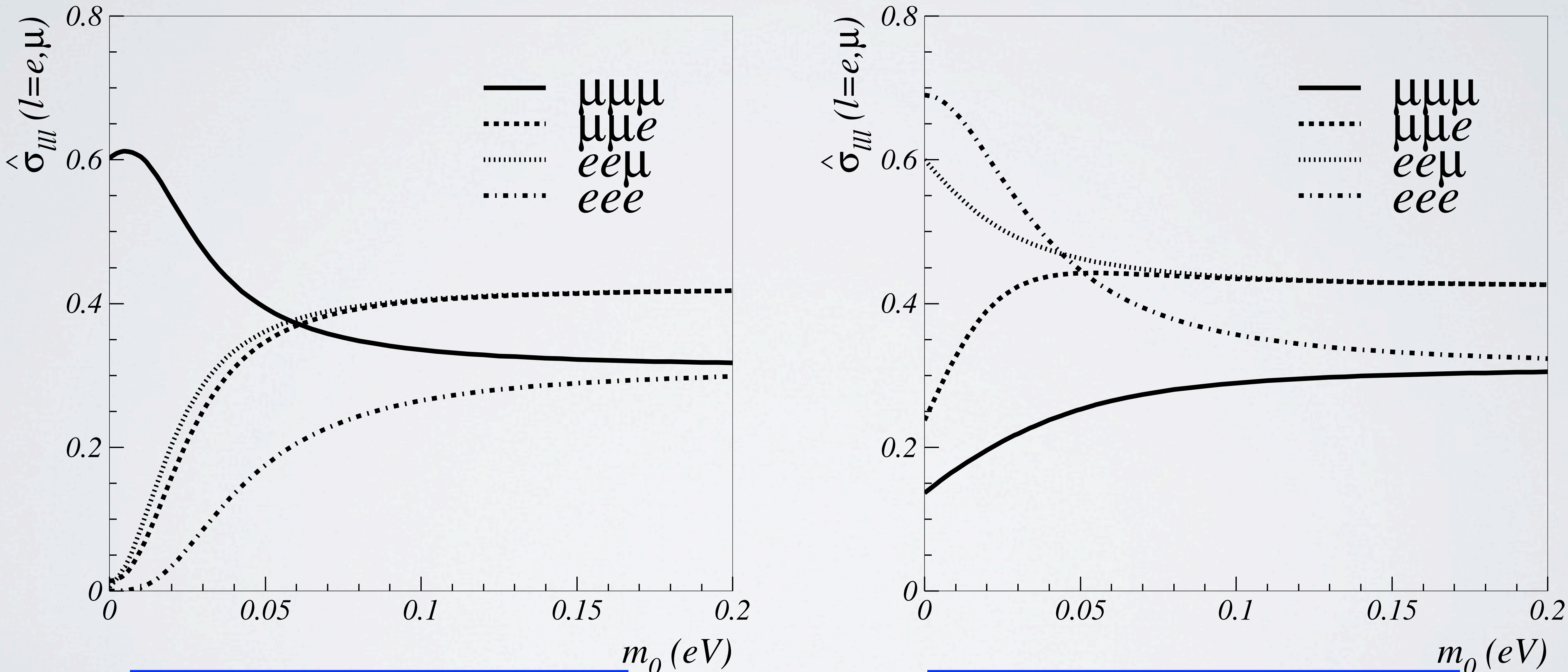
with single production



without

Results

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

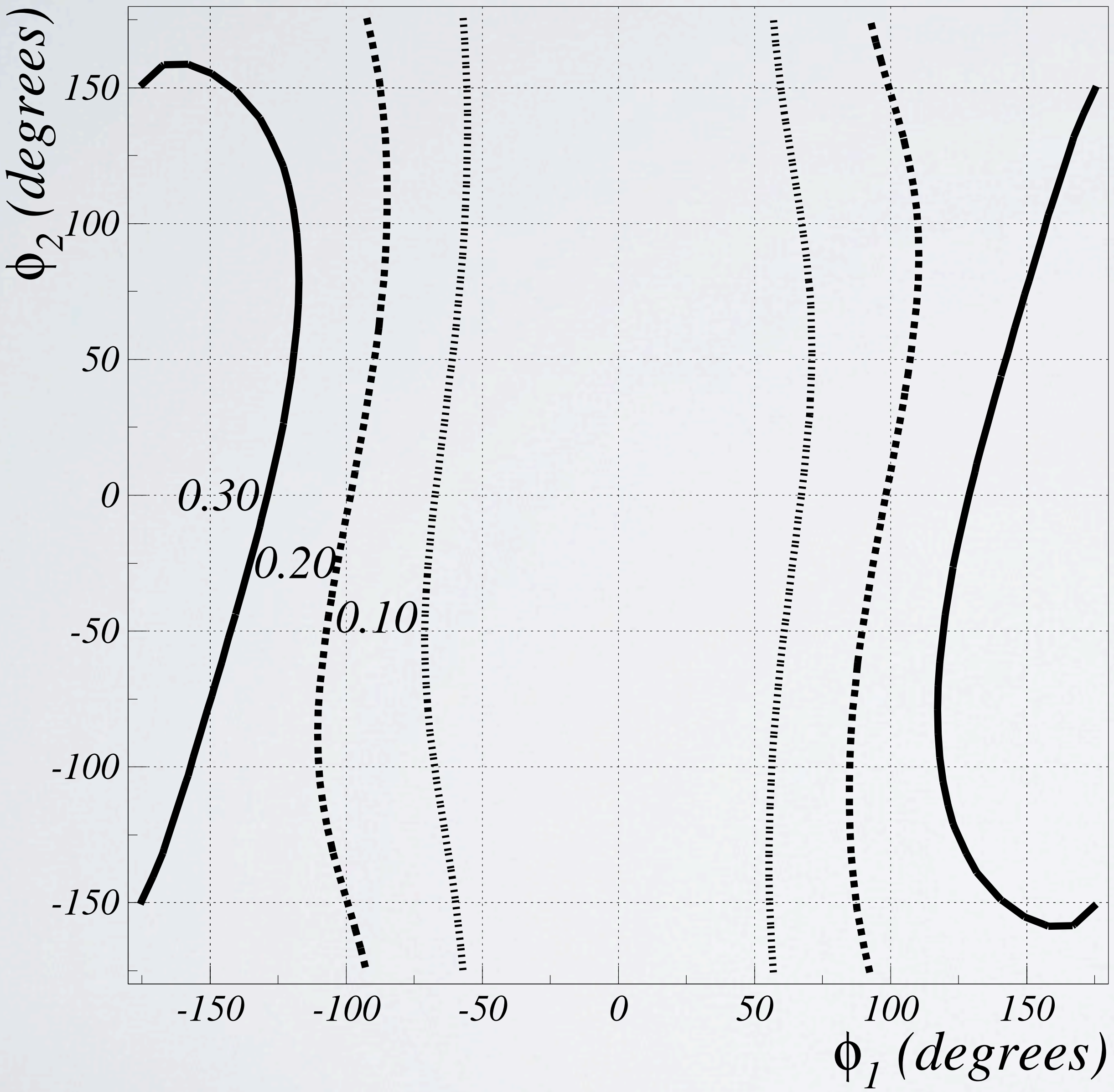


normal hierarchy

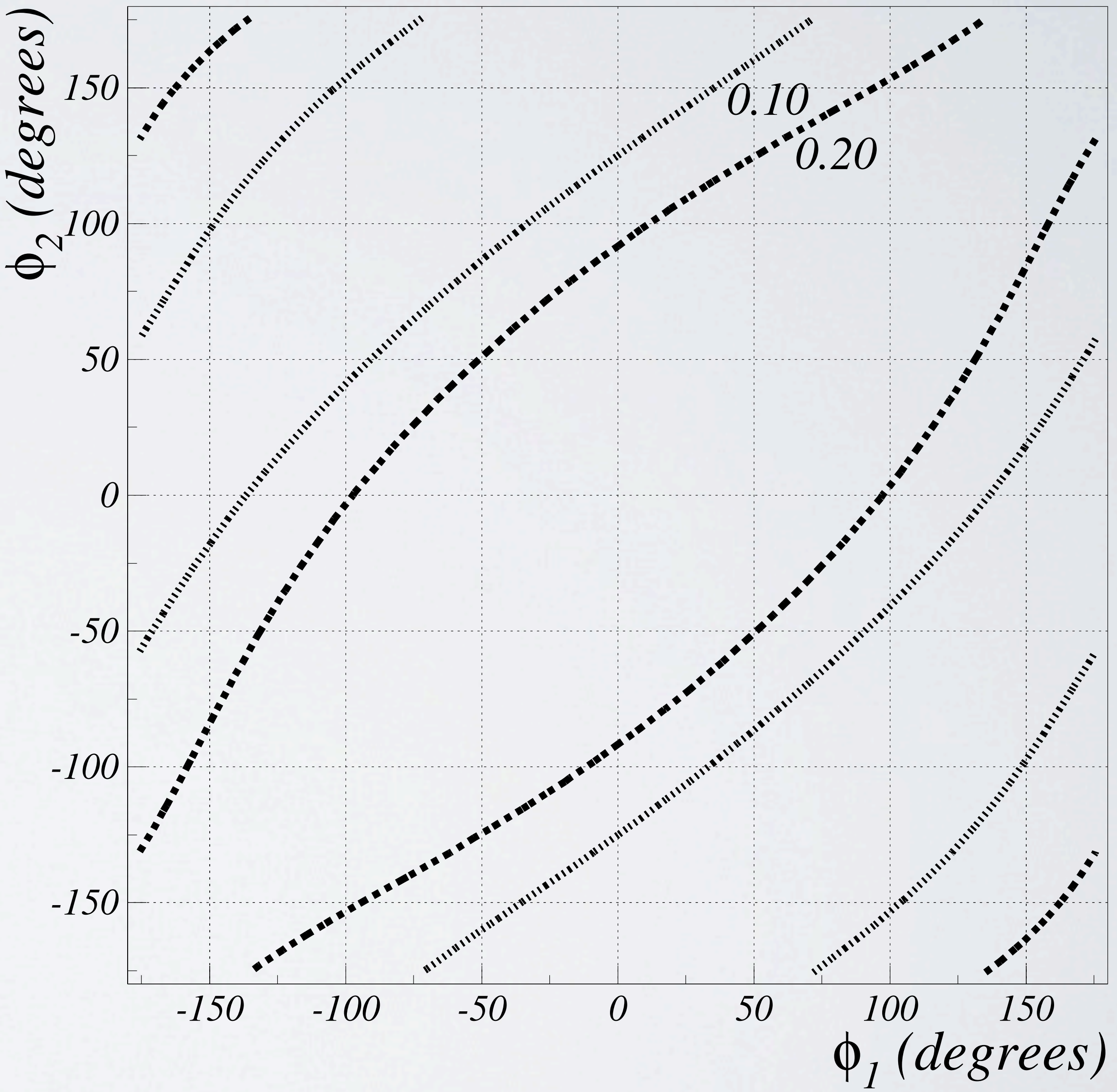
inverted hierarchy

Effects of Majorana Phases

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



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



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

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

- What are the prospects after imposing cuts and comparing to backgrounds?

≥ 3 Lepton Searches

- A search for 3 leptons and more (≥ 3 leptons) will improve the discovery prospects and have more sensitivity to the doubly-charged Higgs boson.
- Impose universal cuts, include detection efficiency, and compare with the 4-lepton search.

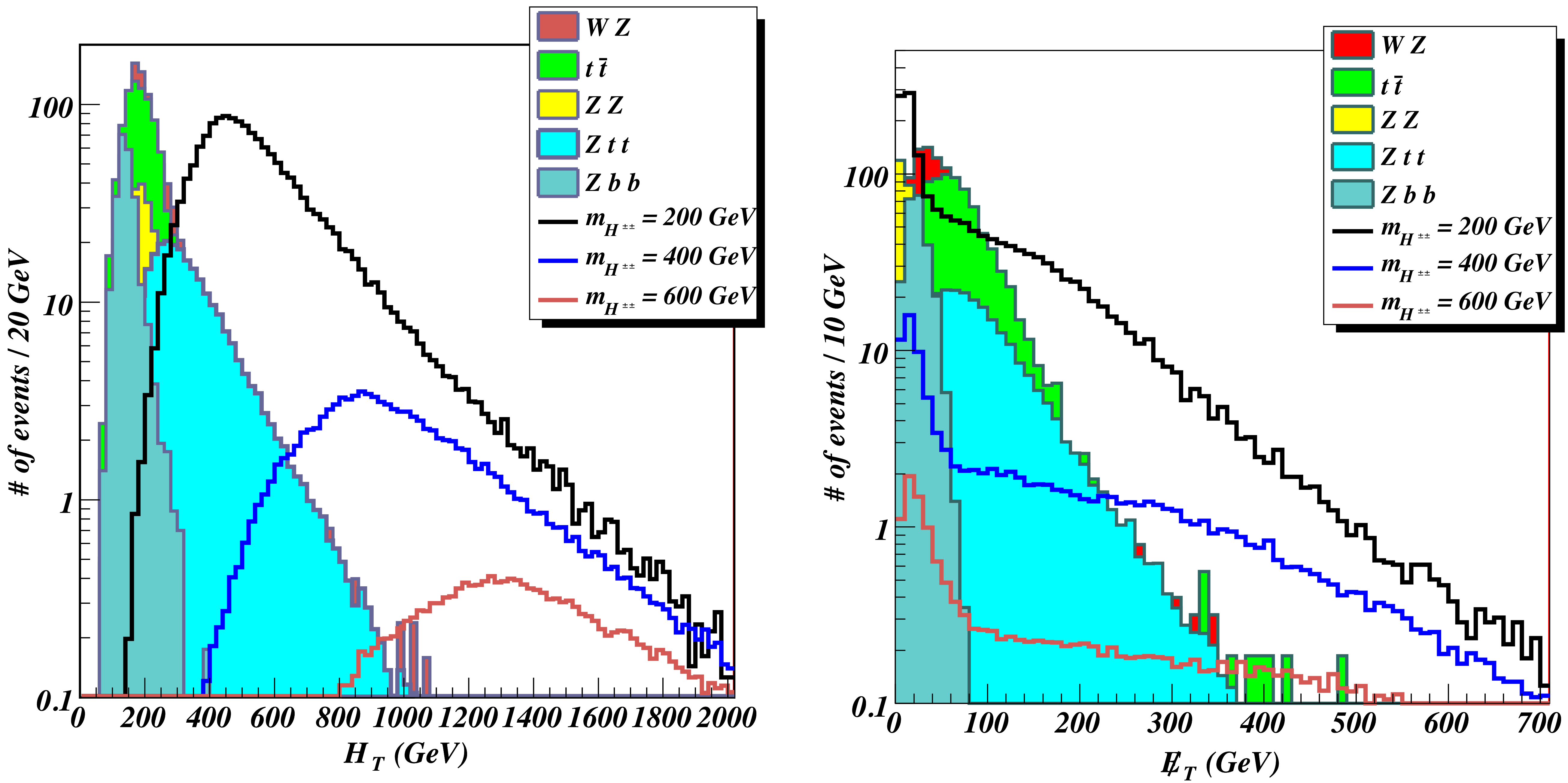
Event Generation

- Implement model in CalcHEP to generate signal events.
- Pass results to Pythia via the LHE interface.
- Include ISR/FSR in Pythia.
- Generate background events in Pythia.
- Use ATLFAST for simple detector simulations (jet construction, particle ID, etc).

Pre-Selection Cuts

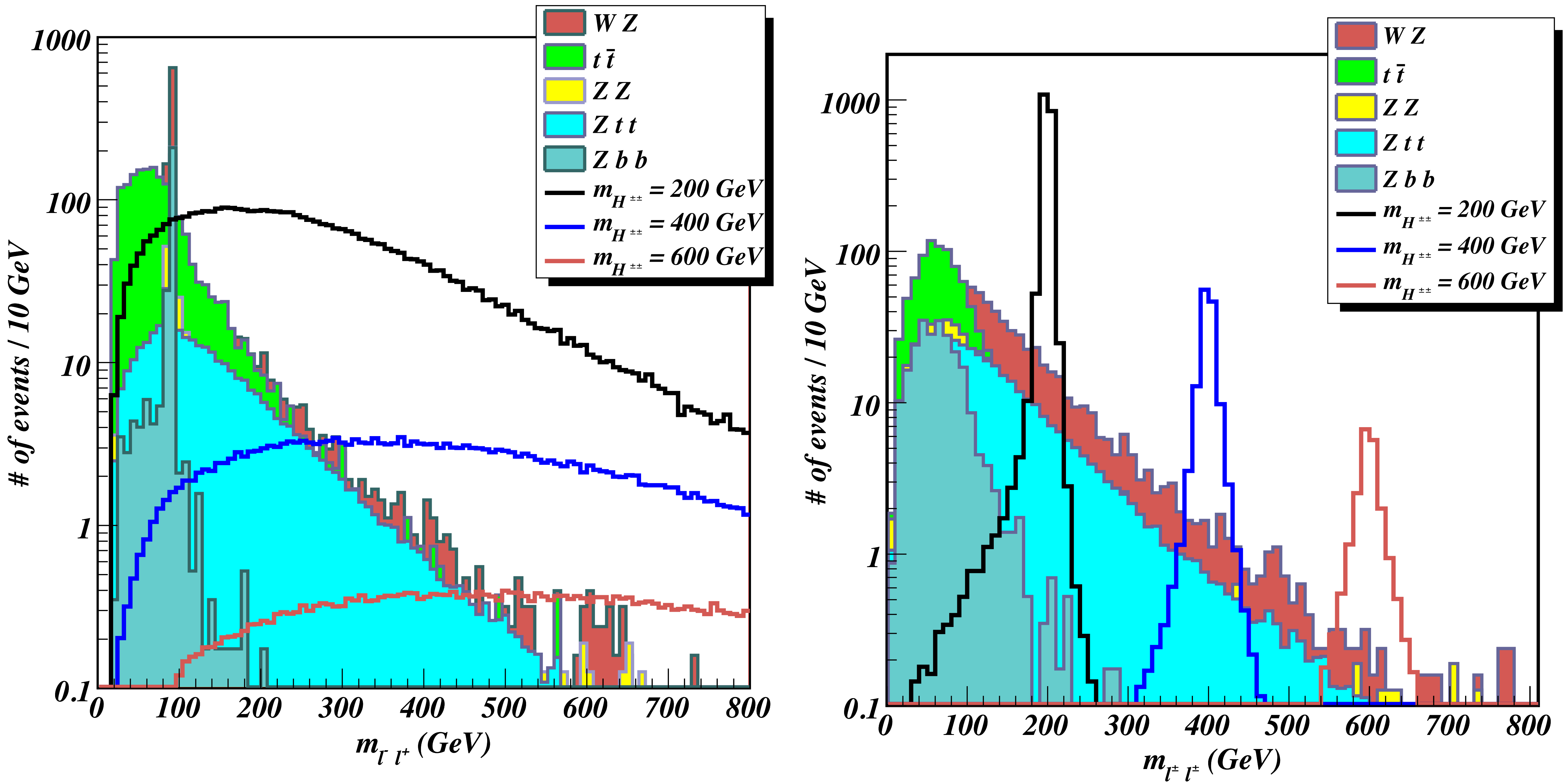
- Exactly four leptons with two for each charge sign (for 4ℓ); 3 or more leptons of different signs (for $\geq 3\ell$).
- Each lepton has $|p_T| > 5$ GeV and $|\eta| < 2.5$.
- At least two of the leptons have $|p_T| > 30$GeV.
- Opposite-sign dilepton invariant mass > 20GeV.

H_T and Missing E_T Distributions



- After imposing pre-selection cuts for CM energy = 14 TeV and L = 10 fb^{-1}.

Invariant Mass Distributions



Opposite-sign (left) and same-sign (right) dilepton invariant mass distributions.

4-Lepton Signature

- Only pair production mechanism contributes to this.
- For definiteness, take $BR(H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}) = BR(H^{\pm} \to \ell^{\pm}\nu) = 100\%$
- H_T = total transverse energy of leptons, including missing E_T from neutrinos.

	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
$\lvert m_{\ell^+\ell^-} - m_Z \rvert > 10\,\mathrm{GeV}$	0.1	2.1	0.3	0	2.1	0.1	330.6	4.1
$H_T > 300\,\mathrm{GeV}$	0	0.4	0	0	1.2	0	327.9	4.1
$H_T > 500\,\mathrm{GeV}$	0	0.1	0	0	0.3	0	222.9	4.1
$\mathcal{S}$							48.7	3.7

Table 4. Background and signal events surviving the cuts for exactly 4-lepton final states. For these numbers we have taken $\mathcal{L} = 10\,\mathrm{fb}^{-1}$ and $\sqrt{s} = 14\,\mathrm{TeV}$.

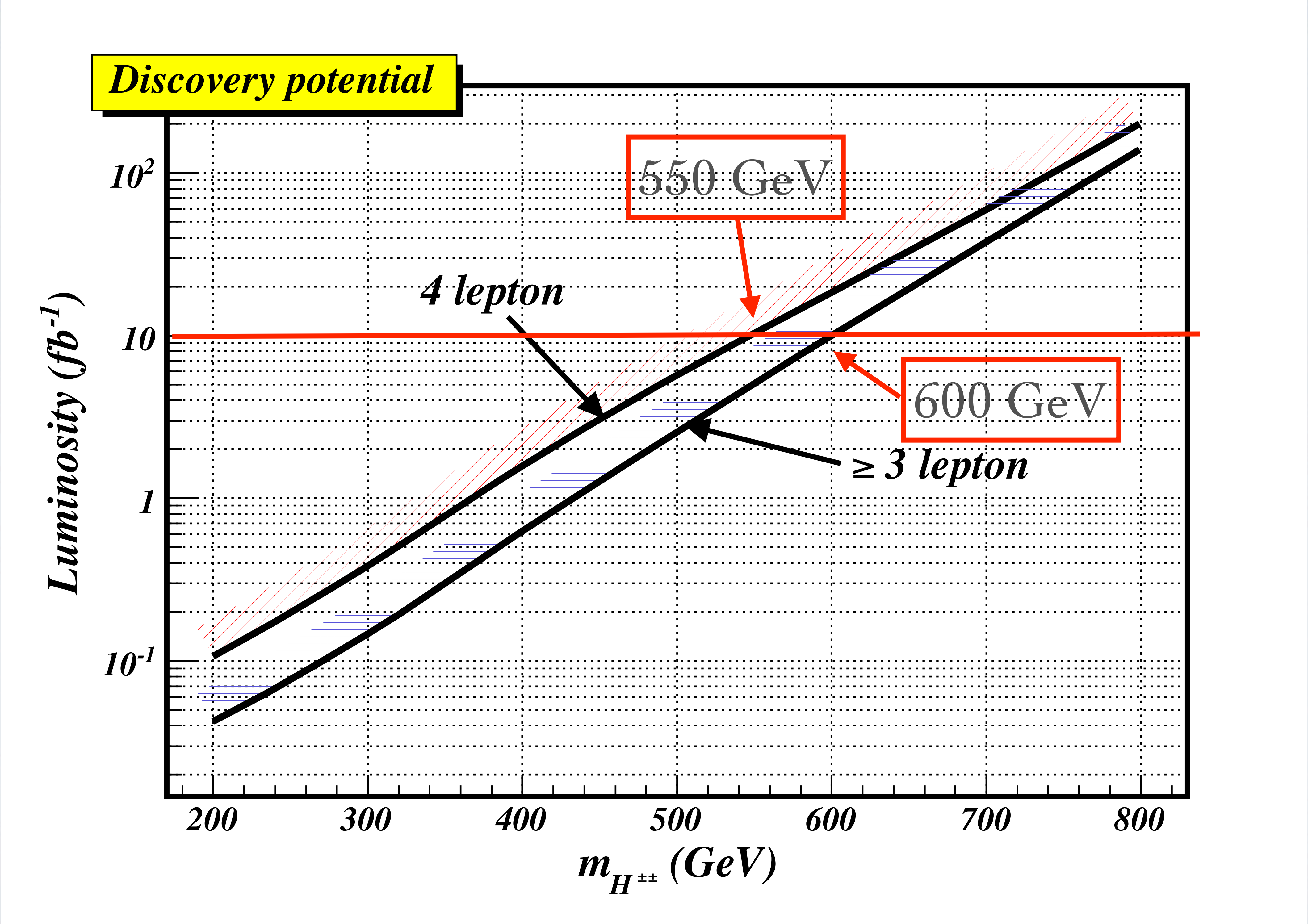
≥ 3-Leptons Signature

- Both production mechanisms contribute.
- Same assumptions and cuts imposed.
- Increased significance $\mathcal{S} = \sqrt{2\left[(s+b)\log\left(1+\frac{s}{b}\right)-s\right]}$

	Backgrounds							Signal ($M_{H^{\pm\pm}}$)	
Cuts ⇓	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
$\lvert m_{\ell^+\ell^-} - m_Z\rvert > 10\,\mathrm{GeV}$	50.9	2.7	12.1	113.2	0.9	33.4	7.4	1397.8	17.3
$H_T > 300\,\mathrm{GeV}$	7.5	1.1	1.6	8.9	0	17	3.4	1351.1	17.3
$H_T > 500\,\mathrm{GeV}$	1.7	0.3	0.4	0.9	0	3.2	0.6	796.2	17.3
$\mathcal{S}$								77.4	5

Table 5. Background and Signal events surviving the cuts for at least 3 leptons in the final state. We have taken $\mathcal{L} = 10\,\mathrm{fb}^{-1}$ and $\sqrt{s} = 14\,\mathrm{TeV}$.

5σ Discovery Potential



Summary

- HTM is motivated by neutrino masses and involves only a few model parameters in the Higgs sector, rendering the model relatively predictive and interesting at LHC.

- Distinctive features of the model:
  - doubly-charged Higgs boson;
  - possibly dominant like-sign dilepton decays;
  - possible lepton flavor violating processes.

- Promising final states depend on the lightest neutrino mass, assumed mass hierarchy, and Majorana phases

Summary

- We include an important production channel for $H^{\pm\pm}$ that has been ignored by the experimentalists at Tevatron.
- We have performed detailed simulations for LHC and compared the $\geq 3\,\ell$ signature with the $4\,\ell$ signature for the search of $H^{\pm\pm}$.
- CMS colleagues at NCU have started analyzing data!