Production of Doubly Charged Higgs Bosons at the LHC

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- Higgs Triplet Model (HTM) and doubly charged scalars ($H^{\pm\pm}$)
- Leptonic decay channels $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$
- Heavy SM-like Higgs boson in HTM with $M_{H_2} > 2M_{H^{\pm\pm}}$
- Gluon-gluon fusion $gg \to H_2$ with decay $H_2 \to H^{++}H^{--}$
- Impact on ongoing search for $q\overline{q} \to \gamma^*, Z^* \to H^{++}H^{--}$ at the LHC

AGA and S. Moretti, arXiv:1106.3427 [hep-ph]

Talk at NExT PhD meeting, Abingdon, 19 July 2011

Charged Higgs Bosons (Scalars)

The Higgs boson (1964) of the Standard Model is a spinless, neutral particle with a vacuum expectation value.

Still undiscovered If exists, how many Higgs bosons?

Classify Higgs bosons by their electric charge

- Neutral: h^0 (SM 1967), H^0,A^0 (2HDM 1973, MSSM 1980...)
- Singly Charged: $H^{\pm}$ (2HDM, MSSM..)
- Doubly Charged: $H^{\pm\pm}$ (this talk)

These three types have received considerable theoretical/experimental attention

(Order of priority: neutral $>$ singly charged $>$ doubly charged)

Models with Doubly Charged Higgs Bosons, $H^{\pm\pm}$

Motivation $\rightarrow$ neutrino mass generation

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

- Higgs Triplet Model: $I = 1, Y = 2$ (tree-level mass for ν)
- LR Symmetric Model: $I = 1, Y = 2$ (tree-level mass for ν)
- Zee-Babu Model: $I = 0, Y = 4$ (radiative mass for ν)

All of these models are in textbooks ("classic models")

I will discuss the Higgs Triplet Model

Konetschny/Kummer 77, Schechter/Valle 80, Cheng/Li 80

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 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: $< \delta^0 > = v_\Delta \sim \mu v^2/M_\Delta^2$

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

Neutrino mass in Higgs Triplet Model (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: $\mathcal{M}_{ij}^{\nu} \sim v_{\Delta} h_{ij}$

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

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

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

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

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

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

I will only discuss $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$

Decays of $H^{\pm}$:

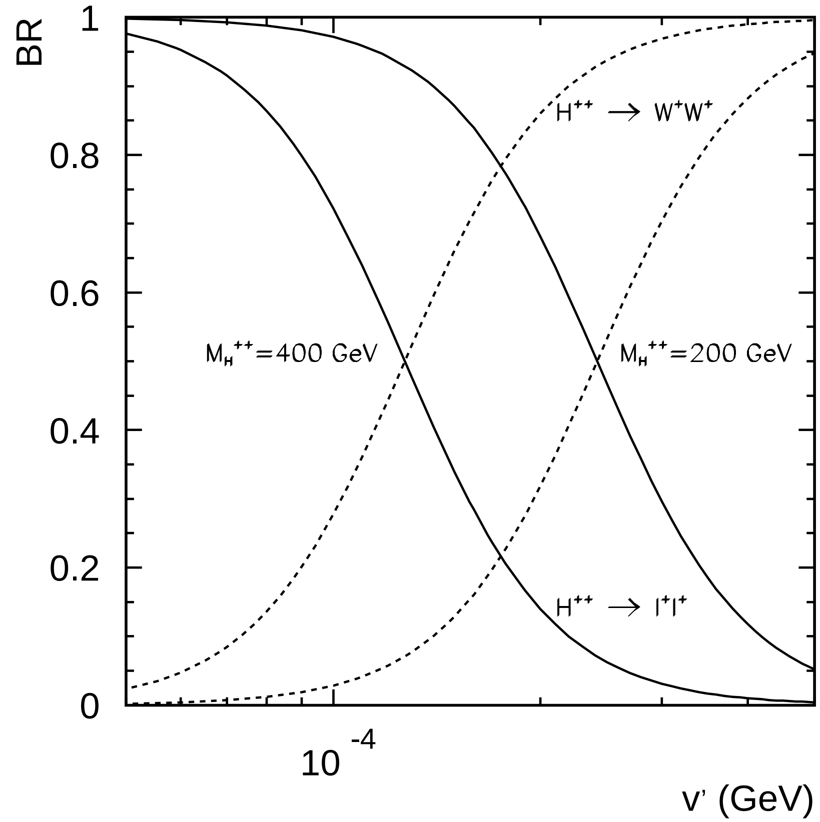
- $\Gamma(H^{\pm} \to \ell_i^{\pm}\nu) > \Gamma(H^{\pm} \to W^{\pm}Z, tb)$ for $v_{\Delta} < 10^{-4}$ GeV

If $h_{ij} > 10^{-6}$ $(> h_{electron})$ then $v_{\Delta} < 10^{-4}$ GeV

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

BR($H^{\pm\pm} \to W^{\pm}W^{\pm}$) and $\sum_{i,j=1}^{3}$ BR($H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$) against triplet vev

Han 07, Asaka/Hikasa 94

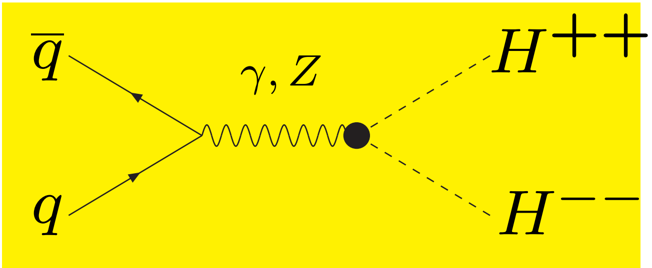


Production of $H^{\pm\pm}$ at Hadron Colliders

LEP (1989 $\rightarrow$ 2000) searched for $e^+e^- \rightarrow H^{++}H^{--}$

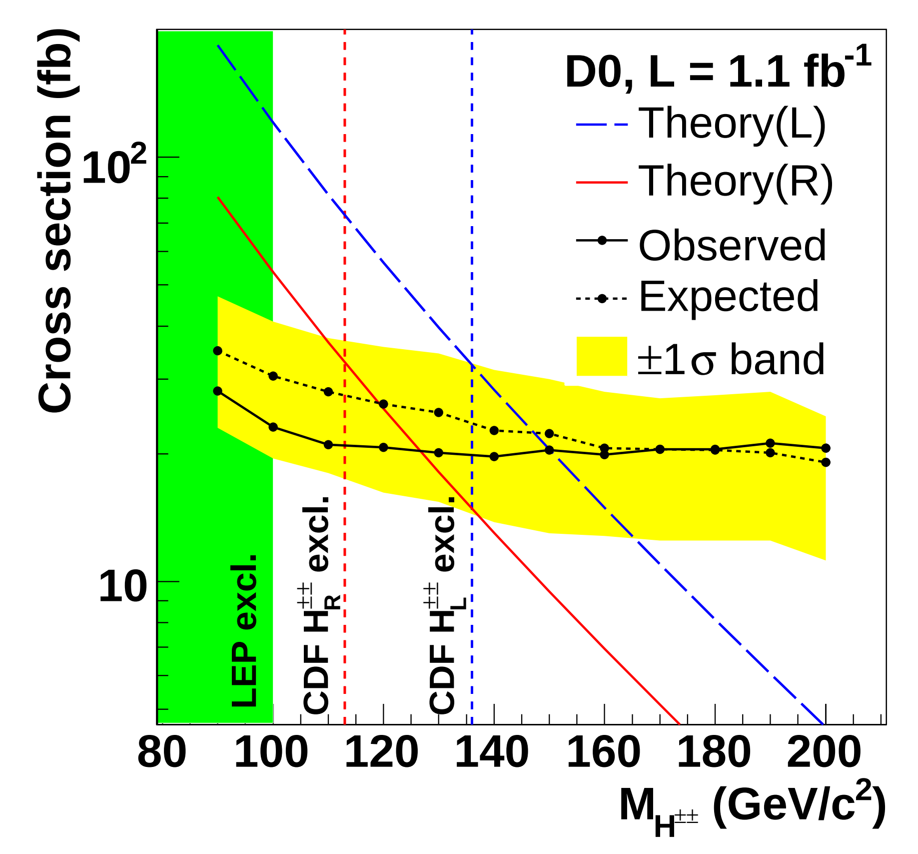
- First searches at a hadron collider in 2003 Tevatron: CDF,D0

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



- $\sigma_{H^{++}H^{--}}$ is a simple function of $M_{H^{\pm\pm}}$ Barger 82, Gunion 89, Raidal 96

Tevatron search (D0, 2007) for $p\bar{p} \to H^{++}H^{--}$, $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$



Mass limit $M_{H^{\pm\pm}} > 150$ GeV for BR($H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$) = 100% (updated $M_{H^{\pm\pm}} > 168$ GeV, 1106.4250[hep-ex])

First search for $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ at LHC!

CMS collaboration with $\mathcal{L}$ =36 pb^{-1} CMS-PAS-HIG-11-001

- Presented at Moriond 2011 with other first Higgs searches
- Assumes production via $q\overline{q} \to \gamma^*, Z^* \to H^{++}H^{--}$
- Includes $q'\overline{q} \to W^* \to H^{\pm\pm}H^{\mp}$ for the first time
- Searches for 3ℓ $(\ell^{\pm}\ell^{\pm}\ell^{\mp})$ and 4ℓ $(\ell^{+}\ell^{+}\ell^{-}\ell^{-})$ signatures
- Backgrounds are smallest for 4ℓ signature
- It is assumed that only $q\overline{q} \to \gamma^*, Z^* \to H^{++}H^{--}$ can give 4ℓ

Summary of LHC and Tevatron limits on $M_{H^{\pm\pm}}$

	ee	$e\mu$	$\mu\mu$	$e\tau$	$\mu\tau$	$\tau\tau$
Tevatron	$>$ 133 GeV	$>$ 113 GeV	$>$ 168 GeV	$>$ 112 GeV	$>$ 144 GeV	$>$ 128 GeV
CMS	$>$ 144 GeV	$>$ 154 GeV	$>$ 156 GeV	$>$ 106 GeV	$>$ 106 GeV	$>$ 80 GeV

	ee	$e\mu$	$\mu\mu$	$e\tau$	$\mu\tau$	$\tau\tau$
Tevatron	0.24 fb^{-1}	0.24 fb^{-1}	7 fb^{-1}	0.35 fb^{-1}	7 fb^{-1}	7 fb^{-1}
CMS	0.036 fb^{-1}	0.036 fb^{-1}	0.036 fb^{-1}	0.036 fb^{-1}	0.036 fb^{-1}	0.036 fb^{-1}

- All limits assume BR$(H^{\pm\pm} \to \ell^\pm \ell^\pm) = 100\%$
- Number of $H^{\pm\pm}$ signal events scales as $[\text{BR}(H^{\pm\pm} \to \ell^\pm \ell^\pm)]^2$
- Limits on $M_{H^{\pm\pm}}$ weakened for BR$(H^{\pm\pm} \to \ell^\pm \ell^\pm) \ll 100\%$

Any other pair-production mechanisms for $H^{++}H^{--}$ at LHC?

Heavy (> 200 GeV) SM-like Higgs with $M_{H_2} > 2M_{H^{\pm\pm}}$

- In HTM, H_2 is mainly composed of isospin doublet scalar $\rightarrow$ "SM-like Higgs" (now being searched for at LHC)
- Phenomenology of H_2 can differ from that of SM Higgs if $M_{H_2} > 2M_{H^{\pm\pm}}$
- The decay $H_2 \rightarrow H^{++}H^{--}$ would be open kinematically
- $M_{H_2} > 200$ GeV necessary since $M_{H^{\pm\pm}} > 100$ GeV from LEP limits
- $M_{H_2} > 200$ GeV in HTM can be made compatible with electroweak precision measurements (which suggest $M_{H_2} < 200$ GeV in SM).

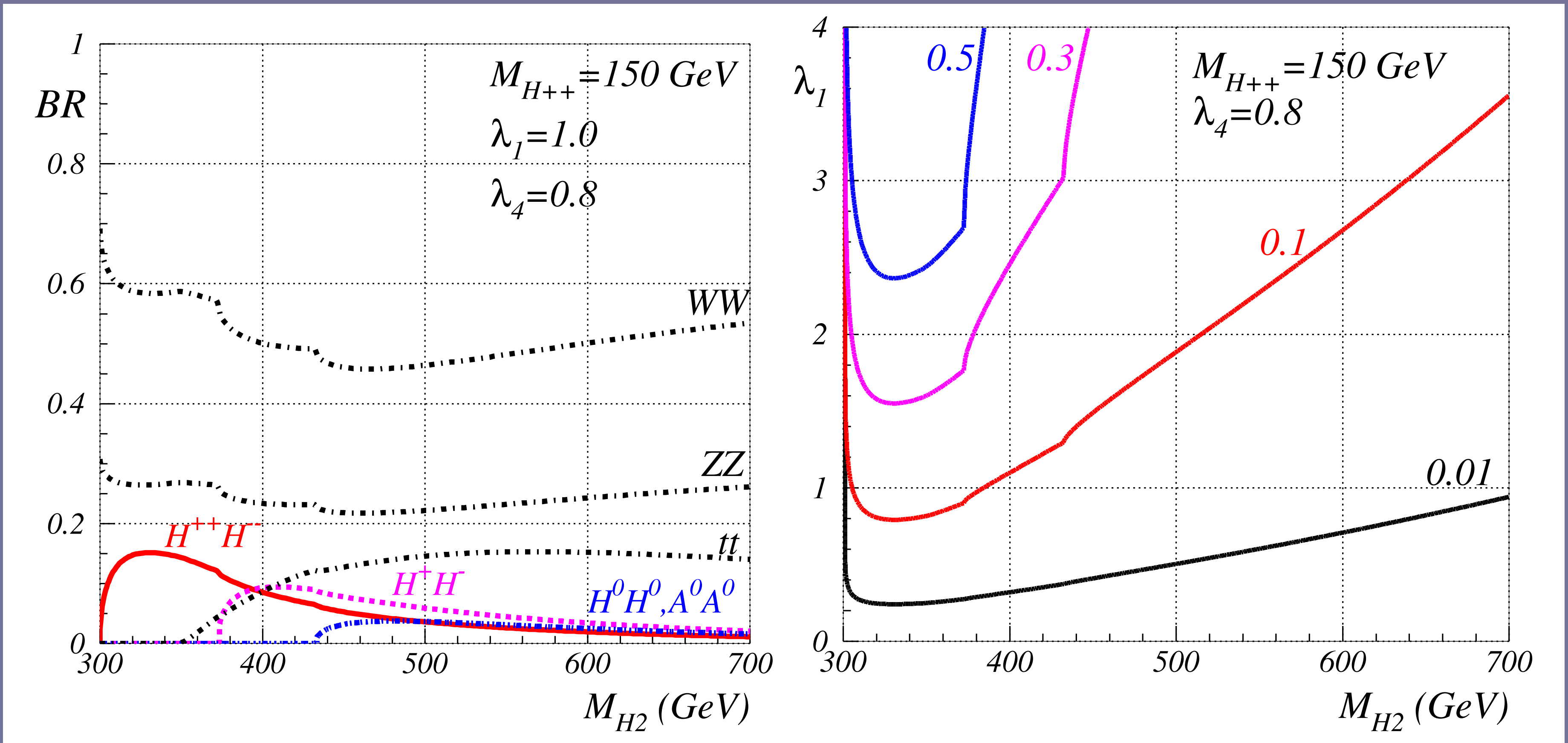
The decay $H_2 \to H^{++}H^{--}$

- Coupling $C_{H_2 H^{++} H^{--}} = \lambda_1 v$ (from $\lambda_1 (H^\dagger H) \mathrm{Tr}\Delta^\dagger\Delta$, and $v = 246$ GeV)
- $\Gamma(H_2 \to H^{++}H^{--}) \sim (\lambda_1 v)^2$
- Competing decays $\Gamma(H_2 \to WW, ZZ) \sim M_{H_2}^3$
- $\mathrm{BR}(H_2 \to H^{++}H^{--})$ will be maximised for:

i) Larger λ_1 and ii) $M_{H_2} = 2M_{H^{\pm\pm}} + \epsilon$

- $H_2 \to H^+H^-, H^0H^0, A^0A^0$ could also be open
- Mass splitting among $M_{H^{\pm\pm}}, M_{H^\pm}, M_{H^0,A^0}$ determined by λ_4
- We consider $\lambda_4 > 0$, for which $M_{H^{\pm\pm}} < M_{H^\pm} < M_{H^0,A^0}$

Branching ratios of H_2 as a function of M_{H_2} and λ_1 for $M_{H^{\pm\pm}} = 150$ GeV



Left panel: Various BRs of H_2

Right panel: Contours of BR($H_2 \to H^{++}H^{--}$)

Gluon-gluon fusion $gg \to H_2$ with decay $H_2 \to H^{++}H^{--}$

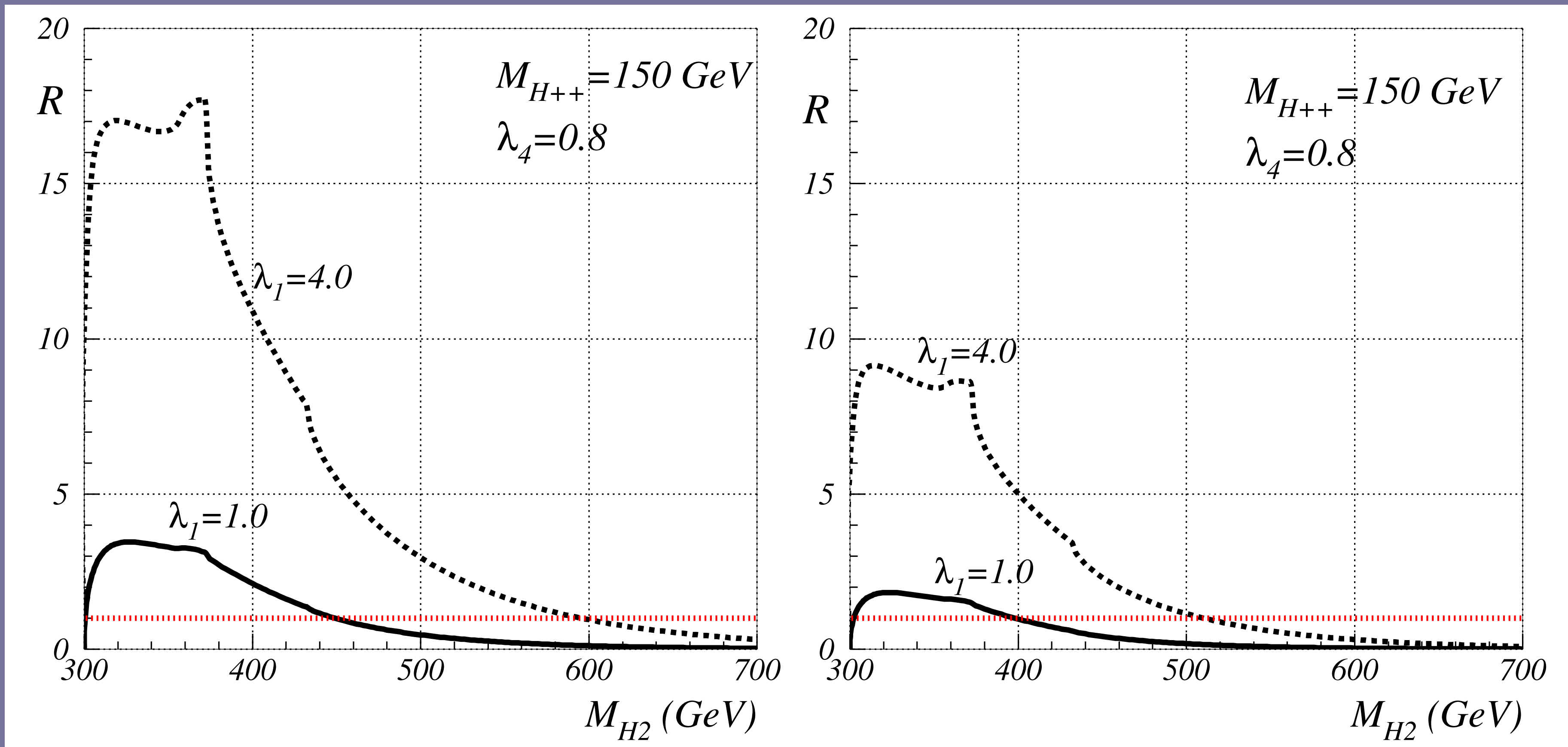
The dominant production mechanism for H_2 at the LHC is $\boxed{gg \to H_2}$

We introduce the ratio R, defined by:

$$R = \frac{\sigma(gg \to H_2) \times \mathrm{BR}(H_2 \to H^{++}H^{--})}{\sigma(q\overline{q} \to \gamma^*, Z^* \to H^{++}H^{--})}$$

- Numerator is a novel mechanism (requires $\mathrm{BR}(H_2 \to H^{++}H^{--}) \neq 0$)
- Denominator is conventional mechanism (used in ongoing searches)
- R is determined by $M_{H^{\pm\pm}}$, M_{H_2} and λ_1

$R = \sigma(gg \to H_2) \times \mathrm{BR}(H_2 \to H^{++}H^{--})/\sigma(q\bar{q} \to H^{++}H^{--})$ as a function of M_{H_2} for $\lambda_1 = 1, 4$



Left panel: LHC with $\sqrt{s} = 14$ TeV

Right panel: LHC with $\sqrt{s} = 7$ TeV

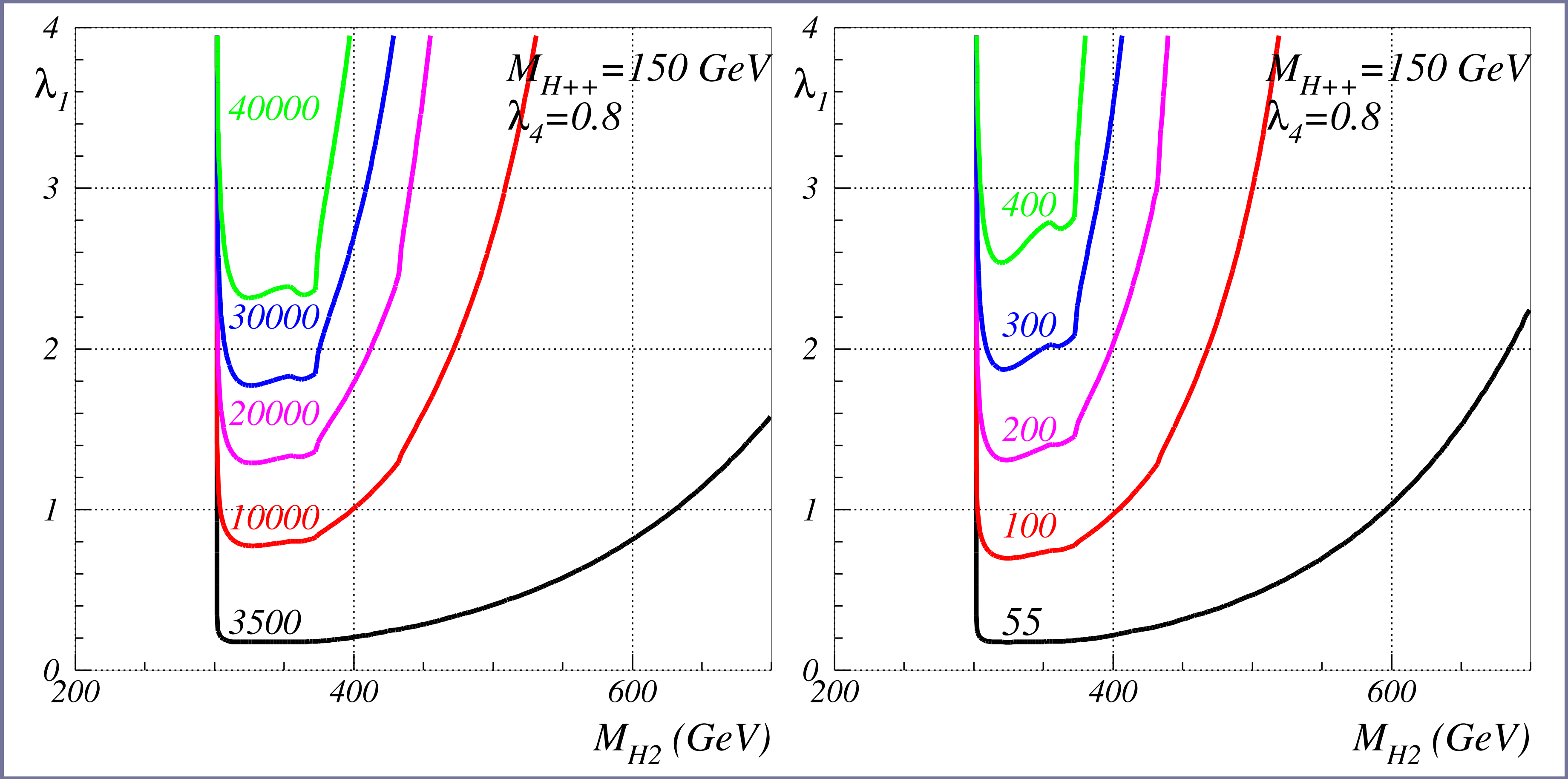
Number of $H^{++}H^{--}$ events at the LHC

$gg \to H_2$ with decay $H_2 \to H^{++}H^{--}$ can contribute significantly to number of $H^{++}H^{--}$ events in a sizeable parameter space of $[\lambda_1, M_{H_2}]$ (with $M_{H_2} > 2M_{H^{\pm\pm}}$):

$$N_{H^{\pm\pm}} = \epsilon \times \mathcal{L} \times [\sigma(q\overline{q} \to \gamma^*, Z^* \to H^{++}H^{--}) + \sigma(gg \to H_2) \times \mathrm{BR}(H_2 \to H^{++}H^{--})]$$

- ϵ is detection efficiency (after all selection cuts are imposed)
- ϵ is different for each decay channel $H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}$
- $\epsilon_{\mu\mu} \sim 0.5$ for $M_{H^{\pm\pm}} = 150$ GeV (similar for $\epsilon_{e\mu}, \epsilon_{ee}$)
- $\epsilon_{\mu\tau} \sim \epsilon_{e\tau} \sim 0.02$, $\epsilon_{\tau\tau} << 0.01$

Number of $H^{++}H^{--}$ events with BR($H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$) = 100% at the LHC



Left panel: $\sqrt{s} = 14$ TeV, $\mathcal{L} = 30$ fb^{-1}

Right panel: $\sqrt{s} = 7$ TeV, $\mathcal{L} = 1$ fb^{-1}

Conclusions

- $H^{\pm\pm}$ is being searched for at the Tevatron and LHC
- $q\overline{q} \to \gamma^*, Z^* \to H^{++}H^{--}$ gives 4ℓ $(\ell^+\ell^+\ell^-\ell^-)$ signature
- If $M_{H_2} > 2M_{H^{\pm\pm}}$, $\text{BR}(H_2 \to H^{++}H^{--})$ can be $> 10\%$
- $R = \sigma(gg \to H_2) \times \text{BR}(H_2 \to H^{++}H^{--})/\sigma(q\overline{q} \to H^{++}H^{--}) > 1$ (max ~ 18)
- Would enable smaller values of $\text{BR}(H^{\pm\pm} \to \ell^\pm\ell^\pm)$ to be probed for a given $M_{H^{\pm\pm}}$
- Scenario of $M_{H_2} > 2M_{H^{\pm\pm}}$ will be tested in $\sqrt{s} = 7$ TeV run of LHC via $H_2 \to H^{++}H^{--}$, $H_2 \to WW$ and $H_2 \to ZZ$

Strategy of most recent search by Tevatron

- $H^{\pm\pm}$ 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

→ 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 $9 \to 12$ fb^{-1}

Tevatron search (D0, 2007) for $p\overline{p} \to H^{++}H^{--}$, $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$

Selection	Preselection S1	Isolation S2	$\Delta\phi < 2.5$ S3	Like sign S4	Third muon S5
$Z/\gamma^* \to \mu^+\mu^-$	69181 ± 4642	58264 ± 3910	4936 ± 333	5.3 ± 1.6	< 0.01
Multijet	4492 ± 120	194 ± 18	18 ± 2	6.3 ± 0.8	0.2 ± 0.1
$Z/\gamma^* \to \tau^+\tau^-$	328 ± 25	269 ± 21	20 ± 3	< 0.01	< 0.01
$t\bar{t}$	38 ± 3	20 ± 1	14 ± 1	0.03 ± 0.01	< 0.01
WW	40 ± 3	34 ± 2	20 ± 1	< 0.01	< 0.01
WZ	19 ± 1	16 ± 1	11 ± 1	2.95 ± 0.20	1.62 ± 0.11
ZZ	10 ± 1	9 ± 1	5 ± 1	0.63 ± 0.05	0.47 ± 0.03
Total background	74108 ± 4644	58806 ± 3910	5024 ± 333	15.2 ± 1.8	2.3 ± 0.2
$M_{H^{\pm\pm}} = 140$ GeV	20.5 ± 2.7	18.5 ± 2.4	16.3 ± 2.1	11.6 ± 1.5	10.1 ± 1.3
Data	72974	58763	4558	16	3

Signal is defined as $\mu^+\mu^+\mu^-$ or $\mu^-\mu^-\mu^+$