Exploring the neutral sector in the triplet-doublet Higgs model

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SEVENTH INTERNATIONAL WORKSHOP

cHarged 2018

Outline

I. Type-II seesaw model presentation
Motivation, inputs, theoretical constraints

II. Experimental searches at LHC
ATLAS dilepton, WW, CMS dilepton PP/AP

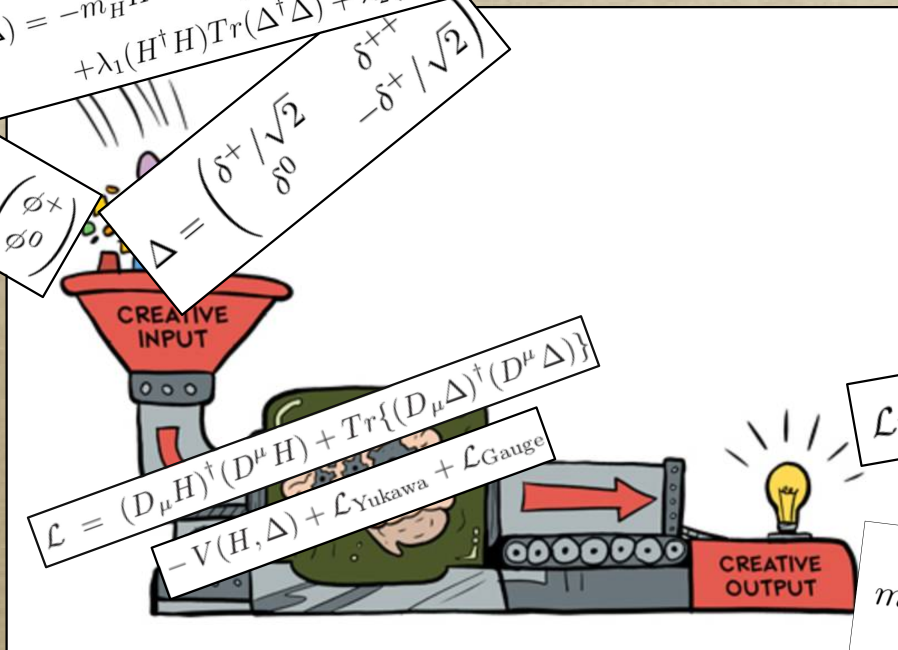
III. Charged sector
Production processes, cross-sections, branching ratio, improving current analyses

IV. Mixing charged and neutral sectors
Cross-sections, productions, decays, final states

Type-II seesaw model

$$V(H,\Delta) = -m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + M_\Delta^2 Tr(\Delta^\dagger \Delta) + [\mu(H^T i\sigma^2 \Delta^\dagger H) + \mathrm{h.c.}]$$
$$+\lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr\Delta^\dagger \Delta)^2 + \lambda_3 Tr(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H$$

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



$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + Tr\{(D_\mu \Delta)^\dagger (D^\mu \Delta)\}$$
$$- V(H,\Delta) + \mathcal{L}_{\mathrm{Yukawa}} + \mathcal{L}_{\mathrm{Gauge}}$$

<u>Neutrinos have mass</u> !
But we don't want right-handed neutrinos
→→→ Doublet-Triplet Higgs model

Higgs doublet + new scalar triplet
→ minima of the extended potential define 2 VEVs : v_d for the doublet, v_t for the triplet
So that $v_t \ll v_d$

$$\mathcal{L}_{Yukawa} \supset -Y_\nu L^T \otimes C \otimes i\sigma^2 \Delta L$$

After EWSB, this term gives a Majorana mass to neutrinos involving v_t

$$m_{H^{\pm\pm}}^2 = \frac{\sqrt{2}\mu v_d^2 - \lambda_4 v_d^2 v_t - 2\lambda_3 v_t^3}{2v_t} \qquad m_{h^0}^2 = \frac{1}{2}\left[A + C - \sqrt{(A-C)^2 + 4B^2}\right]$$
$$m_{H^\pm}^2 = \frac{(v_d^2 + 2v_t^2)[2\sqrt{2}\mu - \lambda_4 v_t]}{4v_t} \qquad m_{H^0}^2 = \frac{1}{2}\left[A + C + \sqrt{(A-C)^2 + 4B^2}\right]$$
$$\tan 2\alpha = \frac{2B}{A - C} \qquad m_A^2 = \frac{\mu\,(v_d^2 + 4v_t^2)}{\sqrt{2}v_t}$$

The particle content of the model is the SM extended to 7 new scalars :
H^{++}, H^+
A^0 (CP-odd)
H^0, h^0 (CP-even)

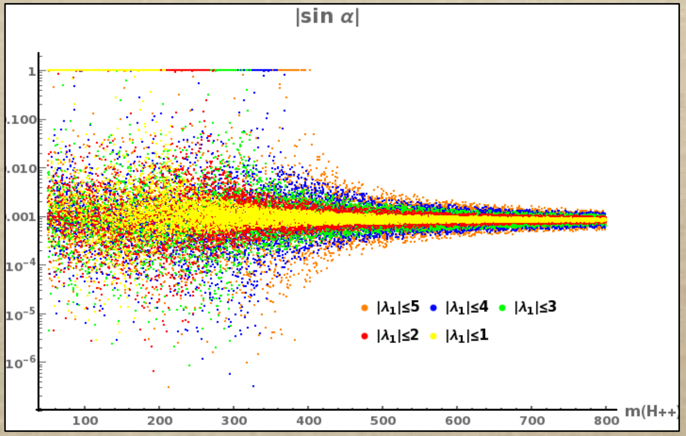
The model variables are λ's and μ from the potential
+ α angle (mixing between SM Higgs and H^0/h^0)

Hypotheses on the model

- choice on the triplet VEV v_t :
EWPT on the rho parameter -> upper constraint on v_t
---> choose to work with $v_t=0.1$ (looked also at $v_t=10^{-6}$)

$$\rho \simeq 1 - 2\frac{v_t^2}{v_d^2}$$

$$\rho_0 = 1.0004^{+0.0029}_{-0.0011}$$



- choice on the SM Higgs :
sin α translates the mixing between SM Higgs and h^0/H^0
---> we start with sin $\alpha \sim 0$, so $h^0 \sim$ SM Higgs

- couplings / model parameters :
Theoretical constraints exist on the λ's such as :
* naturalness : $|\lambda\text{'s}|=O(1)$
* no tachyonic (real mass terms)
* potential bounded by below
* unitarity
* EW vacuum = global minimum

$$\lambda \geq 0 \ \& \ \lambda_2 + \lambda_3 \geq 0 \ \& \ \lambda_2 + \frac{\lambda_3}{2} \geq 0$$

$$\& \ \lambda_1 + \sqrt{\lambda(\lambda_2+\lambda_3)} \geq 0 \ \& \ \lambda_1 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} \geq 0$$

$$\& \ \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2+\lambda_3)} \geq 0 \ \& \ \lambda_1 + \lambda_4 + \sqrt{\lambda(\lambda_2 + \frac{\lambda_3}{2})} \geq 0$$

$$\mu > \frac{\lambda_4 v_t}{2\sqrt{2}}$$

$$\mu > \frac{\lambda_4 v_t}{\sqrt{2}} + \sqrt{2}\frac{\lambda_3 v_t^3}{v_d^2}$$

$$\sqrt{2}\mu v_d^2 + \lambda v_d^2 v_t + 4(\lambda_2+\lambda_3)v_t^3 > 0$$

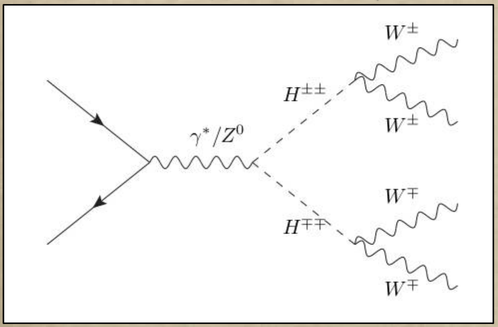
$$-8\mu^2 v_t + \sqrt{2}\mu(\lambda v_d^2 + 8(\lambda_1+\lambda_4)v_t^2) + 4(\lambda(\lambda_2+\lambda_3) - (\lambda_1+\lambda_4)^2)v_t^3 > 0$$

$$\mu < \mu_{\max} \equiv \frac{\lambda}{4\sqrt{2}}\frac{v_d^2}{v_t} + (\lambda_1+\lambda_4)\frac{v_t}{\sqrt{2}} + \mathcal{O}(v_t^2)$$

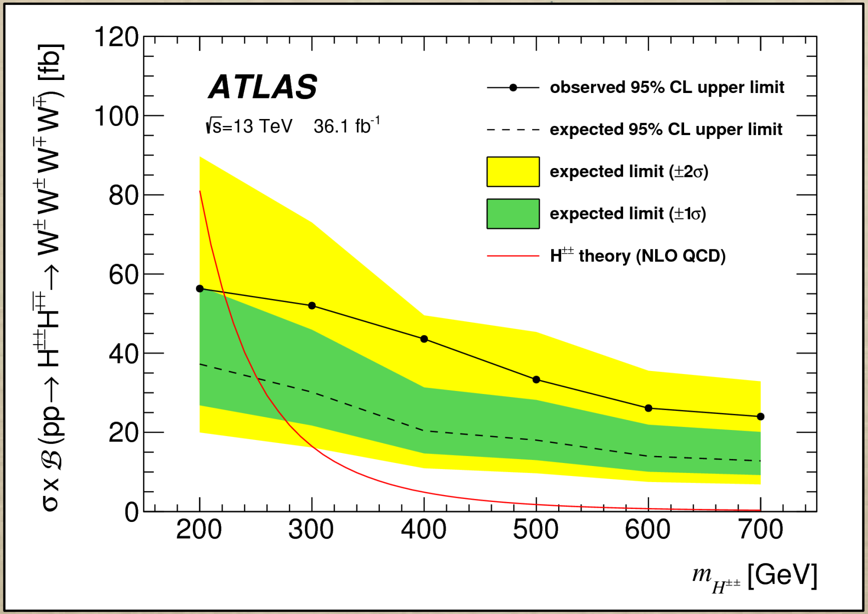
etc ...

- mass spectrum limitations :
Recasted LEP EWPT on S, T, U → maximum mass spliting between charged Higgses ~ 40 GeV

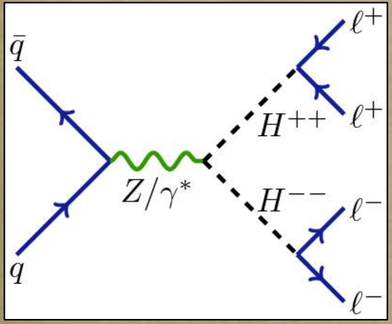
Experimental searches for H^{++}



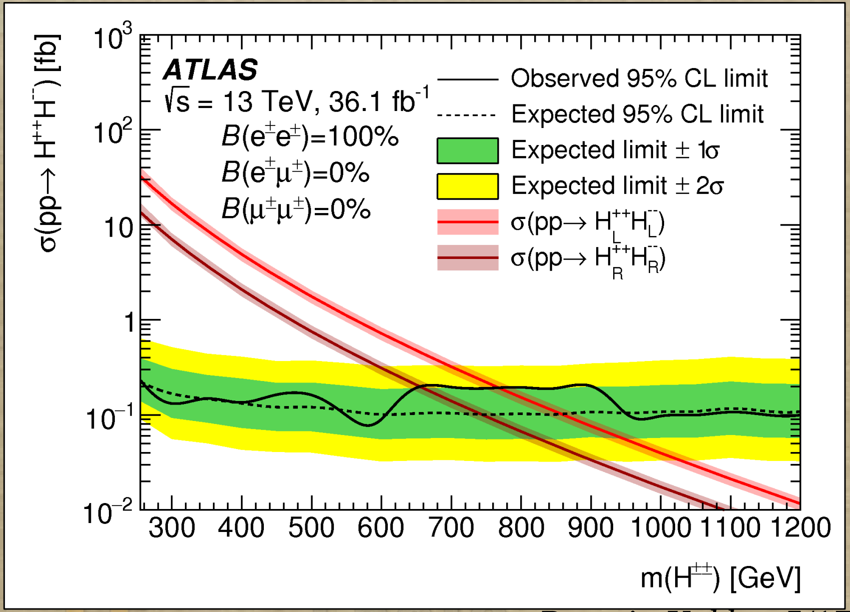
ATLAS-HIGG-2016-09
$H^{++} \to W^+W^+$, $v_t = 0.1$
36.1 fb^{-1} , Type-II seesaw



2LSS, 3L and 4L channels combined
Selection optimized using angular distances, b-veto
MC scan starts at 200 GeV
→ excluded between 200 and 220 GeV

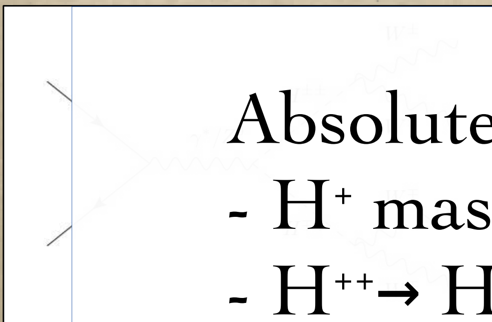


ATLAS-EXOT-2016-07
$H^{++} \to l^+l^+$, $v_t = 0$
36.1 fb^{-1} , Left-Right symmetry



2LSS, 3L and 4L channels combined for different flavour composition.
Left-handed part behaves like in TII-seesaw
→ excluded below ~ 800 GeV (BR dependant)

Experimental searches for H^{++}



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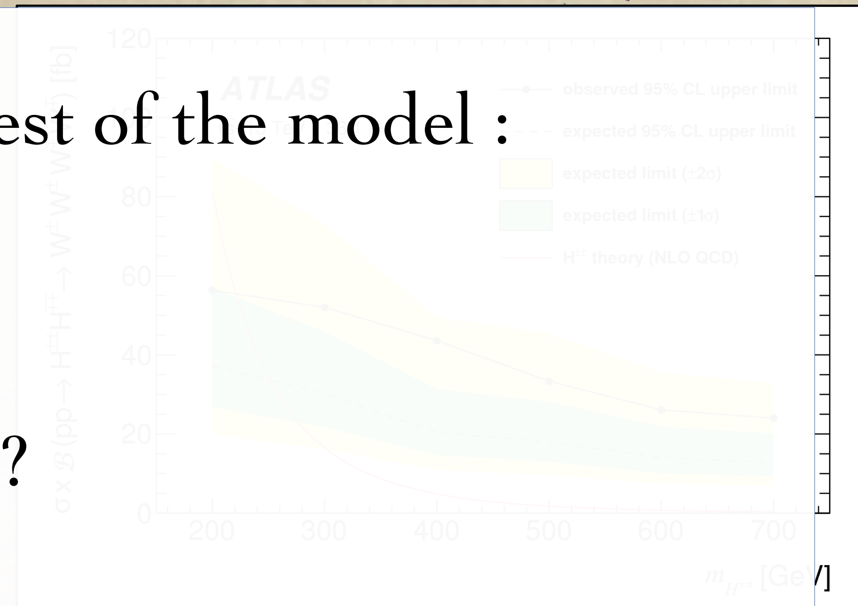
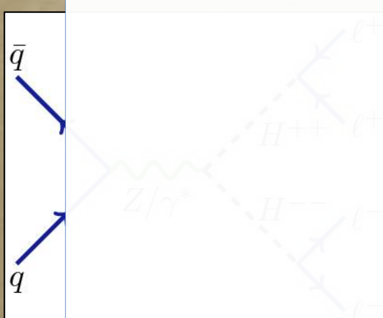


2LSS, 3L and 4L channels combined
Selection optimized using angular distances, b-veto
MC scan starts at 200 GeV
→ excluded between 200 and 220 GeV

Absolutely no mention on the rest of the model :
- H^+ mass
- $H^{++} \to H^+$ cascade decays ?

or

- H^{++}/H^+ associated production ?



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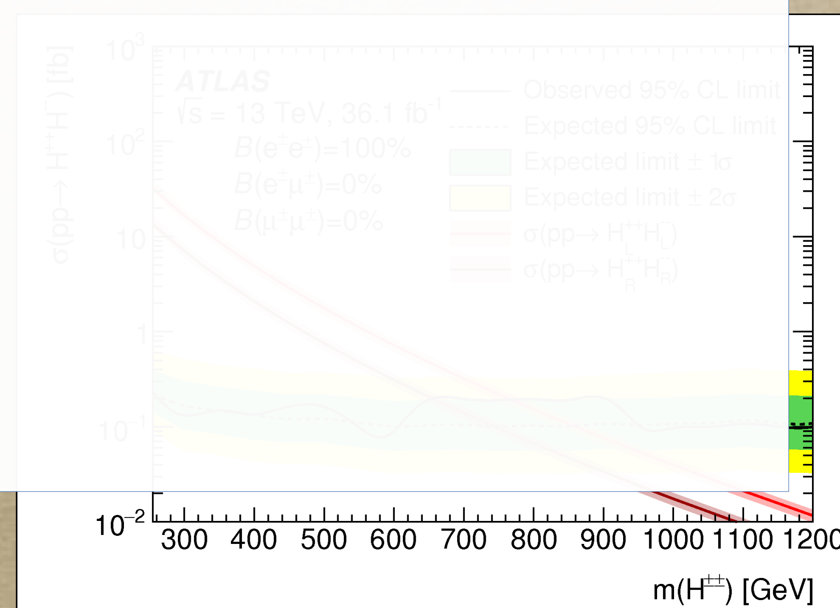
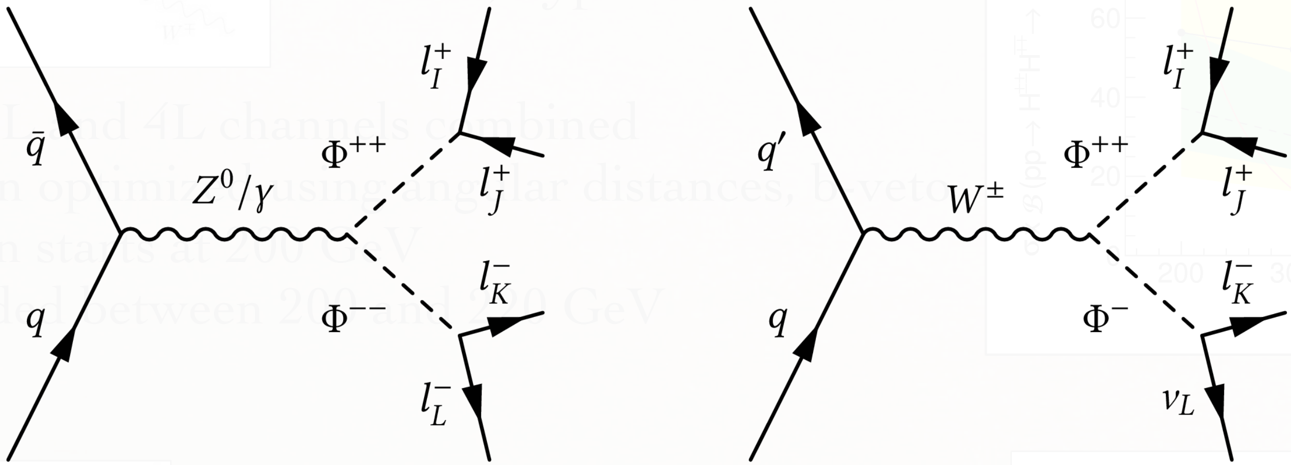


2LSS, 3L and 4L channels combined for different flavour composition.
Left-handed part behaves like in TII-seesaw
→ excluded below ~ 800 GeV (BR dependant)

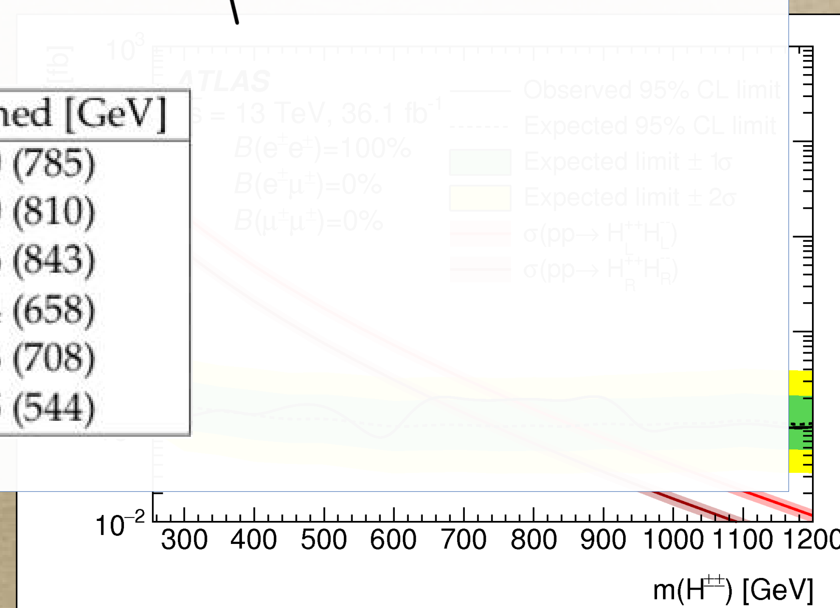
Experimental searches for H^{++}

CMS-PAS-HIG-16-036

$H^{++} \rightarrow l^+l^+$, v_t « small » , mass degeneracy assumed, 12.9 fb^{-1}



Benchmark	AP [GeV]	PP [GeV]	Combined [GeV]
100% $\Phi^{\pm\pm} \rightarrow ee$	734 (720)	652 (639)	800 (785)
100% $\Phi^{\pm\pm} \rightarrow e\mu$	750 (729)	665 (660)	820 (810)
100% $\Phi^{\pm\pm} \rightarrow \mu\mu$	746 (774)	712 (712)	816 (843)
100% $\Phi^{\pm\pm} \rightarrow e\tau$	568 (582)	481 (543)	714 (658)
100% $\Phi^{\pm\pm} \rightarrow \mu\tau$	518 (613)	537 (591)	643 (708)
100% $\Phi^{\pm\pm} \rightarrow \tau\tau$	479 (483)	396 (419)	535 (544)

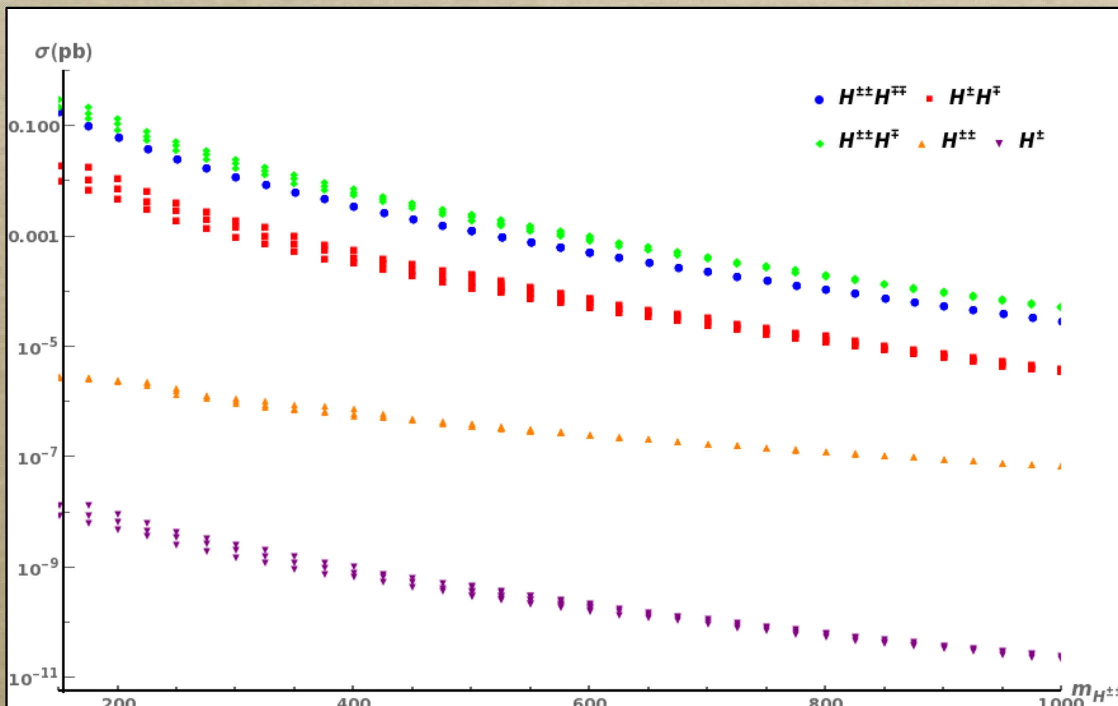


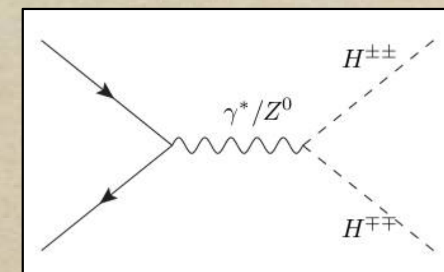
Left-handed part behaves like in TII-seesaw
→ excluded below ~ 800 GeV (BR dependant)

Charged sector processes

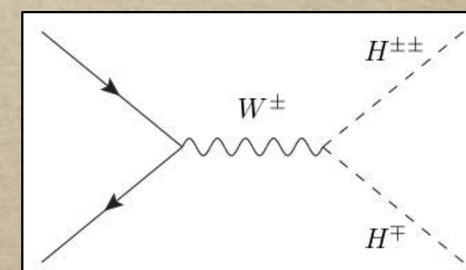
Three production modes : - pair production of the same particle (via γ/Z)
- single production (VBF)
- associated production (via W)

3 scenarios investigated :
$\Delta(H^{++}, H^{+})$= -20, 0, 20 GeV

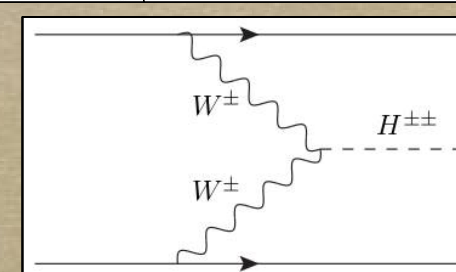




$$H^{++}H^{--}V = -2ie_V(p_{H^{++}} - p_{H^{--}})_\mu$$



$$H^{++}H^{-}W^{-}_{\mu} \approx ig(p_{H^{++}} - p_{H^{-}})_\mu$$



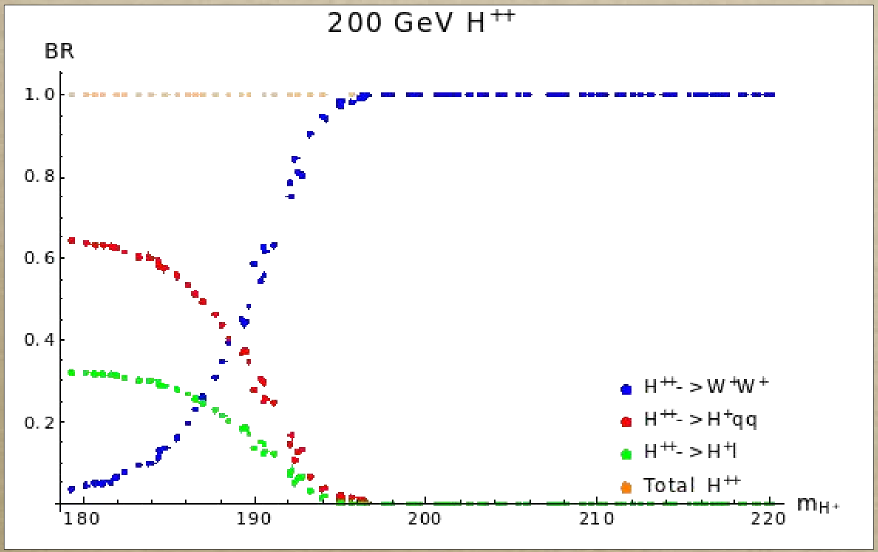
$$H^{++}W^{-}_{\mu}W^{-}_{\nu} = -i\sqrt{2}g^2 v_t g_{\mu\nu}$$

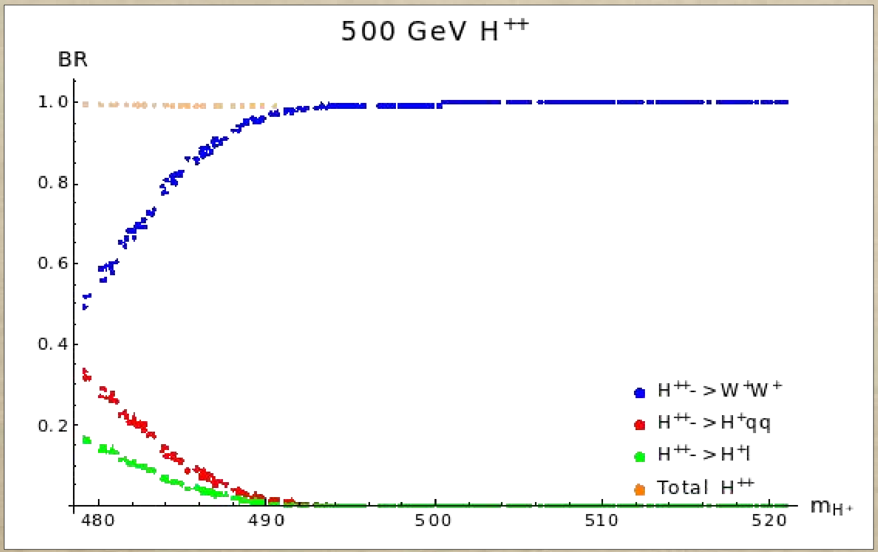
initial state (pp)	sensitivity	final state
$q\bar{q}, \gamma\gamma, Z\gamma, ZZ, W^+W^-$ [gg?]	gauge couplings, $H^{\pm}$, λ_1, h^0	$H^{++}H^{--}$
$q\bar{q}', \gamma W^{\pm}, ZW^{\pm}$	gauge couplings, $H^{\pm\pm}$, $H^{\mp}$	$H^{\pm\pm}H^{\mp}$
$q\bar{q}, \gamma\gamma, Z\gamma, ZZ, W^+W^-$ [gg?]	gauge couplings, $H^{\pm}$, A^0, $2\lambda_1 + \lambda_4$, h^0	$H^{+}H^{-}$

VBF suppressed by v_t contrary to GM

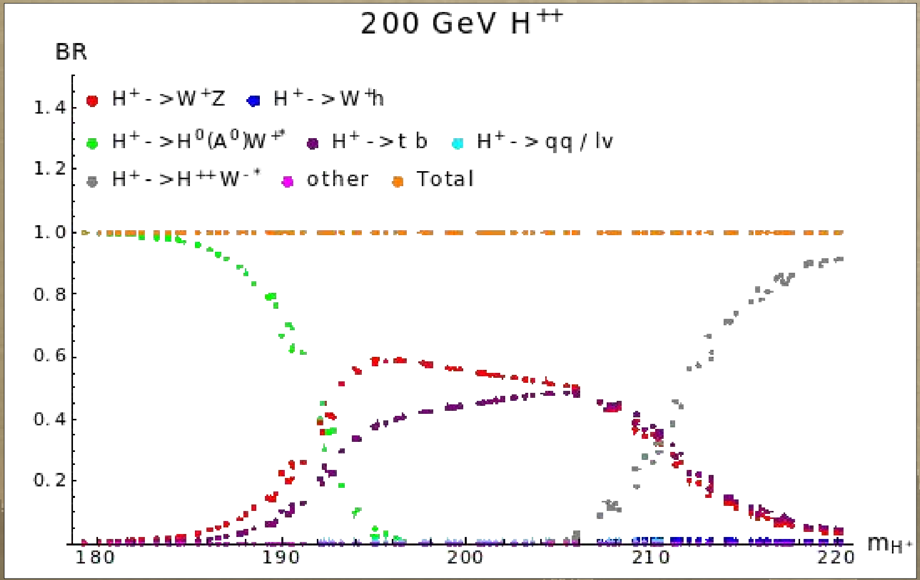
H^{++}/H^{+} branching ratios

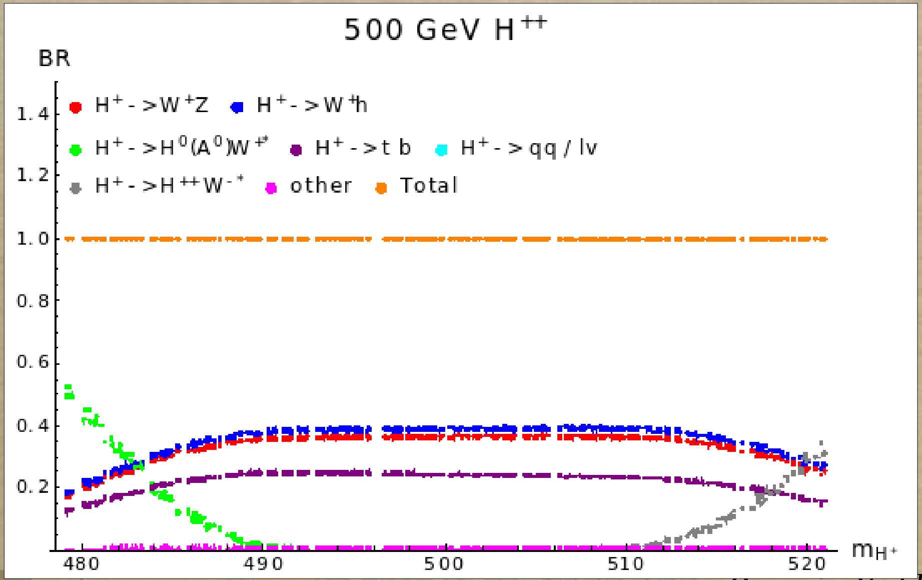
Only 2 decay channels compete : $H^{++} \rightarrow W^{+}W^{+}$ VS cascade $H^{++} \rightarrow H^{+}W^{+*}$





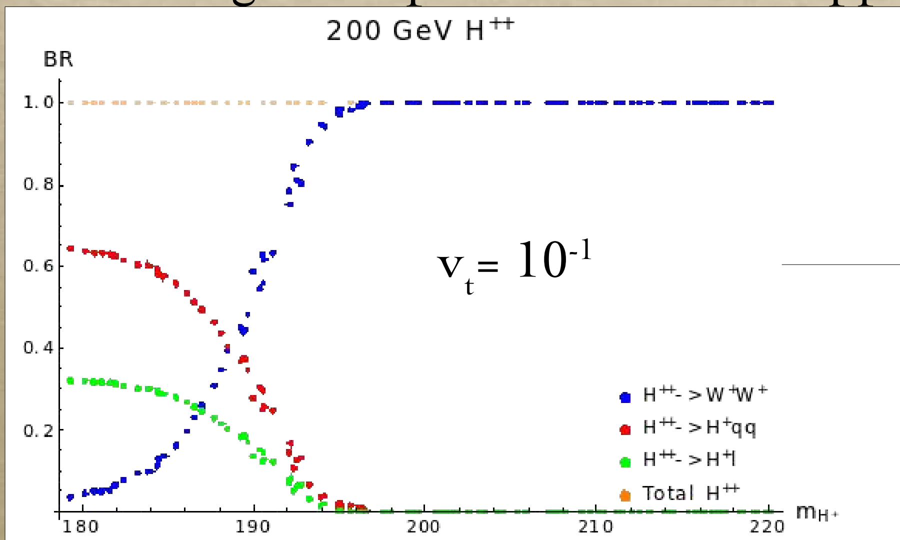
More possibilities : $H^{+} \rightarrow W^{+}Z$ / $W^{+}h^{0}$ VS $H^{+} \rightarrow tb$ VS cascades $H^{+} \rightarrow H^{0}W^{+*}$ / $H^{+} \rightarrow H^{++}W^{-*}$

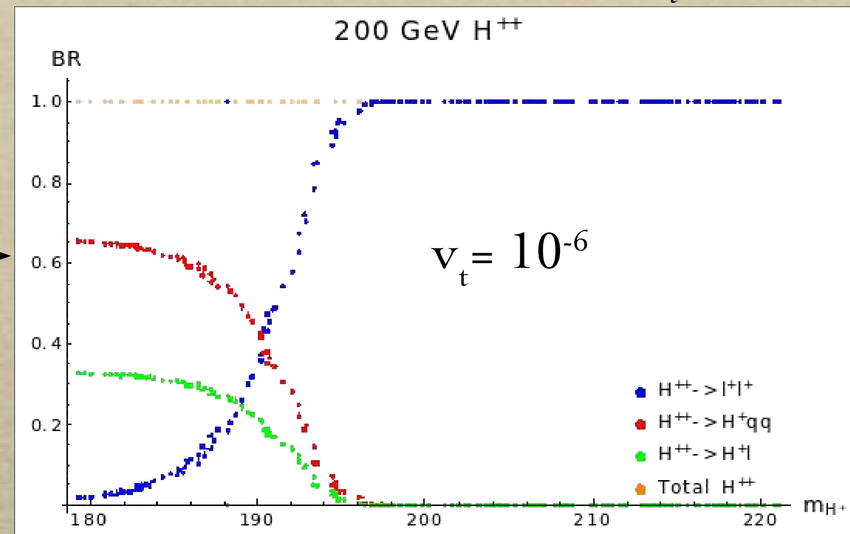




H^{++}/H^{+} BR for low v_t

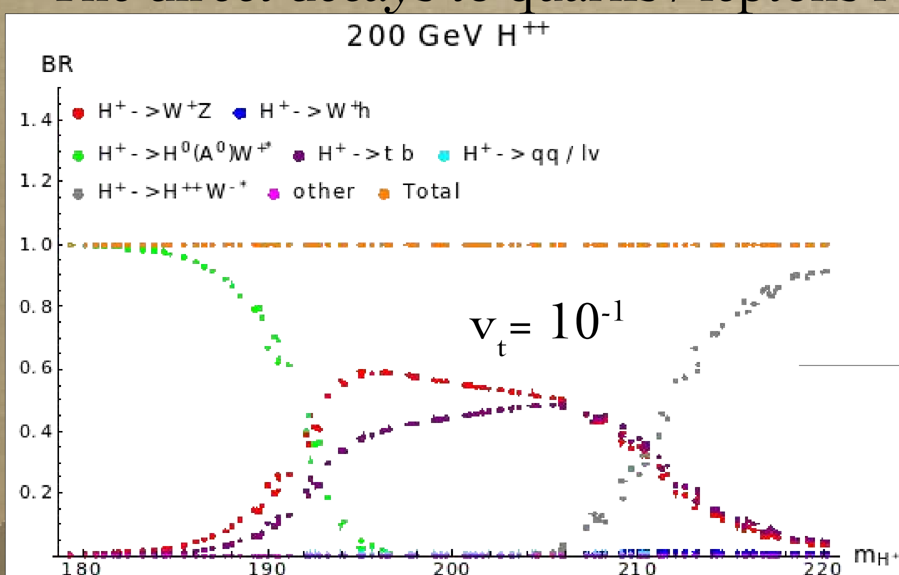
Lowering the triplet VEV to 10^{-6} suppresses all the couplings tuned by v_t

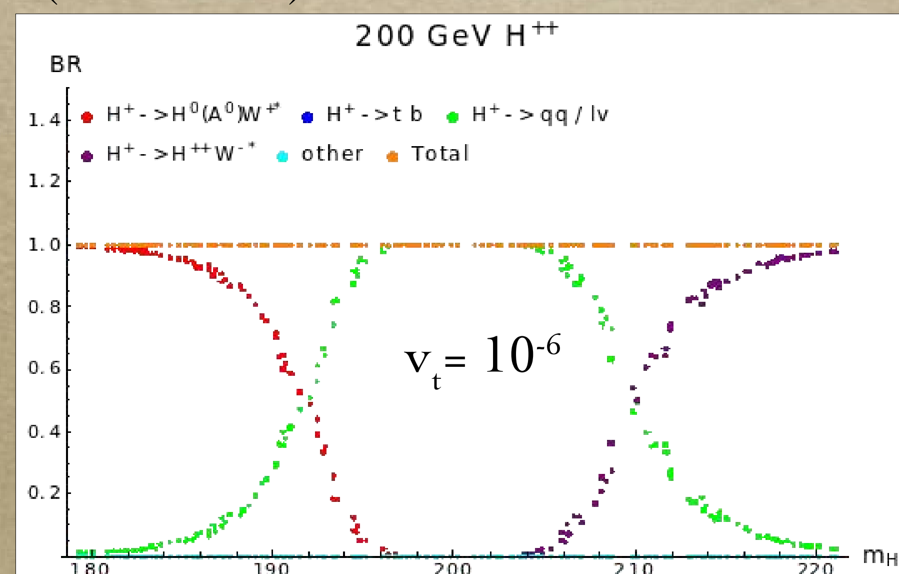




All the channels involving a mixing with the doublet dispear.

The direct decays to quarks / leptons remain (+ cascades)

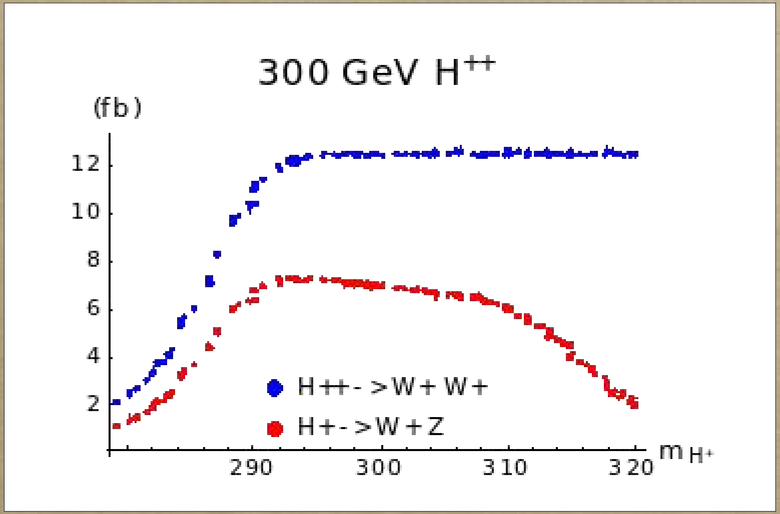




Extending $H^{++} \to W^+W^+$ searches

CMS used $H^{++}H^{--}$ pair and $H^{++}H^{-}$ associated production in dilepton (very low v_t)
→ easy topology

As for larger values of v_t more difficult picture linked to H^+ BRs and combining to PP.
* $H^+ \to tb$ will be canceled by the b-jet veto
* $H^+ \to W^+Z$ and W^+h^0 (with no bb decay) can give additionnal yield, but need to reoptimize selection



Pair production in 4W vs
Associated production in 3W+Z

Preselection from ATLAS-HIGG-2016-09
3L channel

Cut	$H^{++}H^{--}$	$H^{++}H^{-}$
$H^{++} \to WW$ and $H^{+} \to WZ$	557.1	511.9
3 leptons	7.5	7.6
0 b-jet	6.7	6.3
at least 2 jets	4.7	5.1
MET $\geq$ 45 GeV	4.1	4.1
Z-veto on same-sign pair	3.0	1.2

Mixing charged with neutral

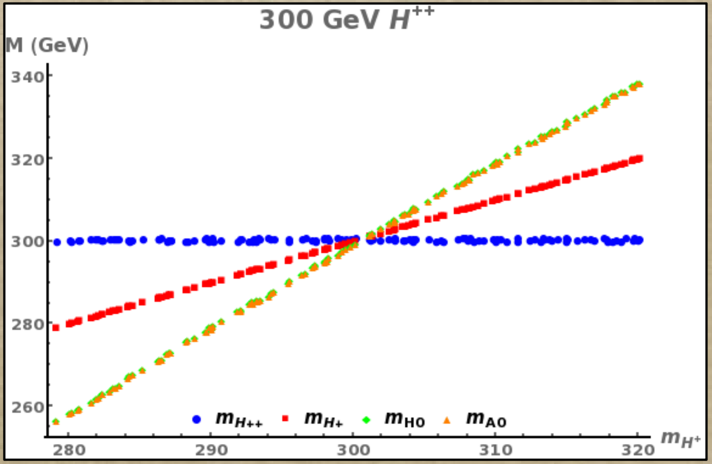
initial state (pp)	sensitivity	final state
$q\bar{q}', \gamma W^{\pm}, ZW^{\pm}$	gauge couplings, $H^{\pm}$, A^0	$H^{\pm}H^0$
$q\bar{q}', \gamma W^{\pm}, ZW^{\pm}$	gauge couplings, $H^{\pm}$, A^0	$H^{\pm}A^0$
$q\bar{q}', \gamma W^{\pm}, ZW^{\pm}$	mixing suppressed [gauge couplings, $H^{\pm}$, A^0]	$H^{\pm}h^0$
$W^{\pm}W^{\pm}$	gauge couplings, $H^{\pm}$	$H^{\pm\pm}H^0$
$W^{\pm}W^{\pm}$	gauge couplings, $H^{\pm}$	$H^{\pm\pm}A^0$
$W^{\pm}W^{\pm}$	mixing suppressed [gauge couplings, $H^{\pm}$]	$H^{\pm\pm}h^0$
$q\bar{q}, ZZ, W^+W^-$	gauge couplings, $H^{\pm}$, A^0, $\lambda_1+\lambda_4, h^0$	H^0H^0
$q\bar{q}, W^+W^-$	gauge couplings, $H^{\pm}$	H^0A^0
$q\bar{q}, W^+W^-$	gauge couplings, $H^{\pm}$	H^0h^0
$q\bar{q}, ZZ, W^+W^-$	gauge couplings, $H^{\pm}, H^0$, $\lambda_1+\lambda_4, h^0$	A^0A^0
$q\bar{q}, W^+W^-$	gauge couplings, $H^{\pm}$	A^0h^0
SM	SM	h^0h^0

$$m_A^2 = \frac{\mu(v_d^2+4v_t^2)}{\sqrt{2}v_t}$$

$$m_{H^0}^2 = \frac{1}{2}\left[A+C+\sqrt{(A-C)^2+4B^2}\right]$$

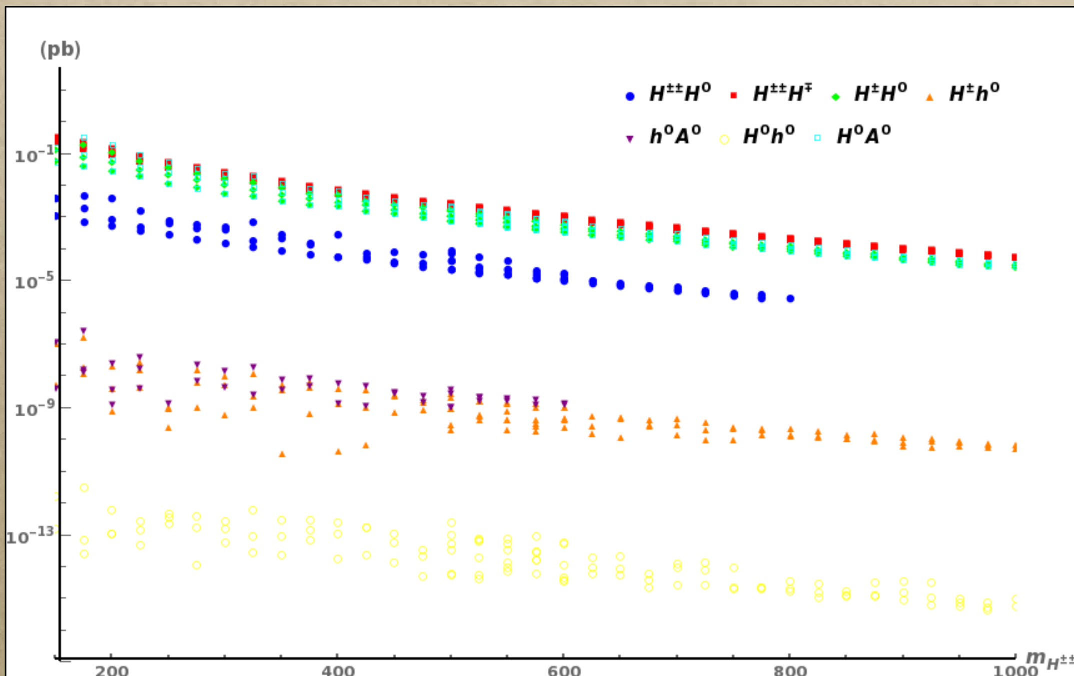
$$A = \frac{\lambda}{2}v_d^2,\quad B = v_d(-\sqrt{2}\mu+(\lambda_1+\lambda_4)v_t)\quad C = \frac{\sqrt{2}\mu v_d^2+4(\lambda_2+\lambda_3)v_t^3}{2v_t}$$

In the $v_t \ll v_d$ range, both CP-odd A^0 and CP-even H^0 have the same mass.



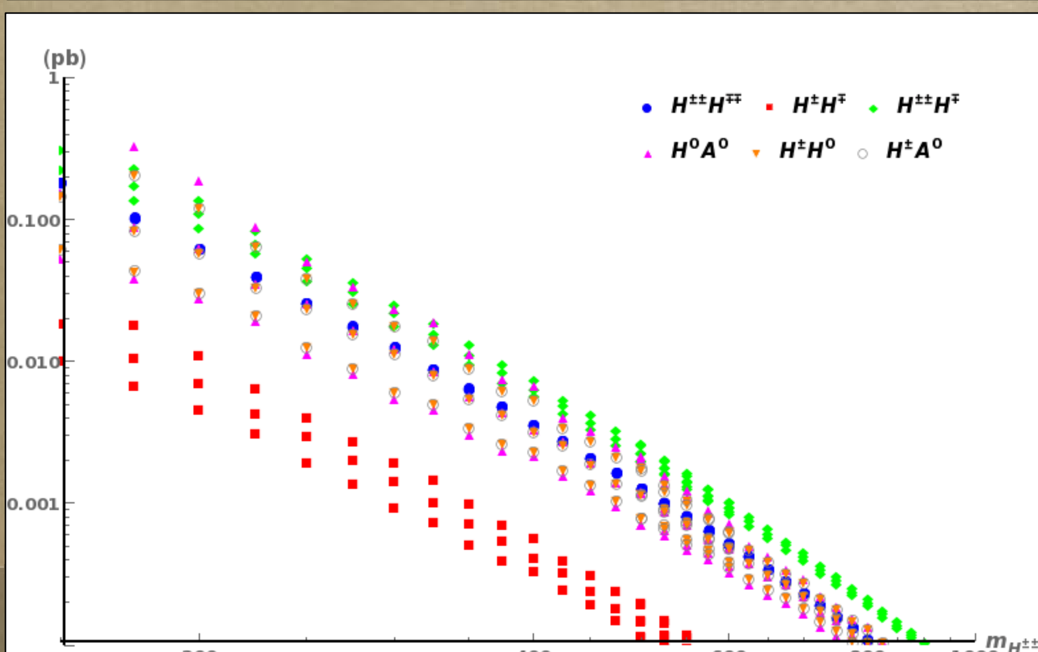
VBF dominant in processes with neutral Higgses from both doublet AND triplet.
Else, subdominant because of v_t suppression.

Mixing charged with neutral



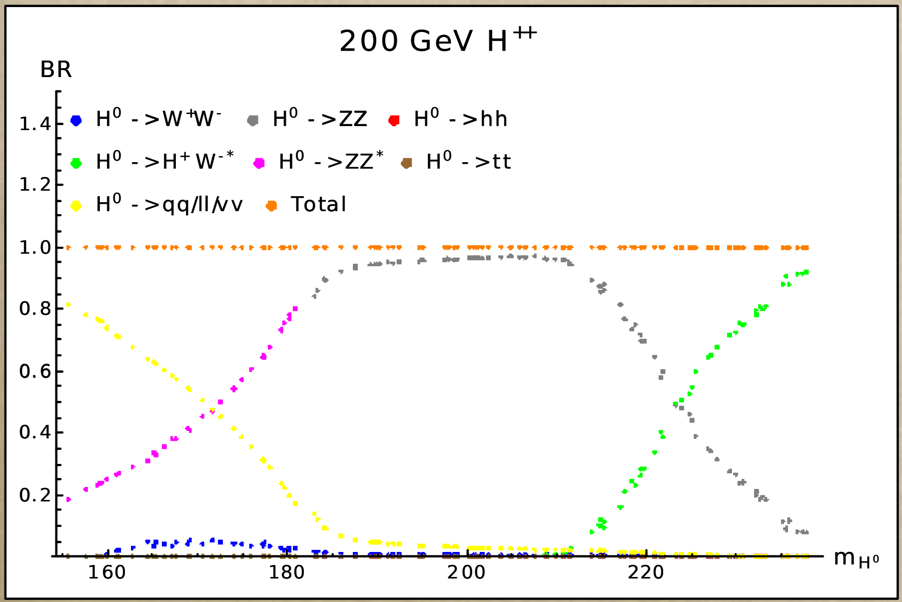
Cross-sections corresponds to
q q > X Y processes

VBF contributions expected to be marginal for $X^{+}Y$ processes, might dominate for h^0H^0

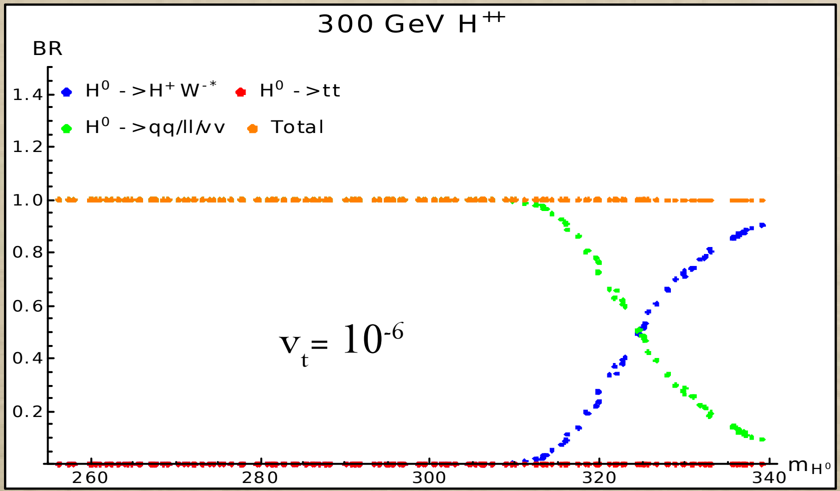


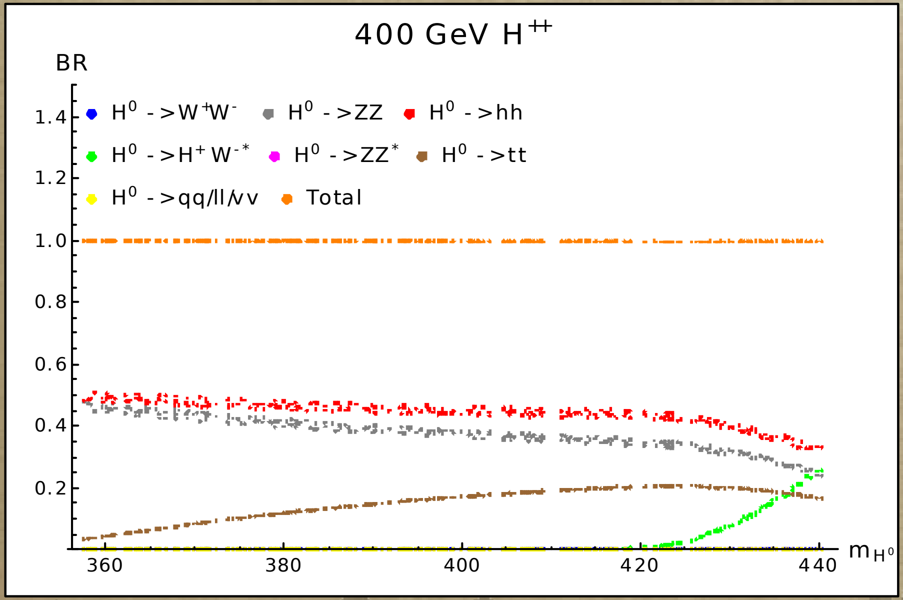
Some processes compare to the dominant charged productions
(H^+H^0/H^+A^0 and H^0A^0)

Neutral H^0/A^0 branching ratios

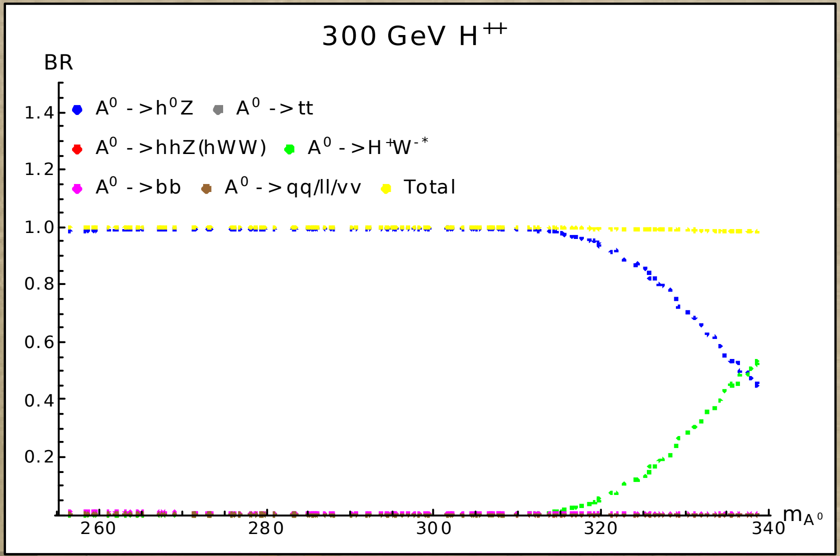


Once every channel is open, competition between $h^0h^0/ZZ/tt$





A0, on a contrary, will go to h^0Z or cascades



Potential final states

Taking the dominant processes in terms of cross section :

- H^+H^0 could go up to 5 leptons with $h^0 \rightarrow WW$ decay or to 3L + b-jets with $h^0 \rightarrow bb$

- H^+A^0 with WZ decays for the charged Higgs and Zh^0 for the neutral would mimic ttZ signature (for $h^0 \rightarrow bb$)

- H^0A^0 can lead to high b-jet signatures with $H^0 \rightarrow h^0h^0$ and $A^0 \rightarrow h^0Z$ without paying too much BR.

$H^+H^0 \rightarrow WZh^0h^0$

Channel	Final state
$W^\pm Z b\bar{b}b\bar{b}$	$3\ell + 4b + 0j$
$W^\pm Z b\bar{b} W^\pm W^\pm$	$3\ell + 2b + 2j$
	$3\ell + 4b + 0j$
	$3\ell + 2b + 4j$
$W^\pm Z W^\pm W^\pm W^\pm W^\pm$	$3\ell + 0b + 8j$
	$3\ell + 2b + 6j$
	$3\ell + 0b + 6j$
	$4\ell + 0b + 6j$
	$4\ell + 2b + 4j$
	$4\ell + 0b + 4j$
	$5\ell + 0b + 2j$
	$5\ell + 2b + 0j$
	$5\ell + 0b + 4j$

Suppression of $BR(h^0 \rightarrow xx)^2$ with respect to H++H-

Conclusions

- Searches for H^{++} have put stringent limits on the dileptonic decays, i.e, on $v_t \ll 1$
- On the contrary, di-bosonic decays are nearly not constrained (200-220 GeV)
- Adding associated production with H^+ could enhance the sensitivity
- But more generally, we have scanned branching ratios of the new scalars
- Production cross-sections have shown that charged-neutral associated production might also yield sizable contributions

Tack

Backup