Doubly-charged Higgs bosons in the diboson decay scenario at the ILC

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Collaboration with

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Physics Letters B726, 316-319 (2013), arXiv:1305.2383 [hep-ph]

LCWS2013 Nov. 11th-15th Univ. of Tokyo

Current Status

- We have found a Higgs boson with 126 GeV at the LHC, which is consistent with the SM Higgs boson.

- Any new particles have not been discovered yet.

➡ The SM seems to be correct. However, …

- The SM cannot explain **neutrino masses**, **dark matter** and **baryon asymmetry of the Universe**.
  We need new physics to explain these phenomena.

- The Higgs sector is often **extended** in new physics models.

- Determination of the true Higgs sector is determination of the direction of NP models.

The time has come to seriously discuss the bottom up approach to determine the structure of the Higgs sector!

The Minimal Higgs Triplet Model

- The Higgs triplet field Δ is added to the SM.

	SU(2)l	U(1)Y	U(1)L
Φ	2	1/2	0
Δ	3	1	-2

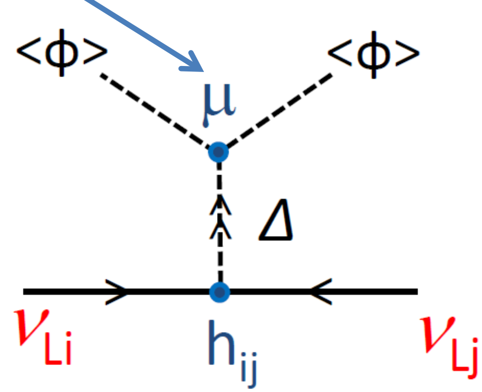
・Neutrino Yukawa interaction:

$$\mathcal{L}_Y = h_{ij}\overline{L_L^{ci}} \cdot \Delta L_L^j$$

・Higgs Potential:

Lepton number breaking parameter

$$V = m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + (\mu\Phi^T i\tau_2\Delta^\dagger\Phi + \text{ h.c.})$$
$$+\lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + \lambda_3\mathrm{Tr}[(\Delta^\dagger\Delta)^2]$$
$$+\lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$



・Neutrino mass matrix

O(0.1) eV

$$(m_\nu)_{ij} = h_{ij}\frac{\mu\langle\phi^0\rangle^2}{M_\Delta^2} = h_{ij}v_\Delta$$

Important predictions

★ **Rho parameter deviates from unity.**

$$\rho_{\text{tree}} \simeq 1 - \frac{2v_\Delta^2}{v^2}$$

$$\rho_{exp} = 1.0004^{+0.0003}_{-0.0004} \longrightarrow v_\Delta < 3.8\ \text{GeV}$$

★ **Extra Higgs bosons**

Doubly-charged $H^{\pm\pm}$, Singly-charged $H^{\pm}$, CP-odd A and **CP-even Higgs boson H**

★ **Characteristic mass relations**

$$m_{H^{++}}^2 - m_{H^+}^2 \simeq m_{H^+}^2 - m_A^2$$

Under $v_\Delta \ll v$

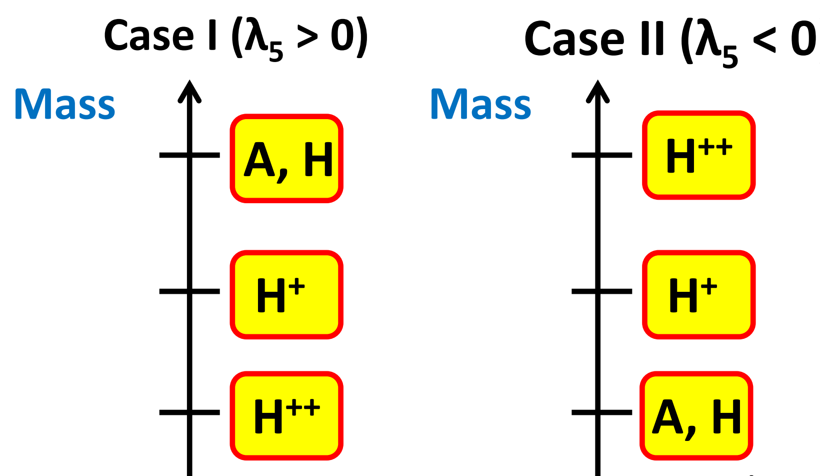
$$m_h^2 \simeq 2\lambda_1 v^2$$

$$M_\Delta^2 \equiv \frac{v_\Phi^2 \mu}{\sqrt{2} v_\Delta}$$

$$m_{H^{++}}^2 \simeq M_\Delta^2 - \frac{v^2}{2}\lambda_5$$

$$m_{H^+}^2 \simeq M_\Delta^2 - \frac{v^2}{4}\lambda_5$$

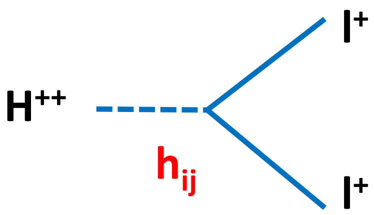
$$m_A^2 \simeq m_H^2 = M_\Delta^2$$



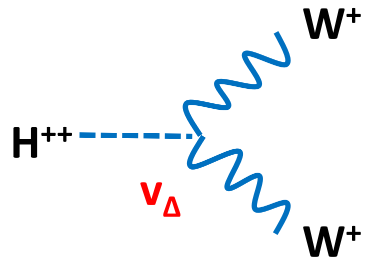
Decay of the doubly-charged Higgs bosons

The decay of H^{++} can be classified into 3 modes.

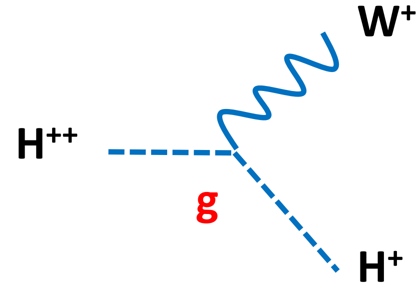
1. Decay via h_{ij}



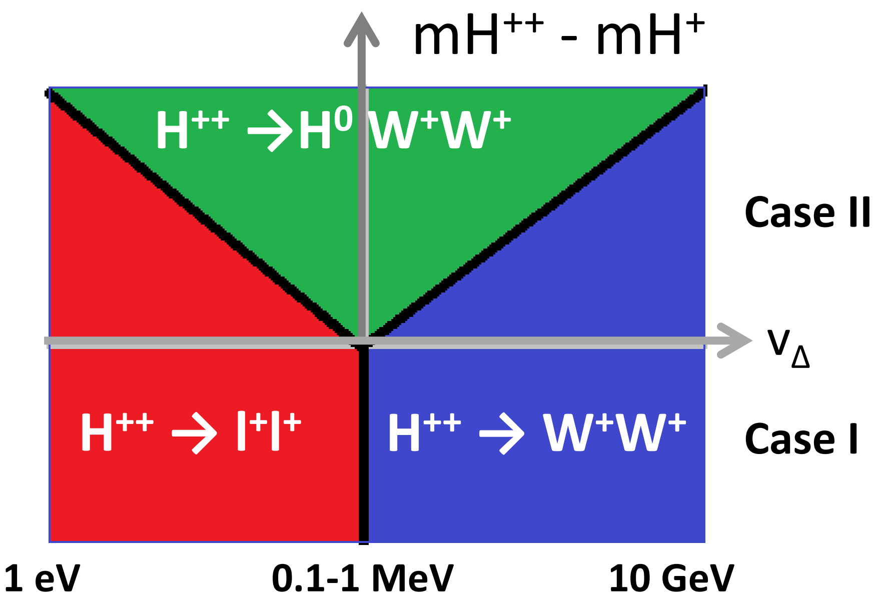
2. Decay via v_Δ



3. Decay via g



Decay of H^{++}



Decay modes of 1 and 2 are related to each other by the relation:

$$(m_\nu)_{ij} = h_{ij} v_\Delta$$

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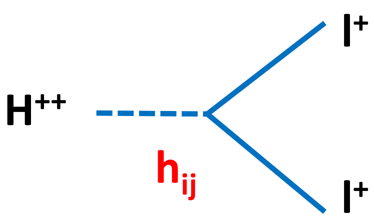
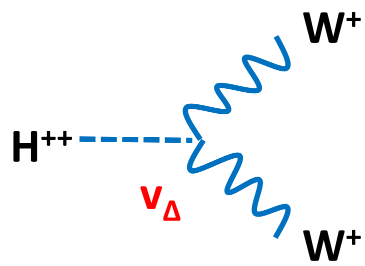


2. Decay via v_Δ



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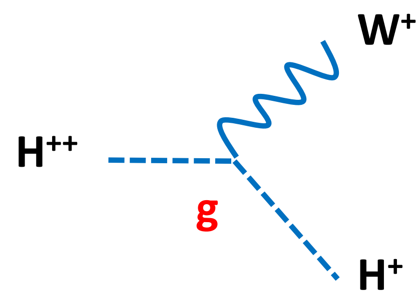
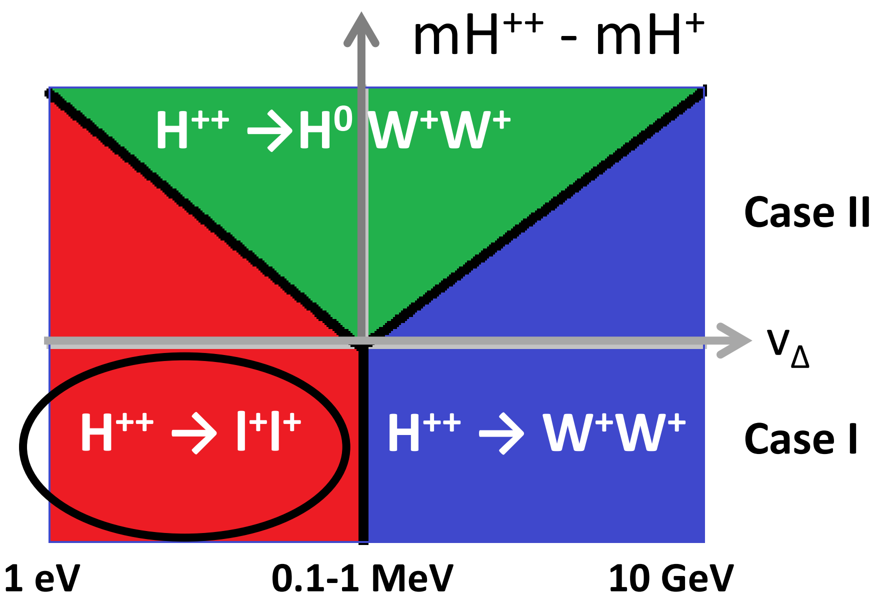


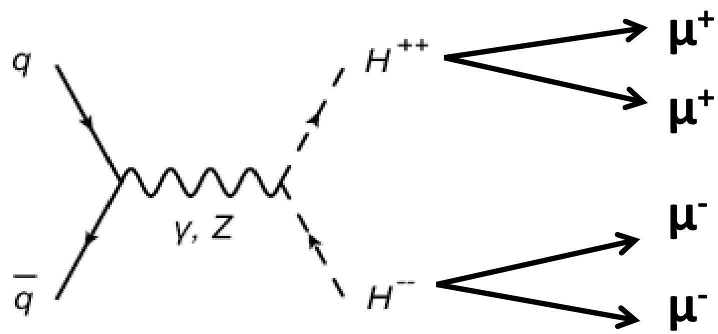
Decay of H^{++}

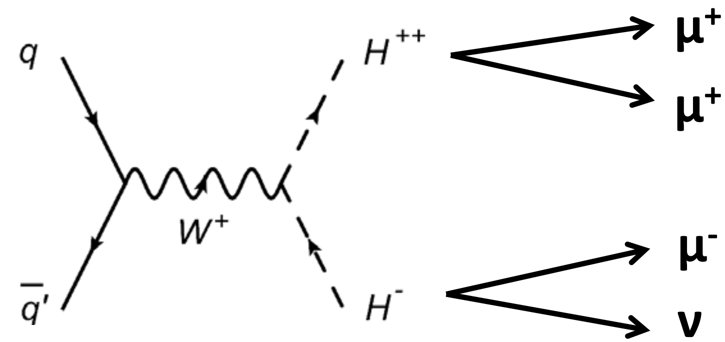


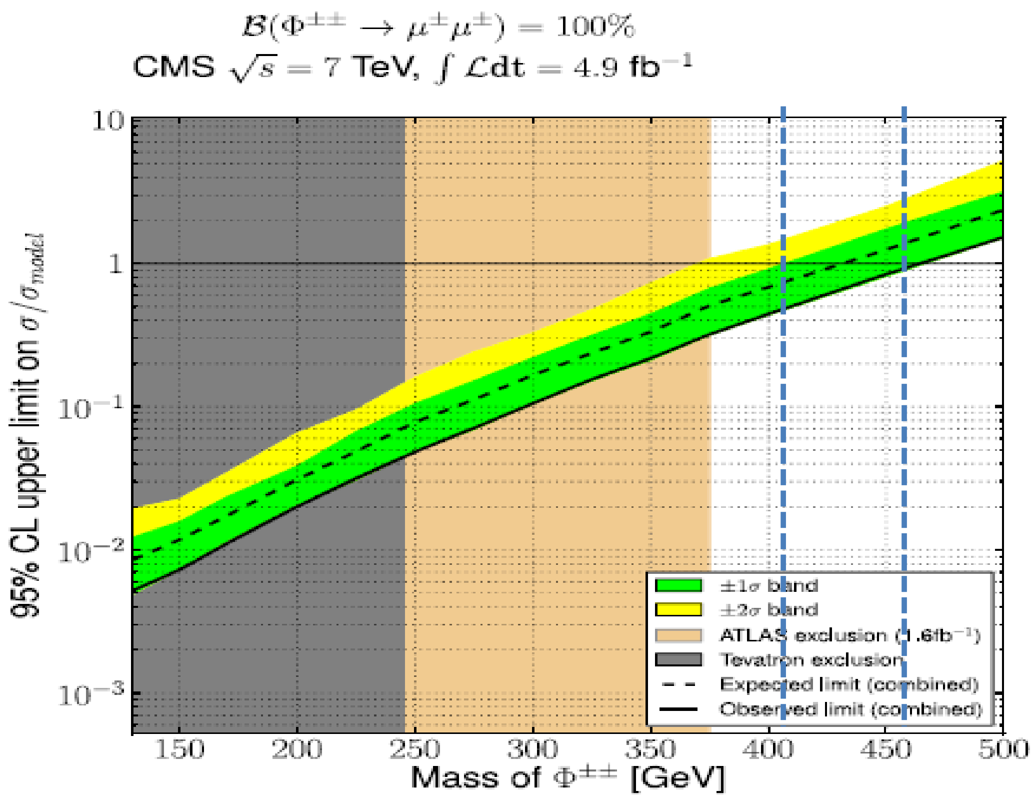
Decay modes of 1 and 2 are related to each other by the relation:

$$(m_\nu)_{ij} = h_{ij} v_\Delta$$

Search for the same-sign dilepton decay H^{++} @LHC



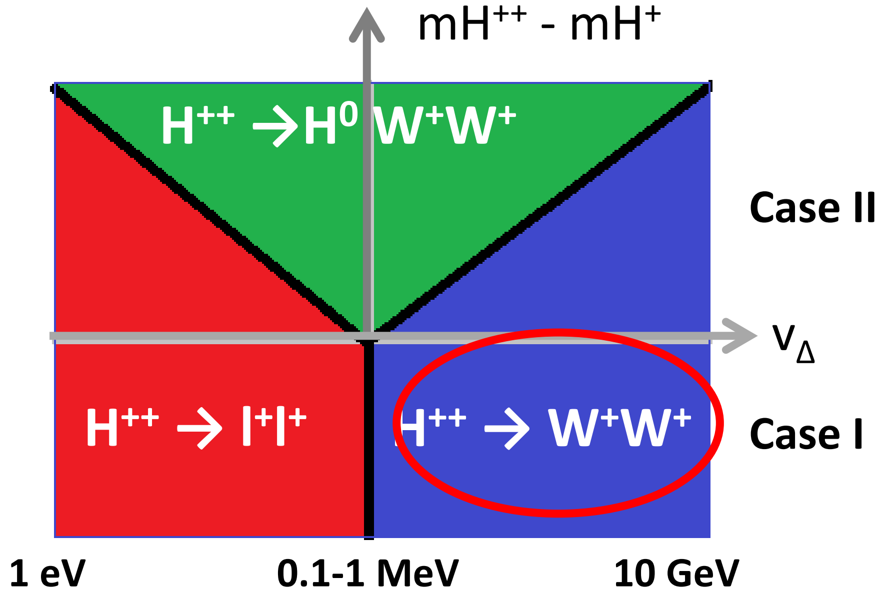




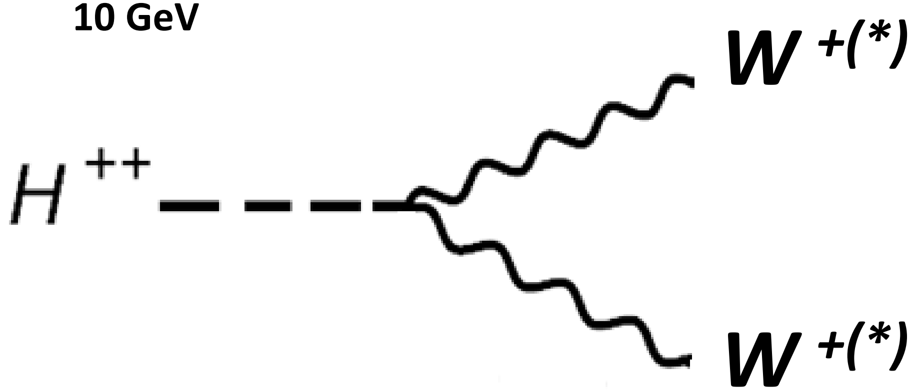
CMS, Eur. Phys. J.C. 72 (2012), 7 TeV, 4.9 fb^{-1}

If H^{++} can mainly decay into the same-sign dilepton, the lower limit for the mass has been taken to be ~400 GeV.

Same-sign diboson decay scenario



Perez, Han, Huang, Li, Wang (2008);
Chiang, Nomura, Tsumura (2012);
Kanemura, KY, Yokoya (2013)

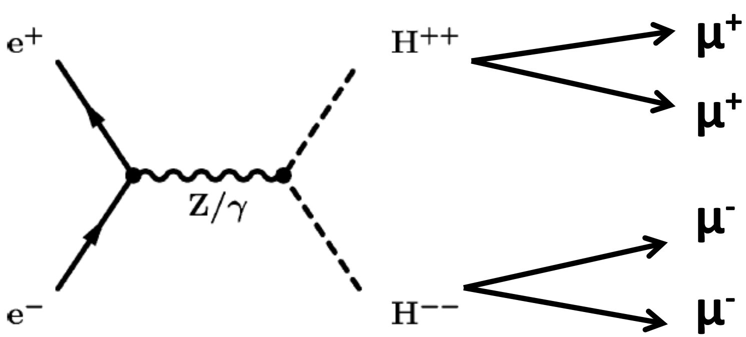


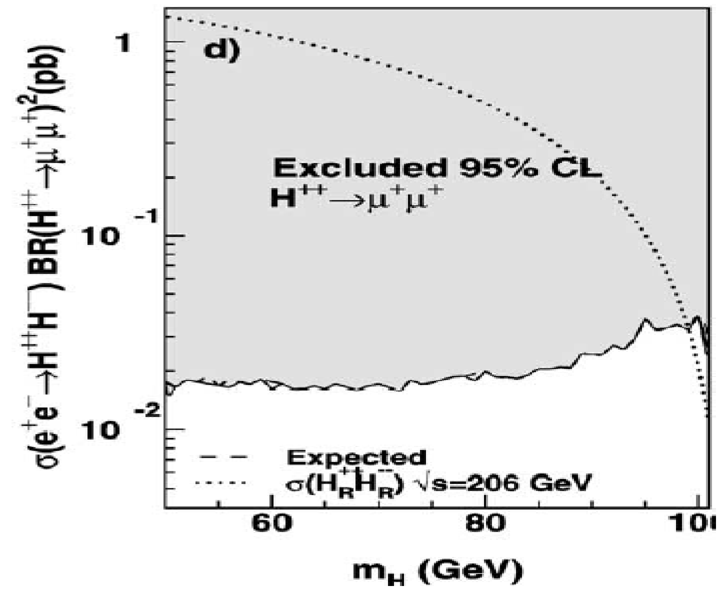
Can we get a mass bound on H^{++} in this scenario?

Bound from LEP

L3, Phys. Lett. B576 (2003), 206 GeV, 624 pb^{-1}

☐ 4-lepton channel (LEPII)





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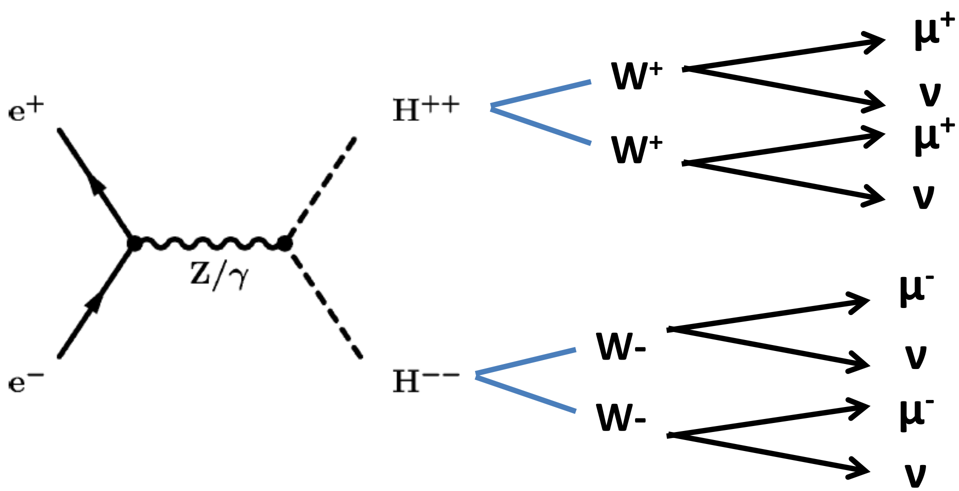

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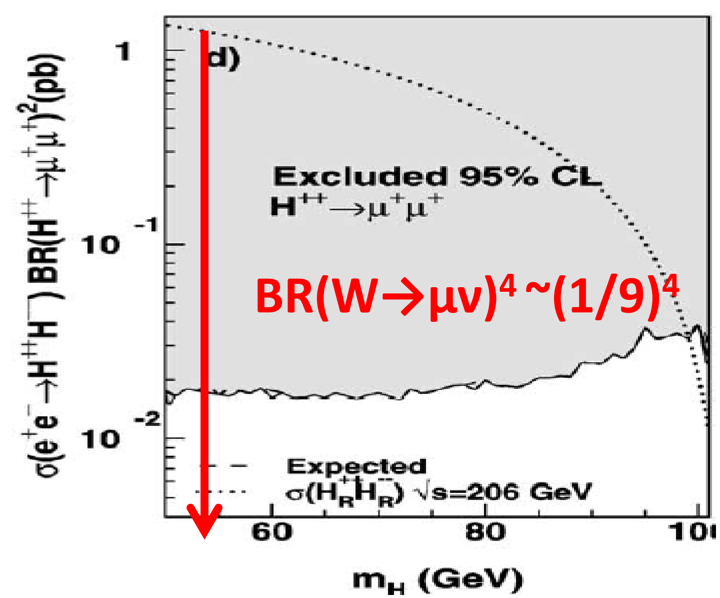
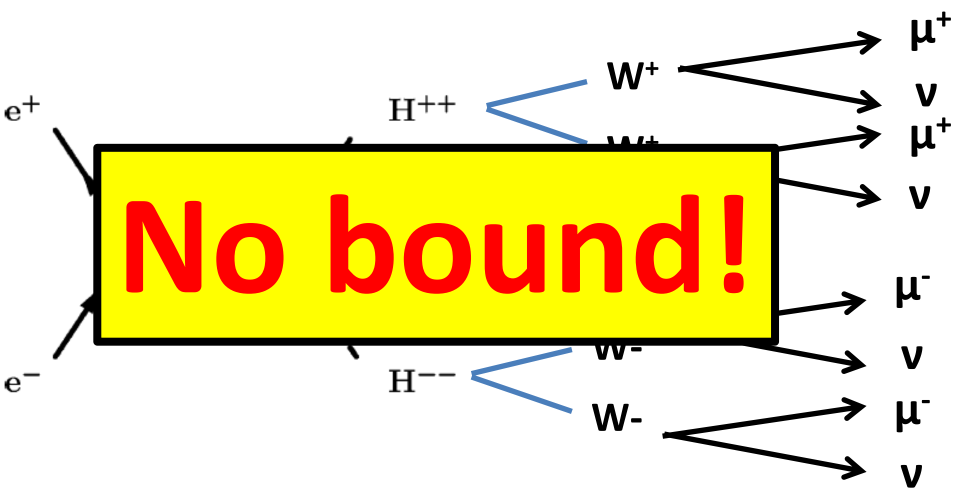
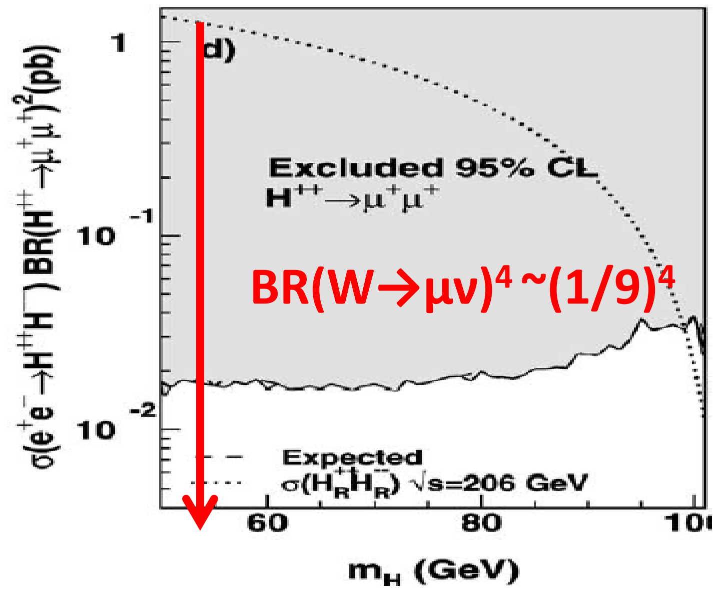


Bound from LEP

L3, Phys. Lett. B576 (2003), 206 GeV, 624 pb^{-1}

- **4-lepton channel (LEPII)**





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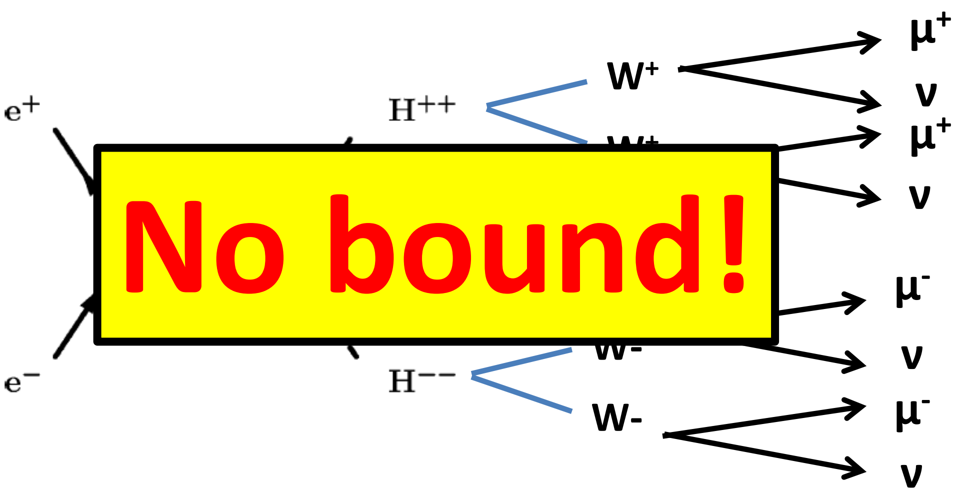
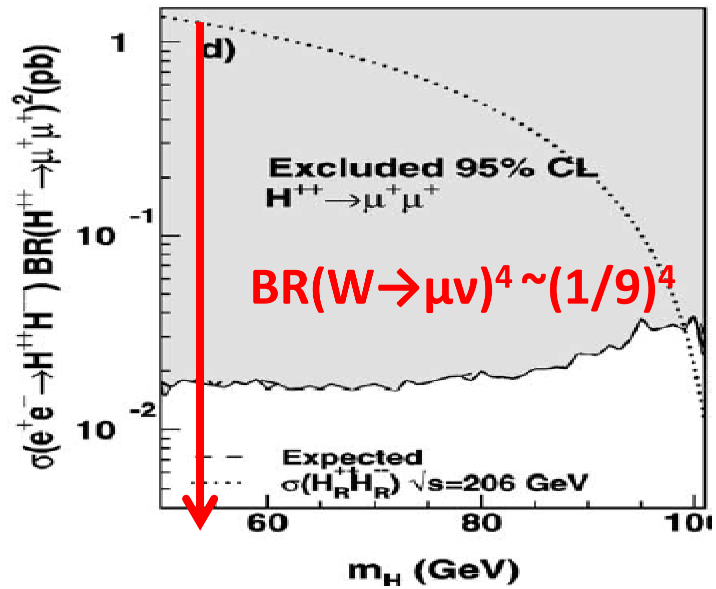
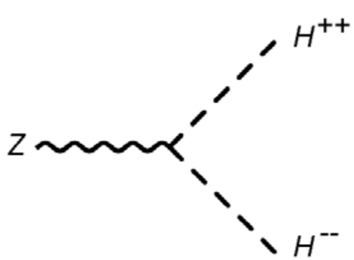


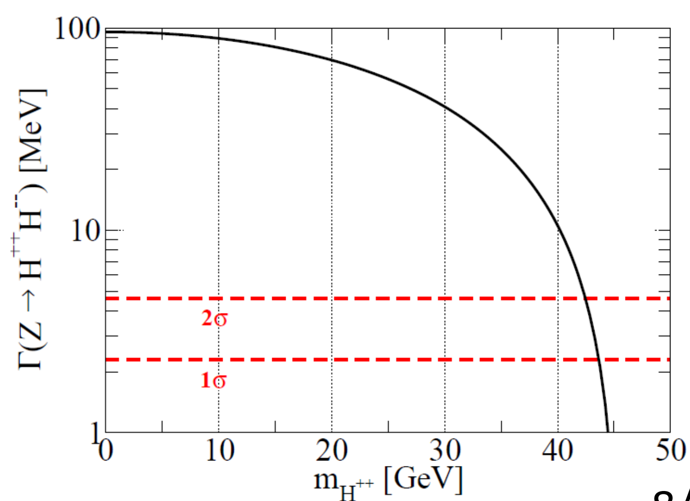


☐ Z boson width

$\Gamma_Z(\text{exp}) = 2.4952 \pm 0.0023$ GeV



mH^{++} > 43 GeV



Bound from LHC

ATLAS, JHEP 1212, (2012)

- ATLAS has provided the 95% CL limit for the cross section of the same-sign dilepton events $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$ and $\mu^{\pm}\mu^{\pm}$.

- The same-sign dimuon event ($\mu^{+}\mu^{+}$) is the most effective to constraint the mass of H^{++}.

$$\sigma(\mu^{+}\mu^{+}) = 15.2 \text{ fb with 7 TeV and 4.7 fb}^{-1}$$

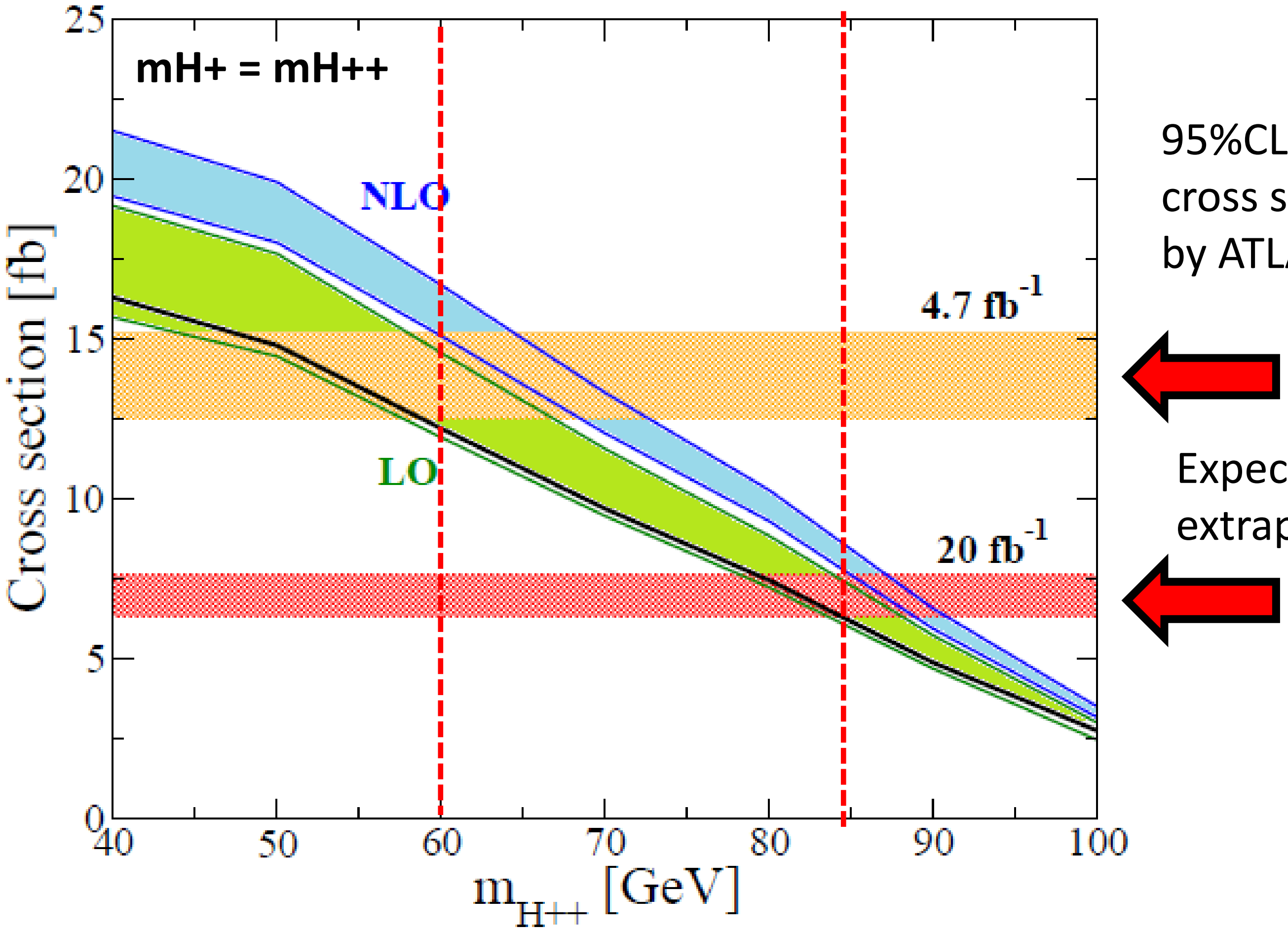
- To compare the experimental bound, we take following cuts;

Basic cut	Invariant mass cut
$\lvert\eta\rvert>2.5$, $p_T > 20$ GeV	$M_{\mu+\mu+} > 15$ GeV

$$15.2 \text{ fb} \quad \text{VS} \quad \sigma(\mu^{+}\mu^{+} + X)\rvert_{cuts}$$

Bound from LHC with 7 TeV

Kanemura, KY, Yokoya



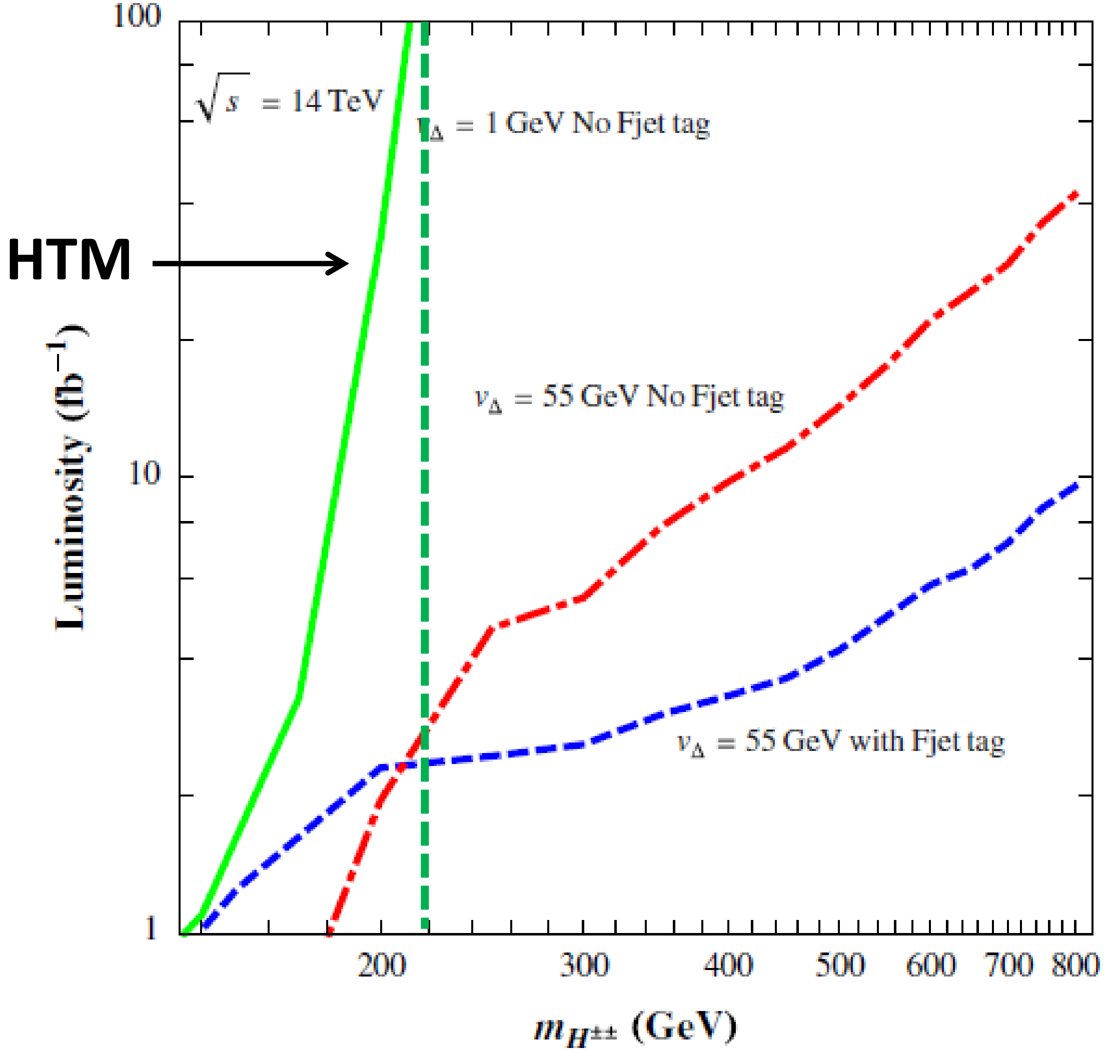
95%CL upper limit for the cross section by ATLAS data (7 TeV, 4.7/fb)

Expected upper limit by the extrapolation of data to 20/fb

We obtained the lower limit to be **60 GeV** by using **4.7 fb^{-1}** data.
The limit can be **85 GeV**, if we extrapolate the data to **20 fb^{-1}**.

Discovery potential at 14 TeV

Chiang, Nomura, Tsumura (2012)



m_{H++} ~ 200 GeV may be reached at the LHC.

Possible scenarios at ILC up to 500 GeV

1. H^{++} will be discovered at the LHC with 14 TeV .

- Direct search : Precise measurements of the properties of H^{++}.
- Indirect search : Deviation in Higgs boson couplings by fixing m_{H++} .

2. H^{++} will **not** be discovered at the LHC with 14 TeV,
   and its mass bound is **smaller** than 250 GeV.

- Direct search : Discovery mode
- Indirect search : Deviation in Higgs boson couplings assuming
  (14 TeV bound) $< m_{H++}$

3. H^{++} will **not** be discovered at the LHC with 14 TeV,
   and its mass bound is **larger** than 250 GeV.

- Direct search : Go to 1TeV ILC or CLIC
- Indirect search : Deviation in Higgs boson couplings assuming
  $m_{H++} > 250$ GeV

Possible scenarios at ILC up to 500 GeV

1. H^{++} will be discovered at the LHC with 14 TeV .

- Direct search : Precise measurements of the properties of H^{++}.
- Indirect search : Deviation in Higgs boson couplings by fixing m_{H++} .

2. H^{++} will **not** be discovered at the LHC with 14 TeV,
   and its mass bound is **smaller** than 250 GeV.

- Direct search : Discovery mode
- Indirect search : Deviation in Higgs boson couplings assuming
  (14 TeV bound) < m_{H++}

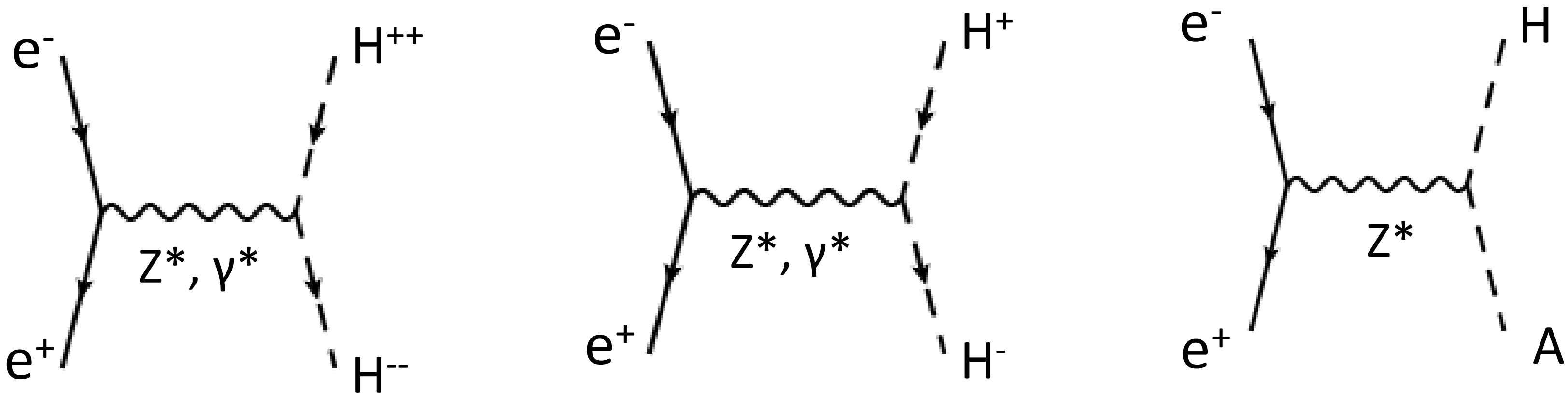
3. H^{++} will **not** be discovered at the LHC with 14 TeV,
   a

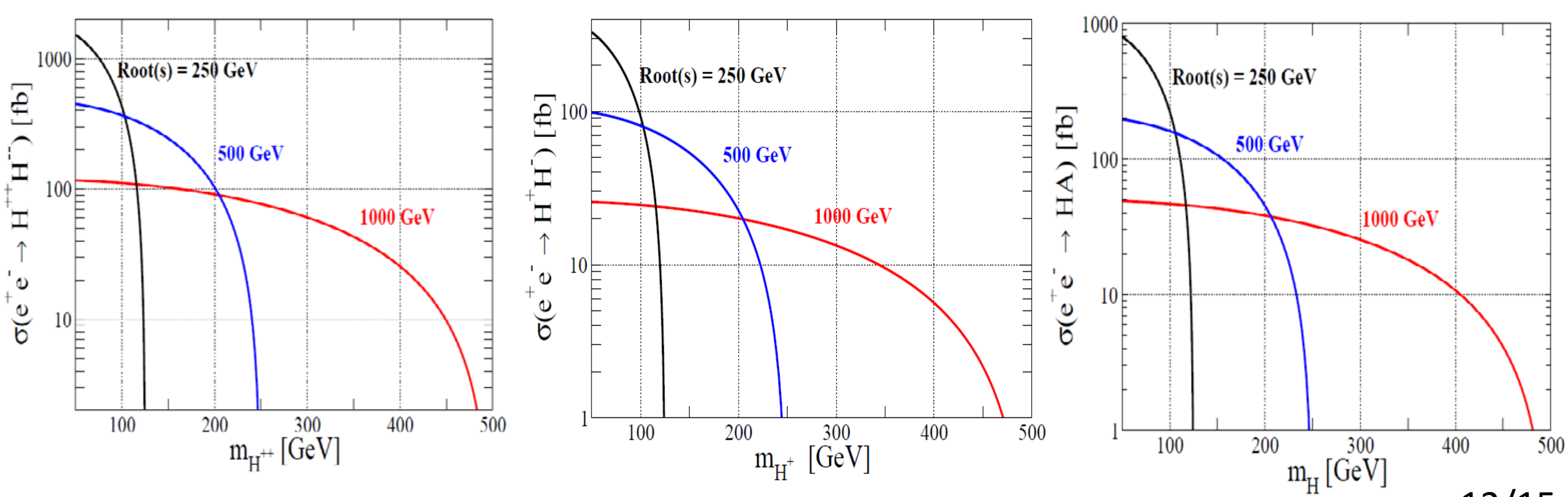
Let us consider the **second** scenario,
e.g., **230 GeV** for H^{++} mass, and discuss
the signature of Δ-like Higgs bosons at the ILC.

H++

Search for triplet-like Higgs bosons at the ILC

- Triplet-like Higgs bosons can be produced in the Drell-Yan pair production.





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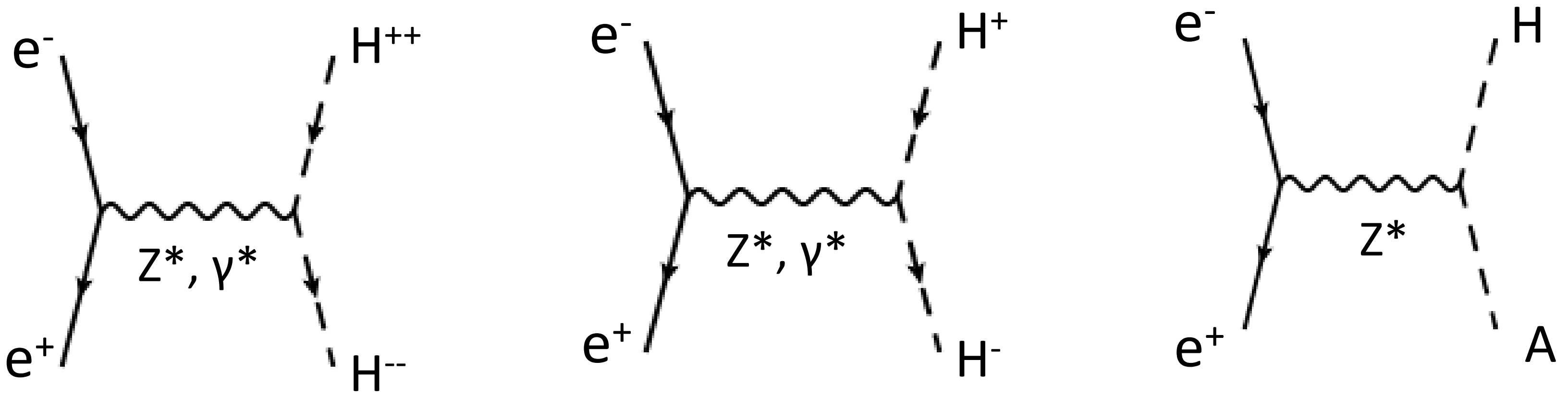
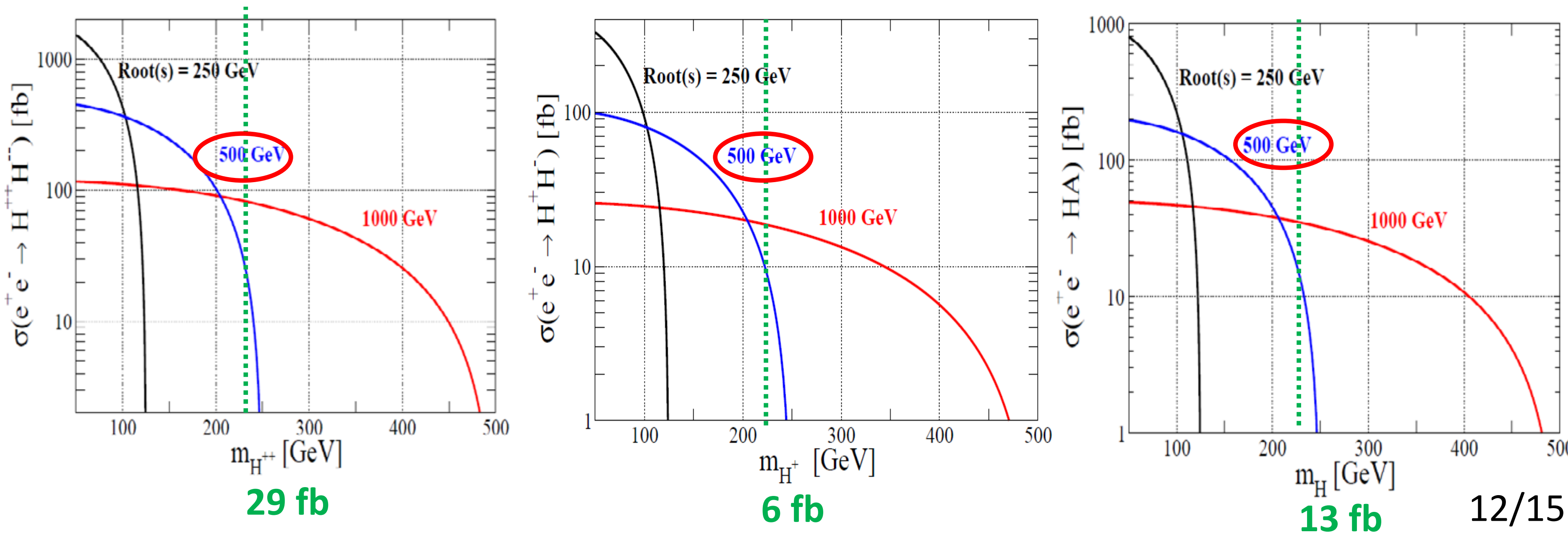
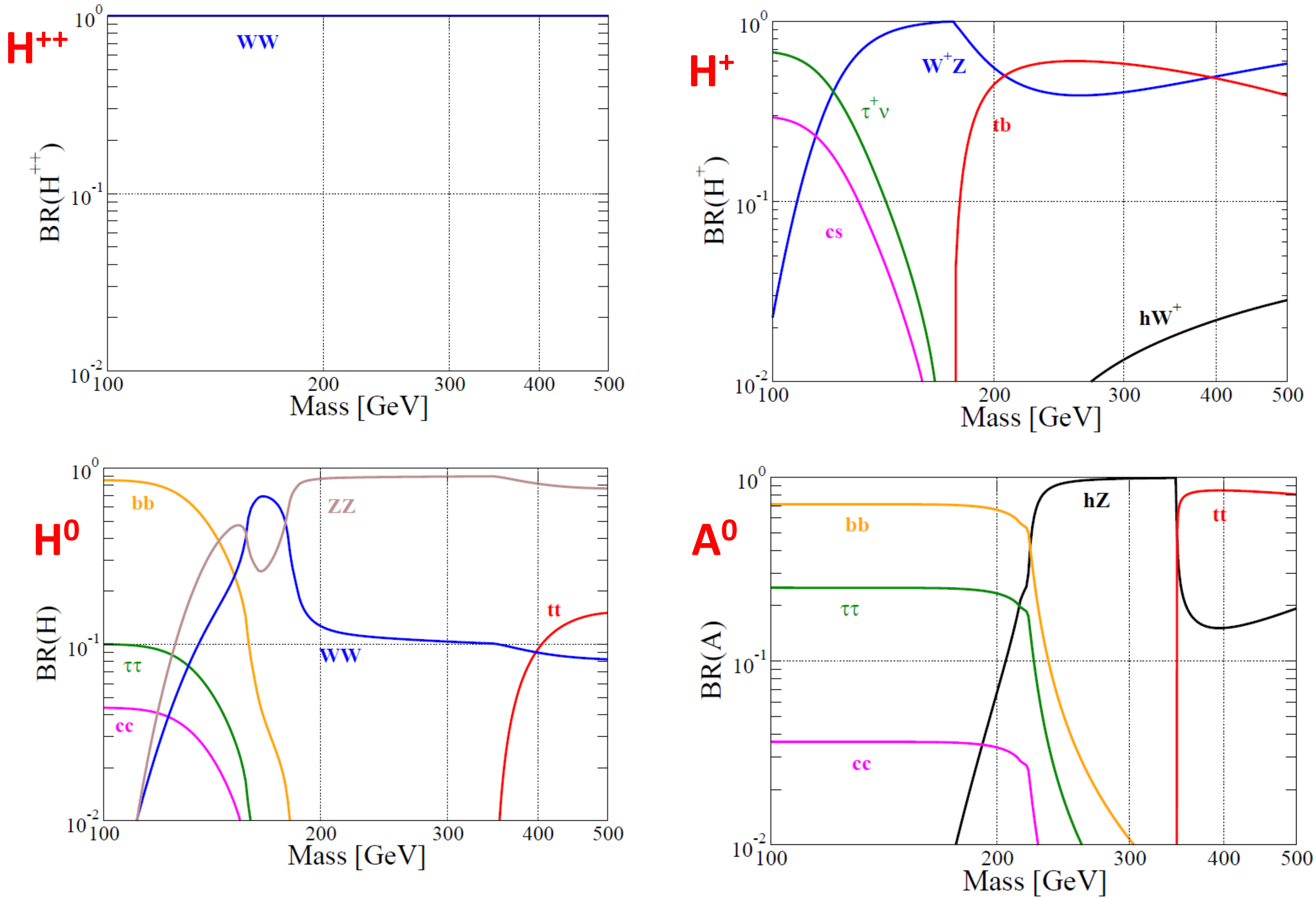


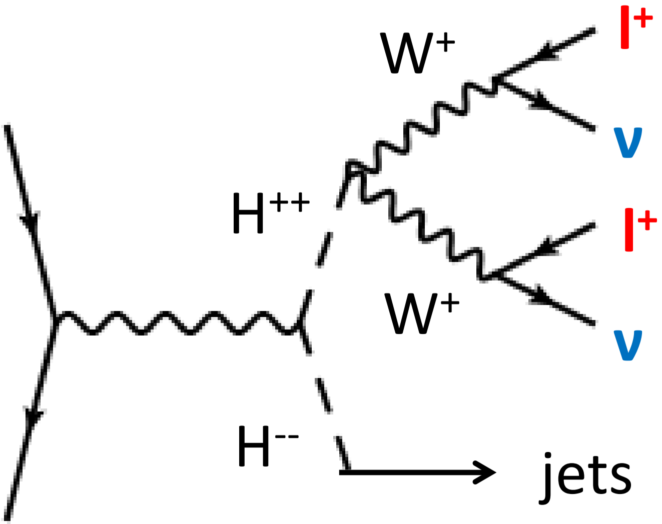


Higgs Decays (v_Δ = 1 GeV, Deg. masses)



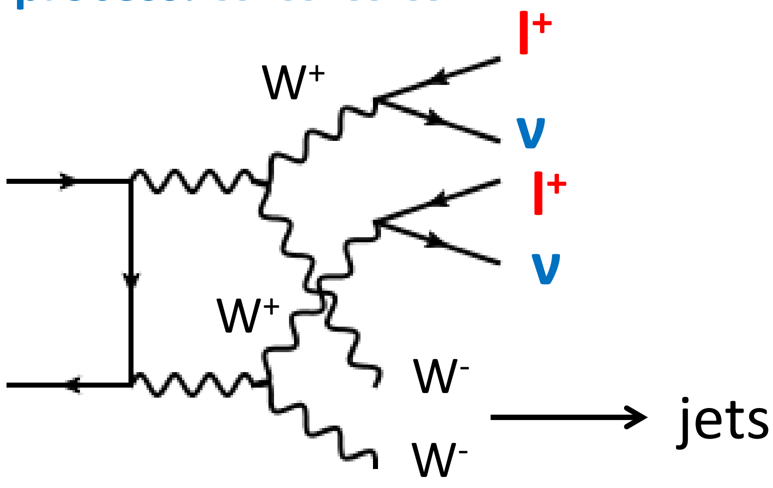
Signal at root(s) = 1 TeV

- **Signal process: SS dilepton + E_{miss} +jets**



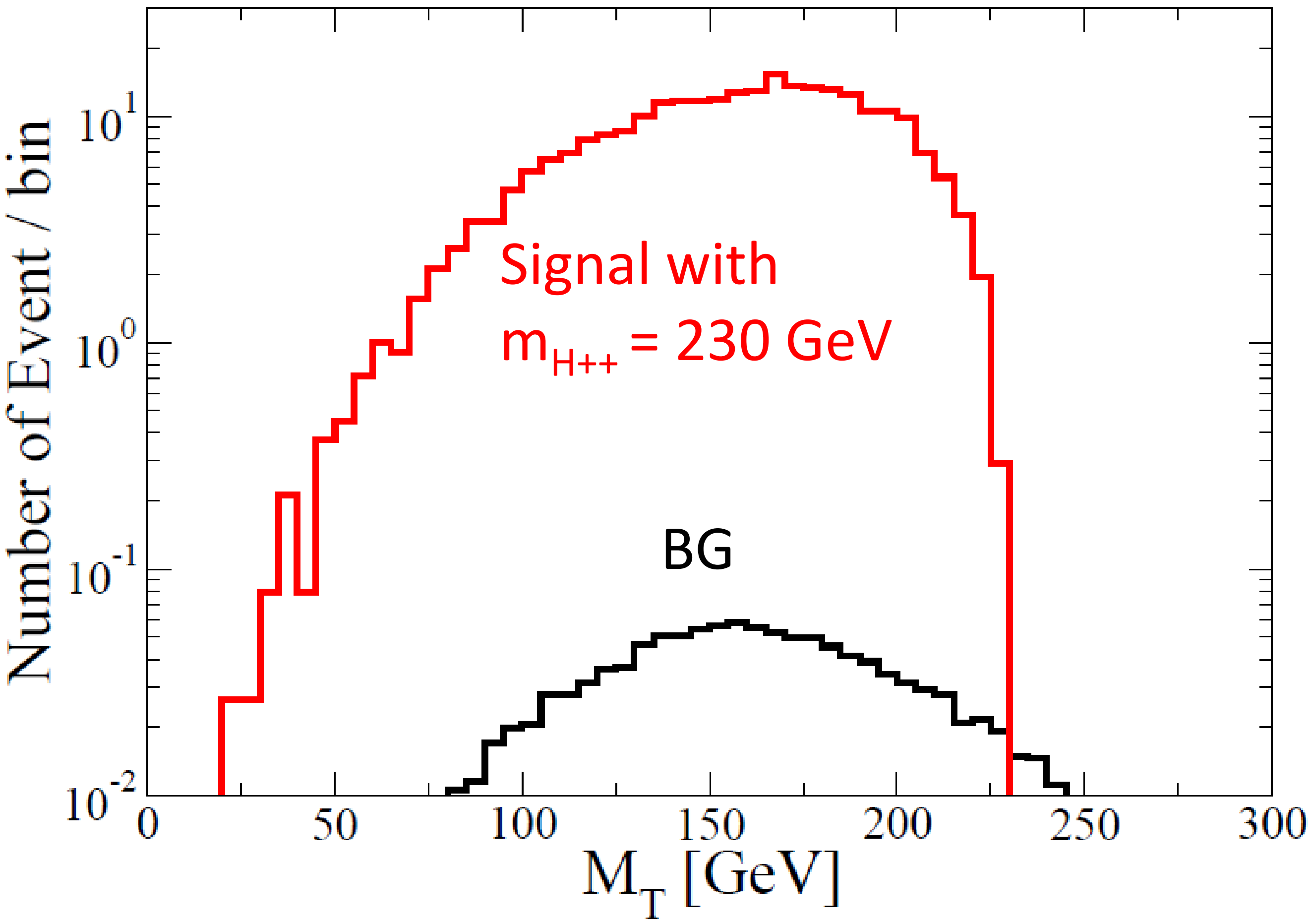
Cross section (final state)
~ 1.2 fb

- **BG process: $W^+W^+W^-W^-$**



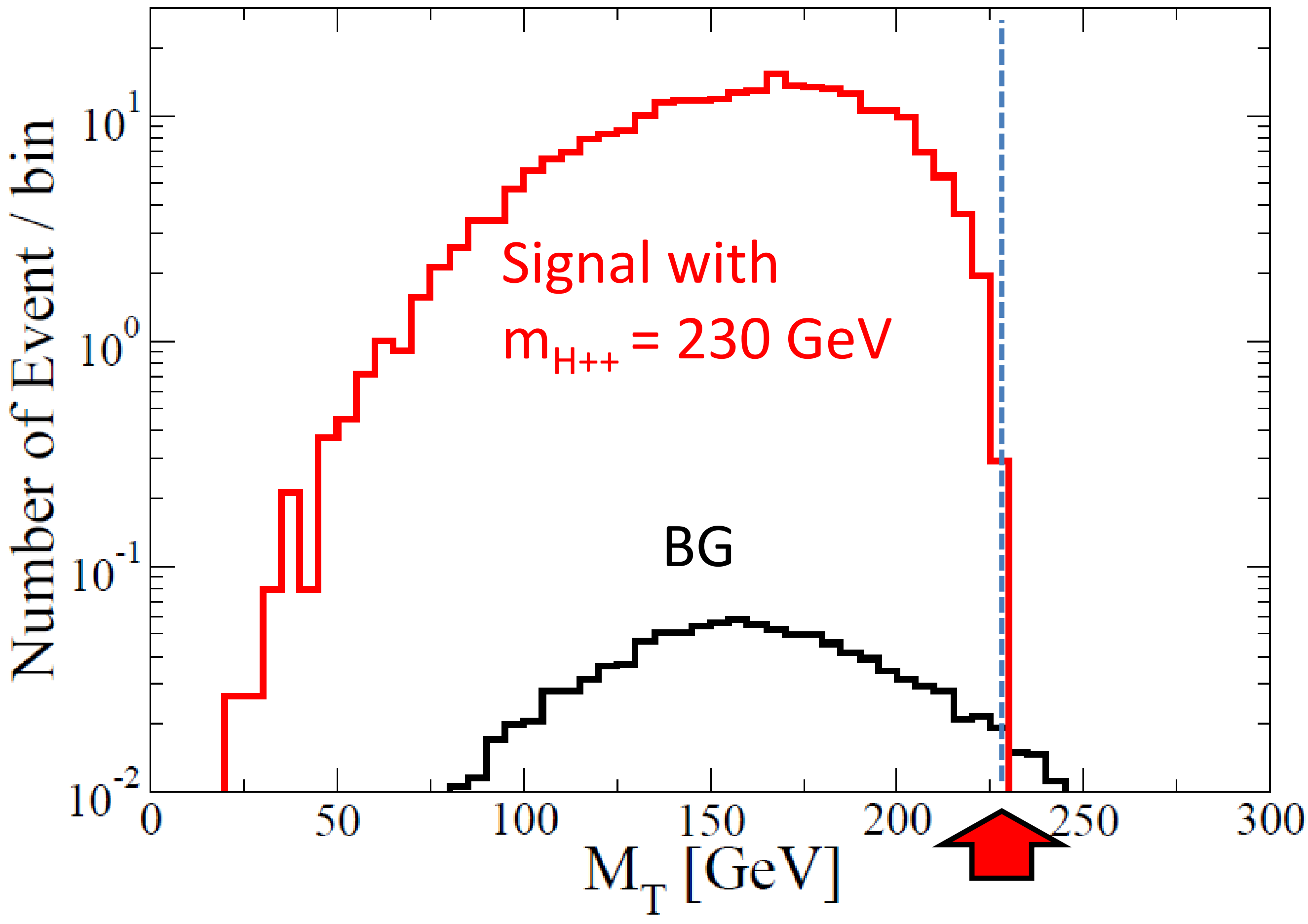
Cross section (final state)
~ 0.0024 fb

Transverse mass distribution @500 GeV



Int. Lum. = 500/fb
Bin size = 5 GeV

Transverse mass distribution @500 GeV



Int. Lum. = 500/fb
Bin size = 5 GeV

Endpoint ~ H^{++} mass

Summary

- The **Higgs Triplet Model** is one of the important possibilities of extended Higgs sectors, where **tiny neutrino masses are explained**.

- We find the new lower bound for the doubly-charged Higgs boson mass; **$mH^{++} > 60$ (85) GeV** from LHC data with 4.7 fb^{-1} (20 fb^{-1}) and 7 TeV.

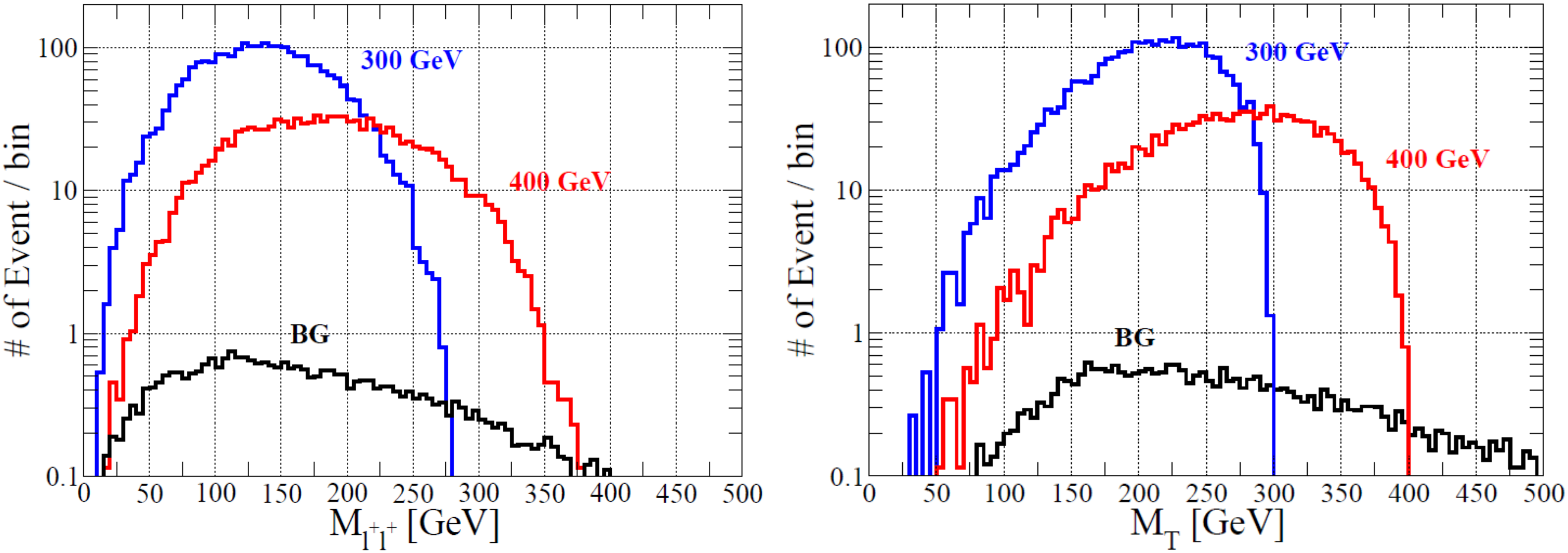
→**Light H^{++} scenario** is allowed by the current experimental data.

- After the 14 TeV run, either the cases will be realized, where H^{++} will be discovered or not, ILC physics is quite important to prove the Higgs Triplet Model.

- If the light H^{++} scenario (such as m_{H++} <250 GeV) is still possible, the direct search (**SS dilepton + missing + jets**) can be used to the discovery channel or precise measurement for H^{++}.

Distributions for the Invariant mass and Transverse mass

Root(s) = 1 TeV
Int. Lum. = 1 ab^{-1}
Bin size = 5 GeV



Decay width for H^{++}

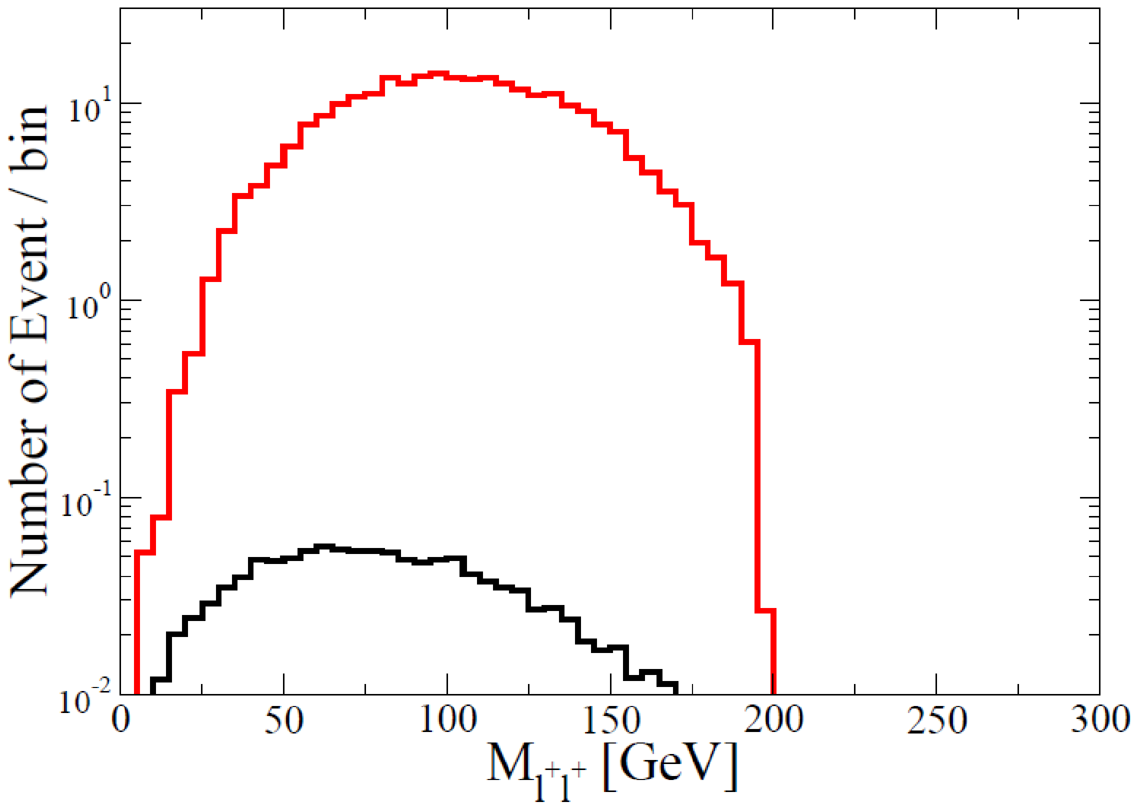
v_Δ = 1 GeV

$m_{H^{++}}$ [GeV]	40	50	60	70	80	90	100
Width [eV]	3.58×10^{-4}	1.89×10^{-3}	7.70×10^{-3}	2.69×10^{-2}	8.63×10^{-2}	0.320	1.86
Basic cut [fb]	20.9	16.7	13.0	10.1	7.63	4.95	2.78
$M_{\ell\ell}$ cut [fb]	16.3	14.8	12.2	9.69	7.45	4.87	2.74

1 eV^{-1} = 1.24 × 10^{-6} m

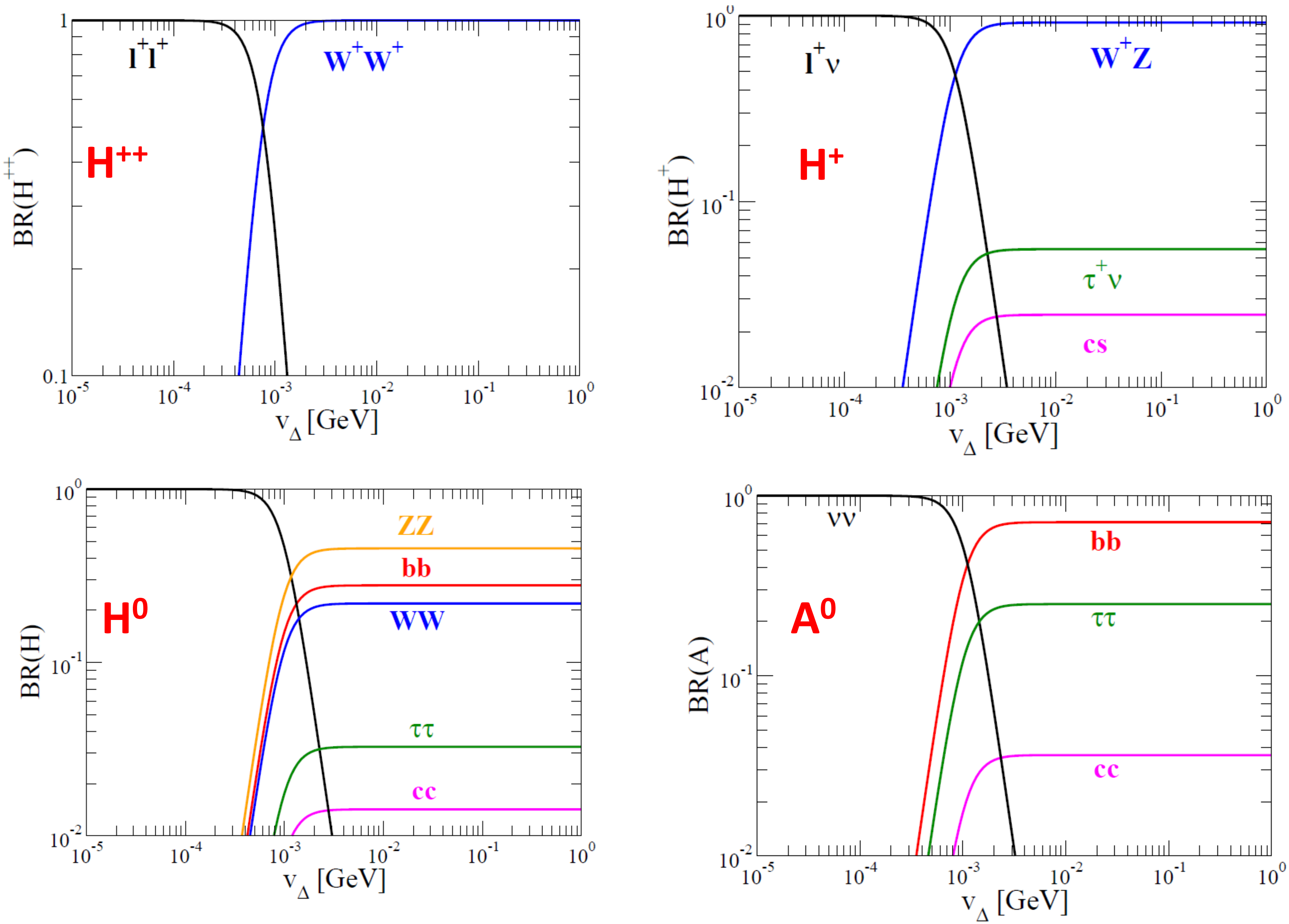
Decay Length: $c\tau = c/\Gamma$ ~ 1mm

Invariant mass distribution

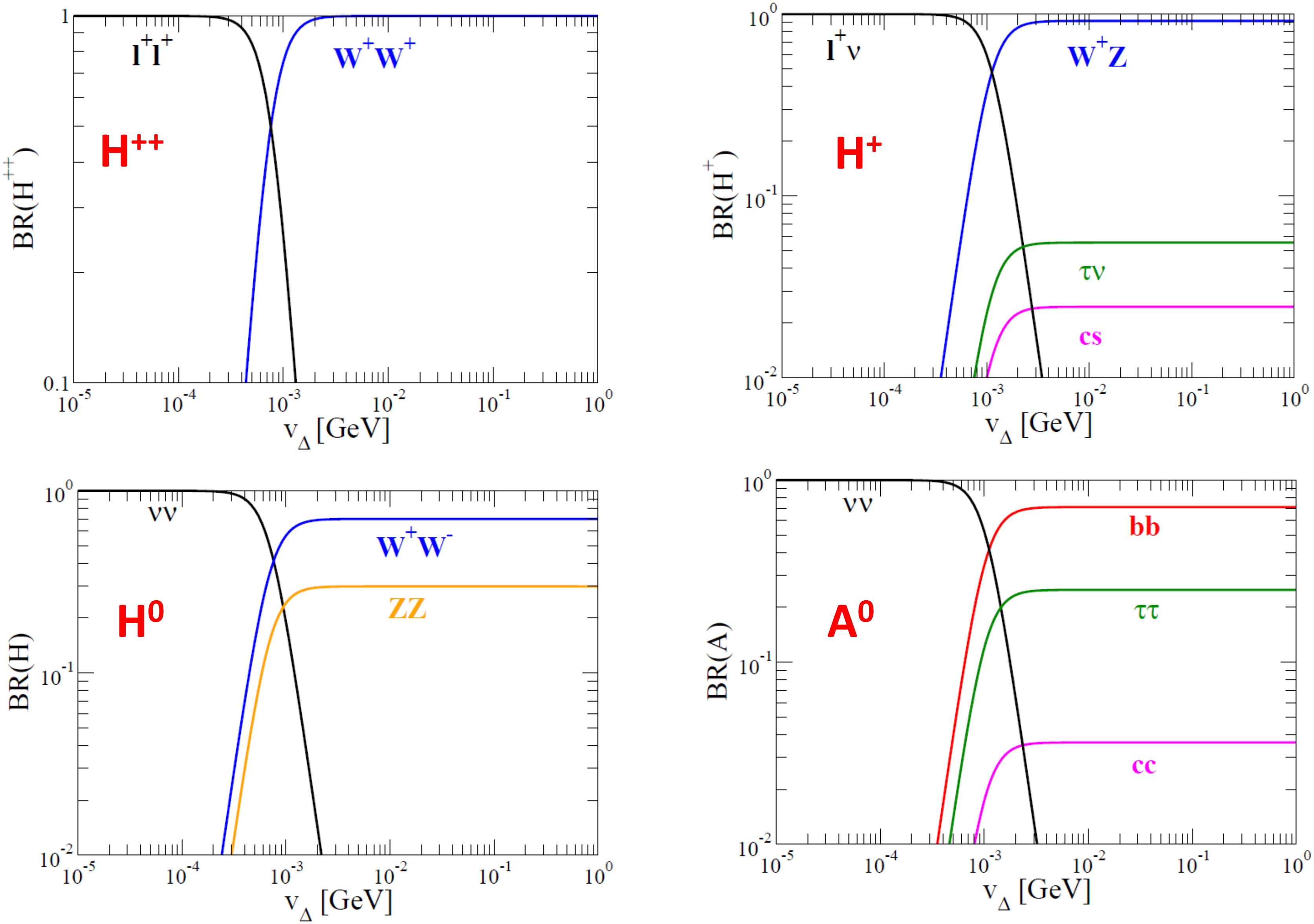


Root(s) = 500 GeV
Int. Lum. = 500/fb
Bin size = 5 GeV

Decays at 150 GeV and α=β



Decays at 150 GeV and α=0



Bound in the same-sign dilepton decay H^{++}

CMS, Eur. Phys. J.C. 72 (2012), 7 TeV, 4.9 fb^{-1}

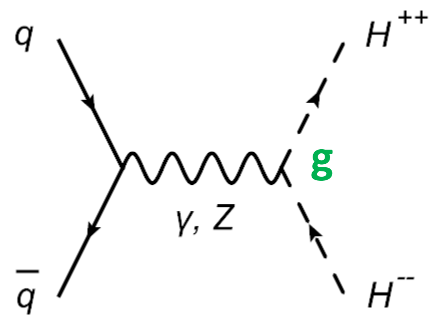
Table 6 Summary of the 95 % CL exclusion limits

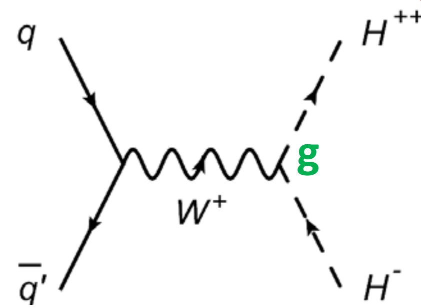
Benchmark point	Combined 95 % CL limit [GeV]	95 % CL limit for pair production only [GeV]
$\mathcal{B}(\Phi^{++} \to e^+e^+) = 100\ \%$	444	382
$\mathcal{B}(\Phi^{++} \to e^+\mu^+) = 100\ \%$	453	391
$\mathcal{B}(\Phi^{++} \to e^+\tau^+) = 100\ \%$	373	293
$\mathcal{B}(\Phi^{++} \to \mu^+\mu^+) = 100\ \%$	459	395
$\mathcal{B}(\Phi^{++} \to \mu^+\tau^+) = 100\ \%$	375	300
$\mathcal{B}(\Phi^{++} \to \tau^+\tau^+) = 100\ \%$	204	169
BP1	383	333
BP2	408	359
BP3	403	355
BP4	400	353

Production mechanisms at the LHC

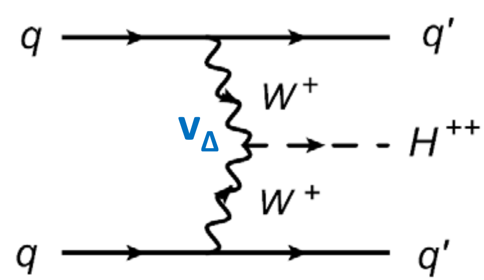
Main production process

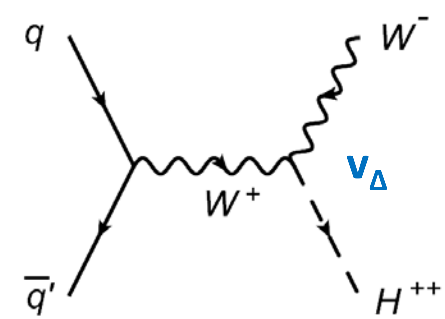
Drell-Yan
- depends on the gauge coupling



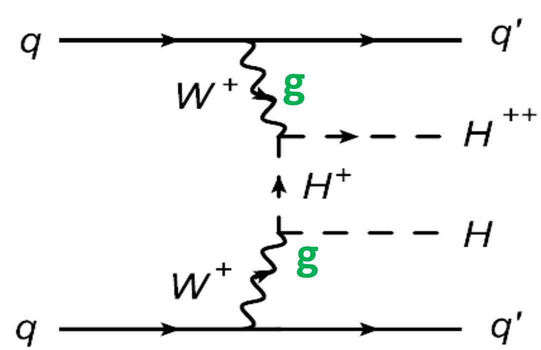


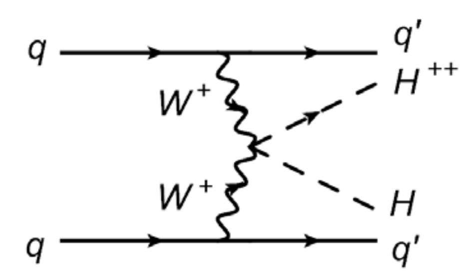
Vector boson fusion, and
W boson associate
- depends on v_Δ → **Suppressed**

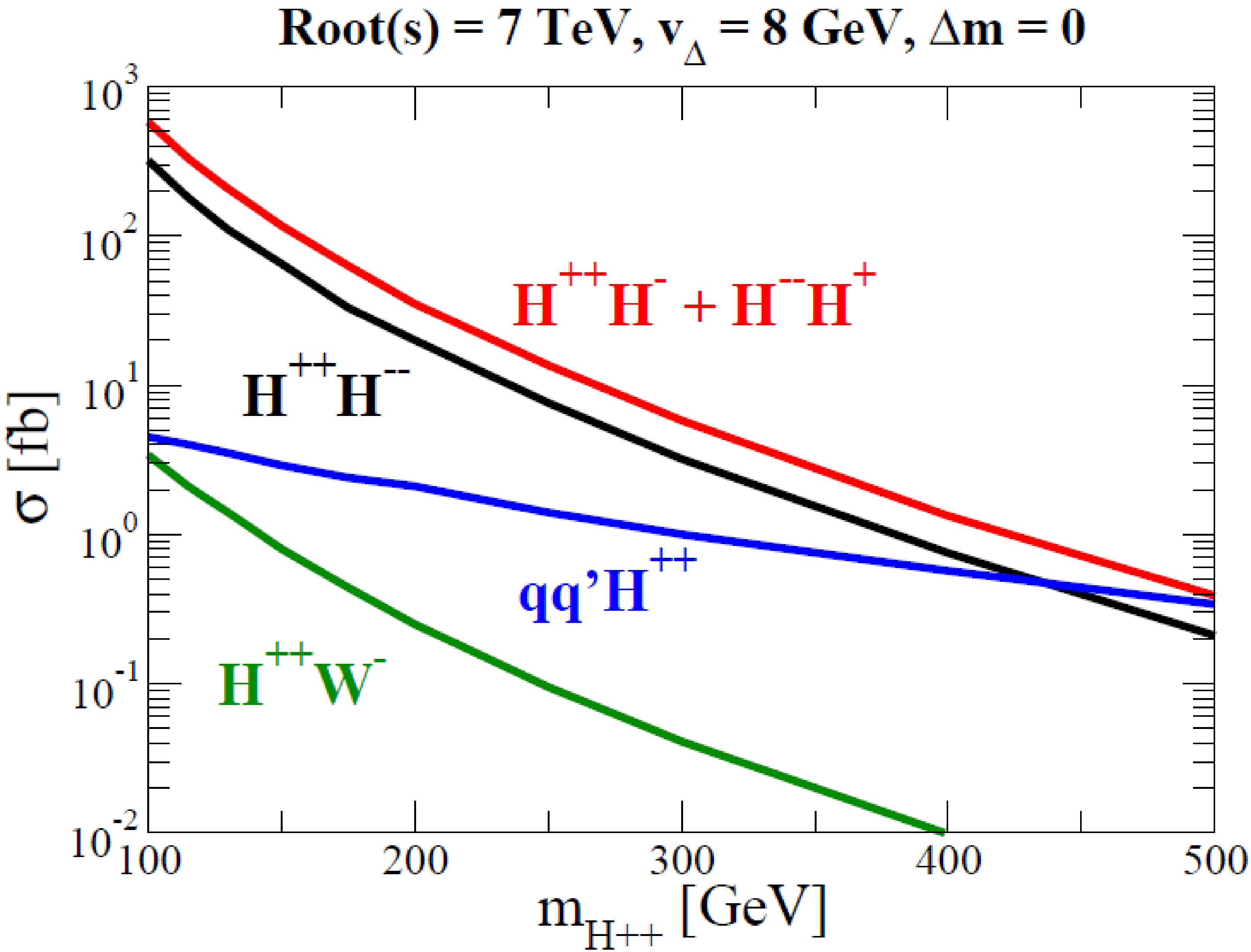




Unitary cancellation works
→ **Suppressed**






Root(s) = 7 TeV, v_Δ = 8 GeV, Δm = 0
H++H- + H--H+
H++H--
qq'H++
H++W-
σ [fb]
m_H++ [GeV]
10^3
10^2
10^1
10^0
10^-1
10^-2
100
200
300
400
500

ATLAS data

ATLAS, JHEP 1212, (2012), 7 TeV, 4.7 fb^{-1}

ATLAS has provided the data for the same-sign dilepton events $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$ and $\mu^{\pm}\mu^{\pm}$.

A.L., Read, J. Phys. G28 (2002)

CLs method

- Background simulation
- Observed # of events

→ 95% CL limit for the event number: N_{95}

$$\sigma_{95}^{\text{fid}} = \frac{N_{95}}{\varepsilon_{\text{fid}} \times \int \mathcal{L} dt}$$

→ 95% CL limit for the signal cross section: σ_{95}

→ 95% CL limit for the mass of H^{++}

ATLAS data

Invariant mass cut
for the dilepton system

ATLAS, JHEP 1212, (2012), 7 TeV, 4.7 fb^{-1}

Mass range	95% C.L. upper limit [fb]					
	expected	observed	expected	observed	expected	observed
	$e^{\pm}e^{\pm}$		$e^{\pm}\mu^{\pm}$		$\mu^{\pm}\mu^{\pm}$	
$m > 15$ GeV	46^{+15}_{-12}	42	56^{+23}_{-15}	64	$24.0^{+8.9}_{-6.0}$	29.8
$m > 100$ GeV	$24.1^{+8.9}_{-6.2}$	23.4	$23.0^{+9.1}_{-6.7}$	31.2	$12.2^{+4.5}_{-3.0}$	15.0
$m > 200$ GeV	$8.8^{+3.4}_{-2.1}$	7.5	$8.4^{+3.4}_{-1.7}$	9.8	$4.3^{+1.8}_{-1.1}$	6.7
$m > 300$ GeV	$4.5^{+1.8}_{-1.3}$	3.9	$4.1^{+1.8}_{-0.9}$	4.6	$2.4^{+0.9}_{-0.7}$	2.6
$m > 400$ GeV	$2.9^{+1.1}_{-0.8}$	2.4	$3.0^{+1.0}_{-0.8}$	3.1	$1.7^{+0.6}_{-0.5}$	1.7
	$e^{+}e^{+}$		$e^{+}\mu^{+}$		$\mu^{+}\mu^{+}$	
$m > 15$ GeV	$29.1^{+10.2}_{-8.6}$	22.8	$34.9^{+12.2}_{-8.6}$	34.1	$15.0^{+6.1}_{-3.3}$	15.2
$m > 100$ GeV	$16.1^{+5.9}_{-4.3}$	12.0	$15.4^{+5.9}_{-4.1}$	18.0	$8.4^{+3.2}_{-2.4}$	7.9
$m > 200$ GeV	$7.0^{+2.9}_{-2.2}$	6.1	$6.6^{+3.5}_{-1.8}$	8.8	$3.5^{+1.6}_{-0.7}$	4.3
$m > 300$ GeV	$3.7^{+1.4}_{-1.0}$	2.9	$3.2^{+1.2}_{-0.9}$	3.2	$2.0^{+0.8}_{-0.5}$	2.1
$m > 400$ GeV	$2.3^{+1.1}_{-0.6}$	1.7	$2.4^{+0.9}_{-0.6}$	2.5	$1.5^{+0.6}_{-0.3}$	1.8
	$e^{-}e^{-}$		$e^{-}\mu^{-}$		$\mu^{-}\mu^{-}$	
$m > 15$ GeV	$23.2^{+8.6}_{-5.8}$	25.7	$26.2^{+10.6}_{-7.6}$	34.4	$12.1^{+4.5}_{-3.5}$	18.5
$m > 100$ GeV	$12.0^{+5.3}_{-2.8}$	18.7	$11.5^{+4.2}_{-3.5}$	16.9	$6.0^{+2.3}_{-1.9}$	10.1
$m > 200$ GeV	$4.9^{+1.9}_{-1.2}$	4.0	$4.6^{+2.1}_{-1.2}$	4.5	$2.7^{+1.1}_{-0.7}$	4.4
$m > 300$ GeV	$2.9^{+1.0}_{-0.6}$	2.7	$2.7^{+1.1}_{-0.6}$	3.5	$1.5^{+0.8}_{-0.3}$	1.7
$m > 400$ GeV	$1.8^{+0.8}_{-0.4}$	2.3	$2.3^{+0.8}_{-0.5}$	2.5	$1.2^{+0.4}_{-0.0}$	1.2

Basic cut

$$|\eta| < 2.5, \quad p_T > 20 \text{ GeV},$$

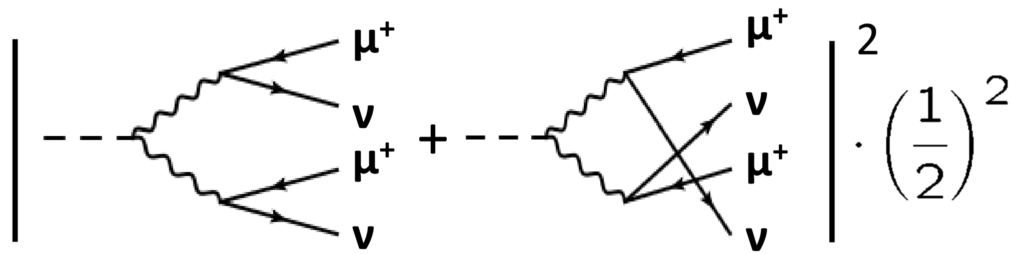
Inv. mass cut

$m > 15$ GeV

BR of $H^{++} \to W^{+(*)}W^{+(*)} \to l^+l^+$ + missing

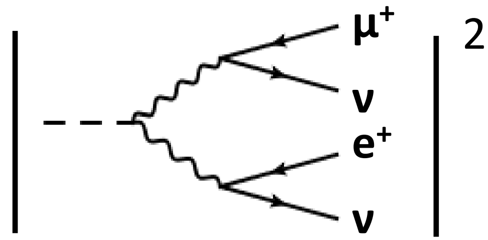
Same flavor

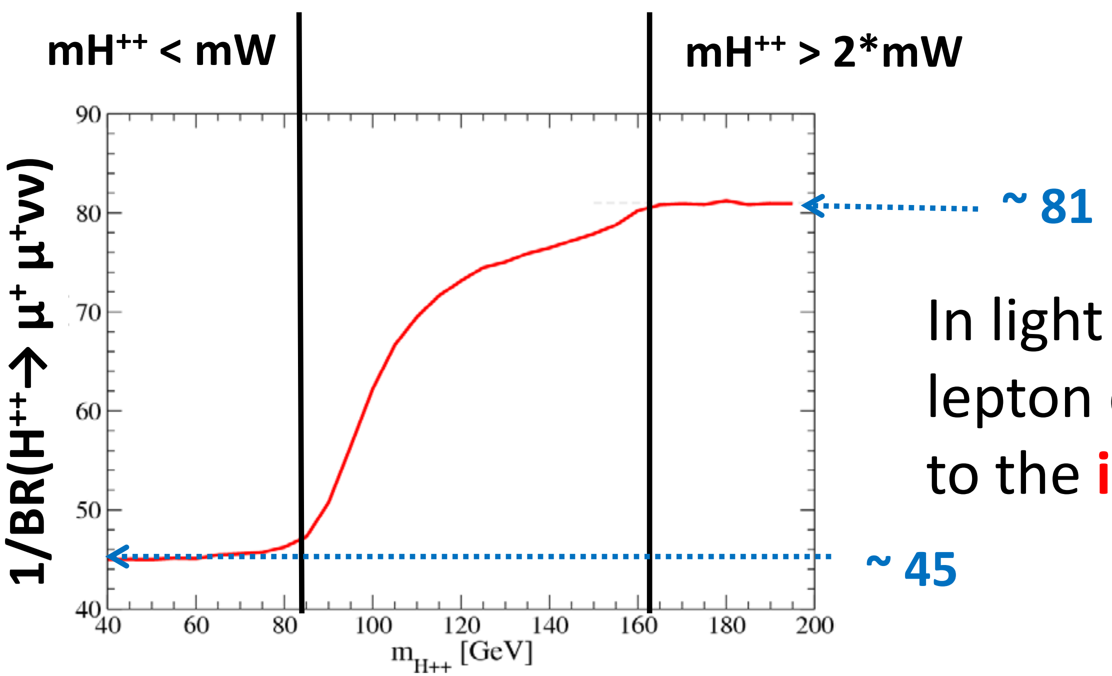
$(e^+e^+,\ \mu^+\mu^+)$



Different flavor

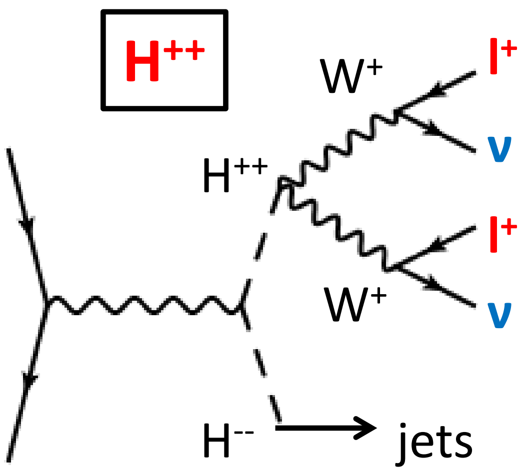
$(e^+\mu^+)$

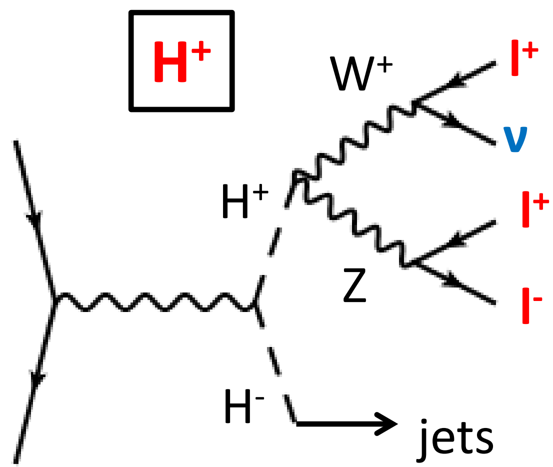


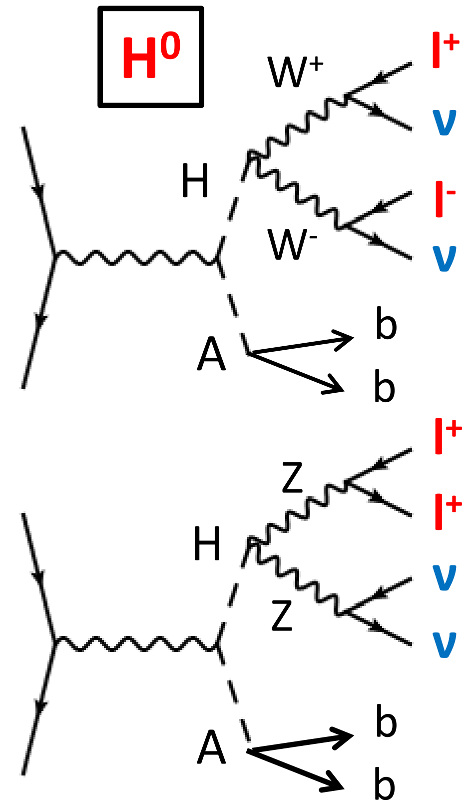


In light H^{++} case, the same-flavor lepton decay is enhanced due to the **interference** effect.

Signatures at root(s) = 500 GeV







- **Signal event**

SS dilepton + E_{miss} +jets	Trilepton + E_{miss} +jets	OS dilepton + E_{miss} +2b jets

- **Cross section (For $l^{\pm} = \mu^{\pm}$ case)**

~1.37 fb	~0.08 fb	~0.97 fb

- **Background**

$W^+W^+W^-W^-$	ZW^+W^-	ttbar, ZW^+W^-