Phenomenology of Twin Higgs Model

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Outline

- Twin Higgs Model
  - Twin Higgs mechanism
  - Left-right Twin Higgs model
  - New particles and model parameters
- Collider phenomenology
  - Heavy top quark
  - Heavy gauge bosons
  - Higgses

Twin Higgs mechanism

Higgs as pseudo-Goldstone boson of a global symmetry

Its mass is protected against radiative corrections

- **Little Higgs mechanism: collective symmetry breaking**
- **Twin Higgs mechanism: discrete symmetry**

Mirror symmetry

Type IA TH: Chacko, Goh, Harnik, hep-ph/0506256
Type IB TH: Chacko, Nomura, Papucci, Perez, hep-ph/0510273

→ **Left-right symmetry**

Type II TH: Chacko, Goh, Harnik, hep-ph/0512088

Left-right Twin Higgs model

- Global U(4) , with subgroup $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauged
- Left-right symmetry: $g_L = g_R$ ($y_L = y_R$)

A linear realization

$$H = \begin{pmatrix} H_L \\ H_R \end{pmatrix}$$

SM Higgs doublet

↓ EWSB

SM neutral Higgs: H

3 eaten by heavy gauge bosons

$$\langle H \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

7 GB

$U(4) \rightarrow U(3)$

$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow SU(2)_L \times U(1)_Y$

Twin Higgs mechanism

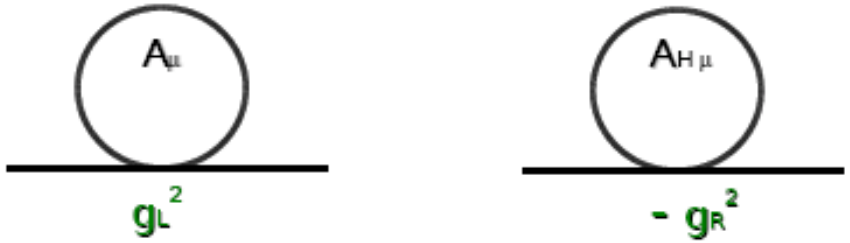
Quadratic divergence forbidden by left-right symmetry

$$\Delta V = \frac{9}{64\pi^2} g_L^2 \Lambda^2 H_L^\dagger H_L + \frac{9}{64\pi^2} g_R^2 \Lambda^2 H_R^\dagger H_R$$

$g_L = g_R = g$

$$\Delta V = \frac{9}{64\pi^2} g^2 \Lambda^2 (H_L^\dagger H_L + H_R^\dagger H_R) = \frac{9}{64\pi^2} g^2 \Lambda^2 H^\dagger H$$

U(4) invariant, does not contribute to the mass of GB



Log contribution: $\Delta V = \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda}{gf}\right) (|H_L|^4 + |H_R|^4)$

$m_H \sim g^2 f / (4\pi)$, natural for $f \sim$ TeV

Left-right Twin Higgs model

Fermion sector:

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = [2,1,1/2]\,, \quad L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = [2,1,-1]\,,$$

$$Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} = [1,2,1/3]\,, \quad L_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} = [1,2,-1]\,,$$

Top quark mass:

$$T_L = [1,1,4/3]\,, \quad T_R = [1,1,4/3]\,,$$

$$y H_R^\dagger Q_R T_L + y H_L^\dagger Q_L T_R + M \bar{T}_L T_R + h.c.$$

Top quark mass eigenstates: SM top and t_H

EW precision constraints on $SU(2)_R$ gauge boson mass $\Rightarrow$ f > 2 TeV

Introduce another Higgs field that only couples to gauge sector

Which has a larger VEV

Left-right Twin Higgs model

- U(4) × U(4), with gauged $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ + LR symmetry

Couple to gauge boson only

$H = \begin{pmatrix} H_L \\ H_R \end{pmatrix}$

SM Higgs doublet

↓ EWSB

SM neutral Higgs: H

$SU(2)_L$ Higgs doublet

$H_1^{\pm}, H_2^0$

$\hat{H} = \begin{pmatrix} \hat{H}_L \\ \hat{H}_R \end{pmatrix}$

3 eaten by heavy gauge bosons

Left 3 Higgses:

neutral Higgs ϕ^0, charged Higgs $\phi^{\pm}$

$U(4) \times U(4) \rightarrow U(3) \times U(3)$

$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow SU(2)_L \times U(1)_Y$

$\langle H \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f_1 \end{pmatrix}$

7 GB

$\langle \hat{H} \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f_2 \end{pmatrix}$

7 GB

$f_2 > f_1$

New particles

- Heavy gauge bosons: W_H, Z_H $\quad m^2_{WH,ZH} \sim g^2(f_1^2+f_2^2)$
- Heavy top: t_H $\quad m^2_{TH} \sim M^2+y^2f_1^2$
- Other $SU(2)_R$ Higgses: $\phi^\pm$ $\quad m^2_{\phi^\pm} \sim g^4/(16\pi^2)f_2^2 \log(\Lambda/gf_2$

  $BH_R^\dagger \hat{H}_R$

  ϕ^0 $\quad m^2_{\phi 0} \sim B\ (f_2/f_1)$

  B: small, $(50\text{-}100\ \text{GeV})^2$
- Other $SU(2)_L$ Higgs $H_1^\pm$ $\quad m^2_{H1\pm,\ H20\pm} \sim \mu$

  H_2^0

  μ: soft symmetry breaking, $O(f_1)$

  $\mu \hat{H}_L^\dagger \hat{H}_L$

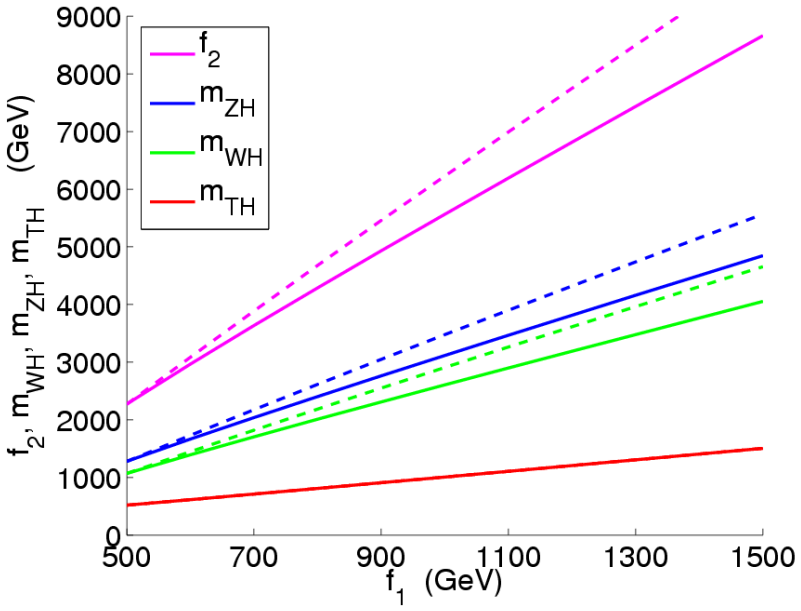
Model parameters

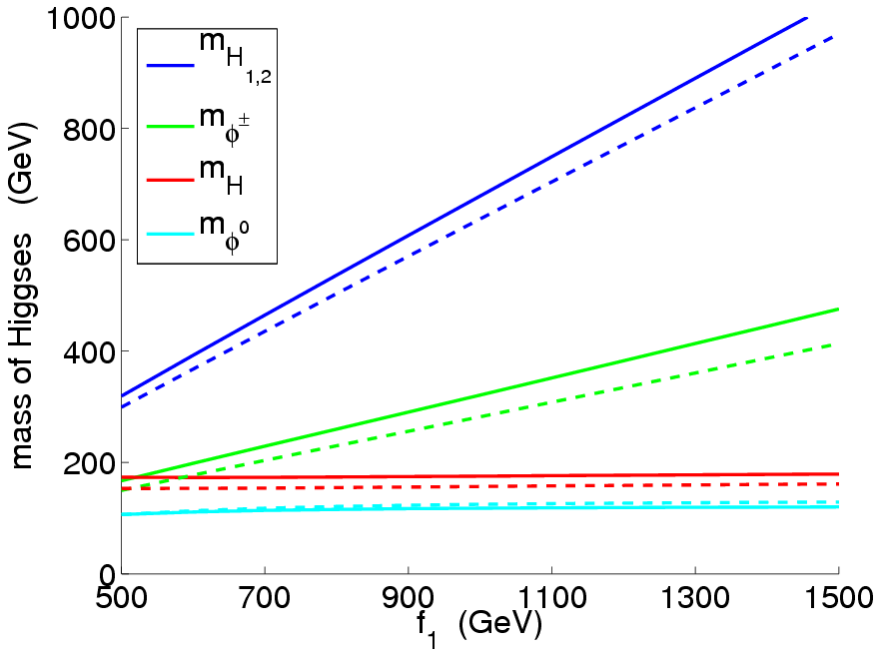
- **Model parameters: f_1, (f_2, y), Λ, M, $\sqrt{B}$, μ**

  fixed by Higgs VEV **fixed by top quark mass**

- **Determine particle masses and interactions**

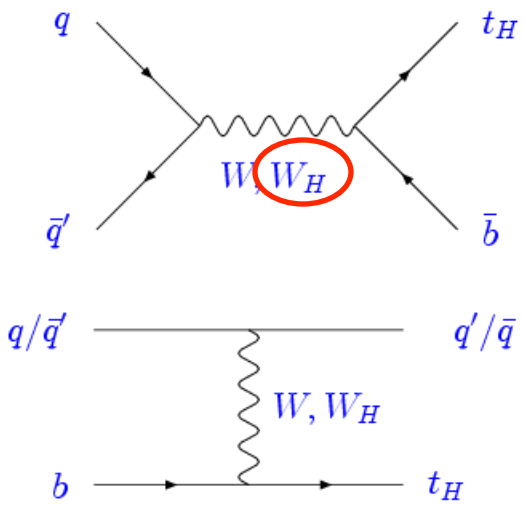
$\Lambda = 4\pi f_1$ or $2\pi f_1$
M=150 GeV
$\sqrt{B}$=50 GeV
$\mu = f_1/2$





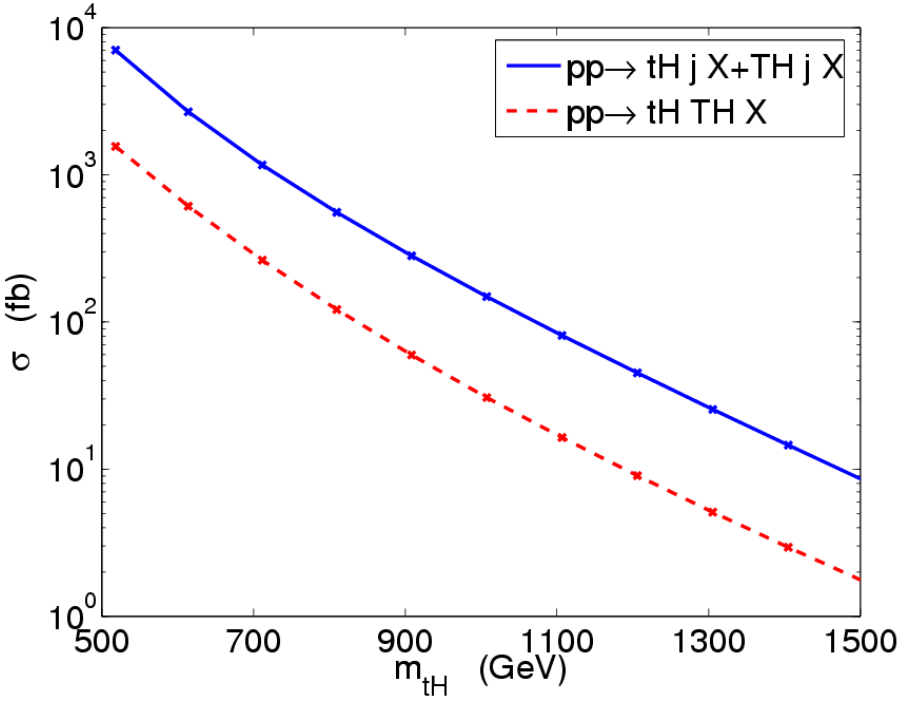
Heavy top t_H production

- **single heavy top production**

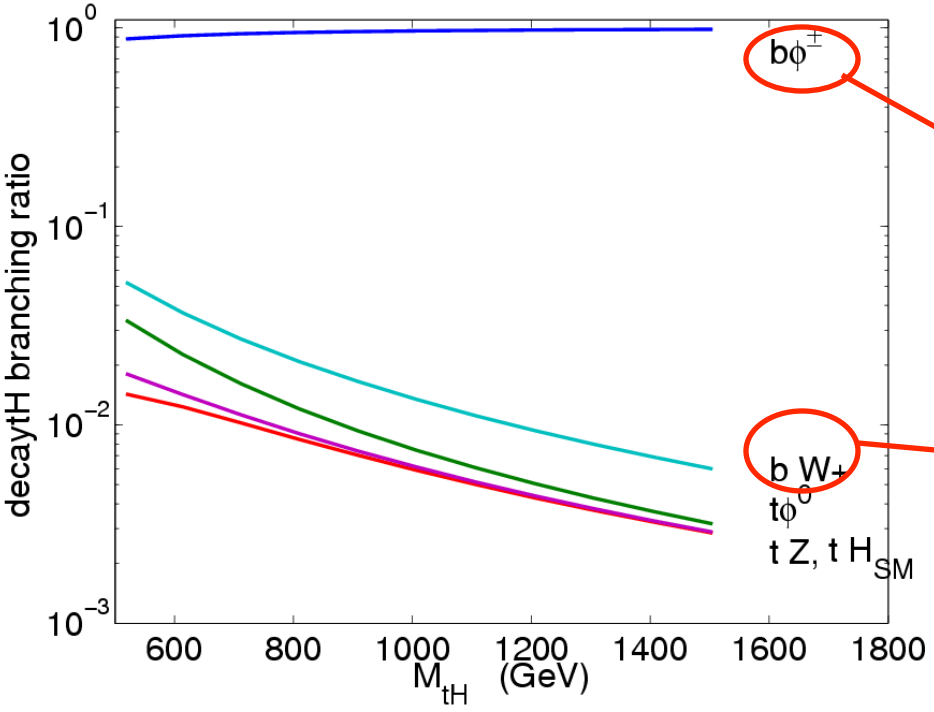


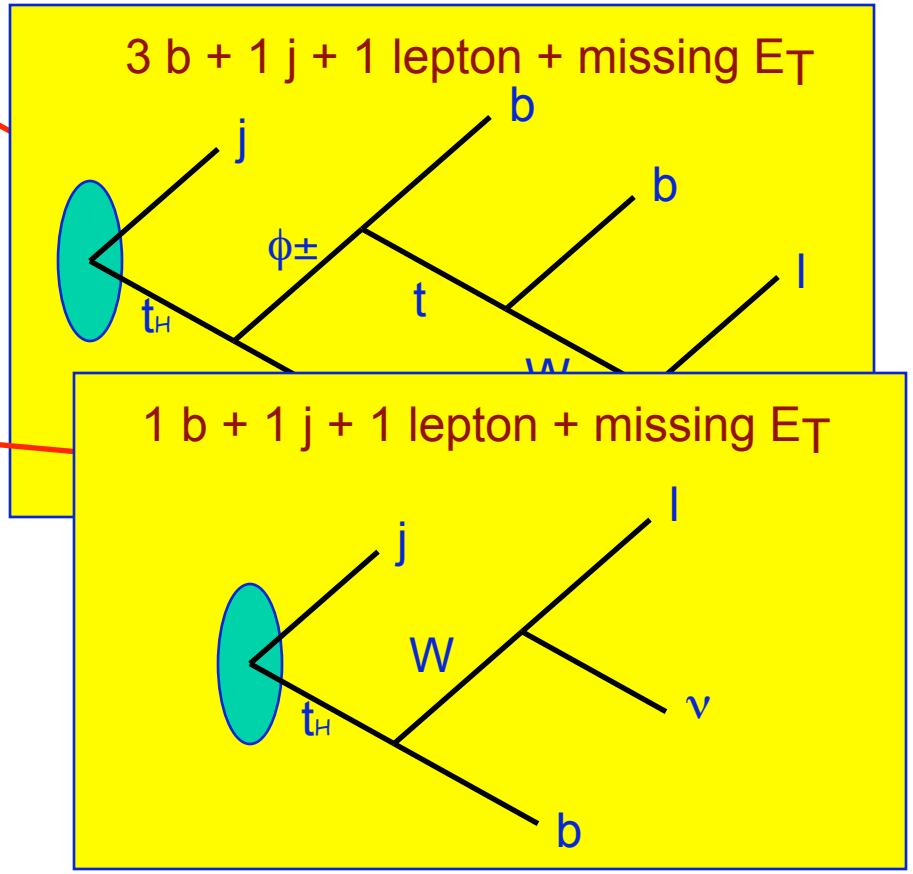
- **heavy top pair production**

$$gg, q\bar{q} \rightarrow t_H \bar{t}_H$$



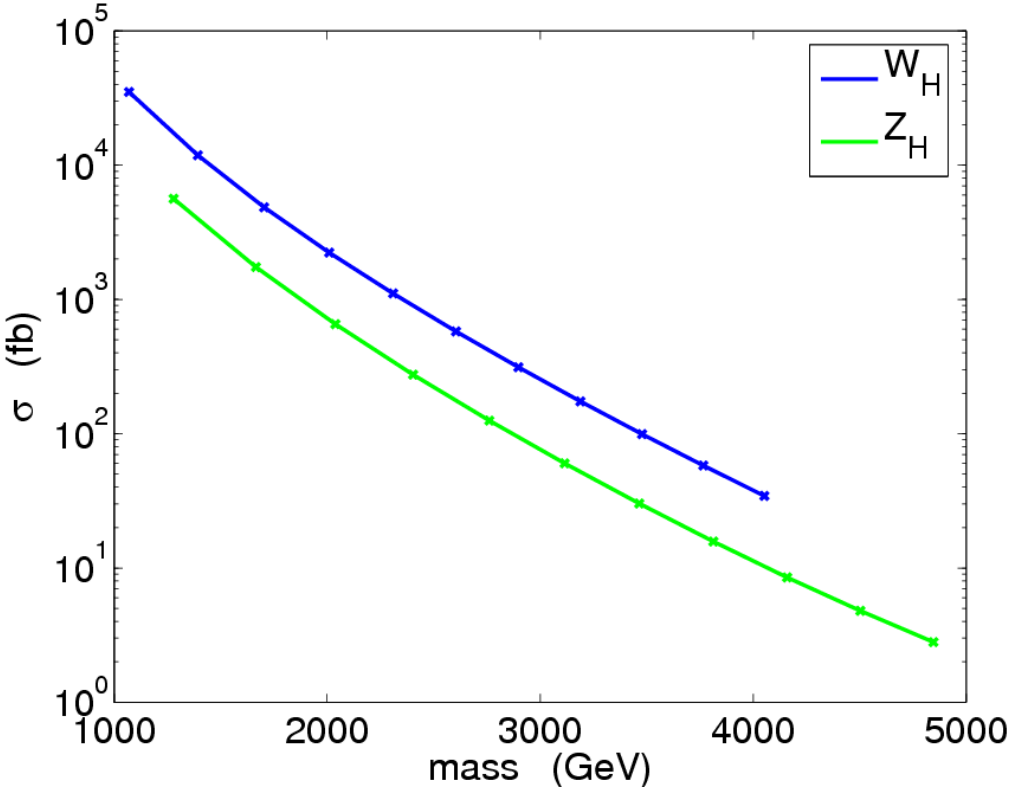
Heavy top t_H decay





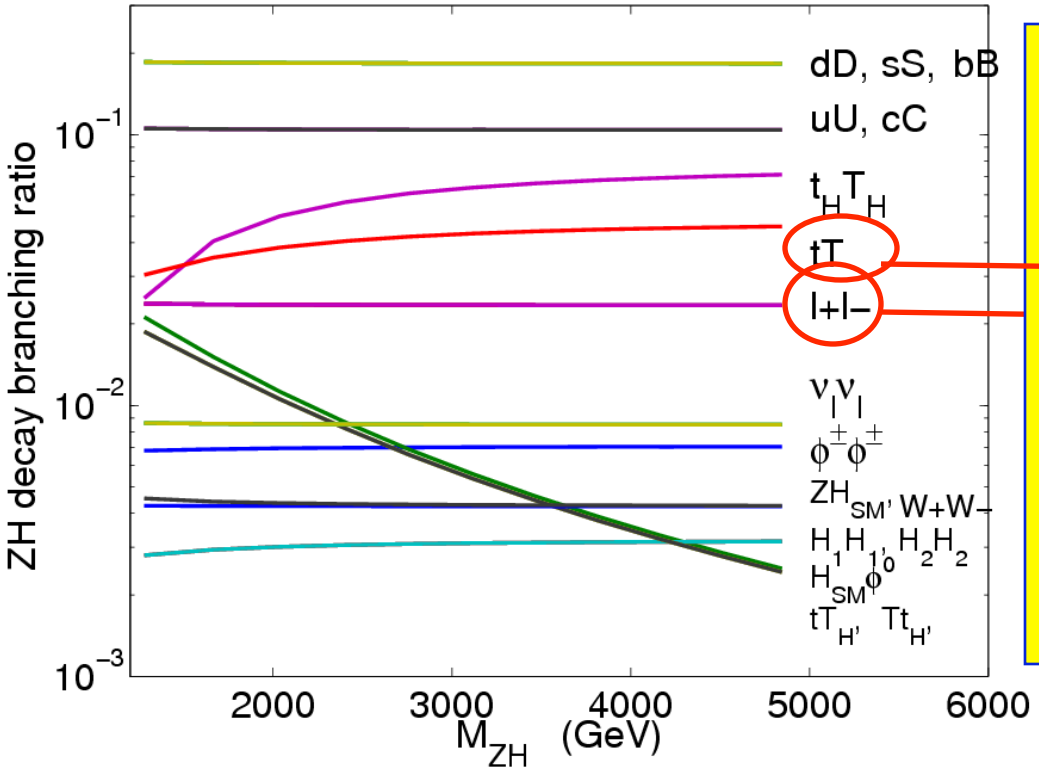
Heavy gauge boson production

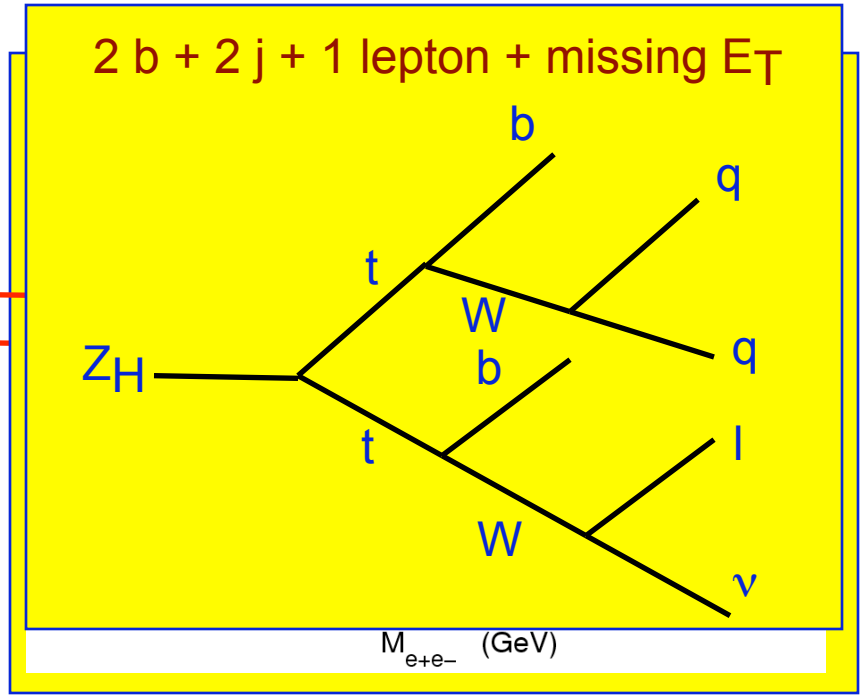
- **Drell-Yan process** $q\bar{q}' \to W_H, Z_H$



Z_H decay

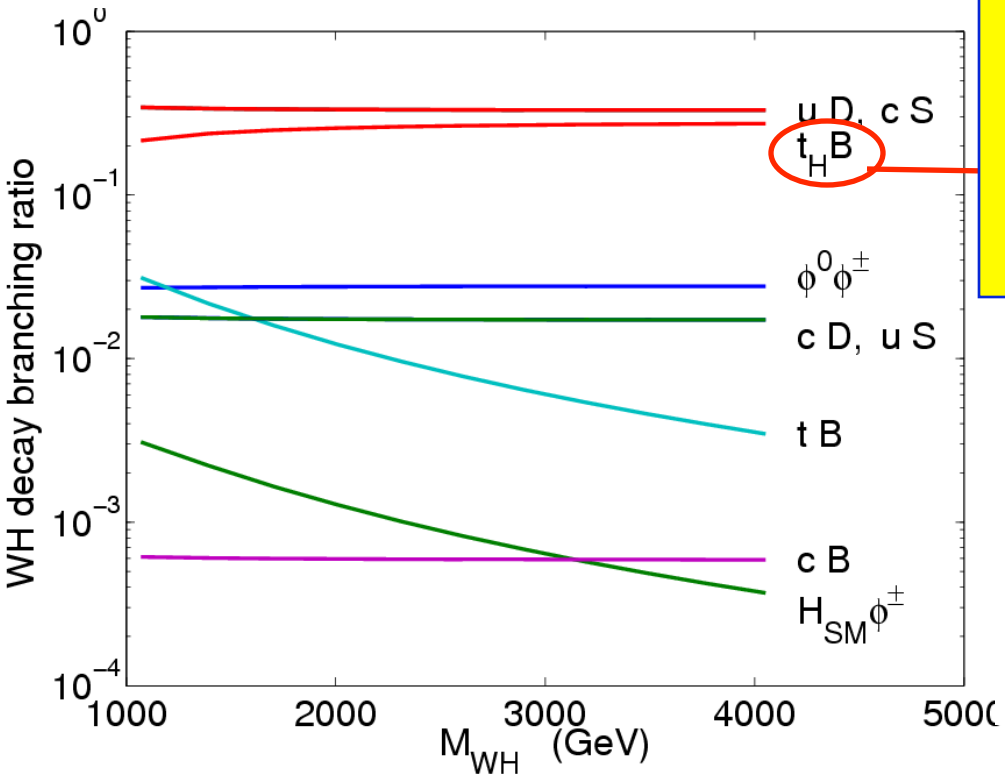
- Z_H


ZH decay branching ratio
10^{-1}
10^{-2}
10^{-3}
2000
3000
4000
5000
6000
M_{ZH} (GeV)
dD, sS, bB
uU, cC
$t_H T_H$
tT
l+l−
$\nu_l \nu_l$
$\phi^{\pm}\phi^{\pm}$
ZH_{SM}, W+W−
$H_1 H_{1'}$, $H_2 H_2$
$H_{SM}\phi^0$
$tT_{H'}$, $Tt_{H'}$


2 b + 2 j + 1 lepton + missing E_T
b
q
t
W
Z_H
b
q
t
l
W
ν
M_{e+e-} (GeV)

W_H decay

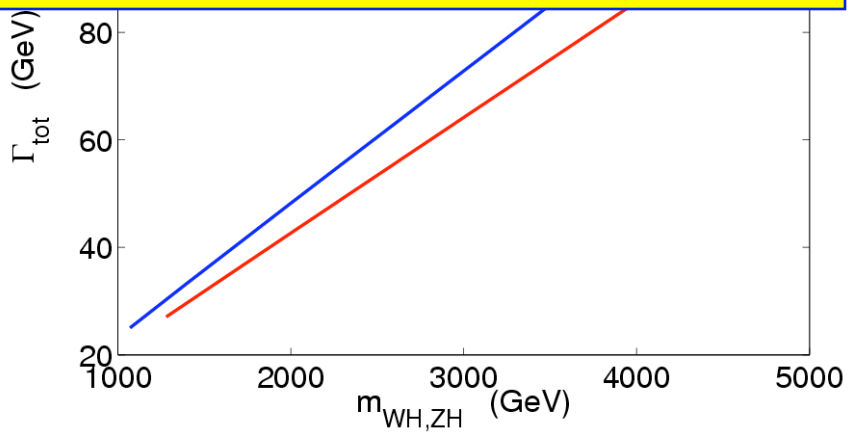
- **W_H**



$t_H \rightarrow b\phi\pm$: 4b + 1 lepton + missing E_T

$t_H \rightarrow bW$: 2b + 1 lepton + missing E_T

$t_H \rightarrow tZ$: 2b + 3 lepton + missing E_T

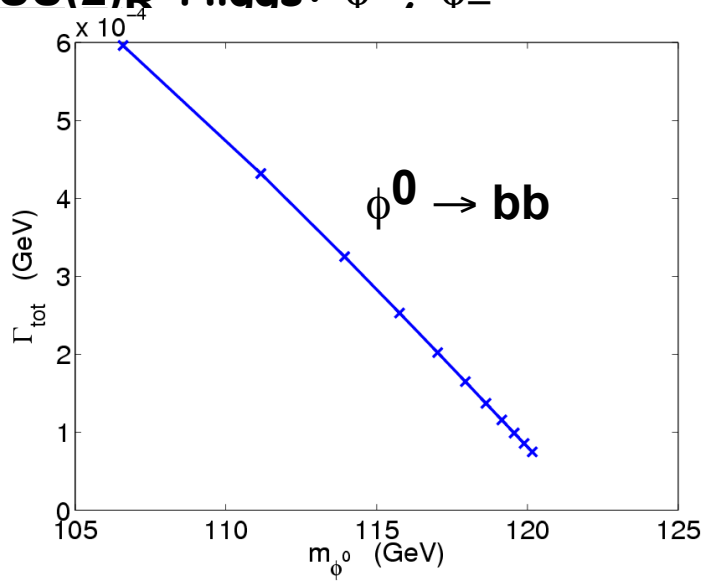


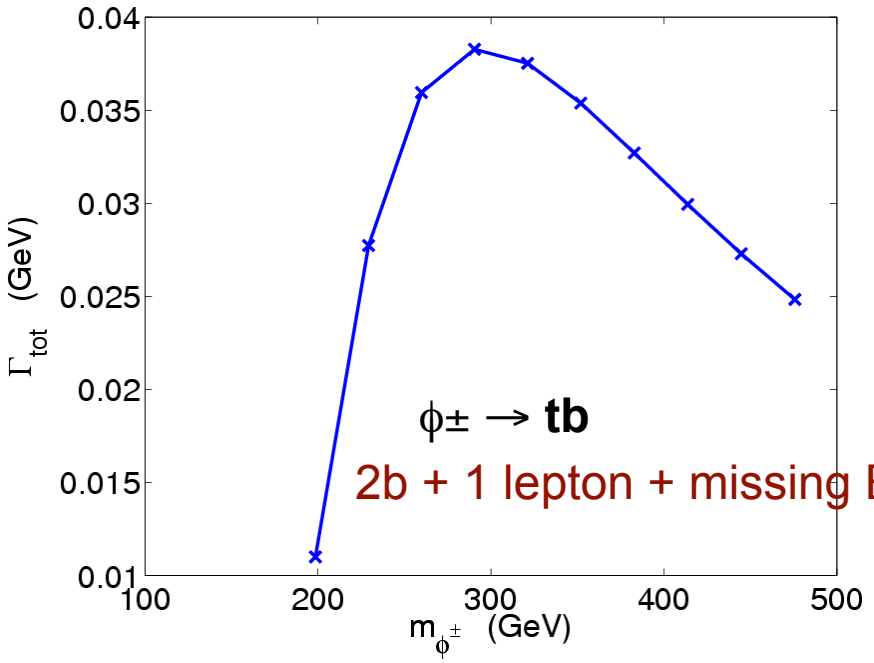
Higgses

SM Higgs

- $m_H \sim 150\text{-}170$ GeV, depending on f_1, Λ and M
- Higgs searches:
  1. $gg \rightarrow H \rightarrow ZZ^* \rightarrow llll$
  2. $gg \rightarrow H \rightarrow WW^* \rightarrow l\nu l\nu$
  3. $WBF \rightarrow qqH \rightarrow qqWW^* \rightarrow qql\nu l\nu$

$SU(2)_R$ Higgs: ϕ^0, $\phi\pm$

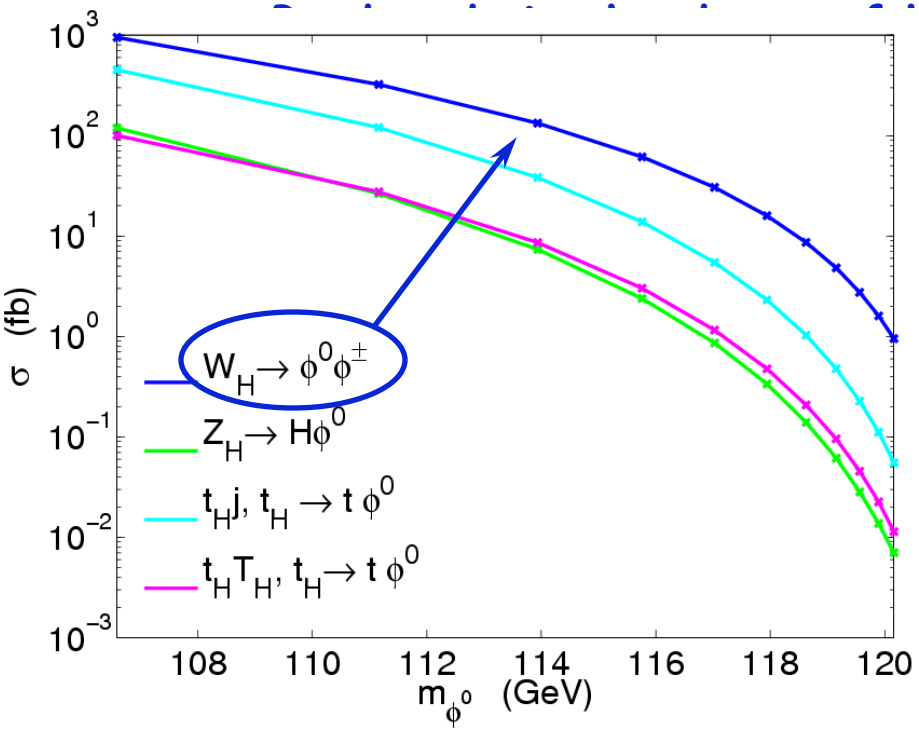


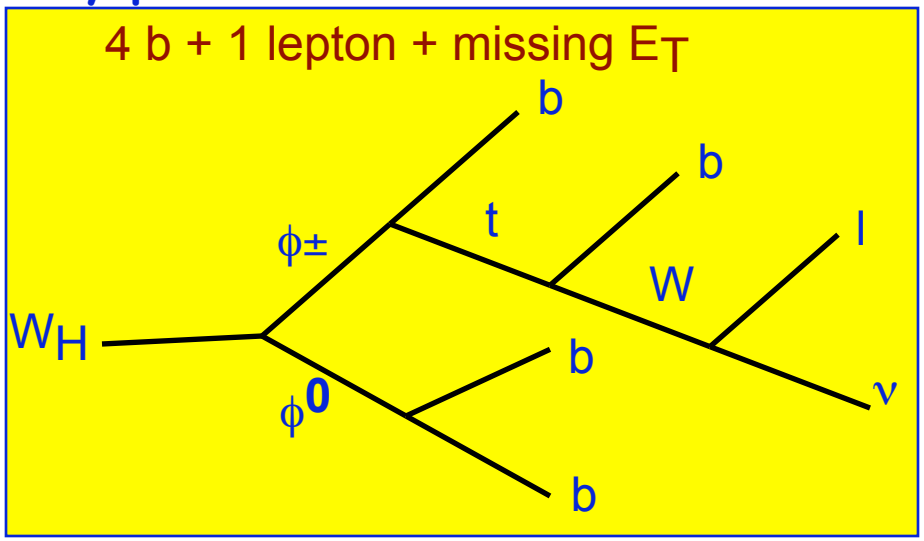


ϕ^0

Neutral Higgs ϕ^0

- $gg \rightarrow \phi^0 \rightarrow bb$, QCD background overwhelming
- no $W\phi^0$, $Z\phi^0$ associated production (no such coupling)
- $bb\phi^0$, $tb\phi^0$, $tt\phi^0$ cross section small
- [illegible] heavy particles

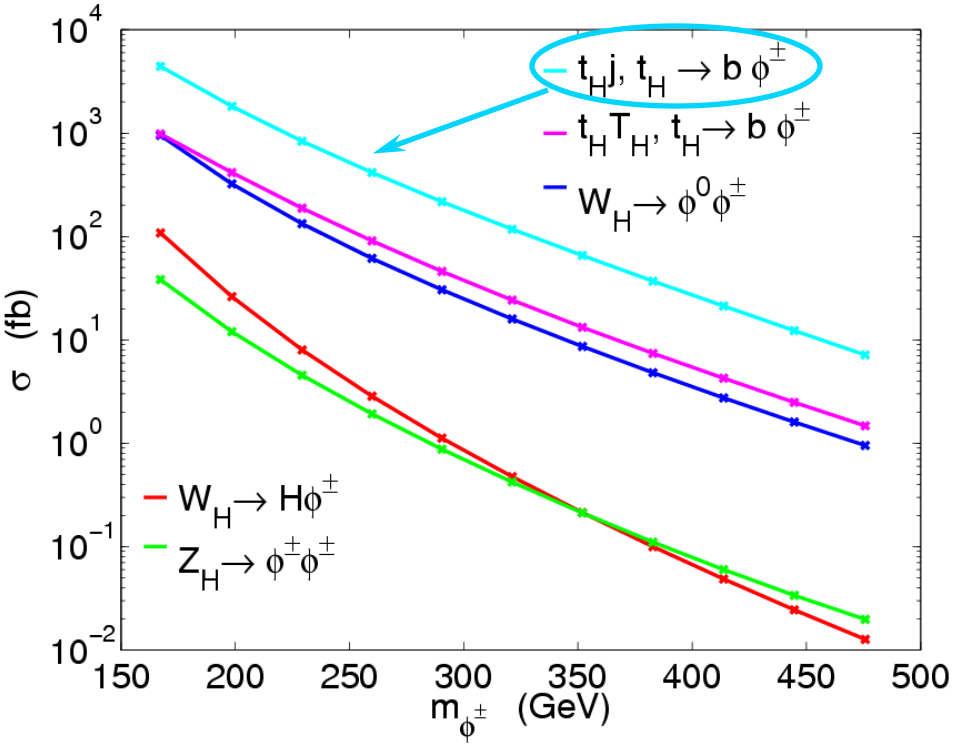


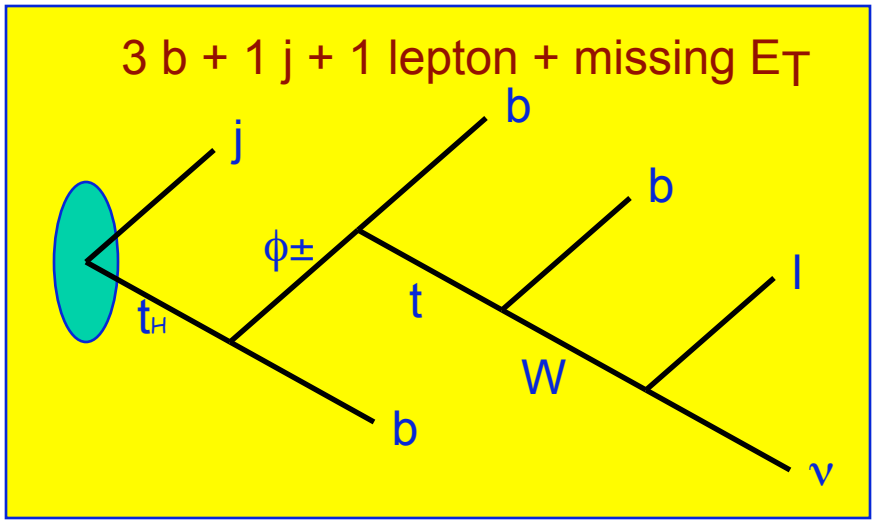


$\phi\pm$

Neutral Higgs $\phi\pm$

- no W$\phi\pm$, Z$\phi\pm$ associated production (no such coupling)
- bb$\phi\pm$, tb$\phi\pm$, tt$\phi\pm$ cross section small
- Produced via the decay of heavy particles





$H_1^{\pm}$, H_2^0

Higgs that couple to gauge boson only: $H_1^{\pm}$, H_2^0

- $H_1^{\pm}H_2^0$, $H_1^{\pm}H_1^{\pm}$, $H_2^0H_2^0$, associated production (small)
- H_2^0 stable : missing energy
- $H_1^{\pm} \rightarrow H_2^0$ + soft jets/leptons

  if decay fast enough: appears as missing energy

  if decay slow: track !

H_2^0: good dark matter candidates

Under current investigation

M=0 case

Top Yukawa: $yH_R^\dagger Q_R T_L + yH_L^\dagger Q_L T_R + h.c.$

f_1 v

$t_H = (T_L, t_R)$, $m_{tH} = yf_1$ $t_{SM} = (t_L, T_R)$, $m_t = yv$

Gauge coupling

- ✓ W – t – b
- × W – t_H – b
- × W_H – t – b
- ✓ W_H – t_H – b
- ✓ Z – t – t
- ✓ Z – t_H – t_H
- × Z – t_H – t
- ✓ Z_H – t – t
- ✓ Z_H – t_H – t_H
- × Z_H – t_H – t

Yukawa coupling

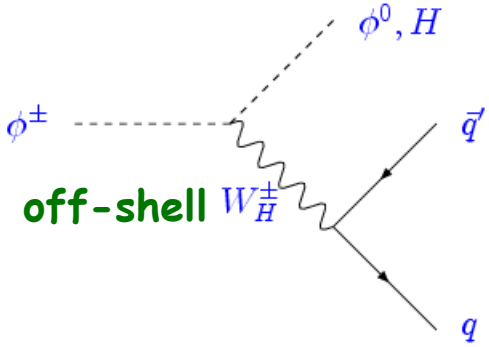
- ✓ ϕ^0 – t_H – t_H
- × ϕ^0 – t – t
- ✓ ϕ^0 – t_H – t
- × $\phi^\pm$ – t – b

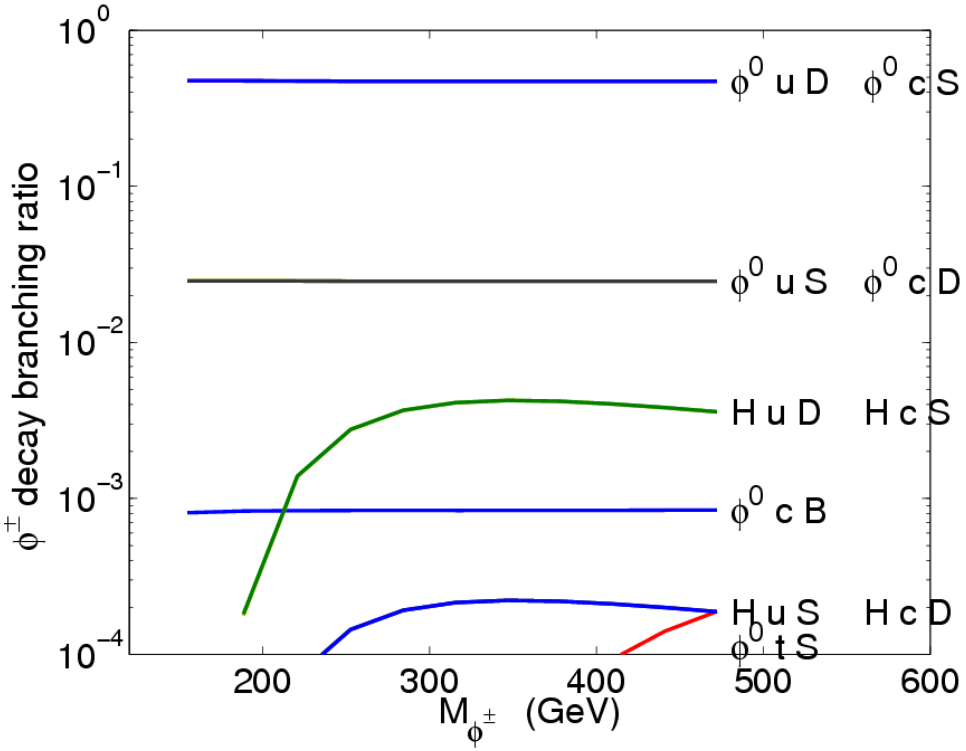
$\phi^\pm$ –X–> t + b (100%)

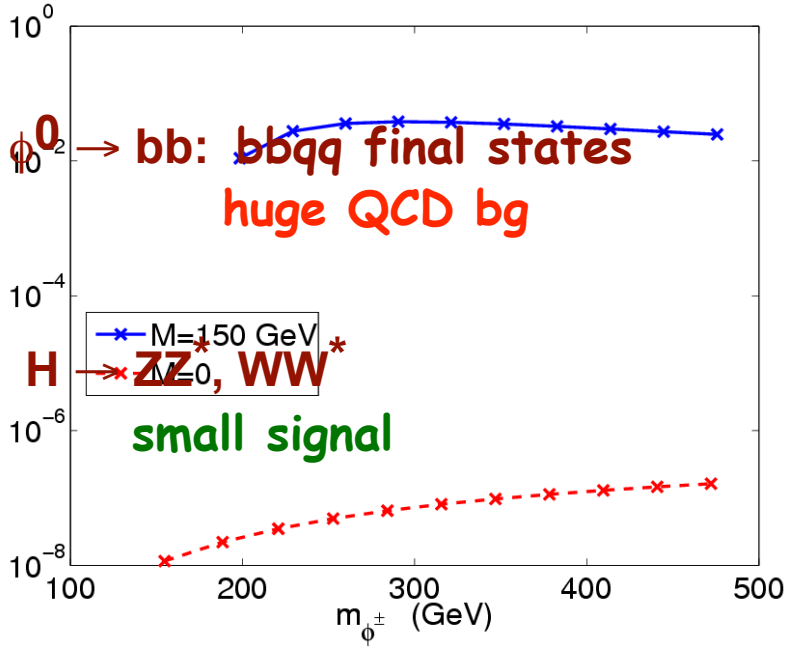
- ✓ H – t – t
- ✓ H – t_H – t_H (small)
- × H – t_H – t

$\phi^{\pm}$ decay

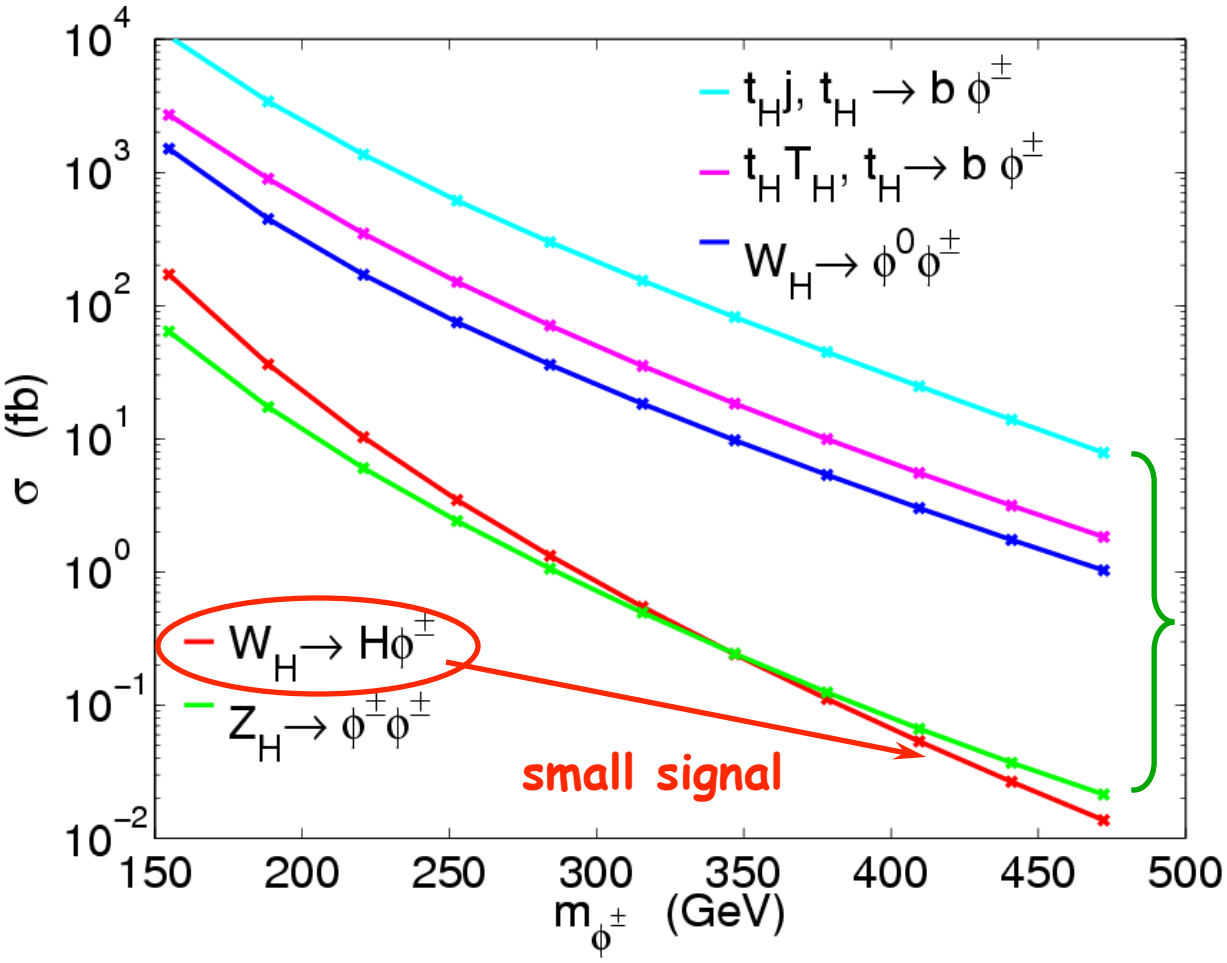
- No two body decay
- Leading decay: 3 body





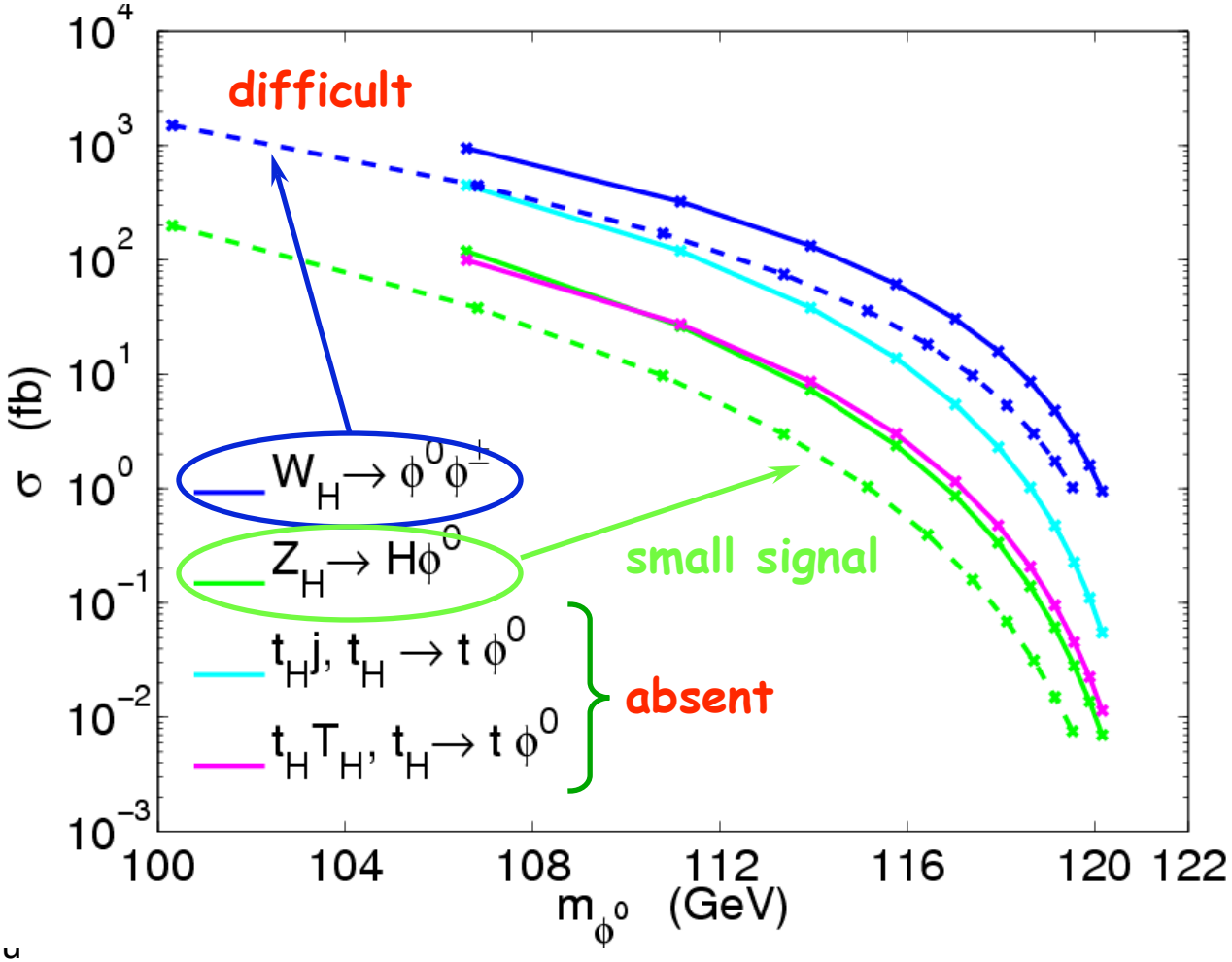


$\phi\pm$ discovery



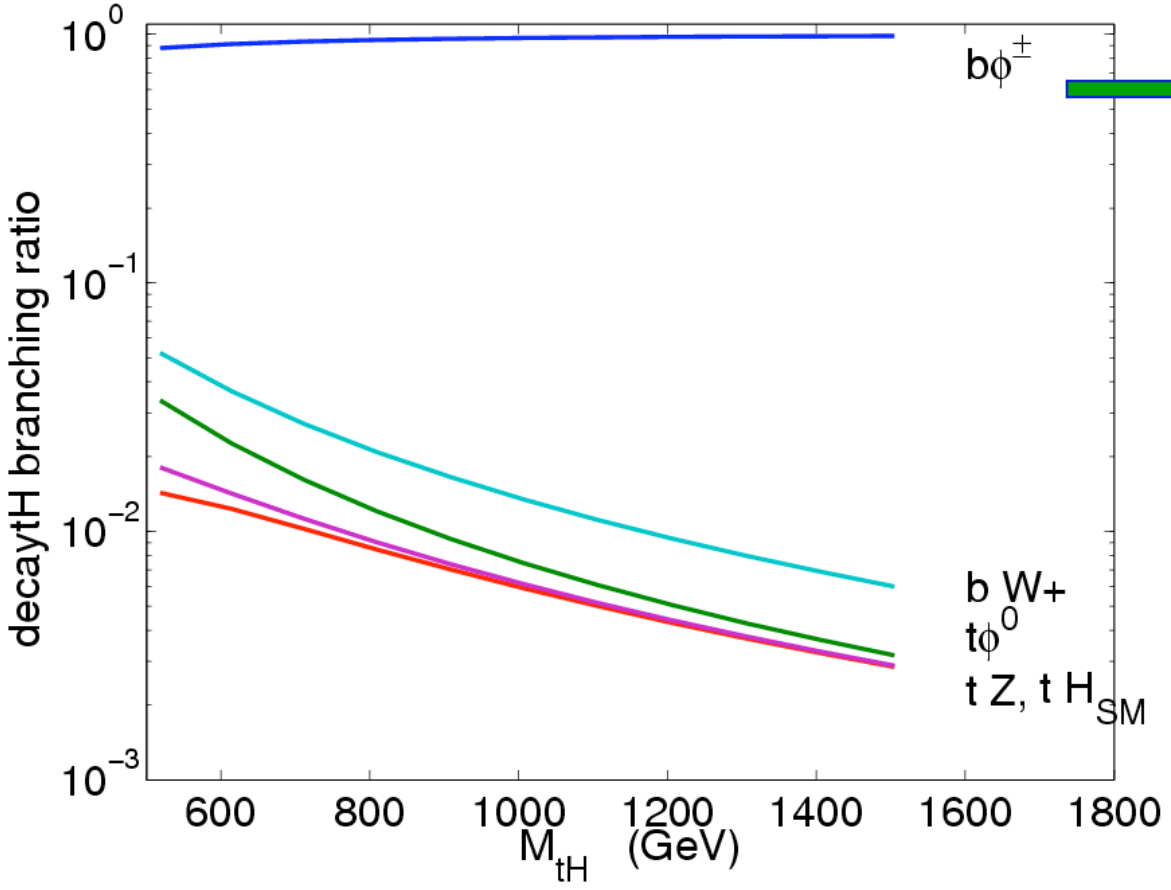
Difficult unless $\phi\pm \to$ Hqq

ϕ^0 discovery



Heavy top t_H discovery

- single, pair production does not change much.
- decay: only $t_H \rightarrow b\,\phi^{\pm}$ (100%)



100%
either huge QCD bg
Or small signal

absent

Heavy gauge boson discovery

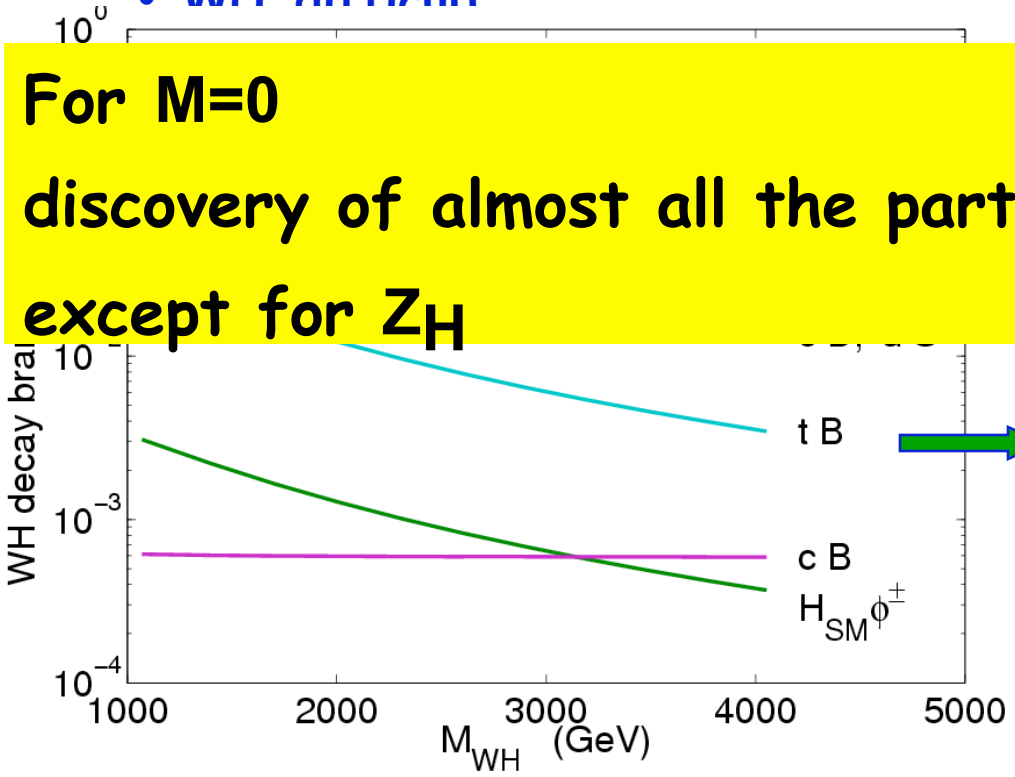
- Z_H, W_H drell-yan cross section does not change
- Z_H: $Z_H \rightarrow ll$ does not change much ✓

  $Br(Z_H \rightarrow t\, t_H) = 0$
- W_H: difficult

For M=0

discovery of almost all the particle are difficult

except for Z_H



absent

Conclusions

- Left-right twin Higgs model: Higgs as pseudo-goldstone boson
  quadratic divergence forbidden by left-right symmetry
- New particles
  - Heavy gauge boson: W_H, Z_H
  - Heavy top quark t_H
  - New Higgses: ϕ^0, $\phi\pm$, $H_1^{\pm}$, H_2^0 (DM)
- $M \neq 0$: rich collider phenomenology
- $M = 0$: difficult except for Z_H ✓
- Future work ✓
  - Pick certain channel for detailed study: background, cuts,…
  - Identify twin Higgs mechanism
  - Dark matter study
  - Comparison with other models, e.g., little higgs