Twin Higgs Model:

From Collider Phenomenology to Dark Matter Implication

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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
- Dark Matter
  - * Relic density
  - * direct and indirect detection

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
phenomenology: R. Barbieri, T. Gregoire and L. Hall, hep-ph/0509242

Left-right symmetry

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

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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

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

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$U(4) \to U(3)$

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

7 GB

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SM Higgs doublet

↓ EWSB

SM neutral Higgs: H

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H_R: 3 eaten by heavy gauge bosons

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Twin Higgs mechanism

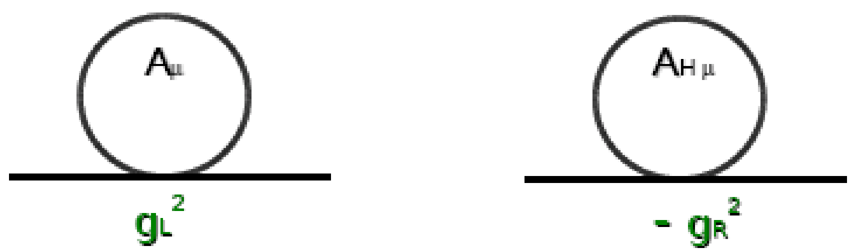
Quadratic divergence forbidden by left-right symmetry

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

$g_L = g_R = g$

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

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:

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

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

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 <u>only couples to gauge sector</u> 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

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Couple to gauge boson only

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

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7 GB

$f_2 > f_1$

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Left 3 Higgses:

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

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7 GB (for $\langle H \rangle$)

7 GB (for $\langle \hat{H} \rangle$)

$f_2 > f_1$

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SM Higgs doublet

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SM neutral Higgs: H

$SU(2)_L$ Higgs doublet

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

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Left 3 Higgses:

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7 GB

$f_2 > f_1$

New particles

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

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

  B: small, $(50\text{-}100\ \text{GeV})^2$
- Other $SU(2)_L$ Higgs $H_1^\pm$ — $m^2_{H1^\pm,\ H2^0} \sim \mu$

  H_{20} — μ: soft symmetry breaking, $O(f_1)$

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

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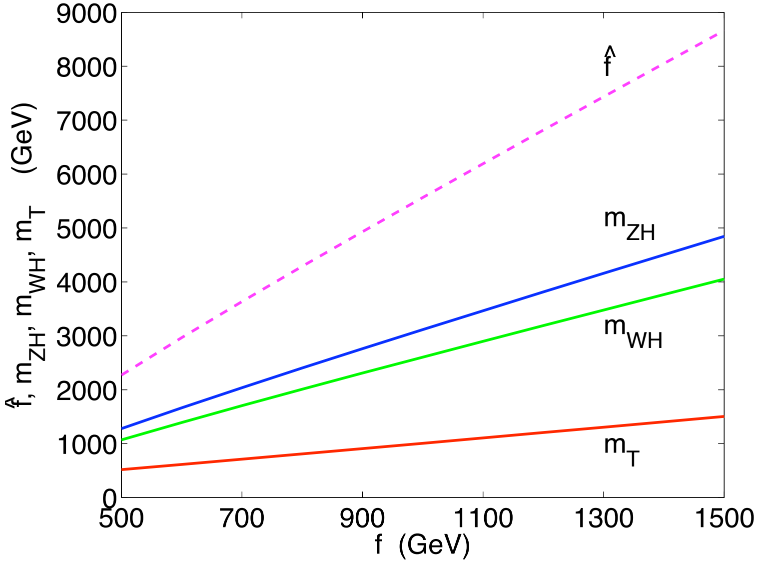
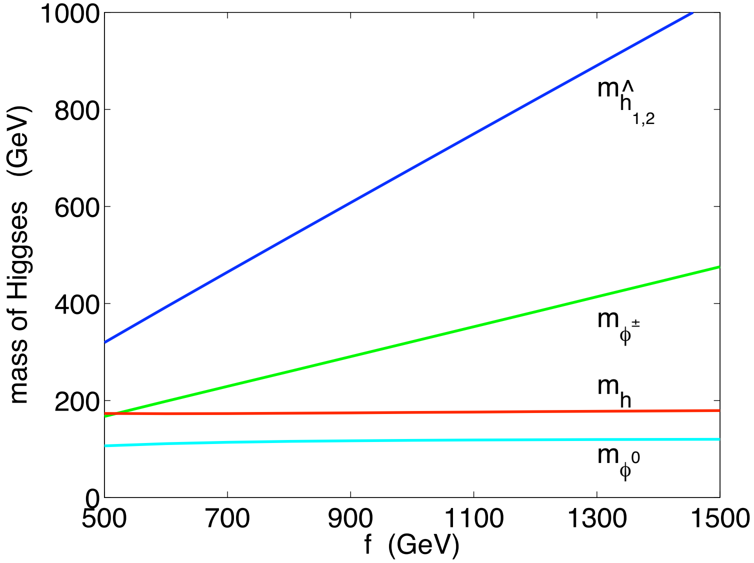
Model parameters

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

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

- Determine particle masses and interactions





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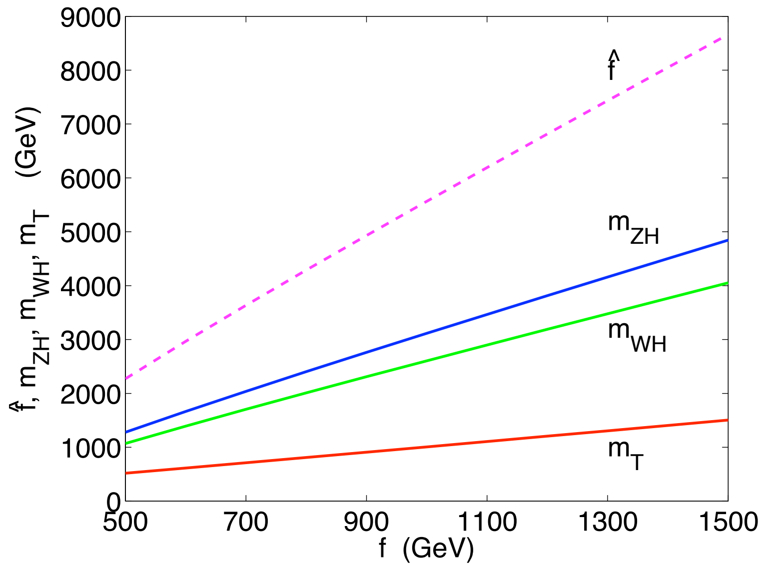

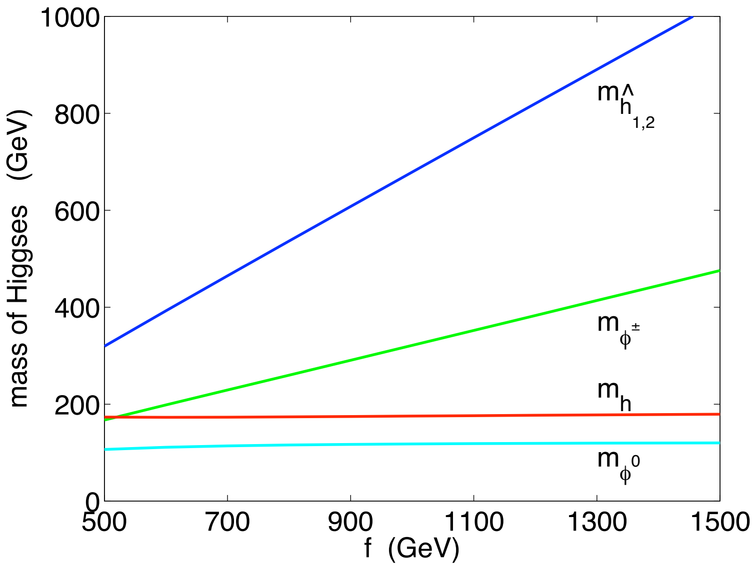

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fixed by Higgs VEV — **fixed by top quark mass**

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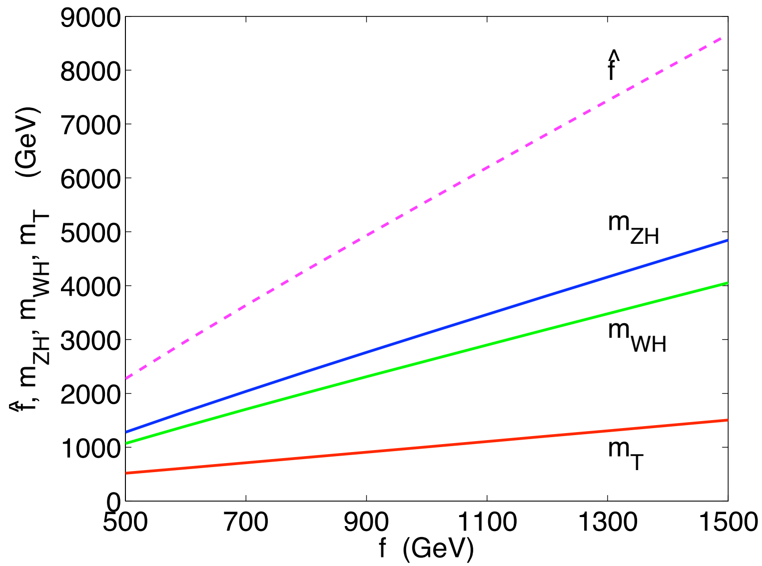
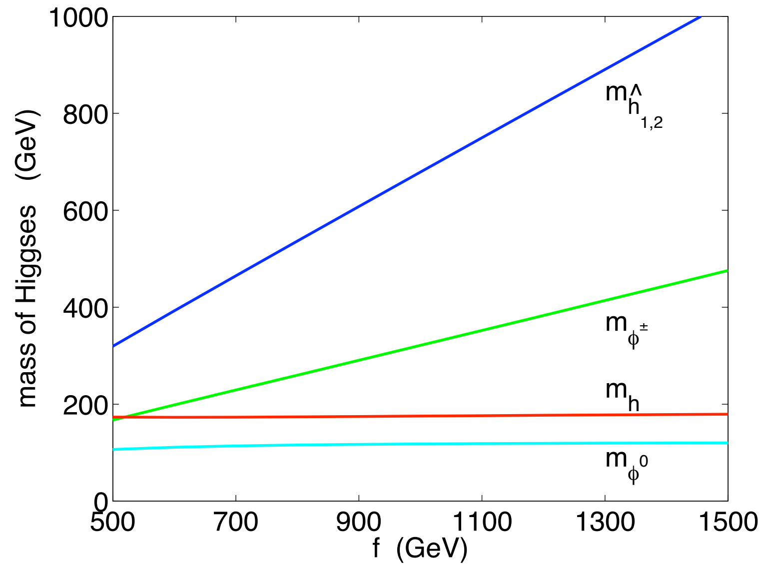




Experimental Constraints

- m_{WH}
  - $m_{\nu R} < m_e$, overproduction of ^{4}He: $m_{WH} > 4$ TeV
  - $m_{\nu R} < m_p$, supernova cooling: $m_{WH} > 23$ TeV

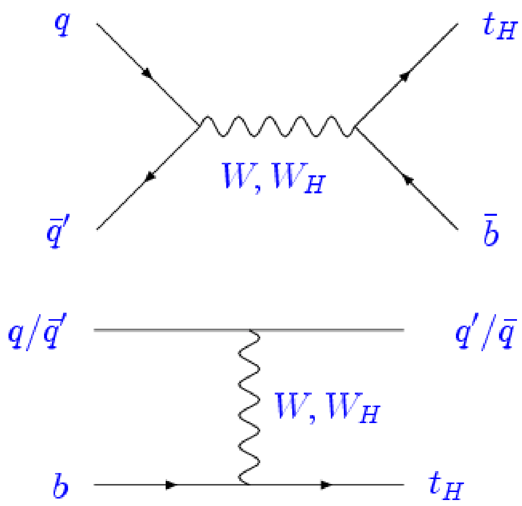
    does not apply in LRTH, $m_{\nu R} \sim f_2^2/\Lambda$
  - K_L-K_S mixing: $m_{WH} > 1.6$ TeV $\rightarrow f_1 > 670$ GeV

    relaxed if $CKM_L \neq CKM_R$
  - direct search limit: $m_{WH} > 800$ GeV

- m_{ZH}
  - Z - ZH mixing: $f_1 > 500 - 600$ GeV
  - precision measurements: $m_{ZH} > 500 - 800$ GeV
  - direct search limit: $m_{ZH} > 630$ GeV (CDF)

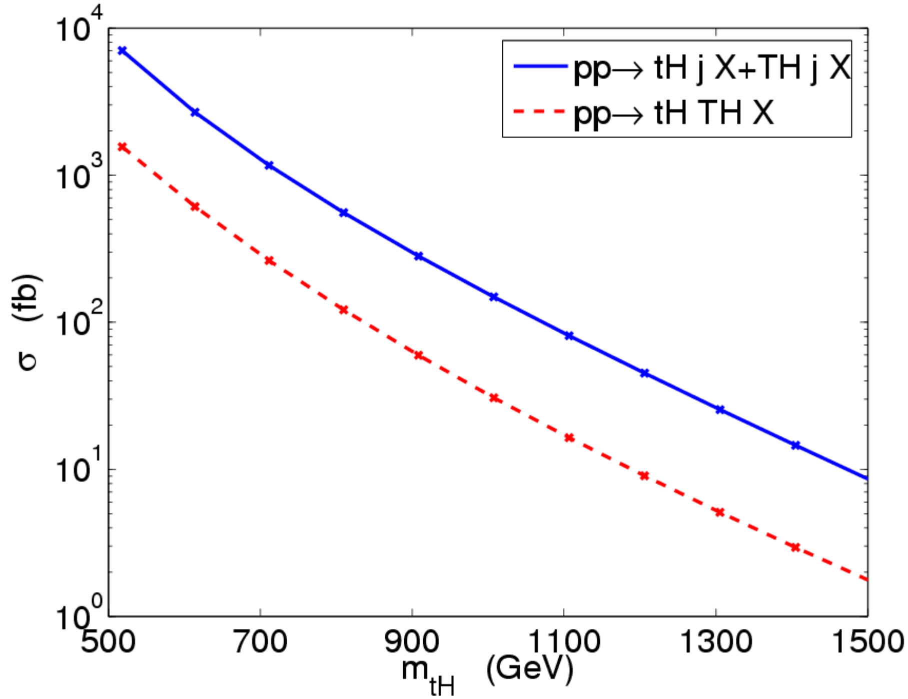
Heavy top t_H production

- **single heavy top production**



- **heavy top pair production**

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



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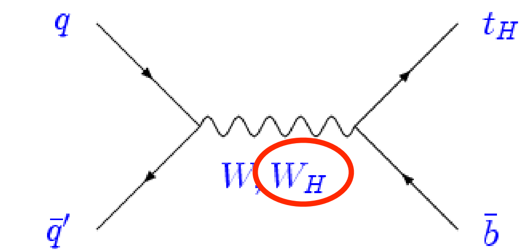

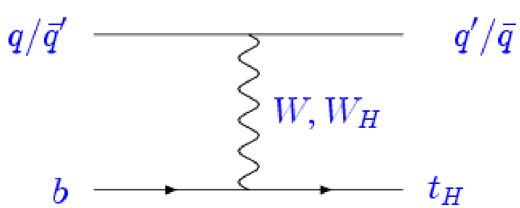

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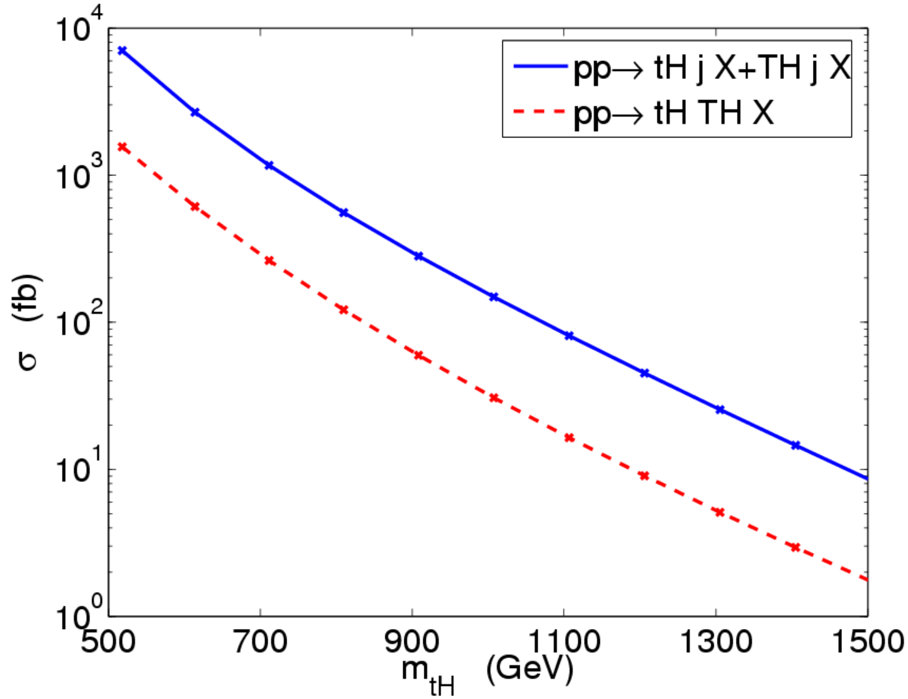
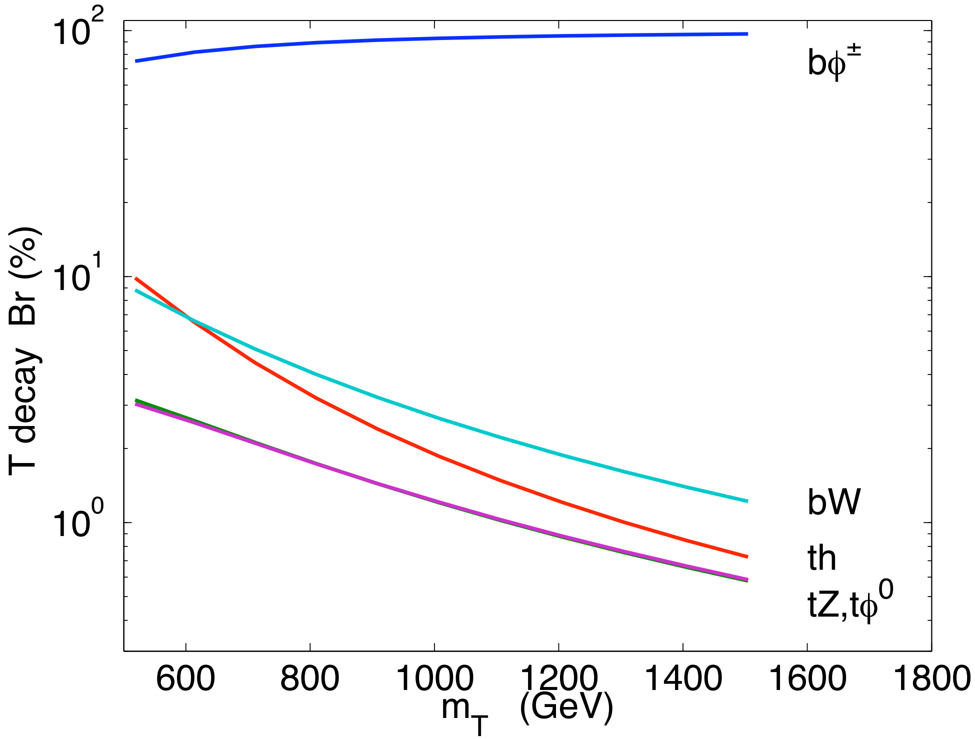


Heavy top t_H decay



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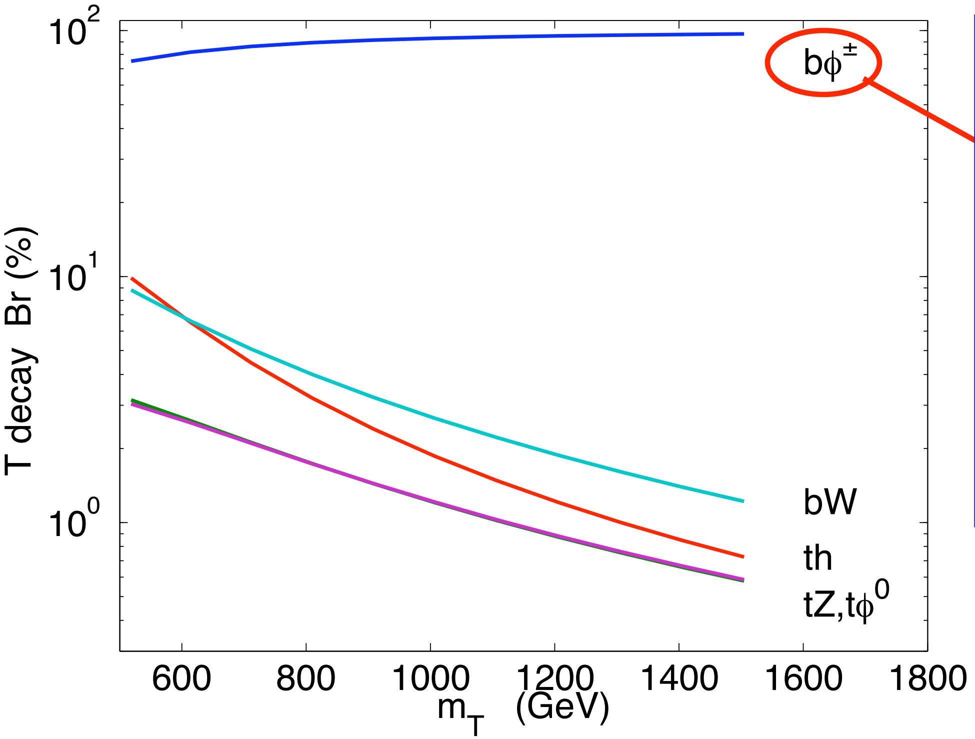

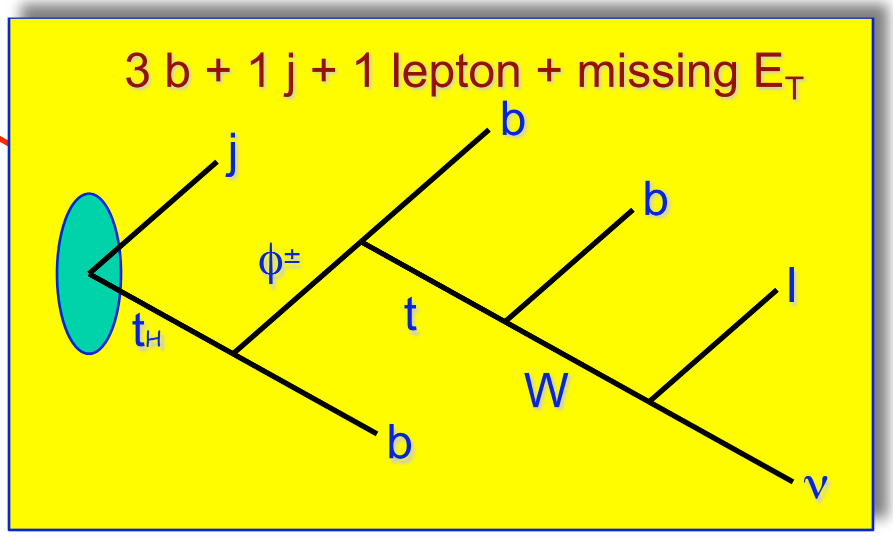

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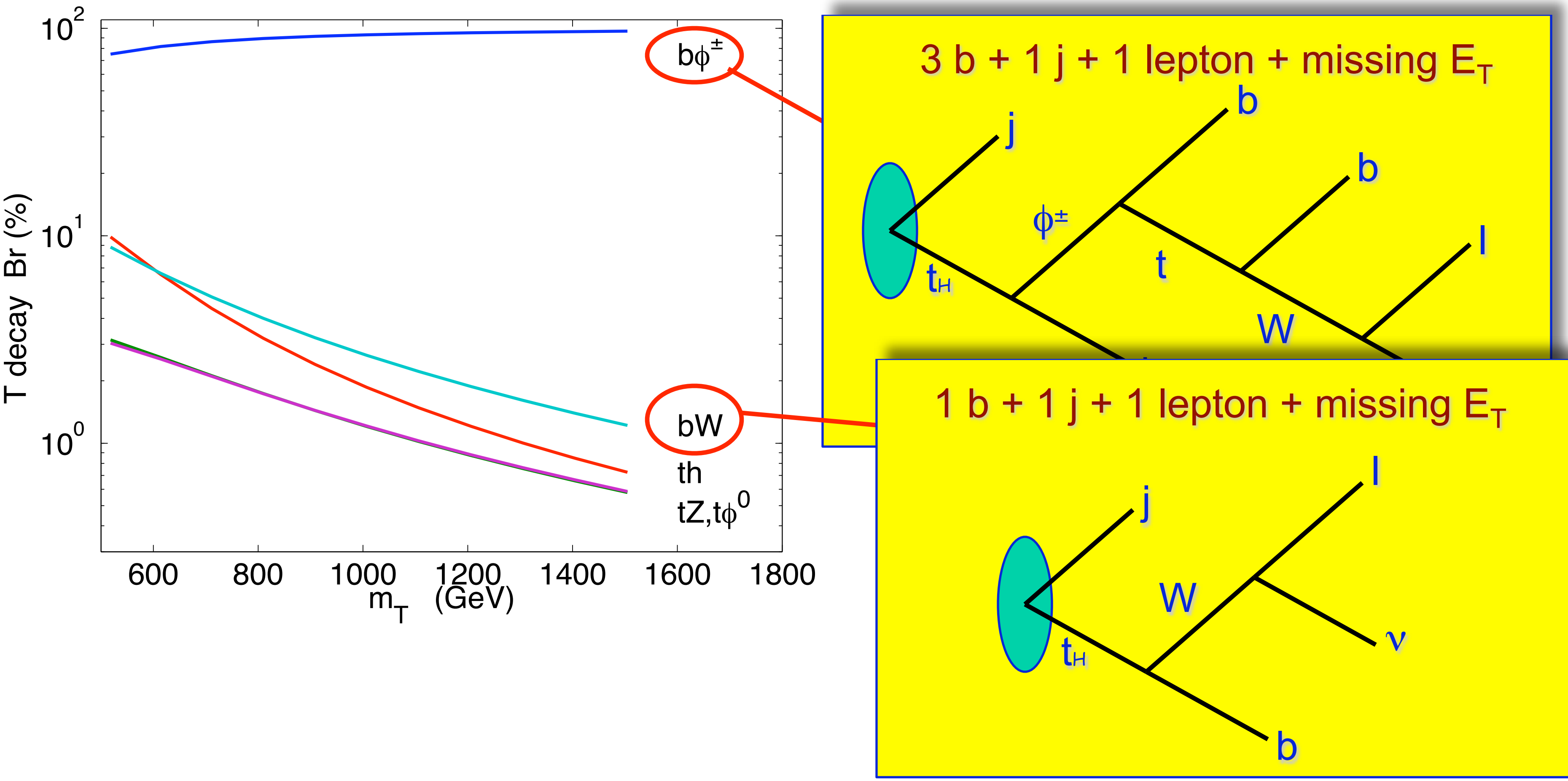
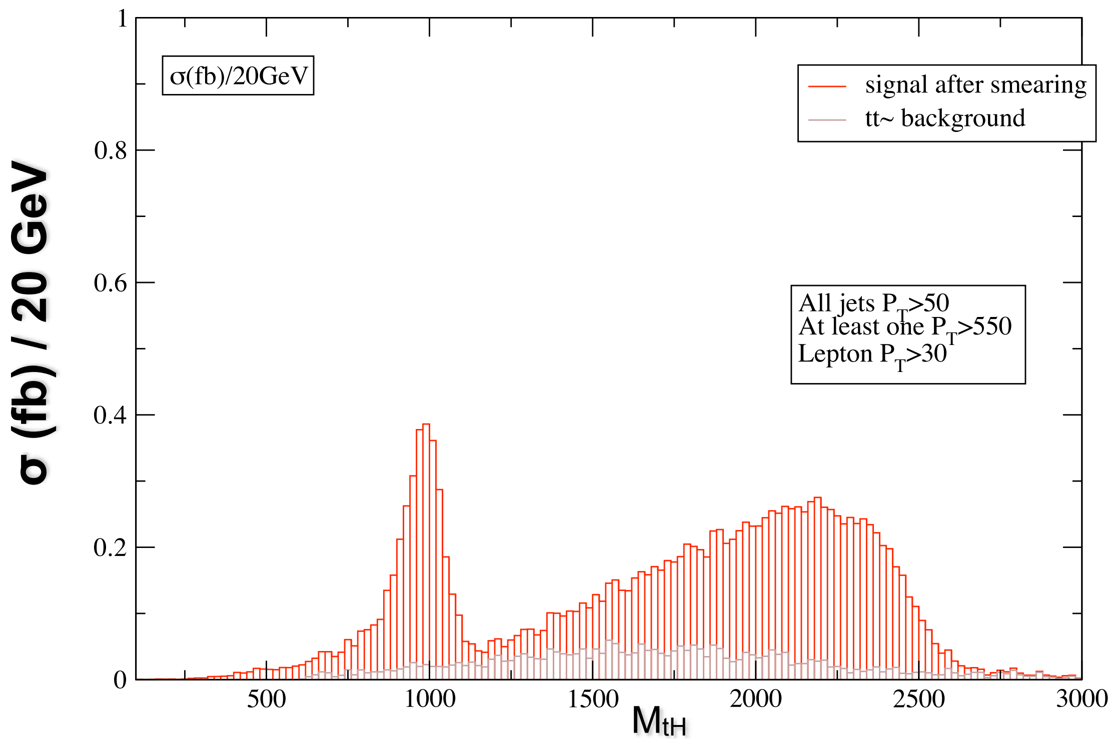


$t_H \to b\ \phi^{\pm}$

- Dominant background tt (one W → lν, one W→ qq), Wjj,Wbb
- Cuts
  - lepton (e or μ) with p_T > 30 GeV, |η|<2.5
  - at least three jets with p_T > 50 GeV
  - one jet with p_T > 550 GeV

f=1000 GeV



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  - $\cos(\theta_{bW})>0.95$

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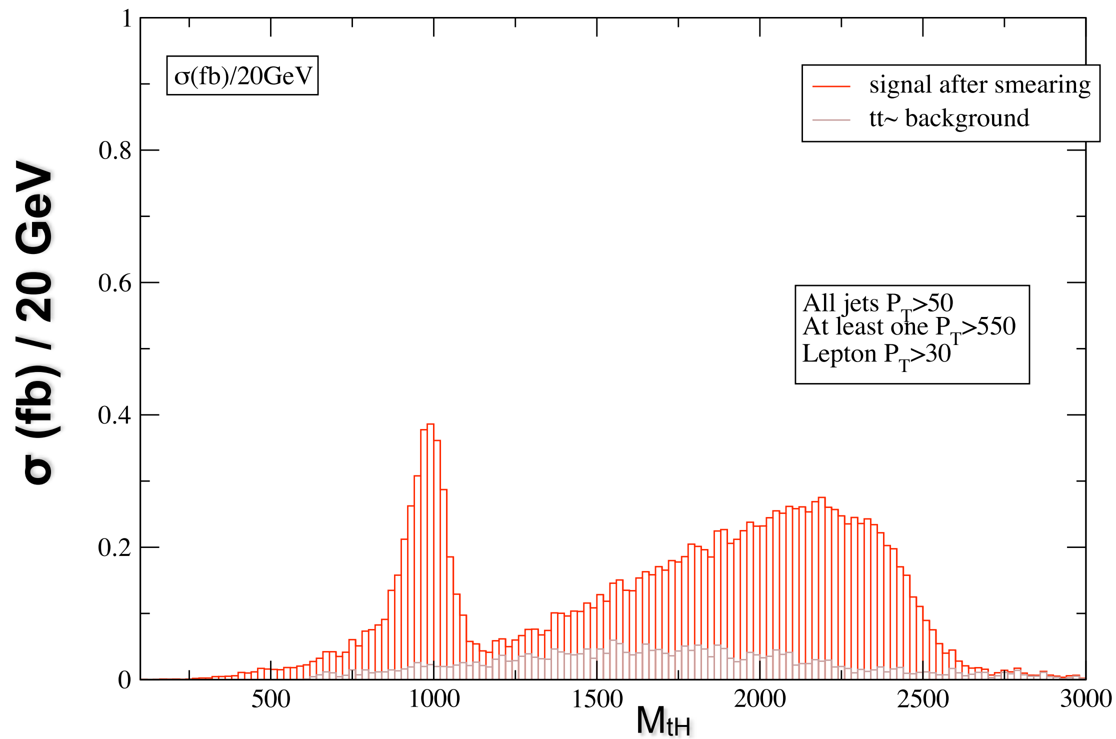

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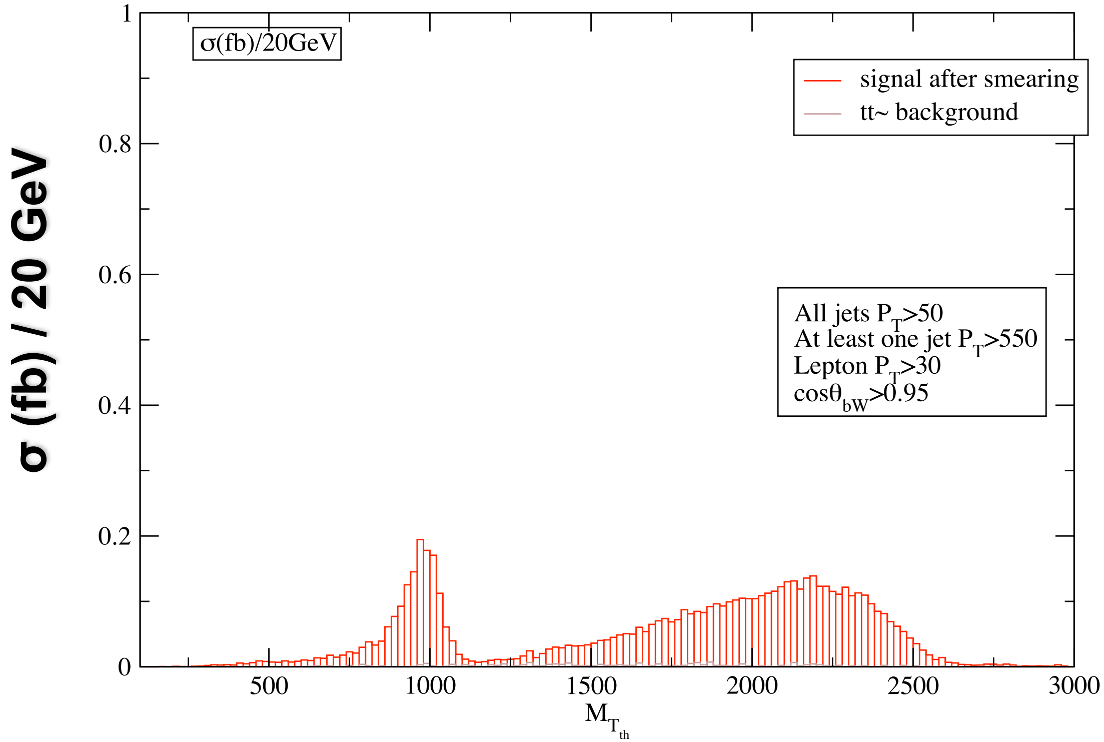

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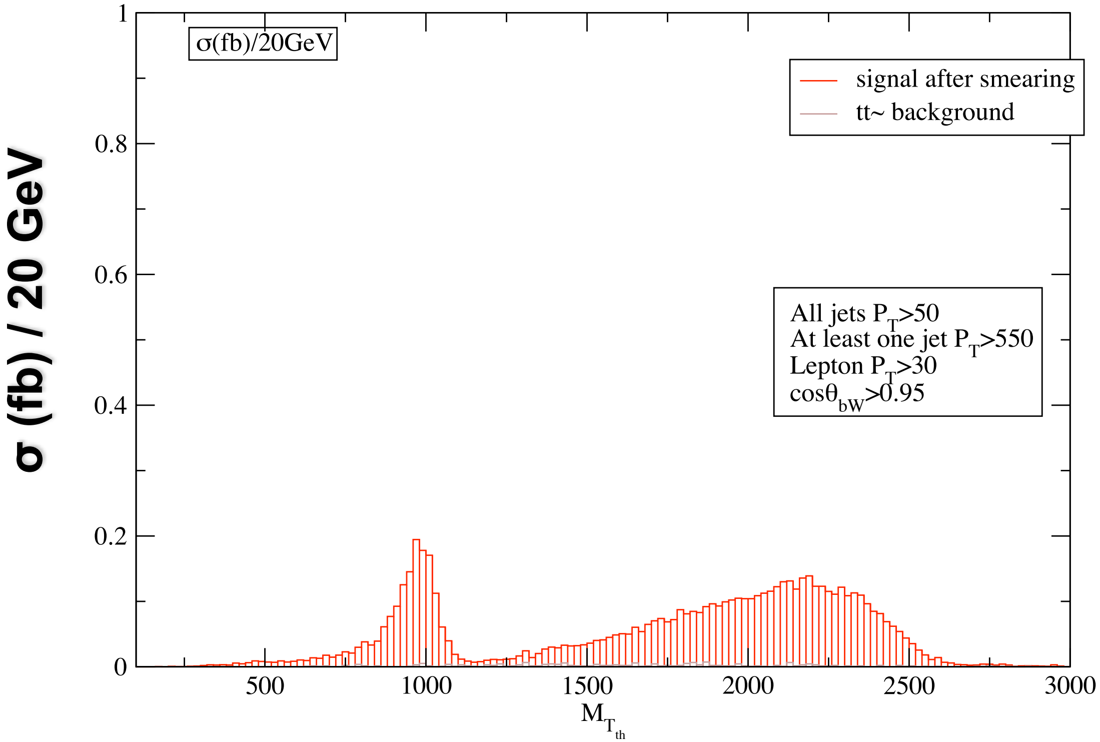
f	S (fb)	S/B	S/√B
600 GeV	8.3	41.5	18.5√L
1000 GeV	6.54	32.7	14.6√L
1500 GeV	0.74	3.7	1.65√L



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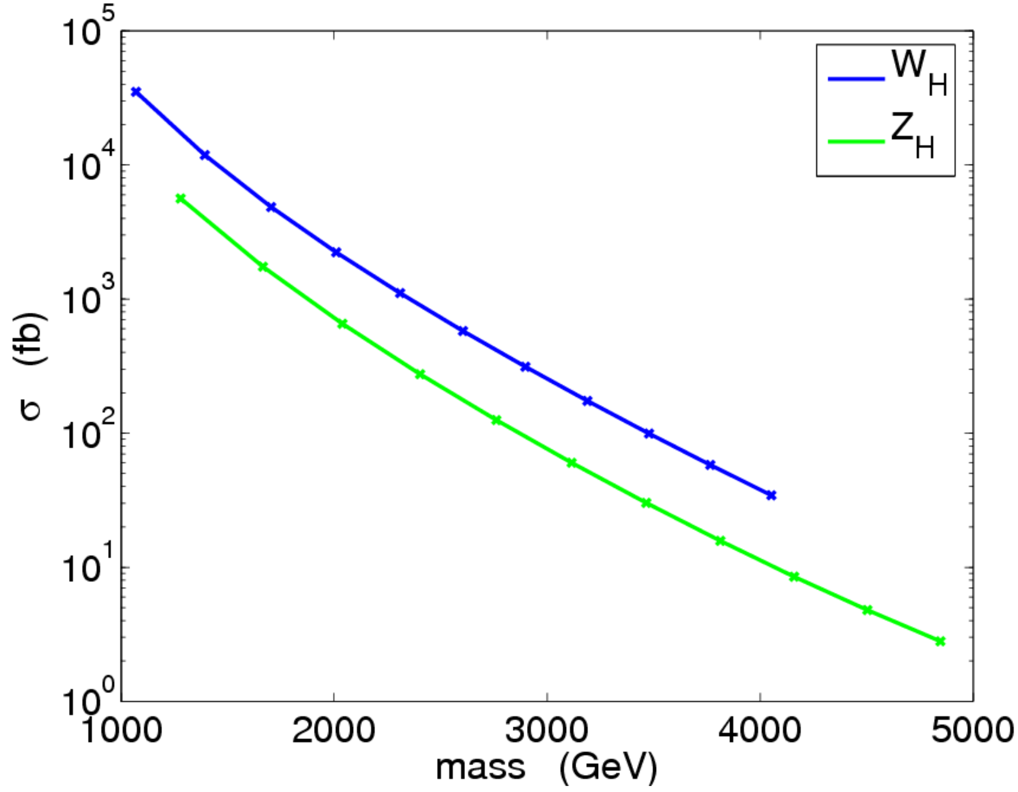
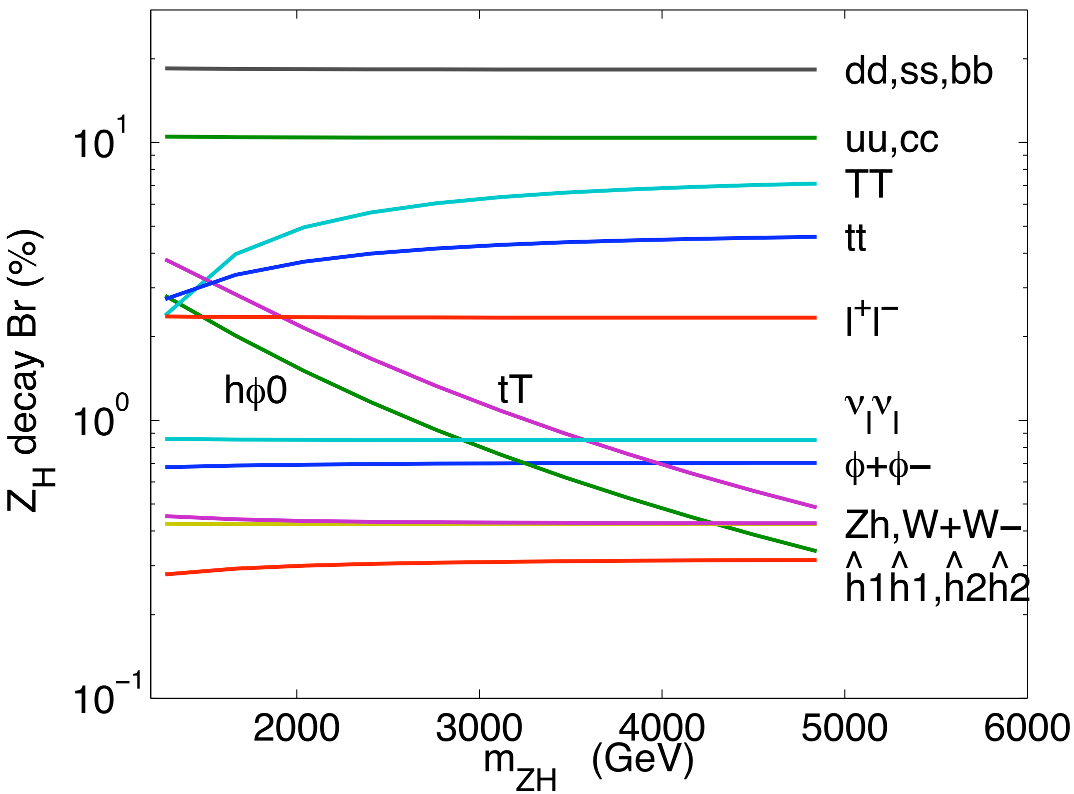
Heavy gauge boson production

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

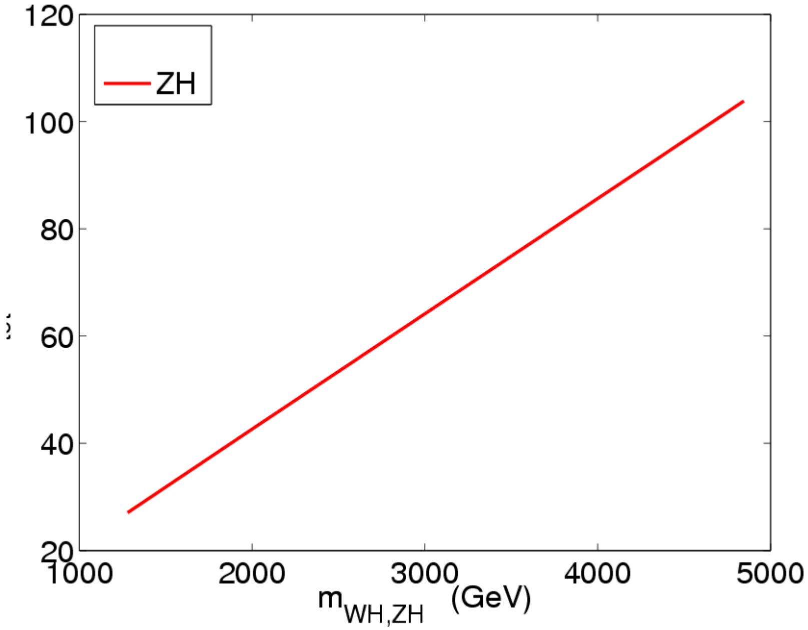


Z_H decay

- Z_H



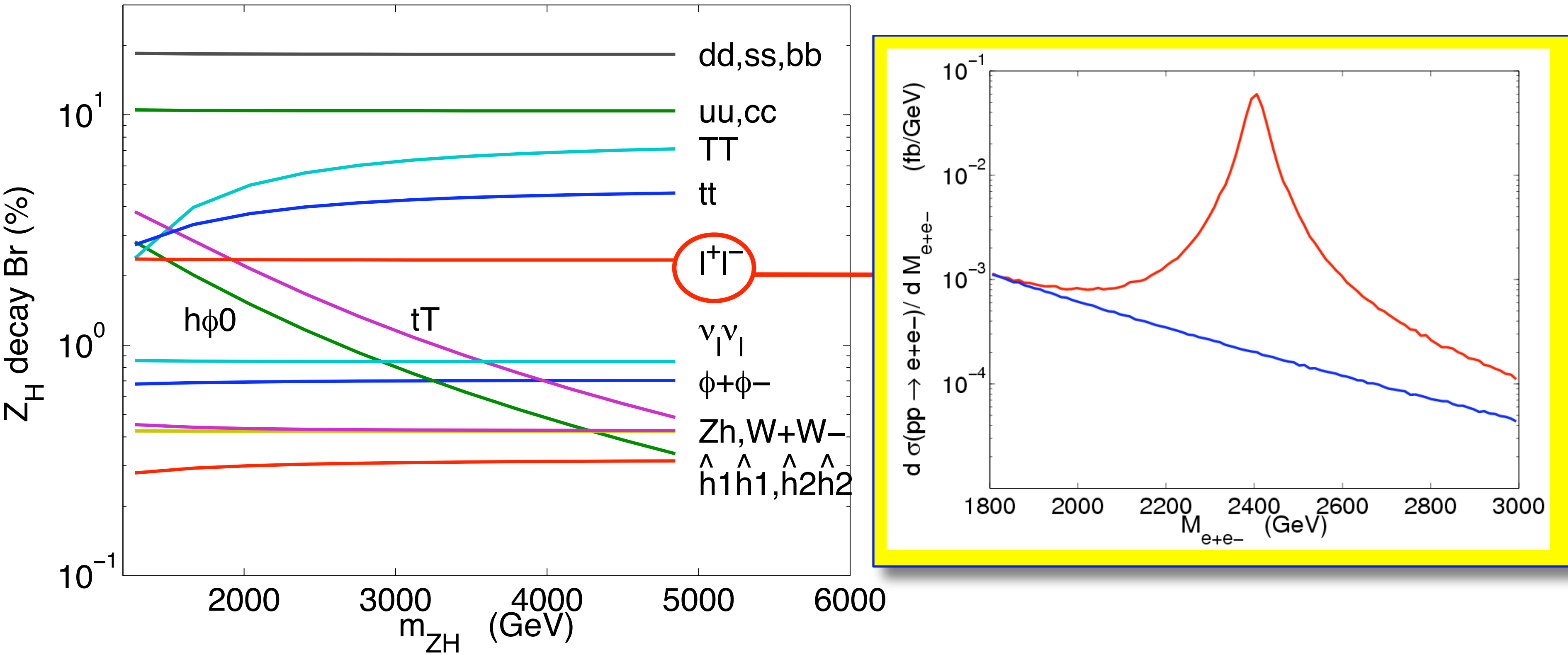
dd,ss,bb
uu,cc
TT
tt
l+l−
hφ0
tT
νlνl
φ+φ−
Zh,W+W−
ĥ1ĥ1,ĥ2ĥ2
ZH decay Br (%)
10^1
10^0
10^−1
2000
3000
4000
5000
6000
mZH (GeV)



ZH
120
100
80
60
40
20
1000
2000
3000
4000
5000
mWH,ZH (GeV)

Z_H decay

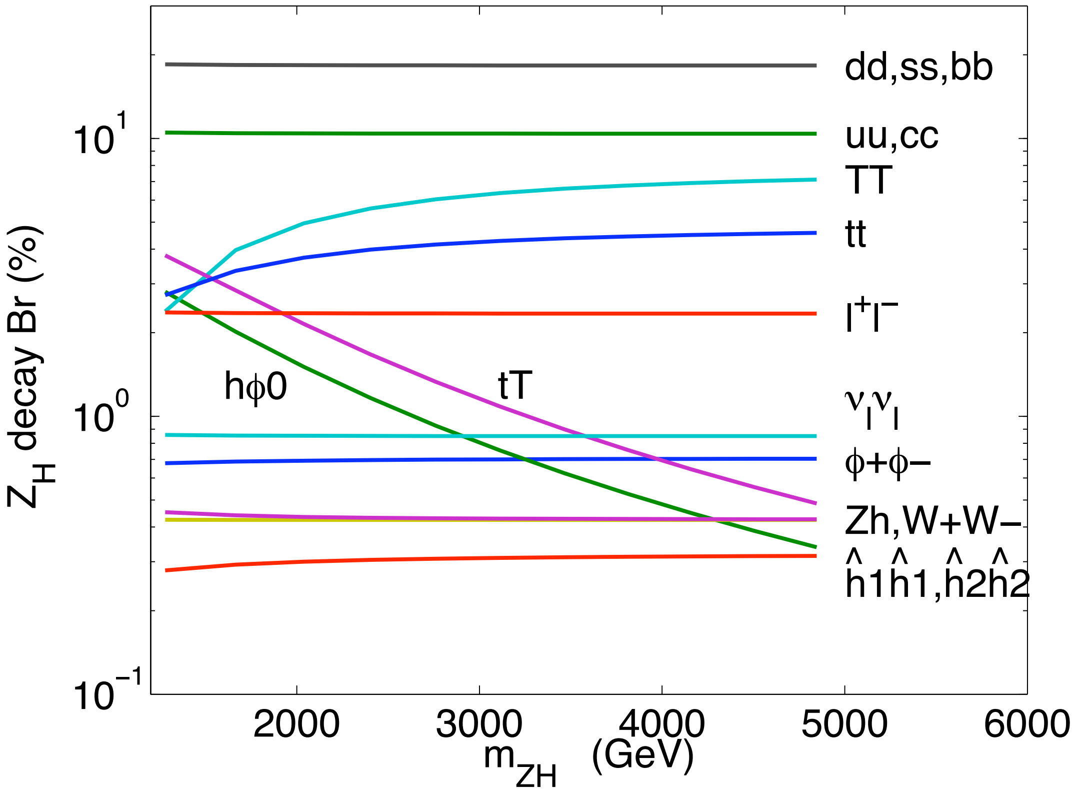
- Z_H



dd,ss,bb
uu,cc
TT
tt
l+l−
hφ0
tT
ν_l ν_l
φ+φ−
Zh,W+W−
ĥ1ĥ1,ĥ2ĥ2
Z_H decay Br (%)
m_ZH (GeV)
10^1
10^0
10^−1
2000
3000
4000
5000
6000
d σ(pp → e+e−)/ d M_e+e− (fb/GeV)
M_e+e− (GeV)
10^−1
10^−2
10^−3
10^−4
1800
2000
2200
2400
2600
2800
3000

Z_H decay

- Z_H



dd,ss,bb
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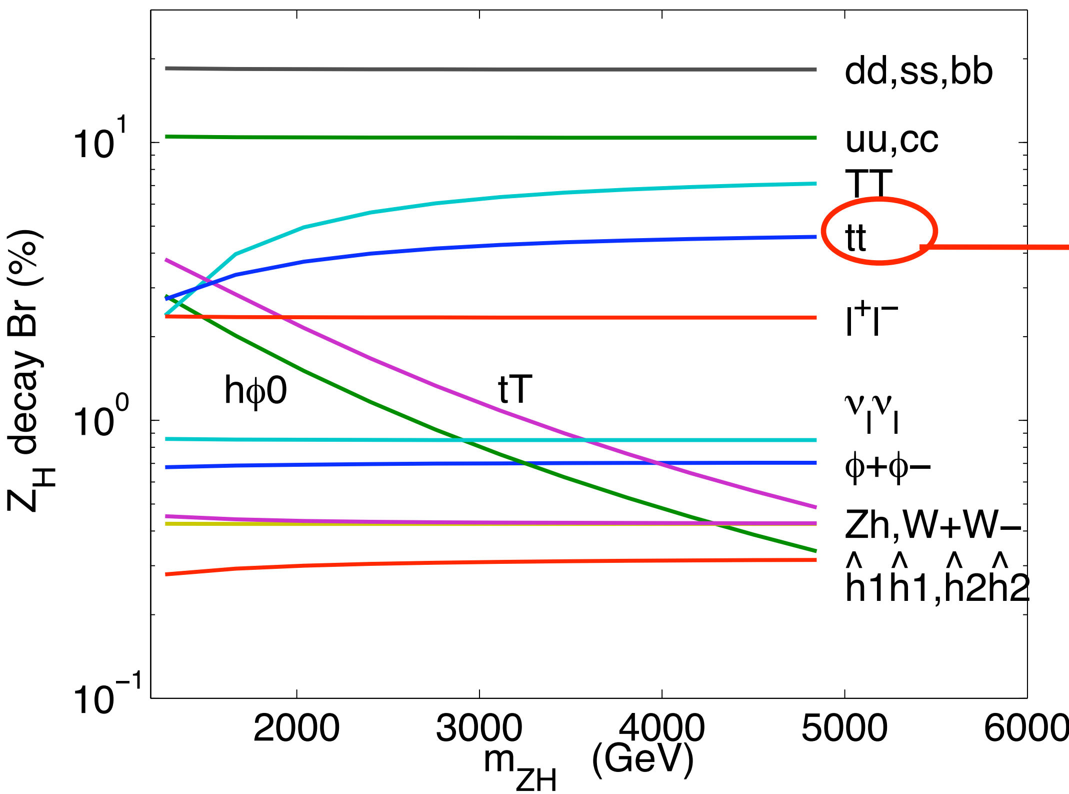
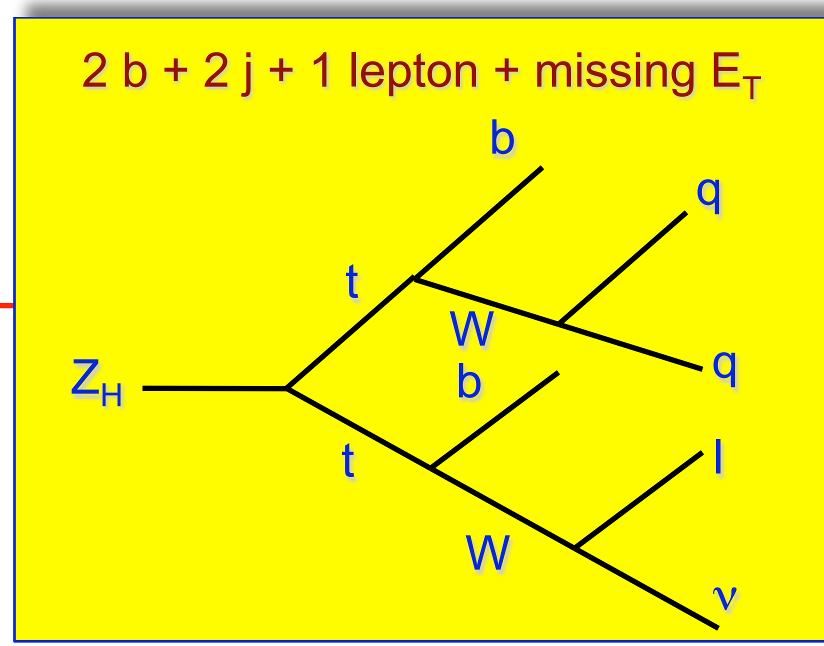
TT
tt
l+l−
hφ0
tT
νlνl
φ+φ−
Zh,W+W−
ĥ1ĥ1,ĥ2ĥ2
10^1
10^0
10^−1
2000
3000
4000
5000
6000
m_ZH (GeV)
Z_H decay Br (%)

Z_H decay

- Z_H



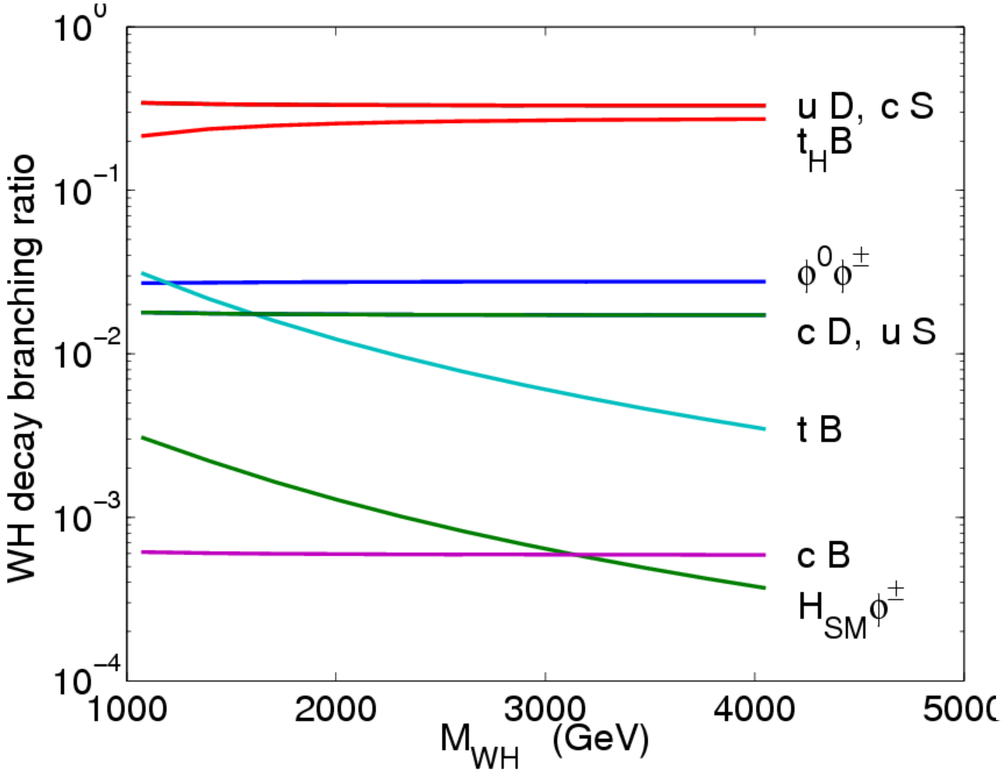
dd,ss,bb
uu,cc
TT
tt
l+l−
hϕ0
tT
νlνl
ϕ+ϕ−
Zh,W+W−
h1h1,h2h2
10^1
10^0
10^−1
2000
3000
4000
5000
6000
mZH (GeV)
ZH decay Br (%)

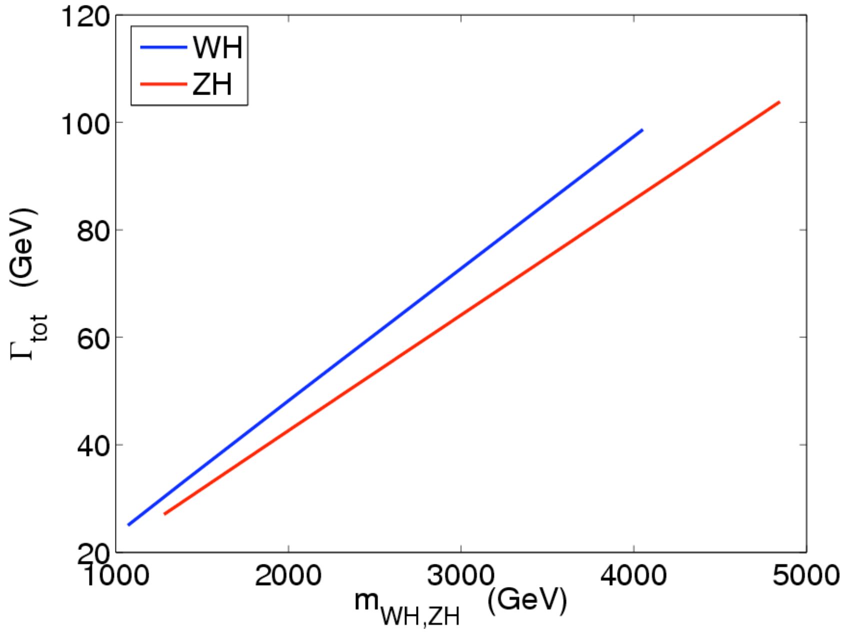


2 b + 2 j + 1 lepton + missing ET
ZH
t
t
W
W
b
b
q
q
l
ν

W_H decay

- **W_H ($m_{\nu R} > m_{WH}$)**

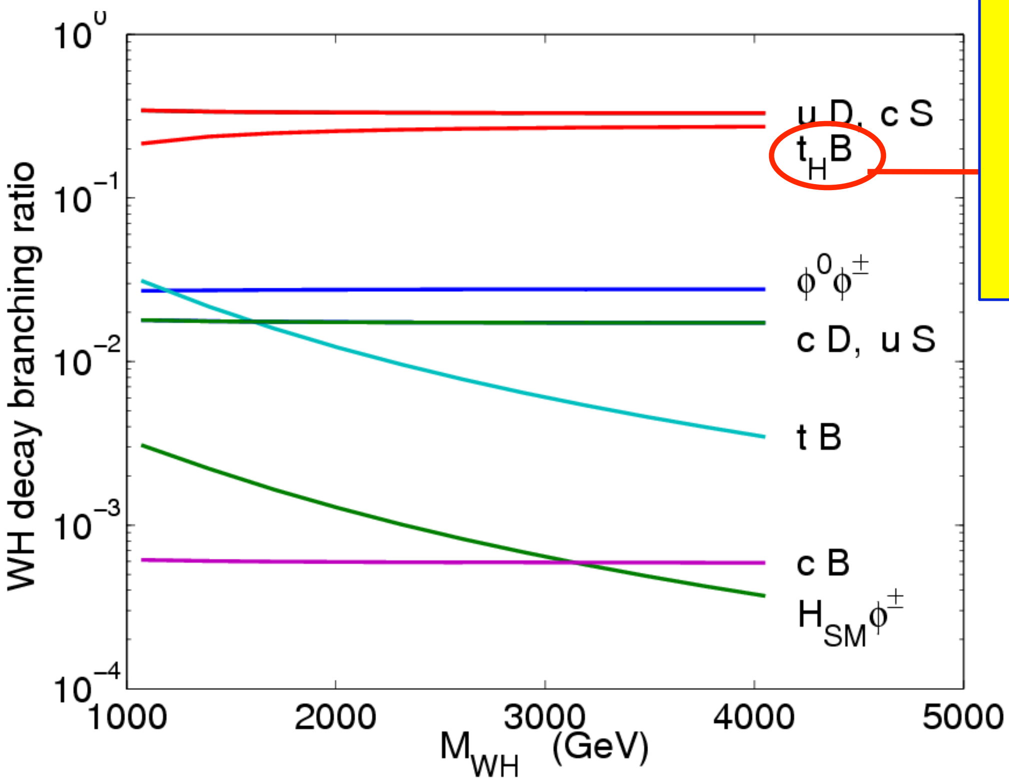




- **W_H ($m_{\nu R} < m_{WH}$), $W_H \rightarrow l\, \nu_R$, Br ~ 9%**

W_H decay

- W_H ($m_{\nu R} > m_{WH}$)



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

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

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

- W_H ($m_{\nu R} < m_{WH}$), $W_H \to l\ \nu_R$, Br ~ 9%

Higgses

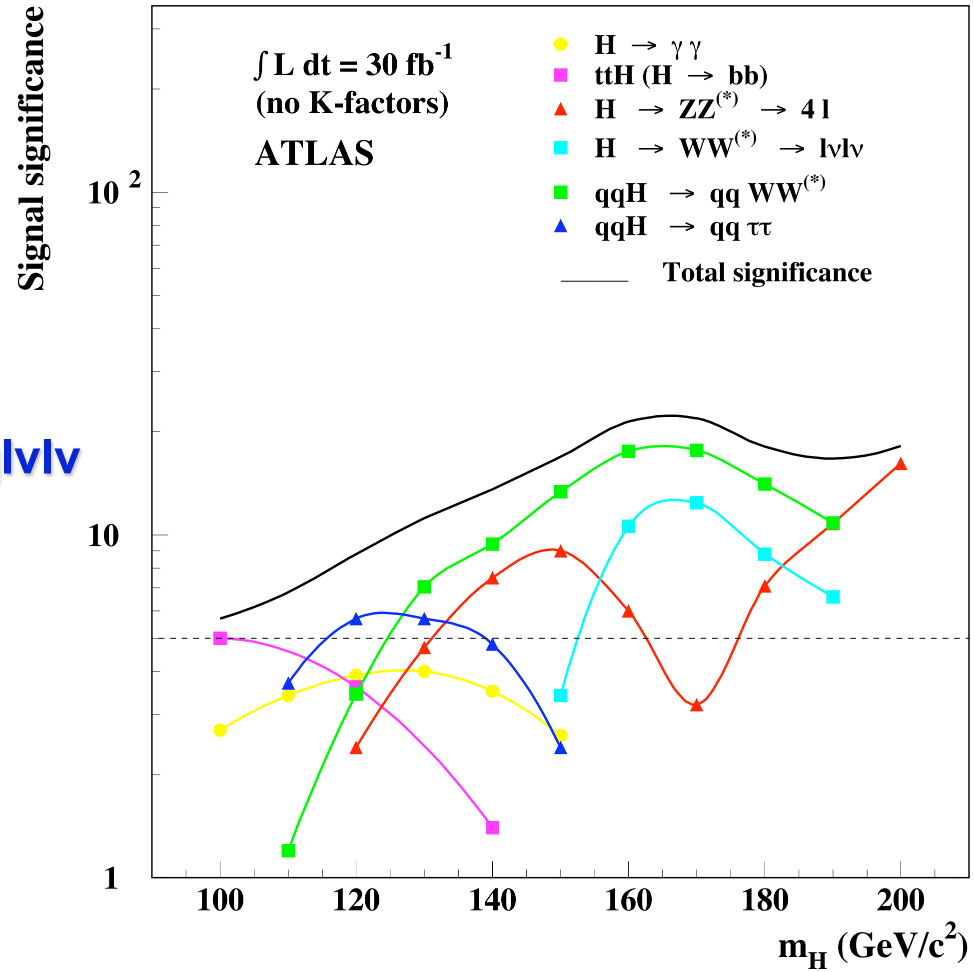
SM Higgs

- $m_H \sim$ 150-170 GeV,

  depending on f_1, Λ and M

- Higgs searches:

  - WBF $\rightarrow$ qqH $\rightarrow$ qqWW* $\rightarrow$ qqlνlν
  - gg $\rightarrow$ H $\rightarrow$ ZZ* $\rightarrow$ llll
  - gg $\rightarrow$ H $\rightarrow$ WW* $\rightarrow$ lνlν



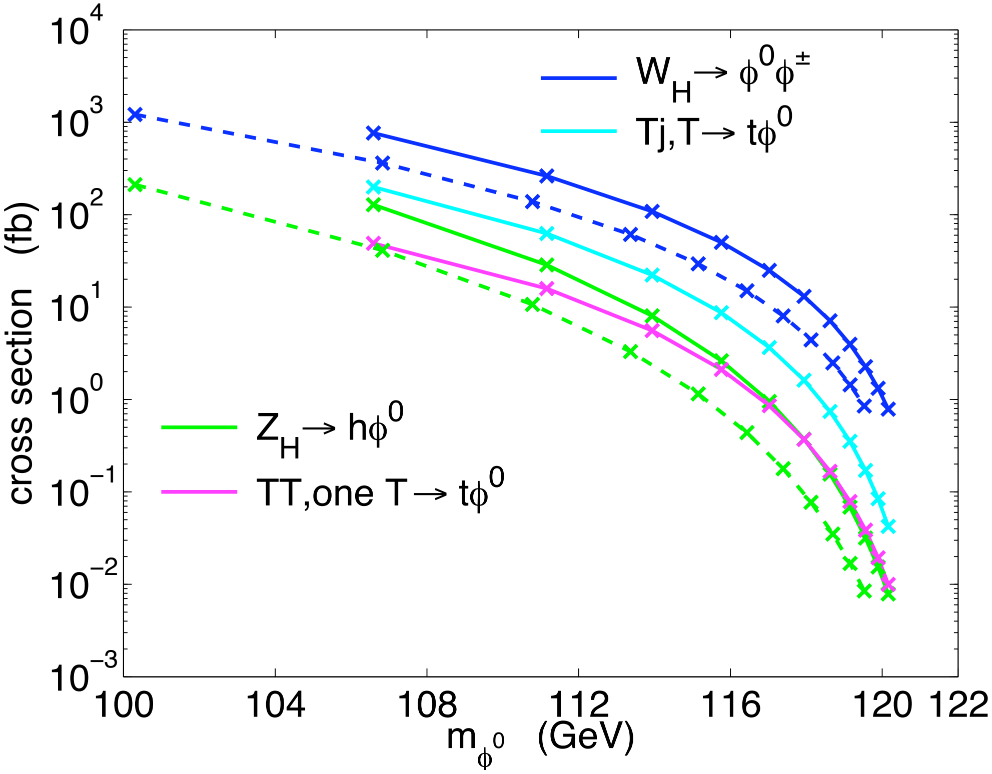
ϕ^0

Neutral Higgs ϕ^0 Difficult to discover

- $\phi^0 \rightarrow bb$, cc, ττ, Γ suppressed by v^2/f^2, Br similar to SM
- γγ generated by t_H loop, Γ suppressed by v^2/f^2, Br similar to SM
- No WW, ZZ coupling, $W\phi^0$, $Z\phi^0$ associated production suppressed
- $gg \rightarrow \phi^0$ generated by t_H loop, suppressed by v^2/f^2
  - $gg \rightarrow \phi^0 \rightarrow \gamma\gamma$ production suppressed
  - $gg \rightarrow \phi^0 \rightarrow bb$ QCD bg huge
- $bb\phi^0$, $tb\phi^0$, $tt\phi^0$ cross section small

ϕ^0

- **Produced via the decay of heavy particles**



ϕ^0

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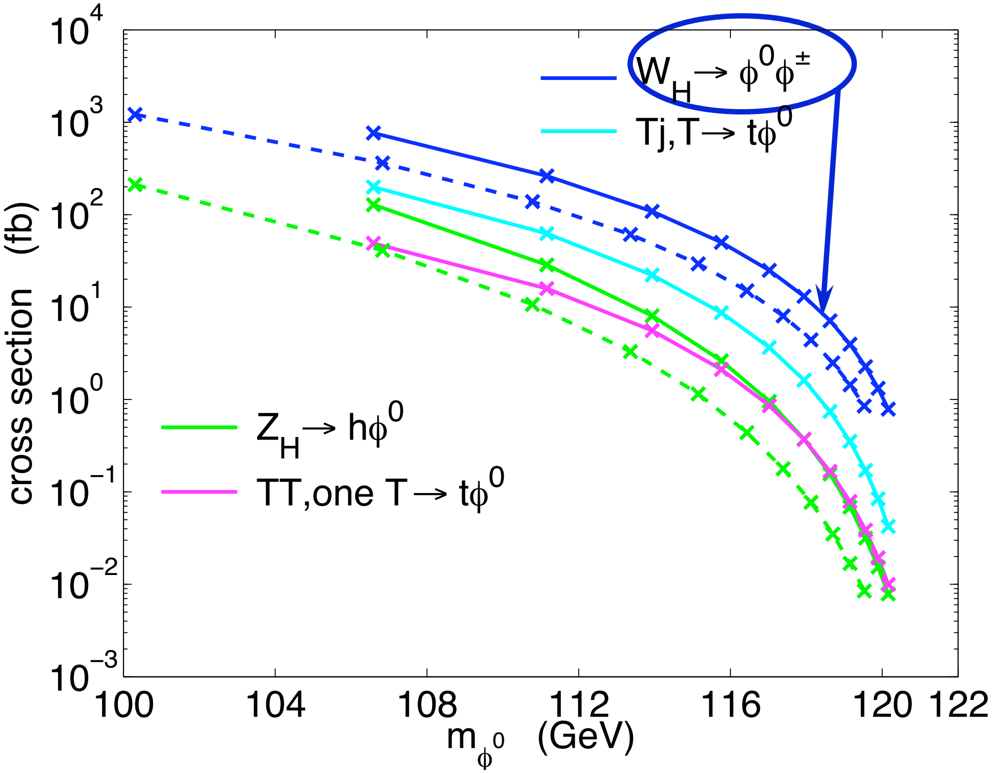

ϕ^0

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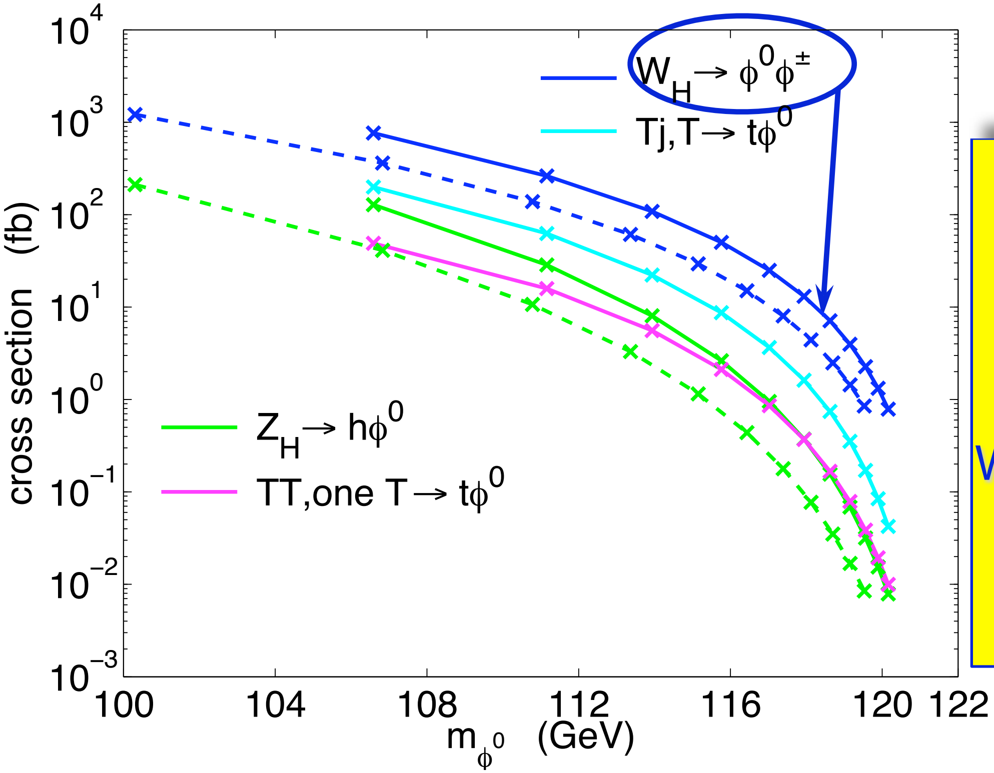
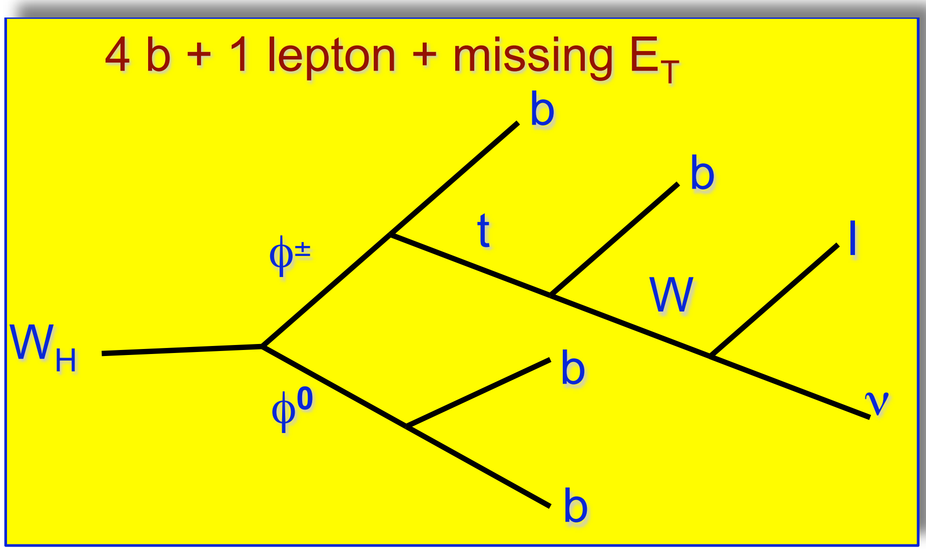
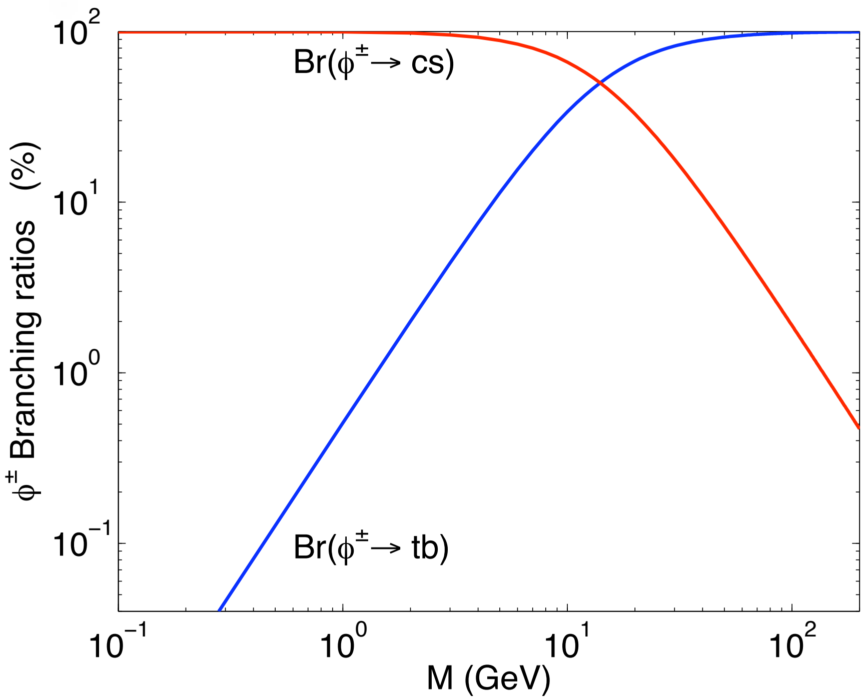




Higgses

Neutral Higgs $\phi^\pm$

- Decay modes depend on M

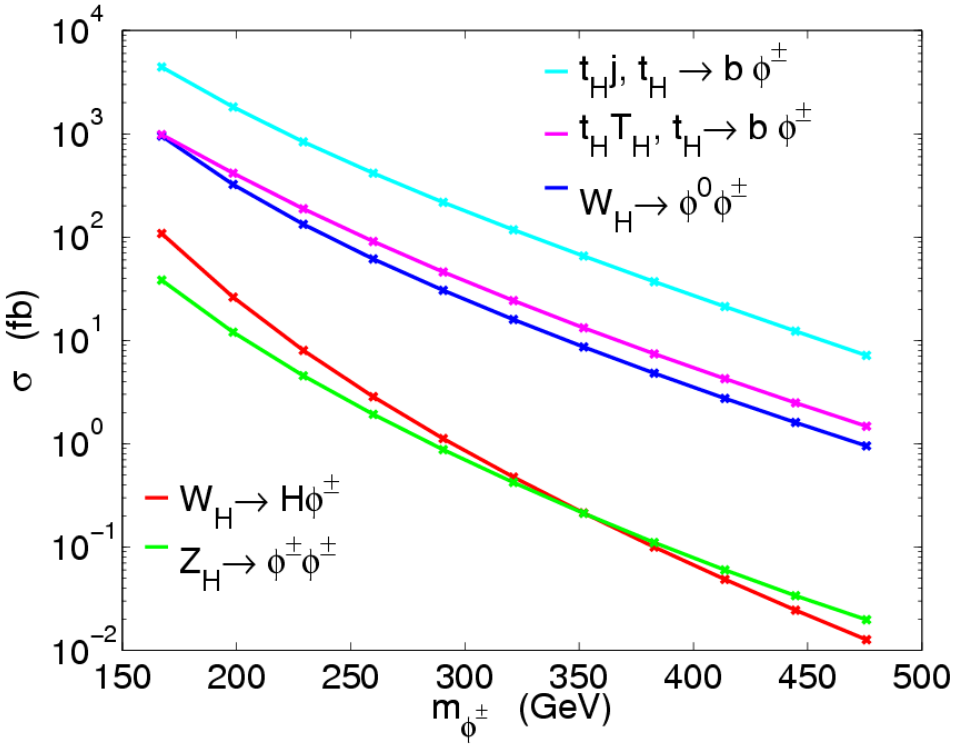


- no $W\phi^\pm$, $Z\phi^\pm$ associated production (no such coupling)
- $bb\phi^\pm$, $tb\phi^\pm$, $tt\phi^\pm$ cross section small

$\phi^{\pm}$

Charged Higgs $\phi^{\pm}$

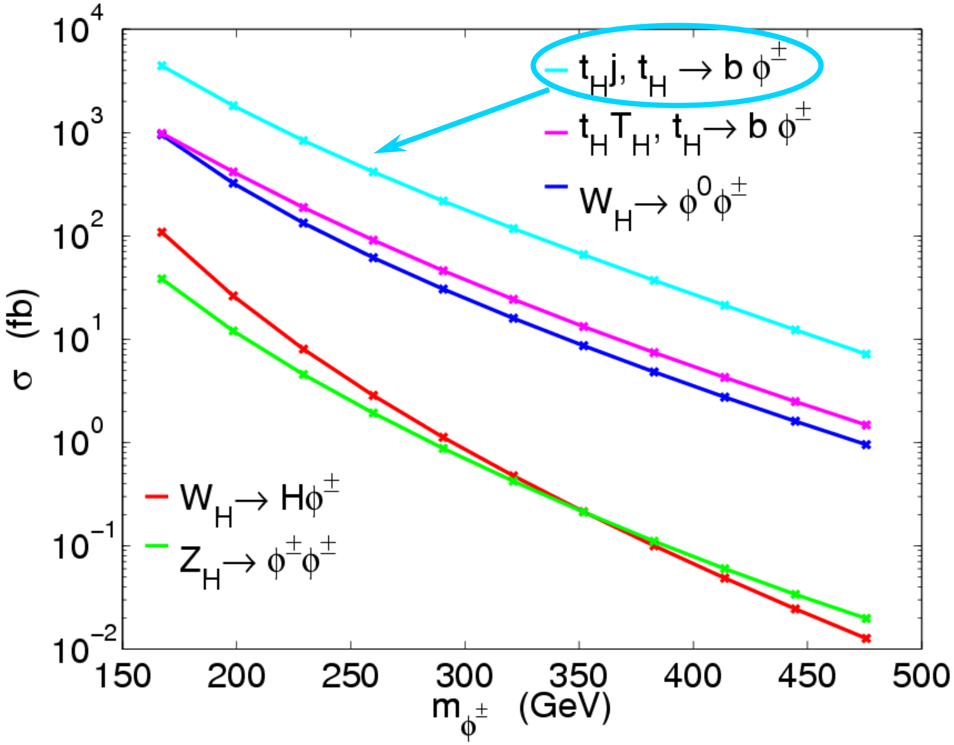
- **Produced via the decay of heavy particles**



$\phi^{\pm}$

Charged Higgs $\phi^{\pm}$

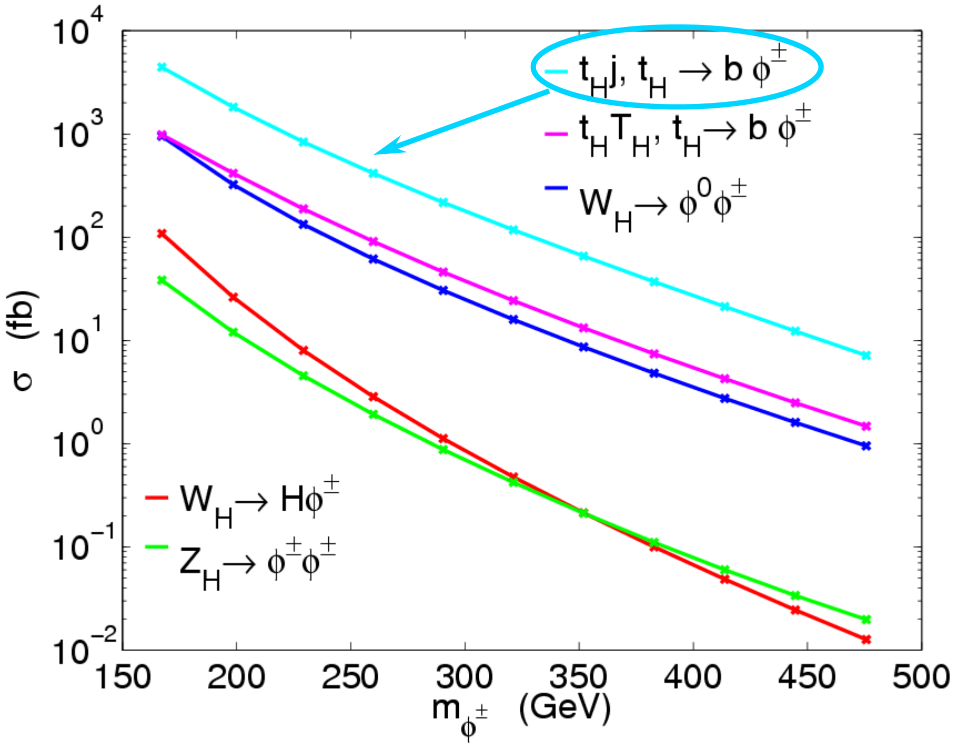
- Produced via the decay of heavy particles

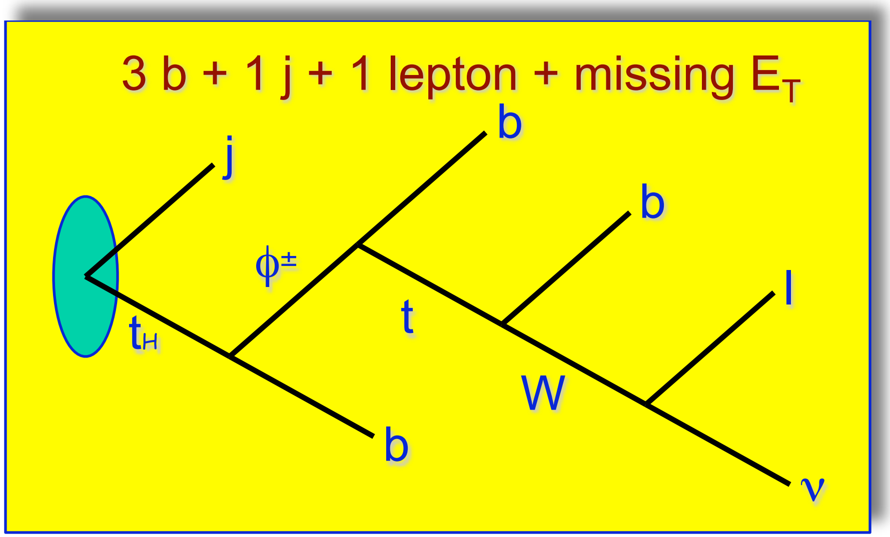


$\phi^{\pm}$

Charged Higgs $\phi^{\pm}$

- **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

More later ...

M=0 case

Top Yukawa:

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

($H_R \leftarrow f_1$, $H_L \leftarrow v$)

$t_H = (T_L, t_R)$, $m_{tH} = yf_1$

$t_{SM} = (t_L, T_R)$, $m_t = yv$

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

- ✓ $\phi^0 - t_H - t_H$
- ✗ $\phi^0 - t - t$
- ✗ $\phi^0 - t_H - t$

- ✓ $\phi^\pm - t_H - b$
- ✗ $\phi^\pm - t - b$

- ✓ $H - t - t$
- ✓ $H - t_H - t_H$ (small)
- ✗ $H - t_H - t$

M=0 case

Top Yukawa: $y H_R^\dagger Q_R T_L + y H_L^\dagger Q_L T_R + h.c.$

($H_R^\dagger \to f_1$, $H_L^\dagger \to v$)

$t_H = (T_L, t_R)$, $m_{tH} = y f_1$

$t_{SM} = (t_L, T_R)$, $m_t = yv$

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

- ✓ $\phi^0 - t_H - t_H$
- ✗ $\phi^0 - t - t$
- ✗ $\phi^0 - t_H - t$
- ✓ $H - t - t$
- ✓ $H - t_H - t_H$ (small)
- ✗ $H - t_H - t$
- ✓ $\phi^\pm - t_H - b$
- ✗ $\phi^\pm - t - b$ ⟸ $\phi^\pm \to t + b$ (100%)

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

- ✓ $W - t - b$
- ✗ $W - t_H - b$
- ✗ $W_H - t - b$
- ✓ $W_H - t_H - b$

- ✓ $Z - t - t$
- ✓ $Z - t_H - t_H$
- ✗ $Z - t_H - t$
- ✓ $Z_H - t - t$
- ✓ $Z_H - t_H - t_H$
- ✗ $Z_H - t_H - t$

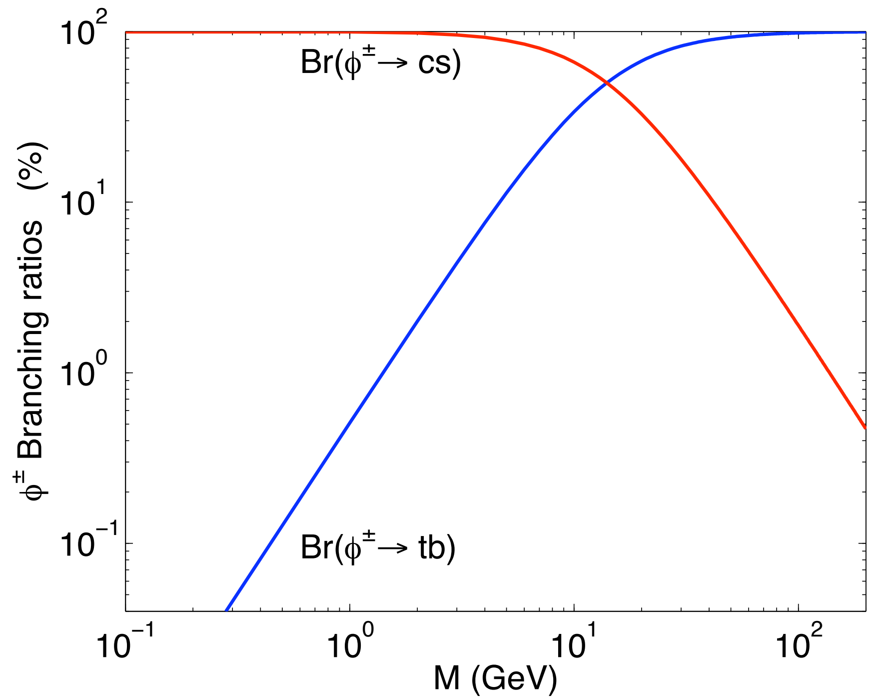
Yukawa coupling

- ✓ $\phi^0 - t_H - t_H$
- ✗ $\phi^0 - t - t$
- ✗ $\phi^0 - t_H - t$

- ✓ $H - t - t$
- ✓ $H - t_H - t_H$ (small)
- ✗ $H - t_H - t$

- ✓ $\phi^\pm - t_H - b$
- ✗ $\phi^\pm - t - b$ ⟵ $\phi^\pm$ ~~→~~ $t + b$ (100%)

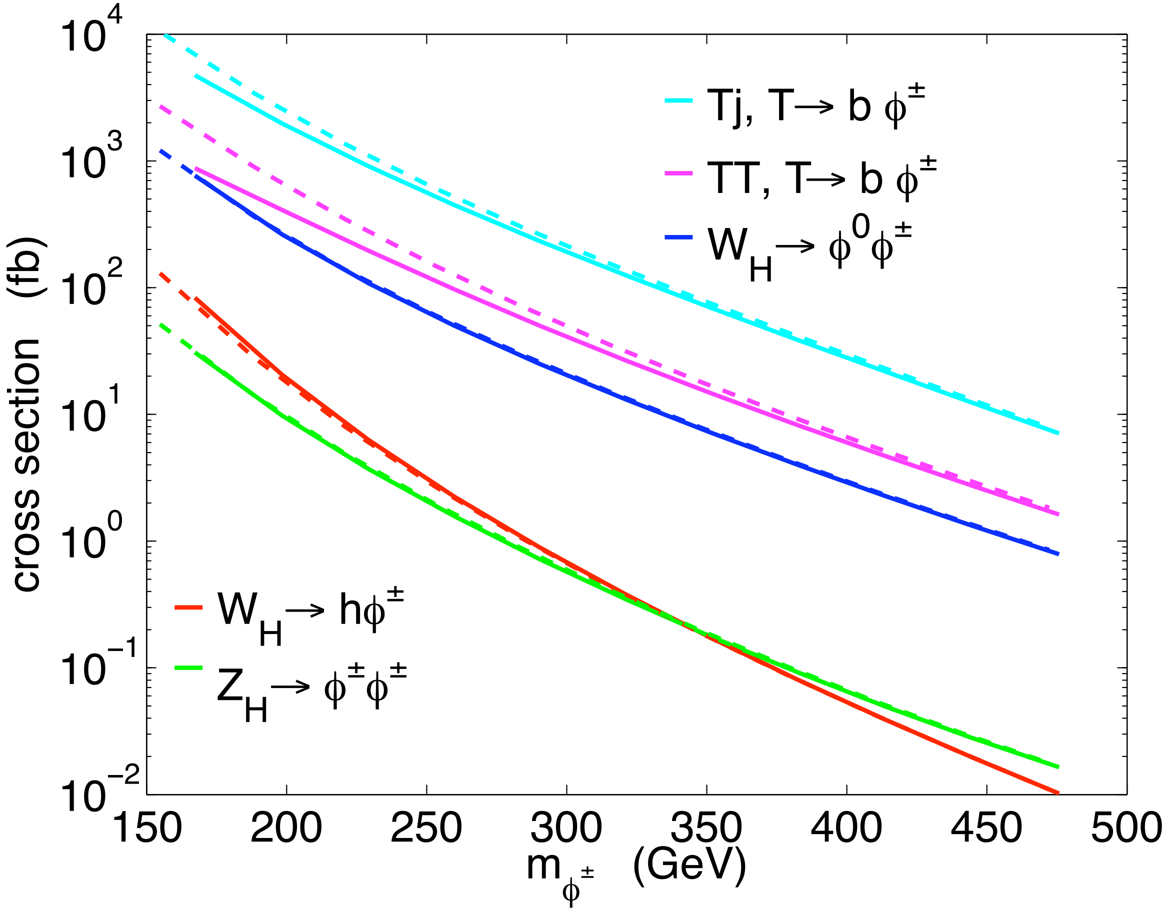
$\phi^{\pm}$ decay



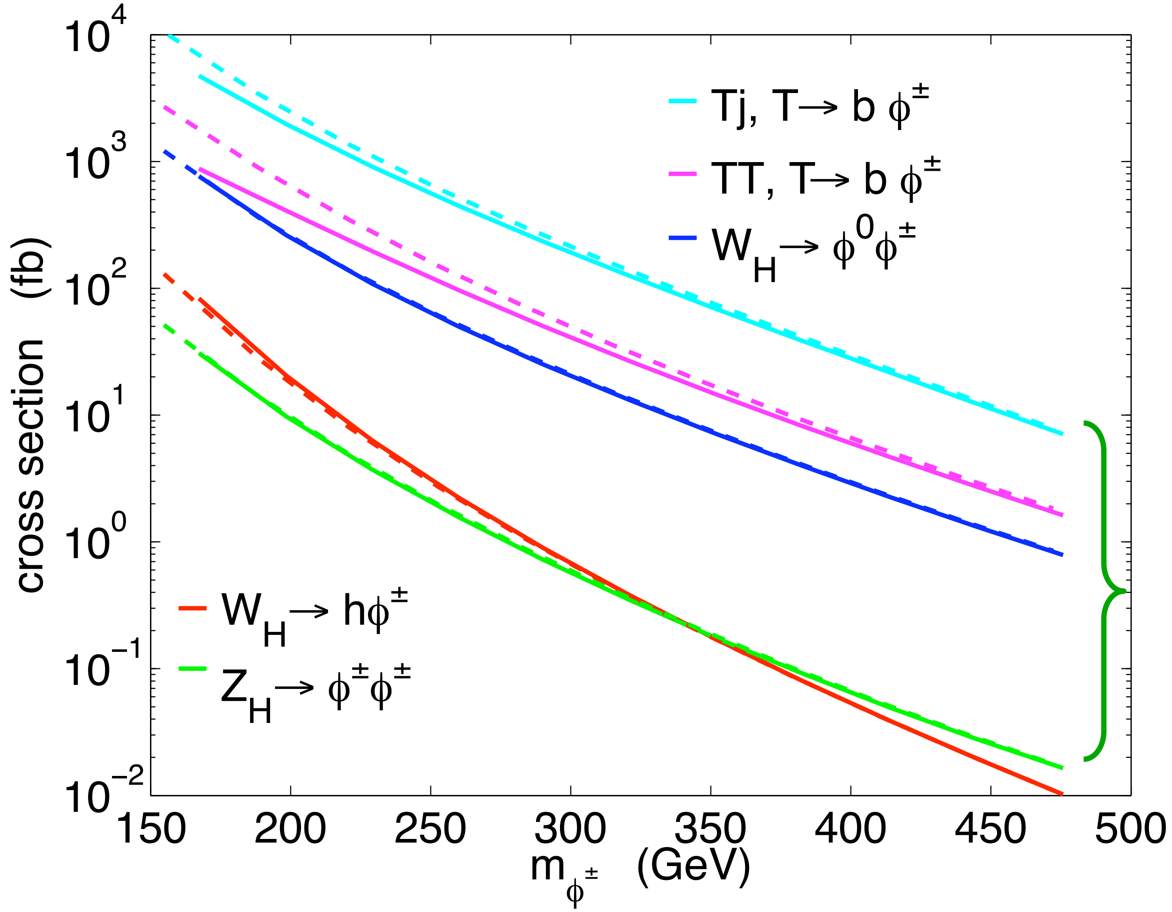
$\phi^{\pm} \rightarrow$ cs for M < 1 GeV

discovery becomes difficult due to QCD background

$\phi^{\pm}$ discovery

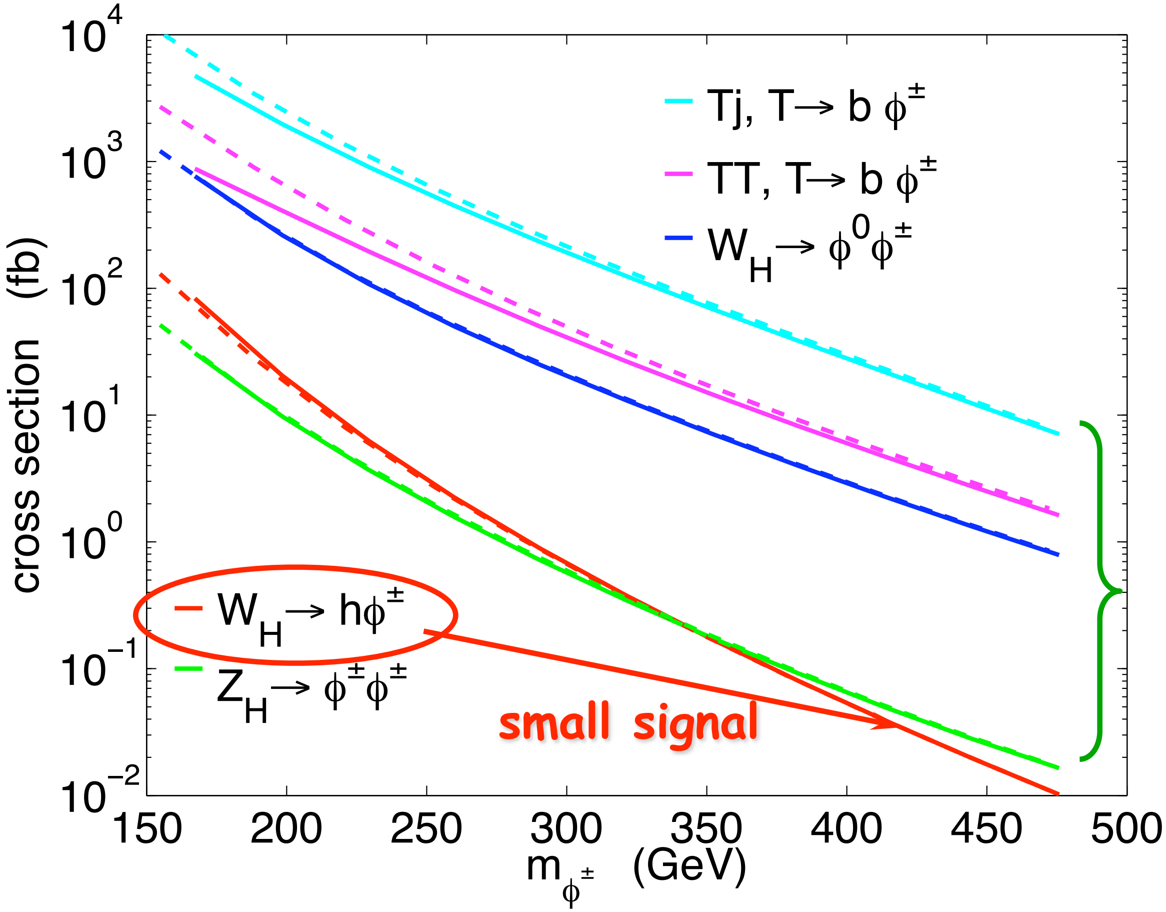


$\phi^{\pm}$ discovery



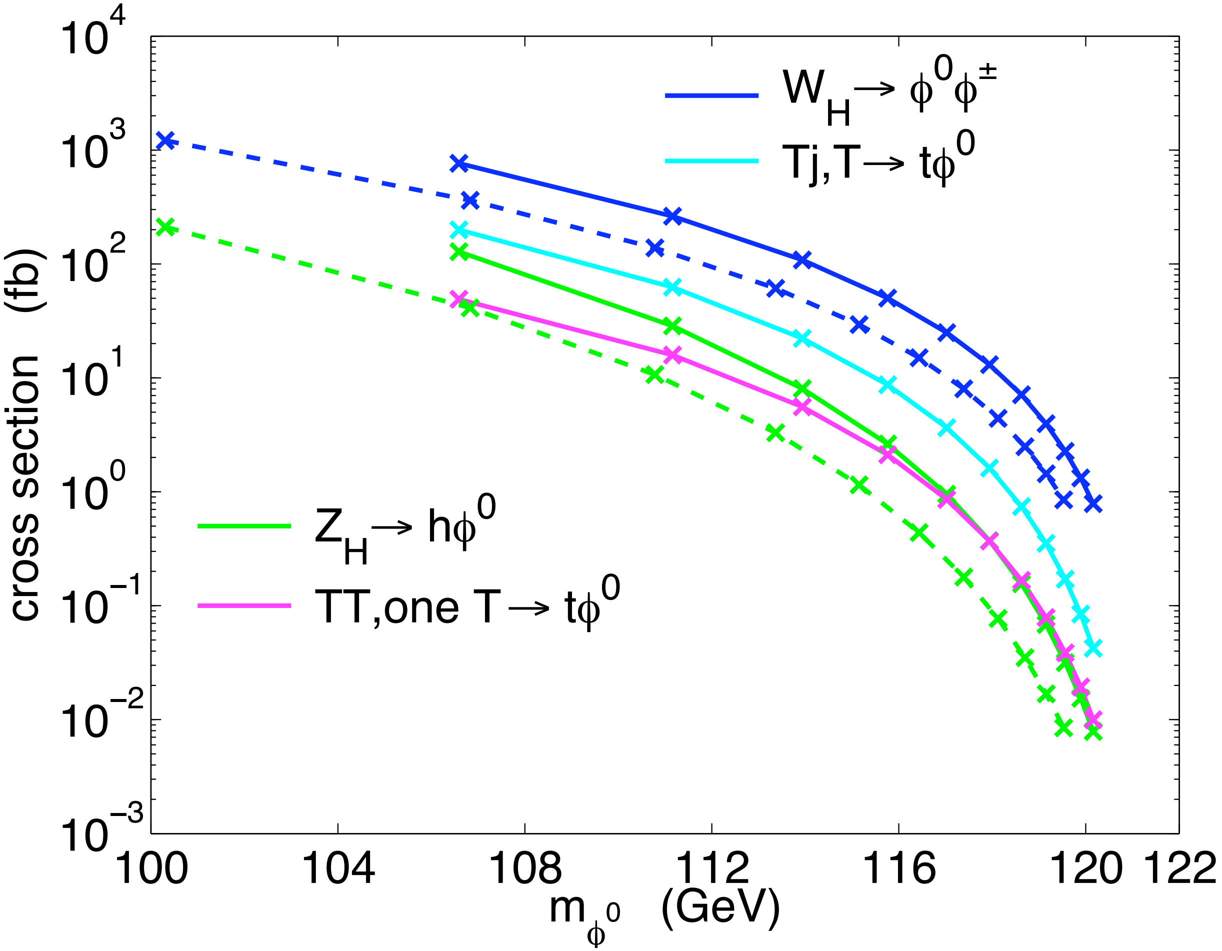
Difficult huge QCD bg

$\phi^{\pm}$ discovery

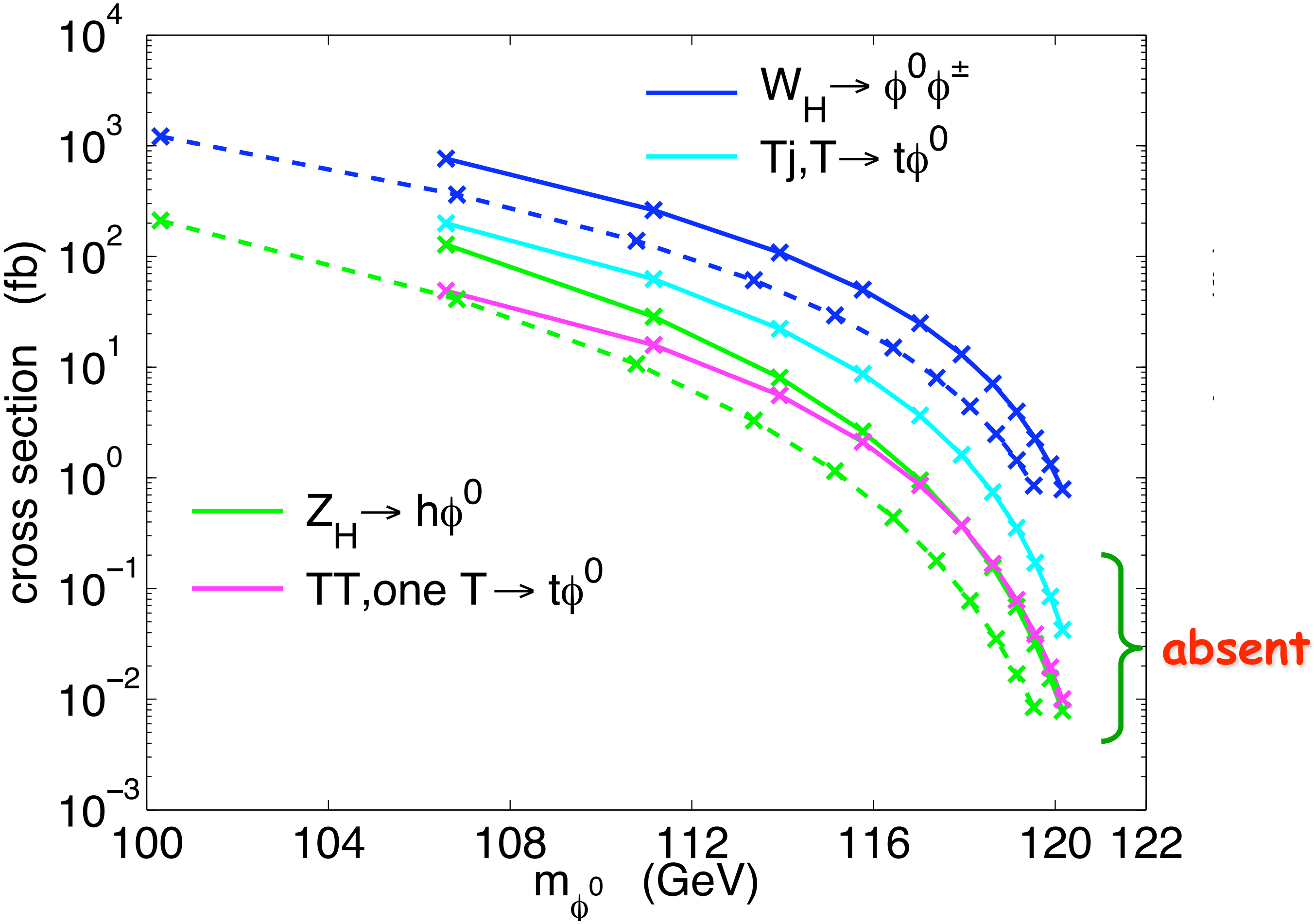


Difficult
huge QCD bg

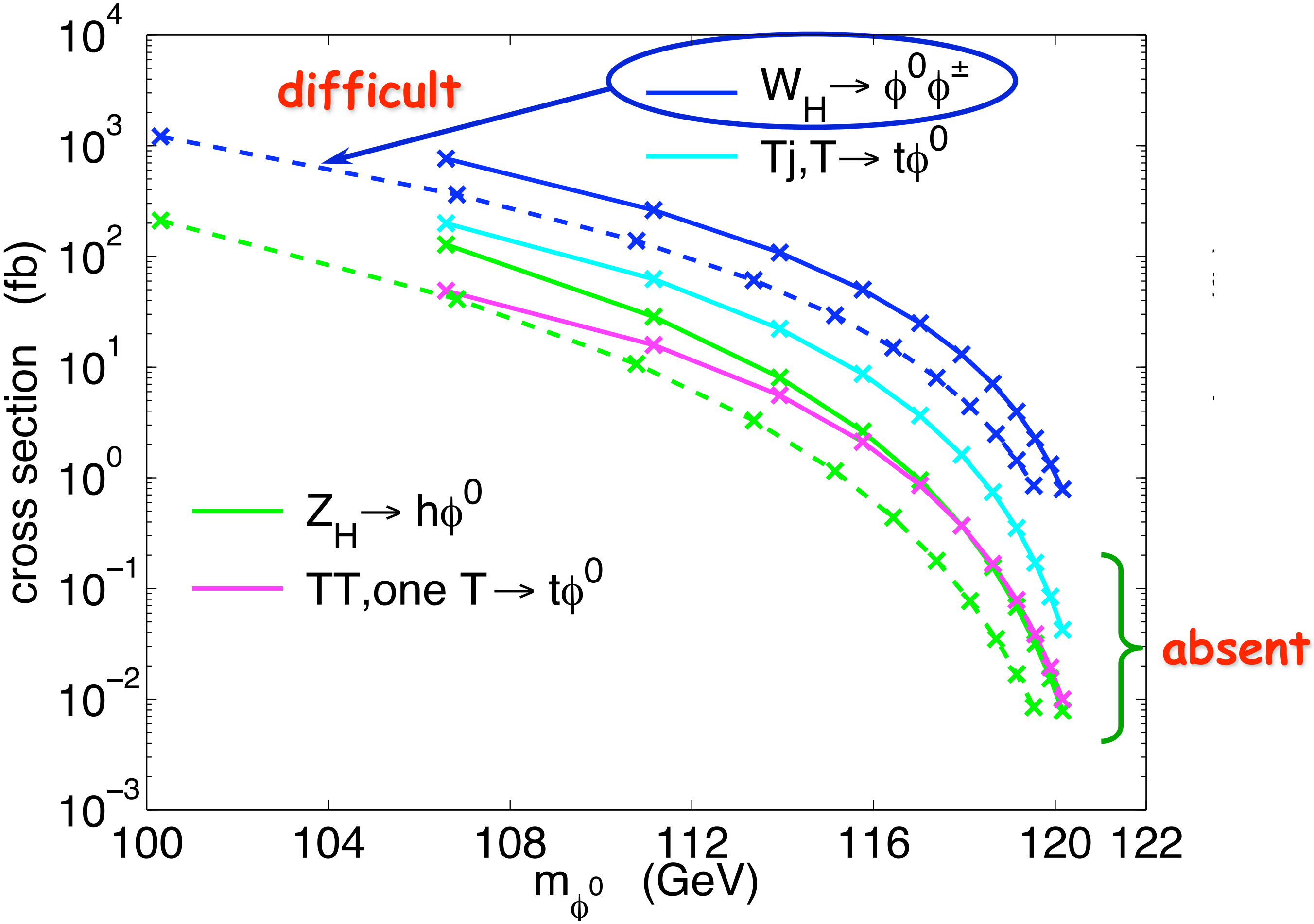
ϕ^0 discovery



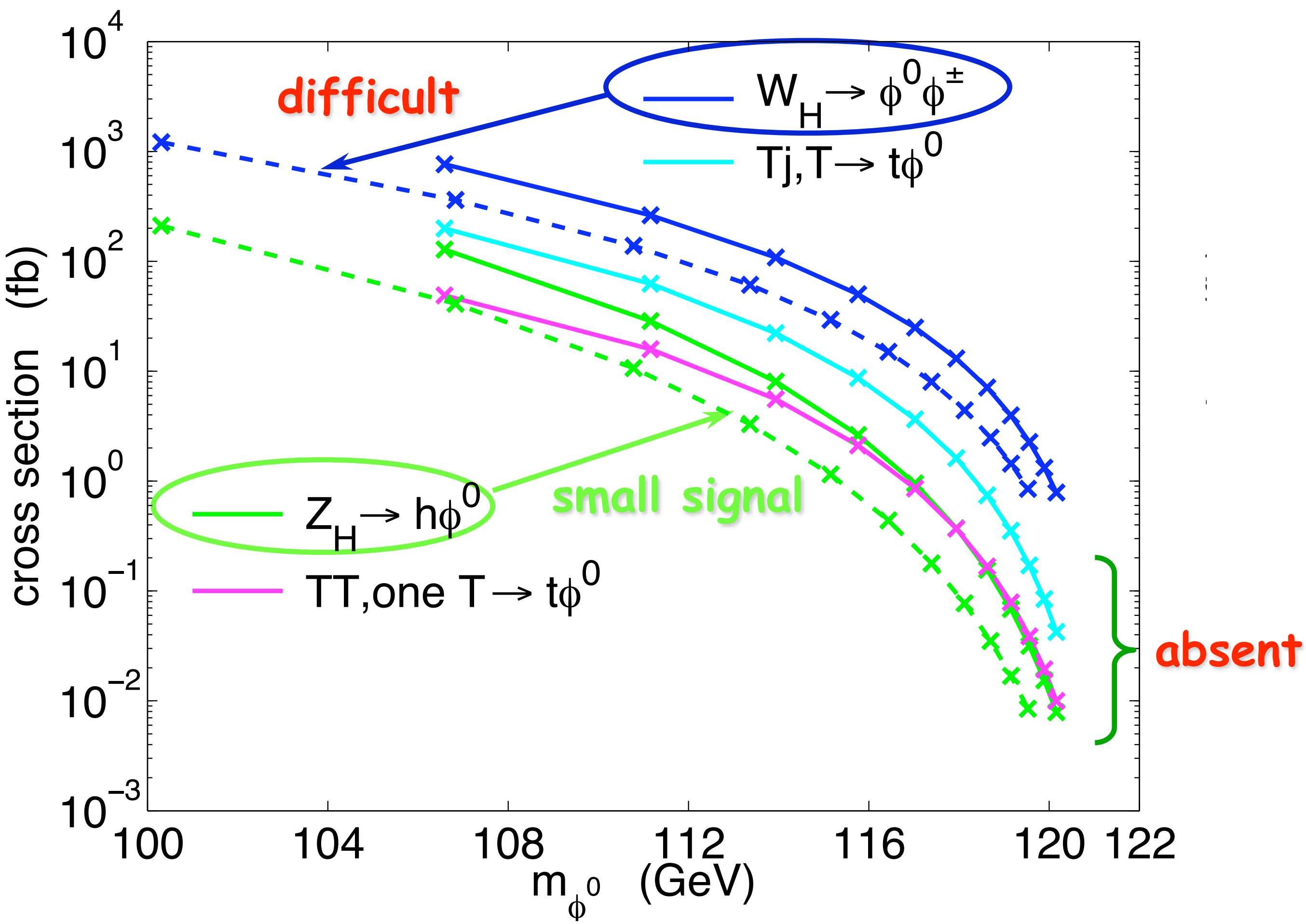
ϕ^0 discovery



ϕ^0 discovery

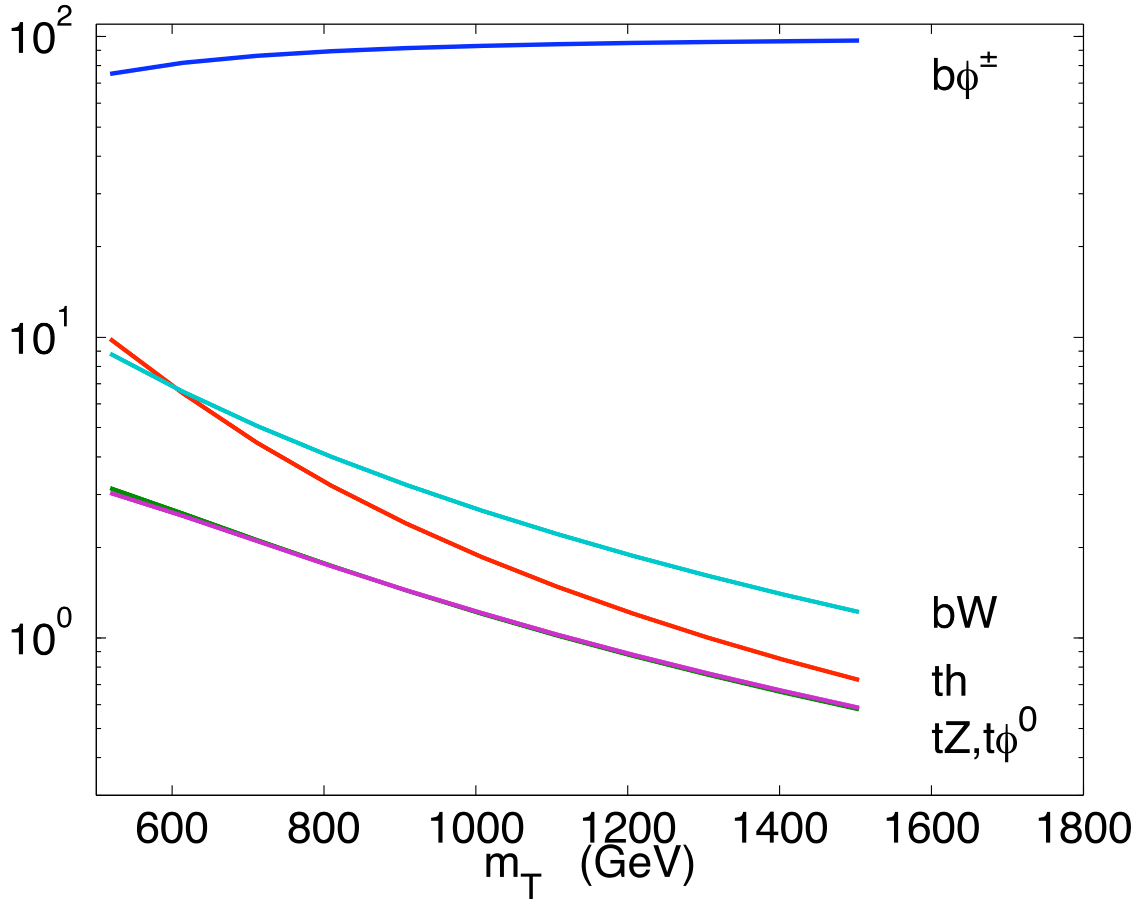


ϕ^0 discovery



Heavy top t_H discovery

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



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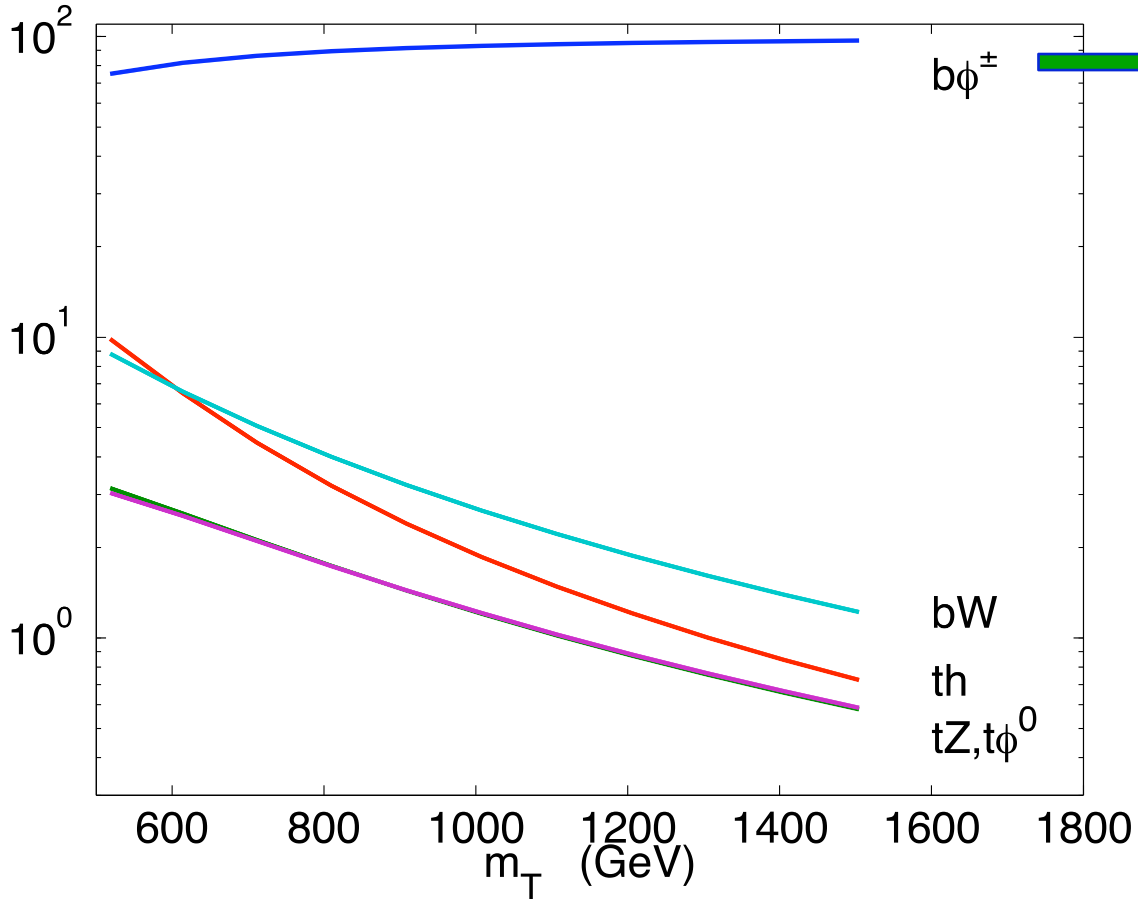

100%
huge QCD bg

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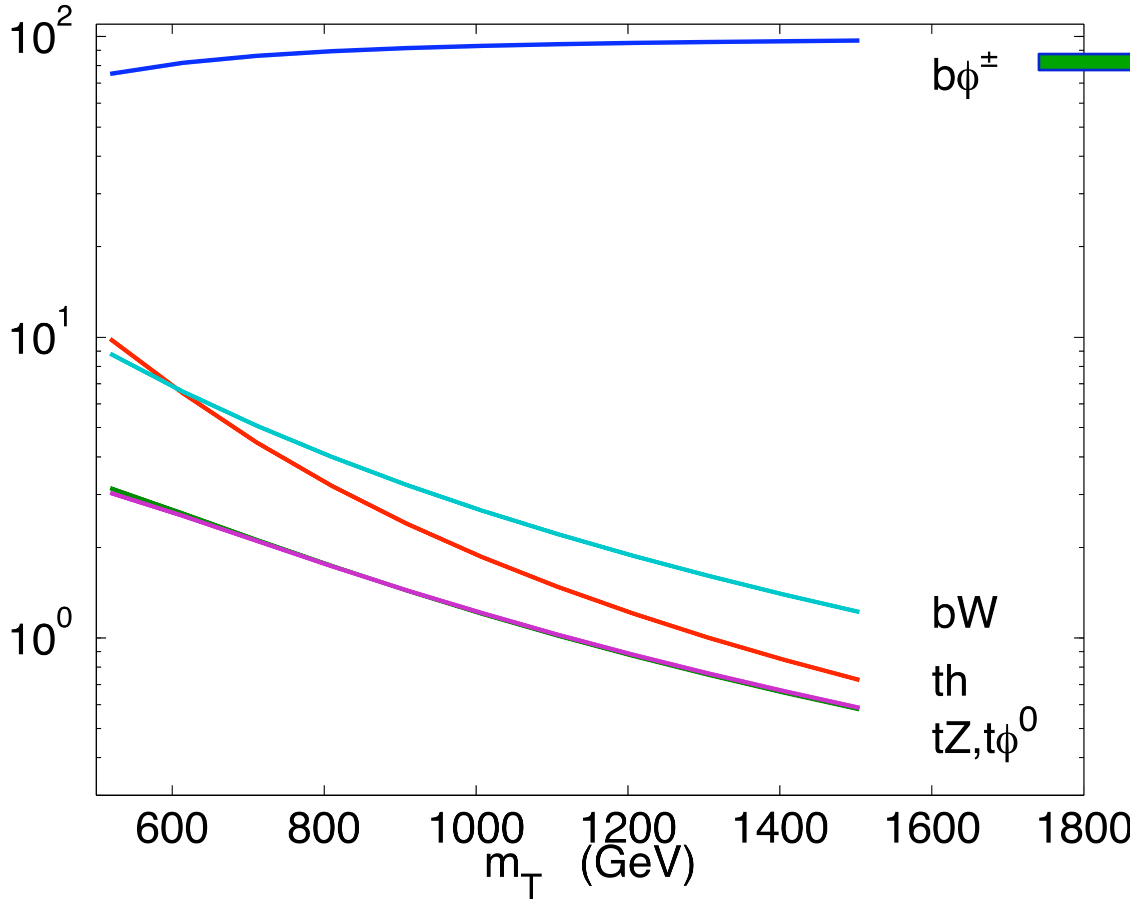


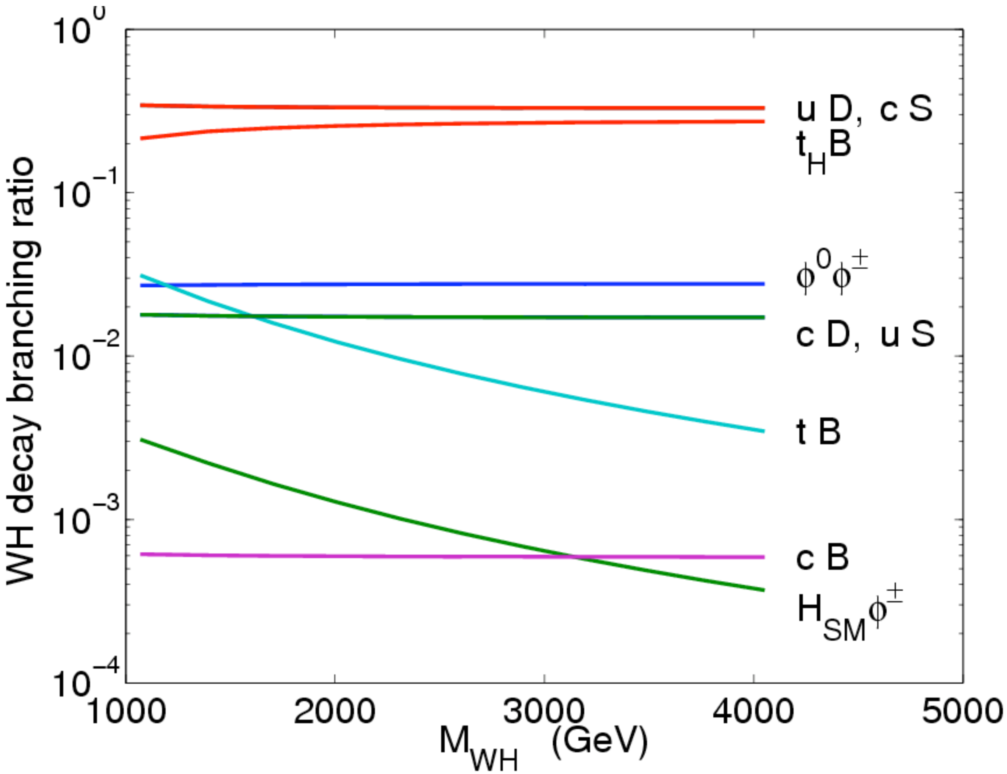
100%
huge QCD bg

absent

Heavy gauge boson discovery

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

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



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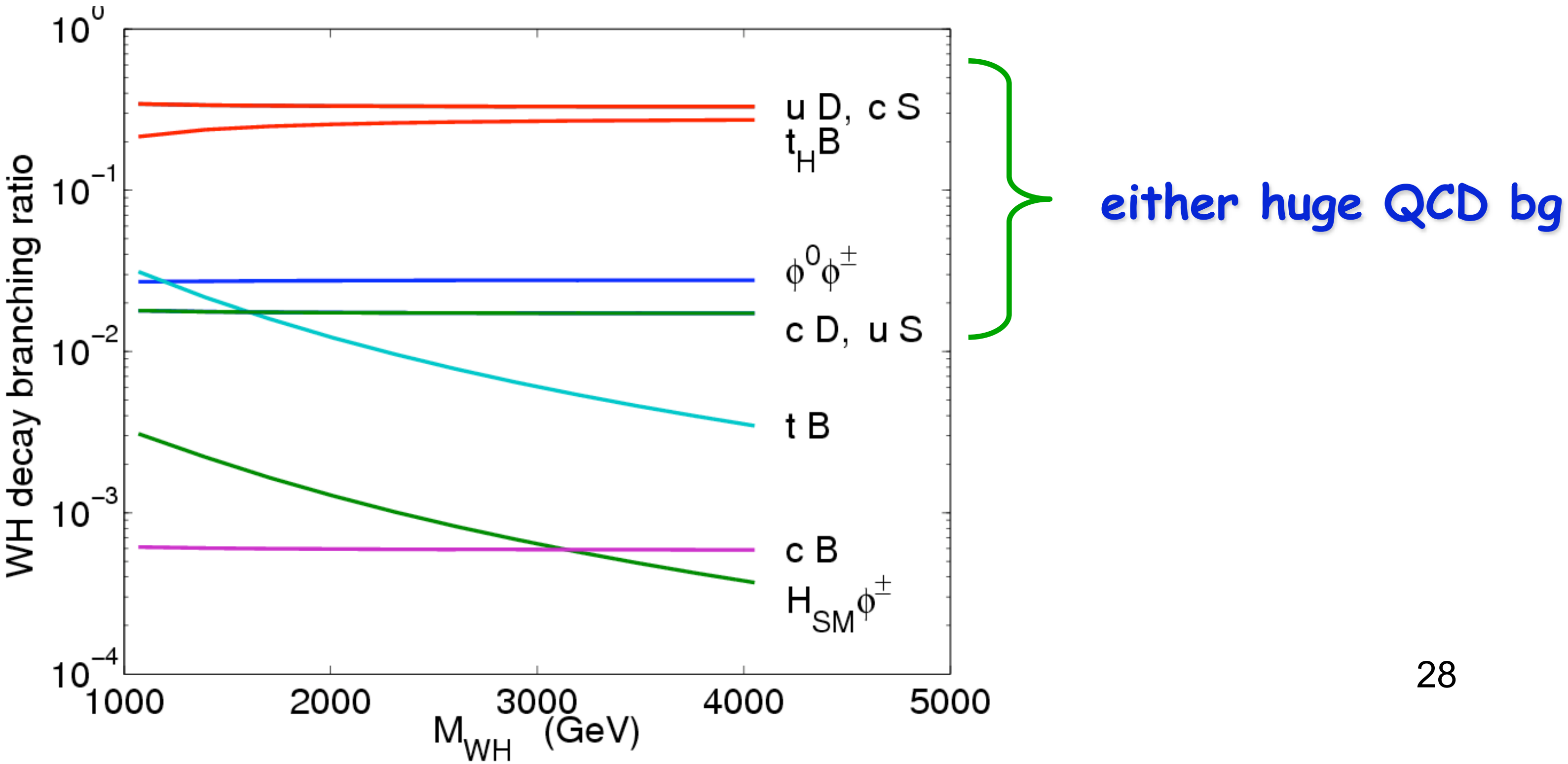

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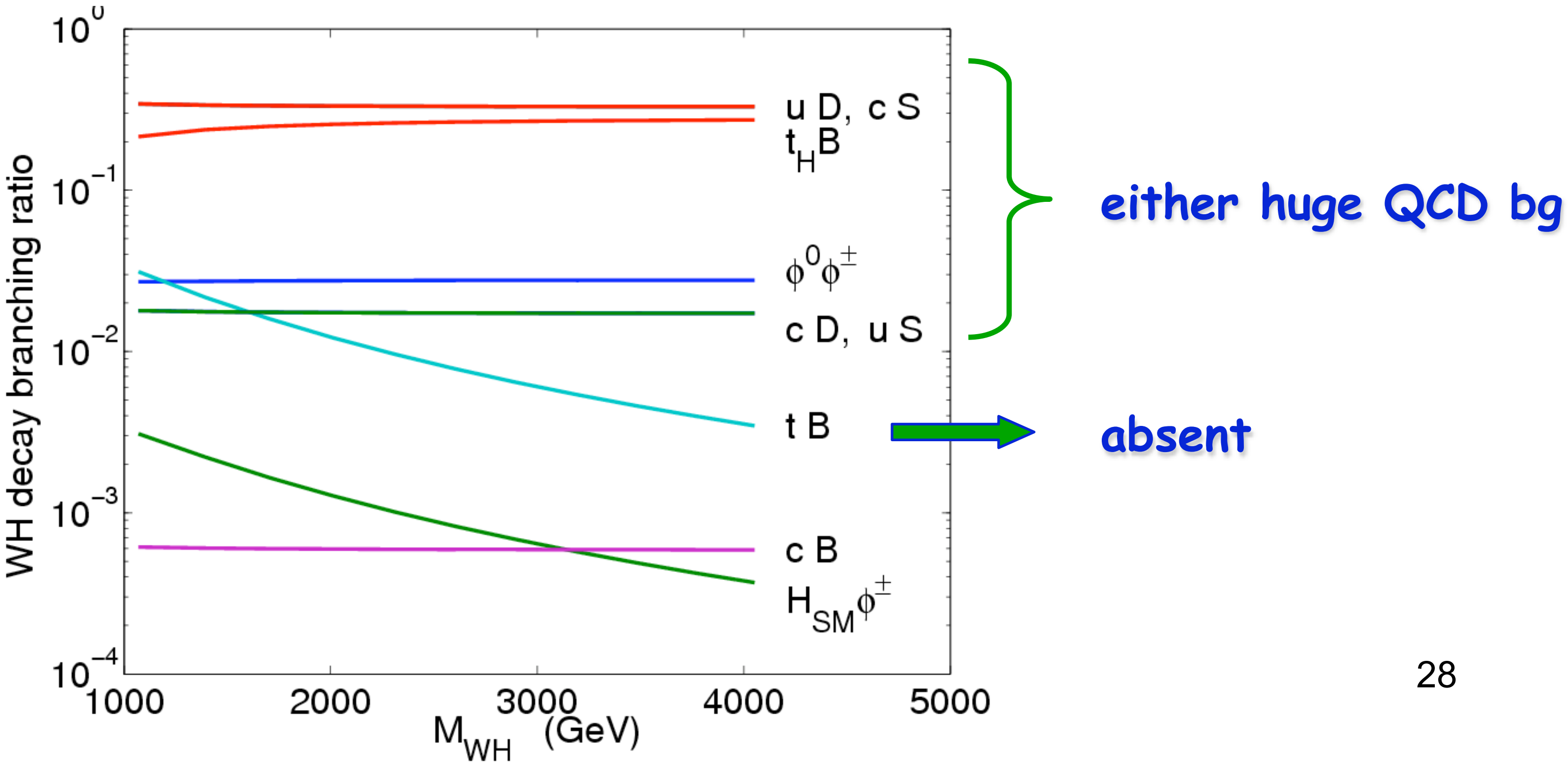

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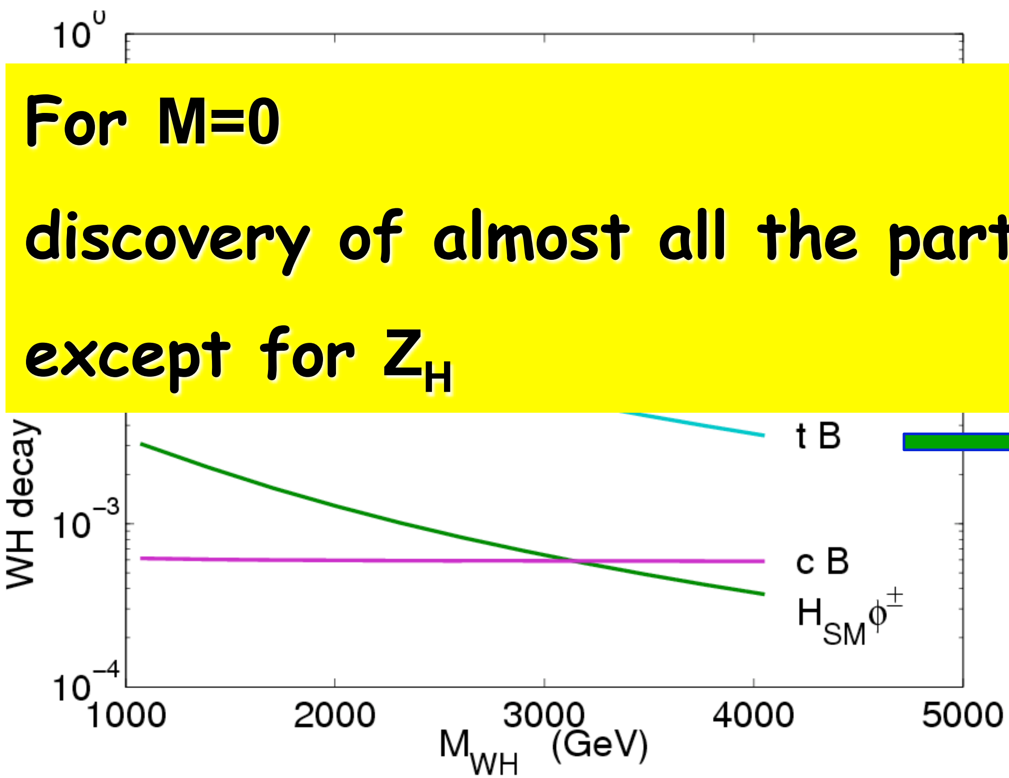


absent

For M=0

discovery of almost all the particle are difficult

except for Z_H

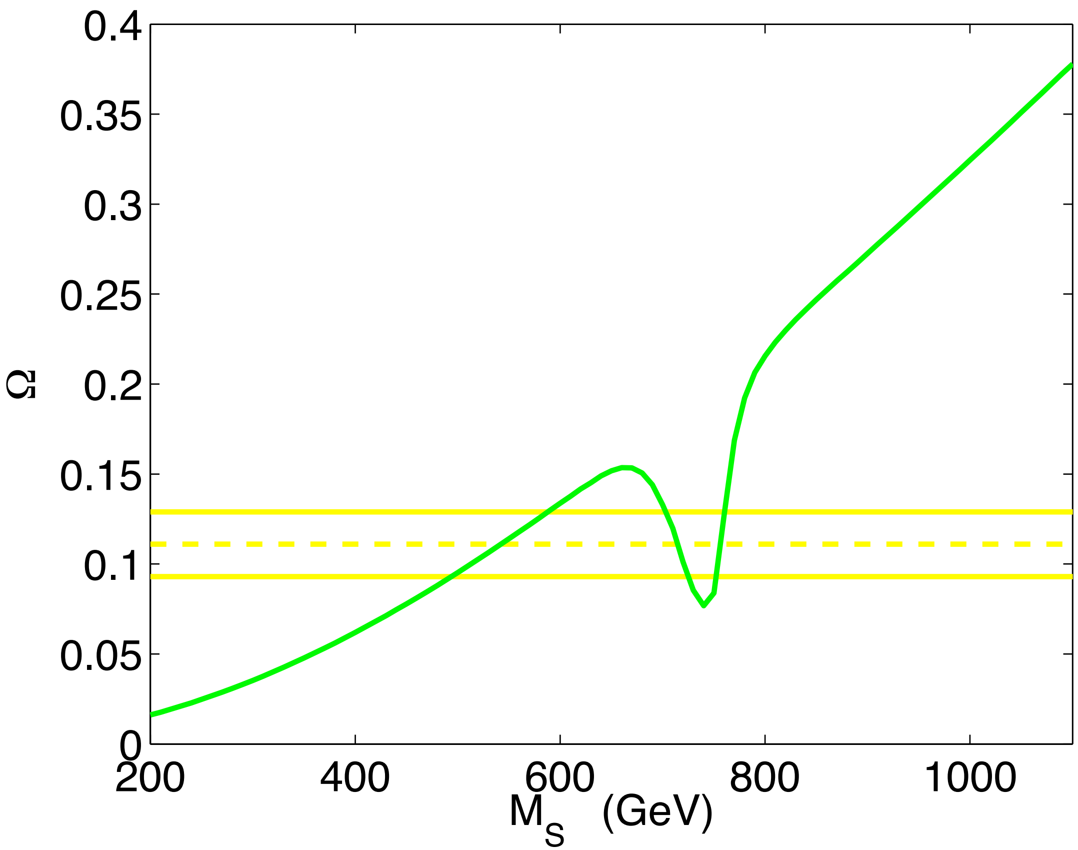
Dark Matter

$H_2^0 = S + iA$

Similar to the dark matter scenario in
R. Barbieri, L. Hall, V. Rychkov, hep-ph/0603188
L. Honorez, E. Nezri, J. Oliver, M. Tytgat, hep-ph/0612275

- $|m_S - m_A| >$ a few GeV to avoid constraints from DM direct detection
- coannihilation of S, A, and $H_1^{\pm}$

$\delta_1 = m_A - m_S$
$\delta_2 = m_{H1} - m_S$



f=560 GeV $\delta_1 = 2\delta_2 = 2$ GeV

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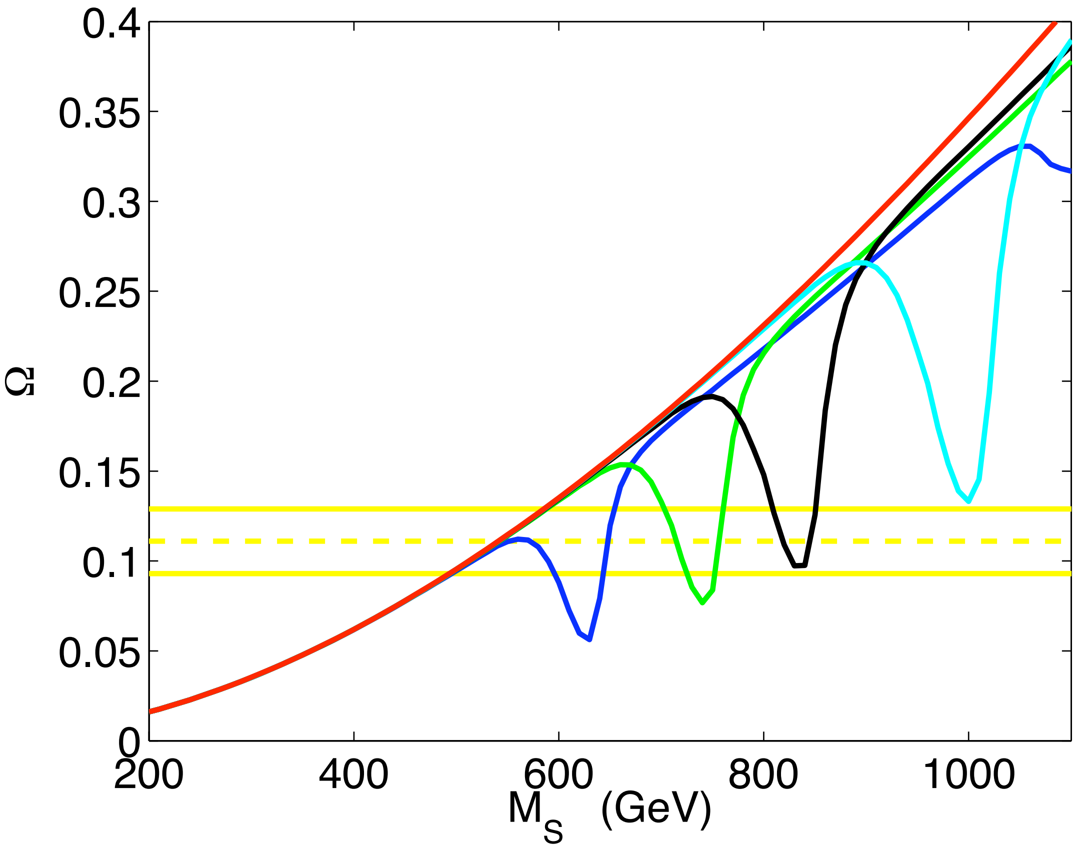

f=1000 GeV
f=700 GeV
f=610 GeV
f=560 GeV
f=500 GeV

$\delta_1 = 2\delta_2 = 2$ GeV

Dark Matter

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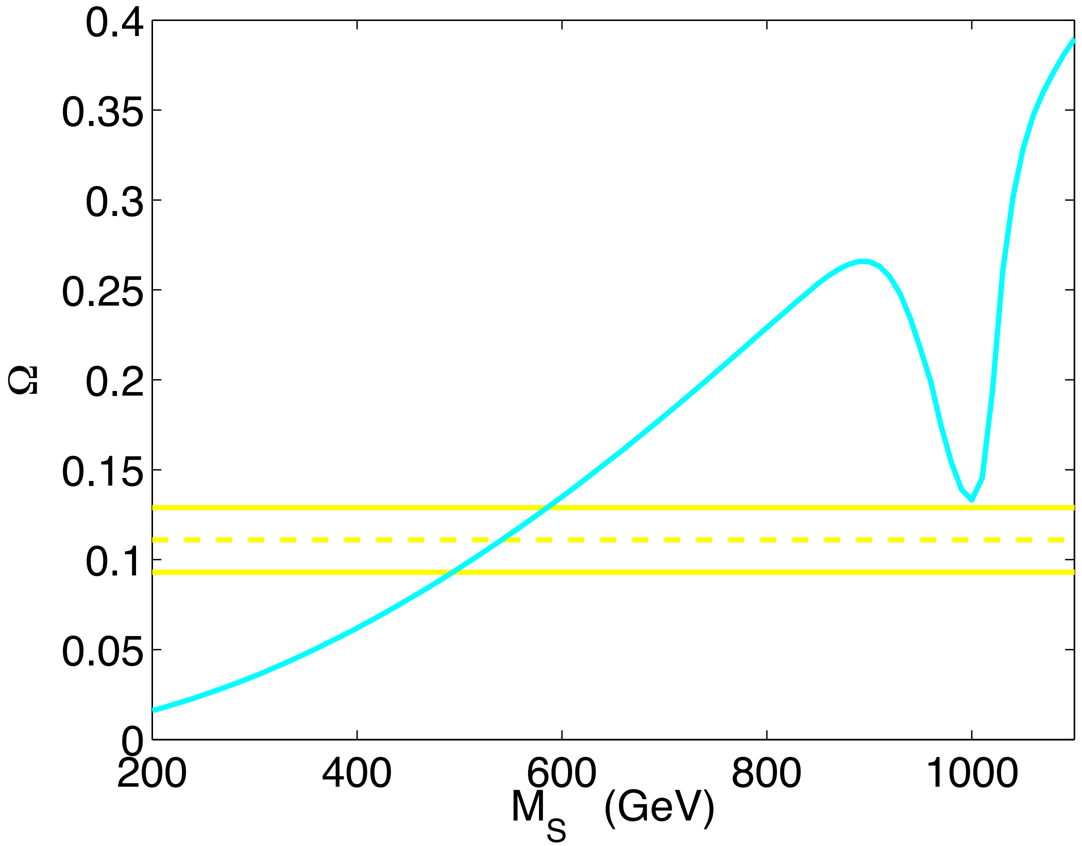
$\delta_2 = m_{H1} - m_S$



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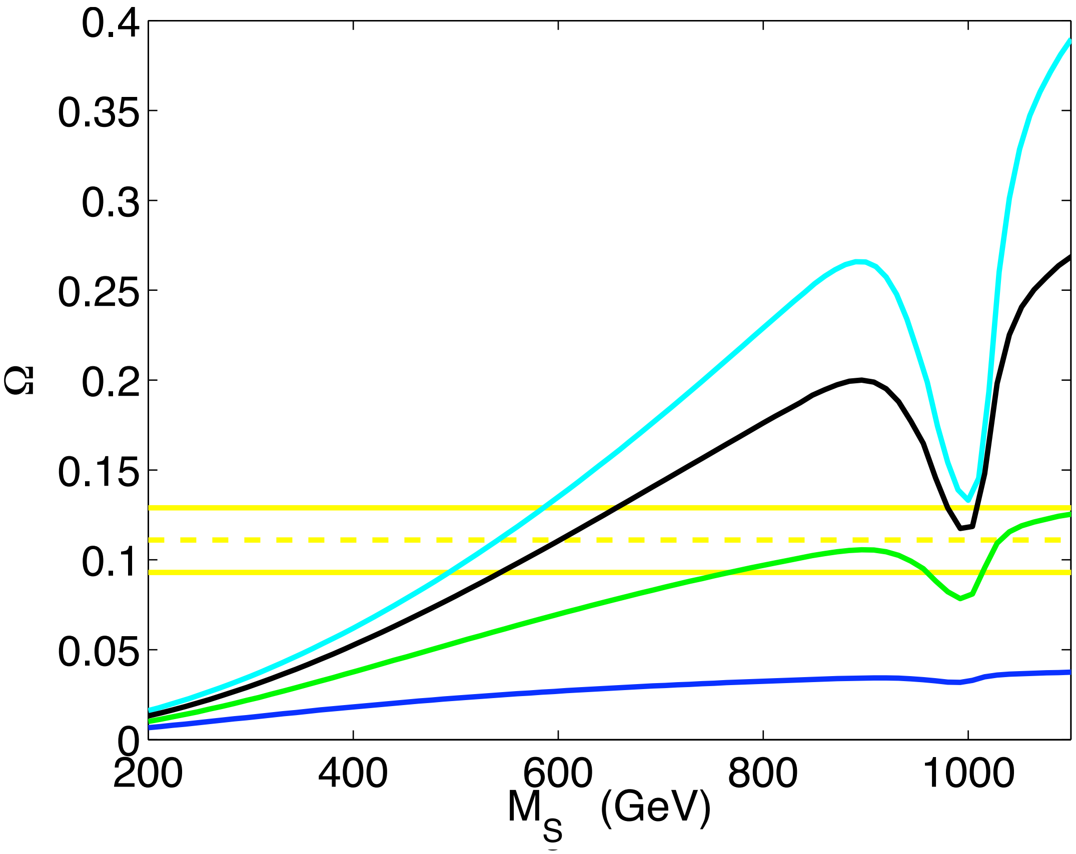


f=700 GeV

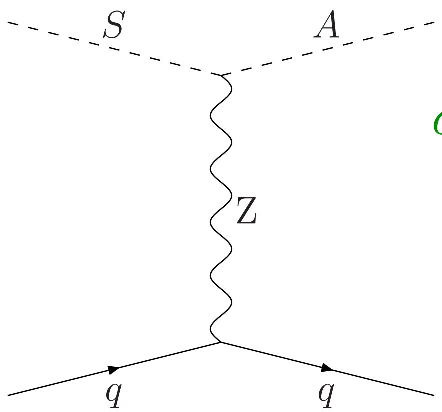
$\delta_1 = 2\delta_2 = 2$ GeV

$\delta_1 = 2\delta_2 = 5$ GeV

$\delta_1 = 2\delta_2 = 10$ GeV

$\delta_1 = 2\delta_2 = 20$ GeV

Direct Detection

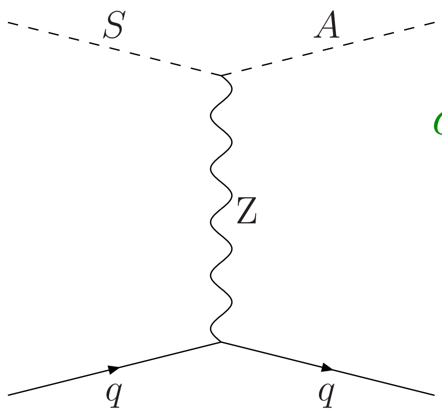


$$\sigma_{SI(Z)} = \frac{G_F^2 m_N^2}{2\pi}(N-(1-s_W^2)Z)^2 \sim 10^{-31}\mathrm{cm}^2$$

Current CDMS limit: 10^{-43} cm^2

Avoid such constraints if $|m_S - m_A|$> a few GeV

Direct Detection



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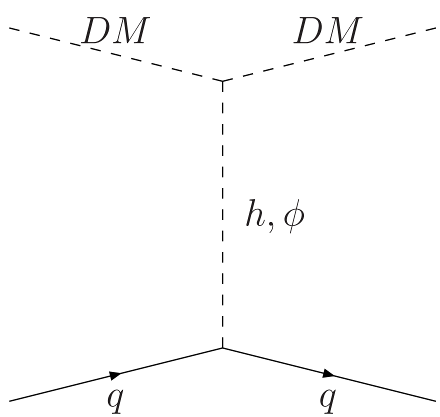
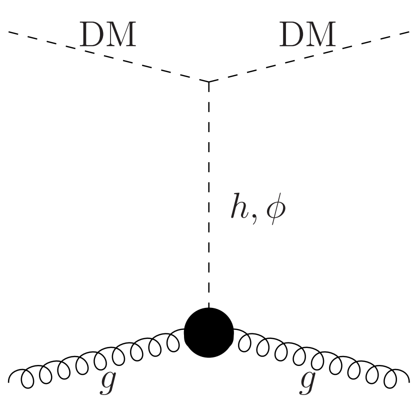
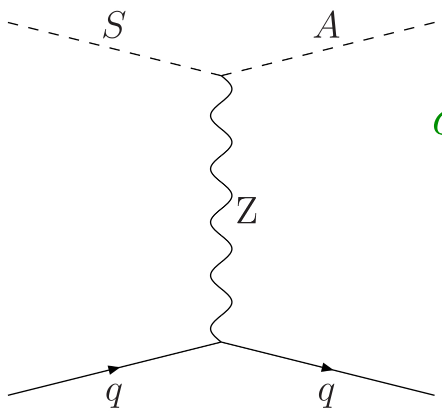




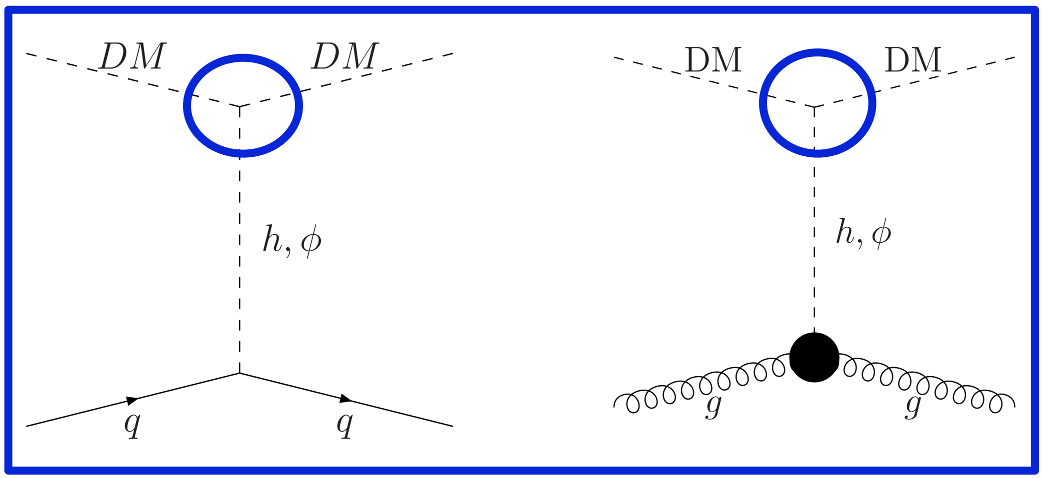
Direct Detection



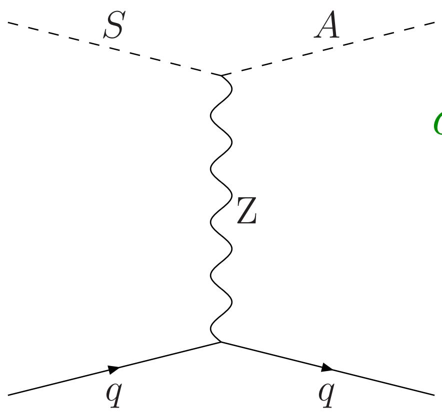
$$\sigma_{SI(Z)} = \frac{G_F^2 m_N^2}{2\pi}(N - (1 - s_W^2)Z)^2 \sim 10^{-31}\text{cm}^2$$

Current CDMS limit: 10^{-43} cm^2

Avoid such constraints if $|m_S - m_A| >$ a few GeV



Direct Detection



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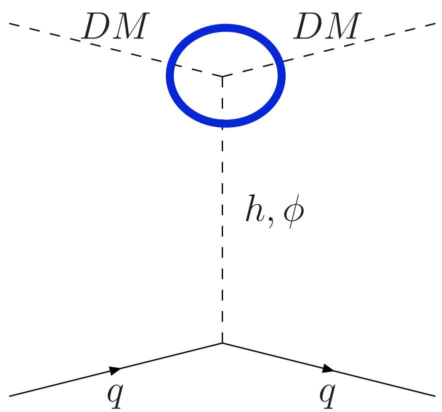
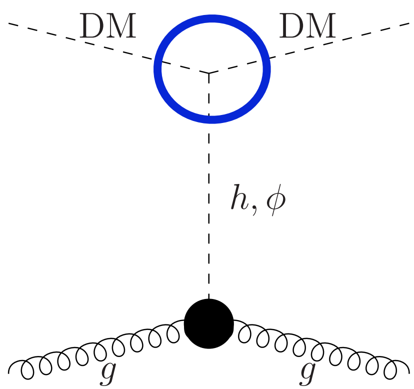
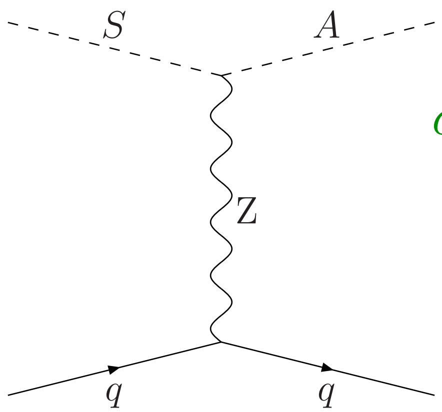




Small coupling, ~ a few GeV

about 10 times smaller than the natural size, ~ λ v

Direct Detection



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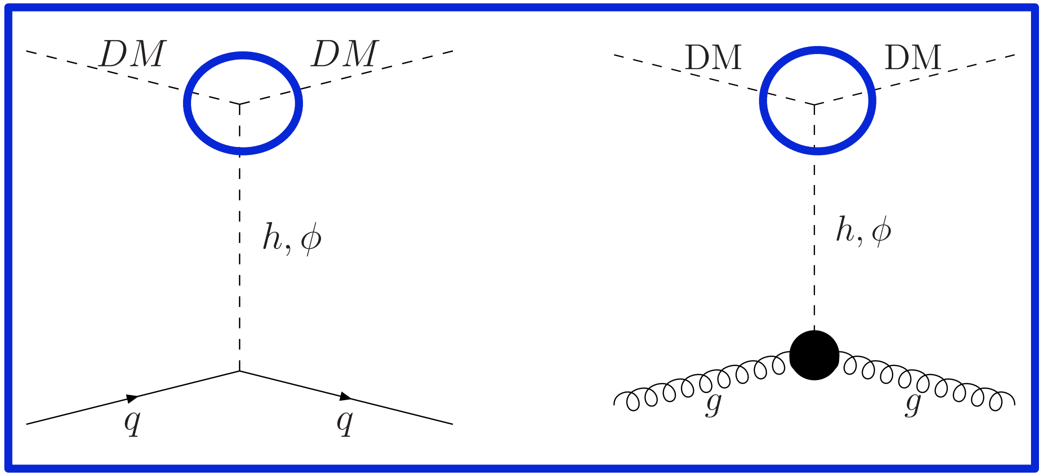


Small coupling, ~ a few GeV

about 10 times smaller than the natural size, ~ λ v

Difficult!

Indirect Detection

$$\Phi_\gamma = \frac{N_\gamma \sigma v}{8\pi M_{DM}^2} \int_{\text{line of sight}} \rho^2(l) \mathrm{d}l$$

$$J = \frac{1}{8.5 \text{ kpc}} \left(\frac{1}{0.3 \text{ GeV/cm}^3}\right)^2 \frac{1}{\Delta\Omega} \int \mathrm{d}\Omega \int \rho^2 \mathrm{d}l$$

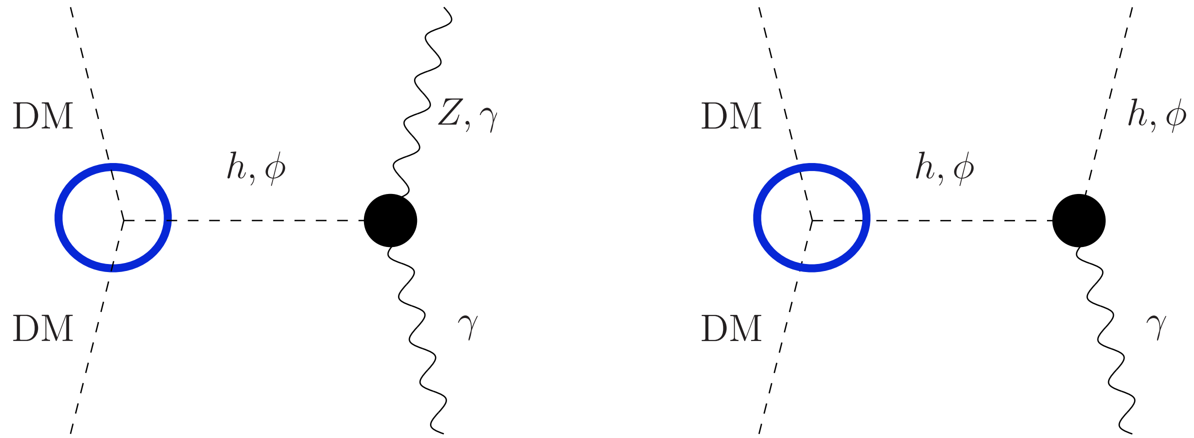
$$\Phi_\gamma = N_\gamma \left(\frac{\sigma v}{1 \text{ pb}}\right) \left(\frac{100 \text{ GeV}}{M_{DM}}\right)^2 J\Delta\Omega \times (2.75 \times 10^{-10}) \text{ s}^{-1}\text{cm}^{-2}$$

For ground based Atmospheric Cerenkov telescopes (ACTs), $\Delta\Omega = 10^{-3}$ sr
J: 10^3 for NFW profile, 10^5 for Moore et. al. profile

Exps:

- space-based telescope GLAST: $E_{th} \sim 2$ GeV, $\Phi \sim 10^{-10}$ sec^{-1} cm^{-2}
- ACTs VERITAS and HESS: $E_{th} \sim 50$ GeV, $\Phi \sim (1\text{-}5) \times 10^{-12}$ sec^{-1} cm^{-2}

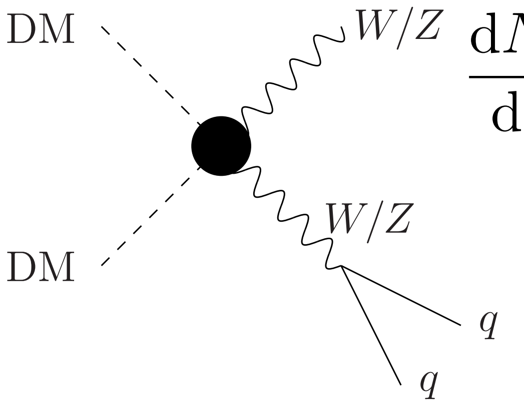
Monochromatic Photon



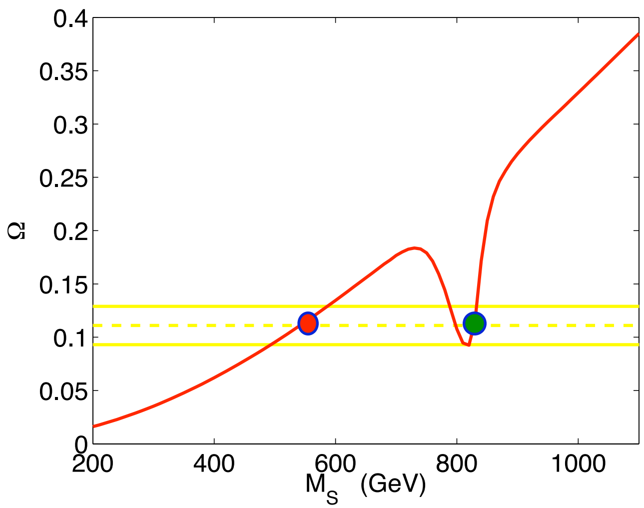
Small coupling

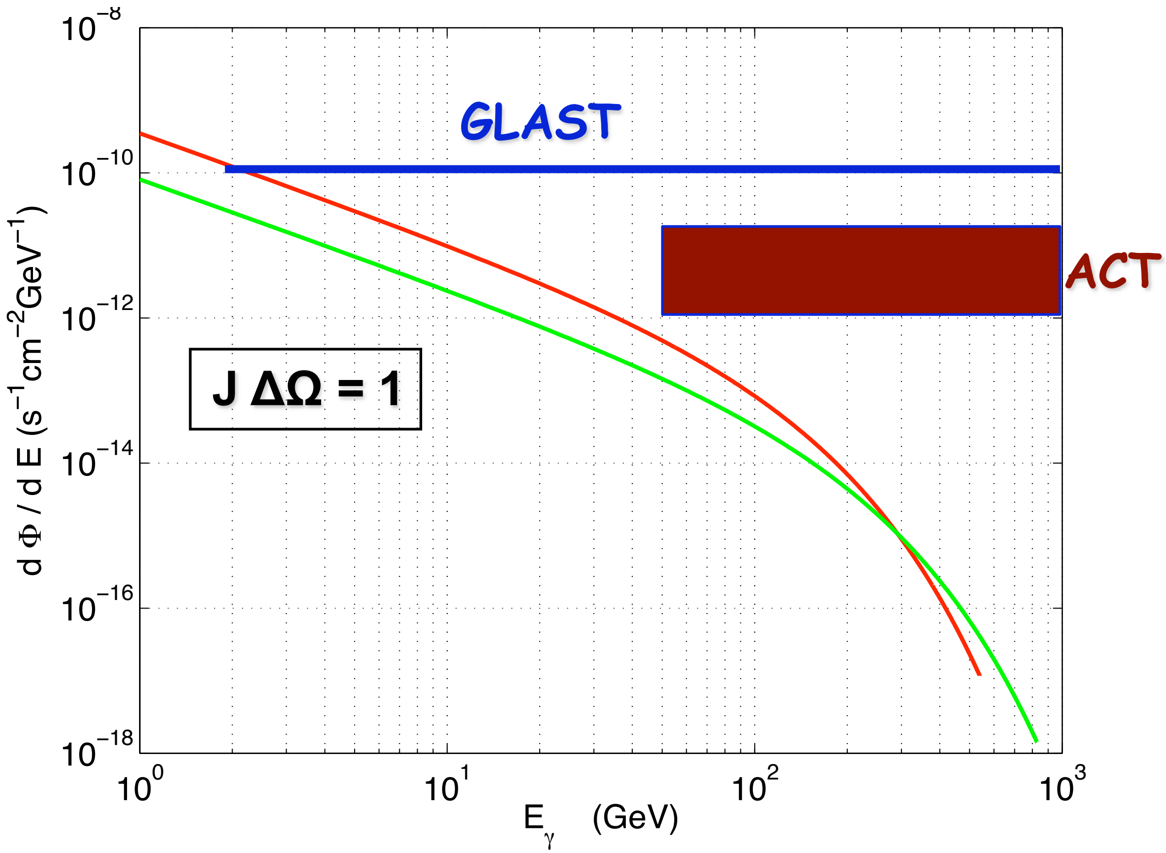
Can not be observed at future exp

Fragmentation Photon



$$\frac{dN_\gamma}{dx} = 0.73 x^{-1.5} e^{-7.8x} \text{ for } WW/ZZ, \quad x = \frac{E_\gamma}{M_{DM}}$$





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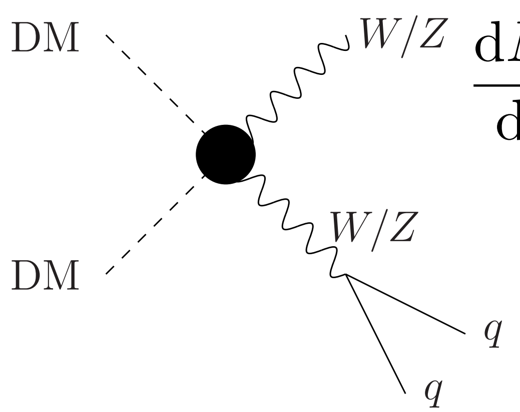
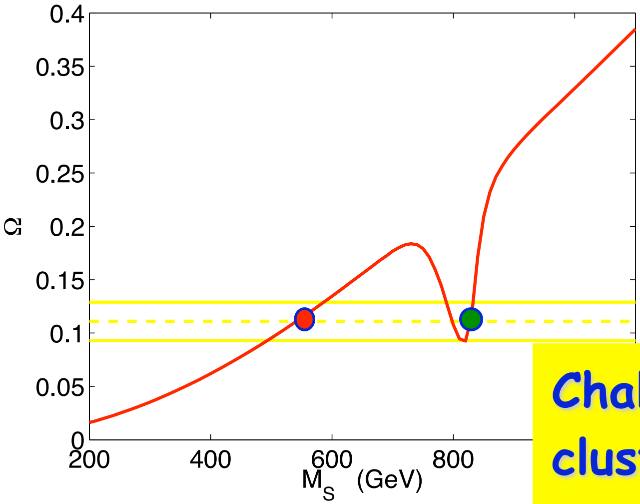
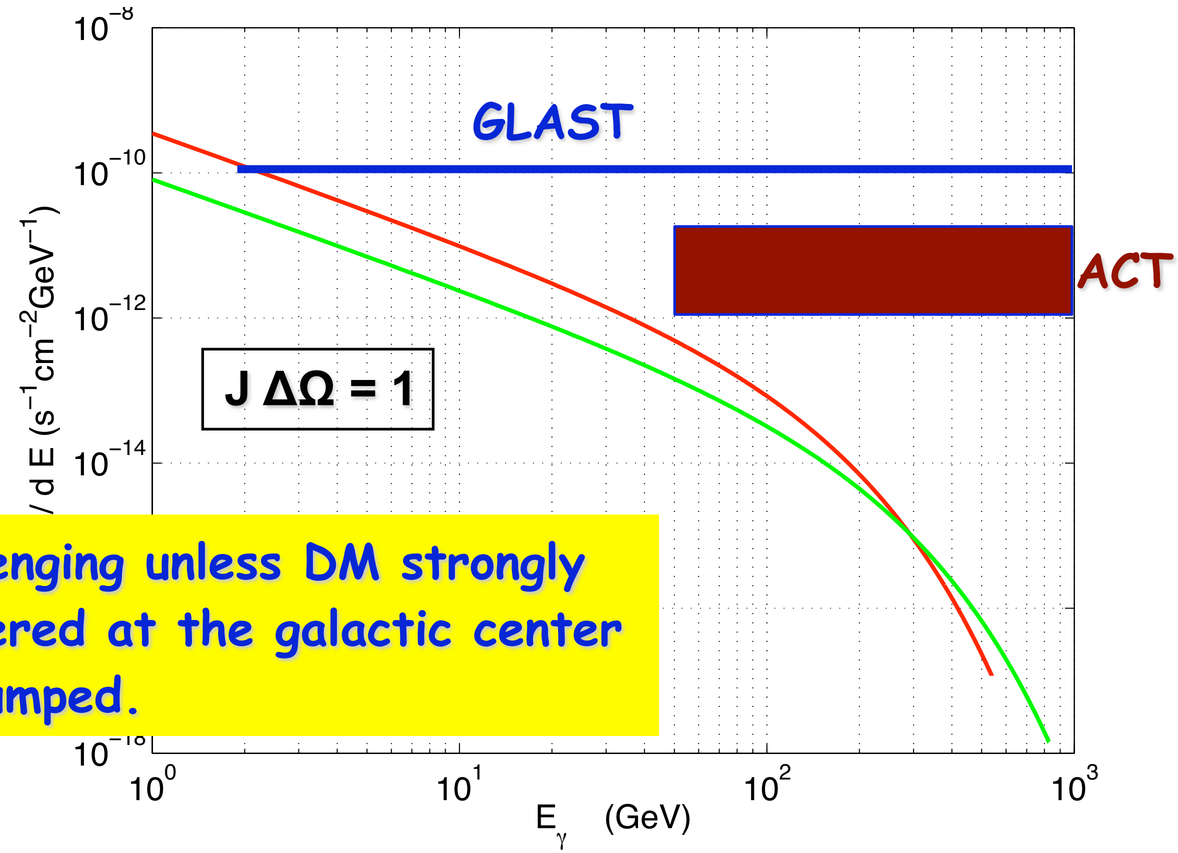
Fragmentation Photon



$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = 0.73x^{-1.5}\mathrm{e}^{-7.8x} \text{ for } WW/ZZ, \quad x = \frac{E_\gamma}{M_{DM}}$$





Challenging unless DM strongly clustered at the galactic center or clumped.

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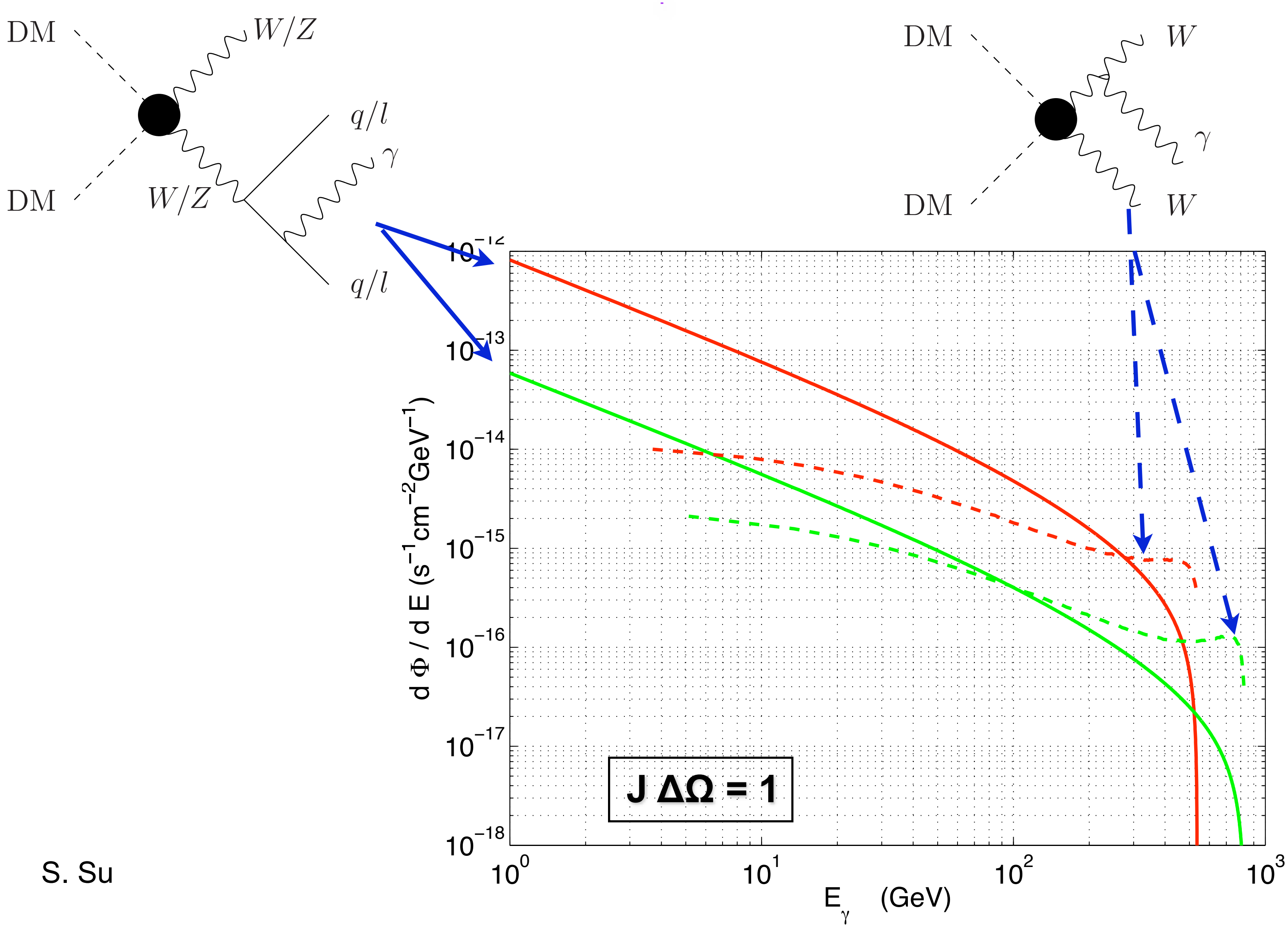
Final State Radiation Photon



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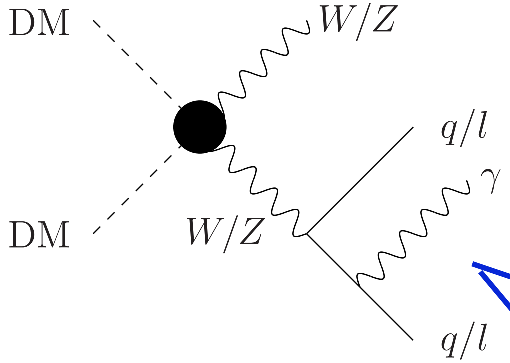
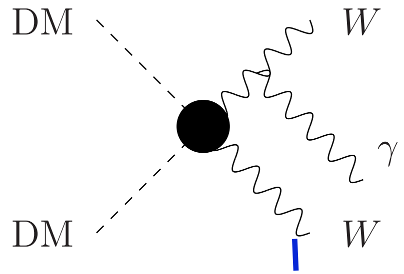
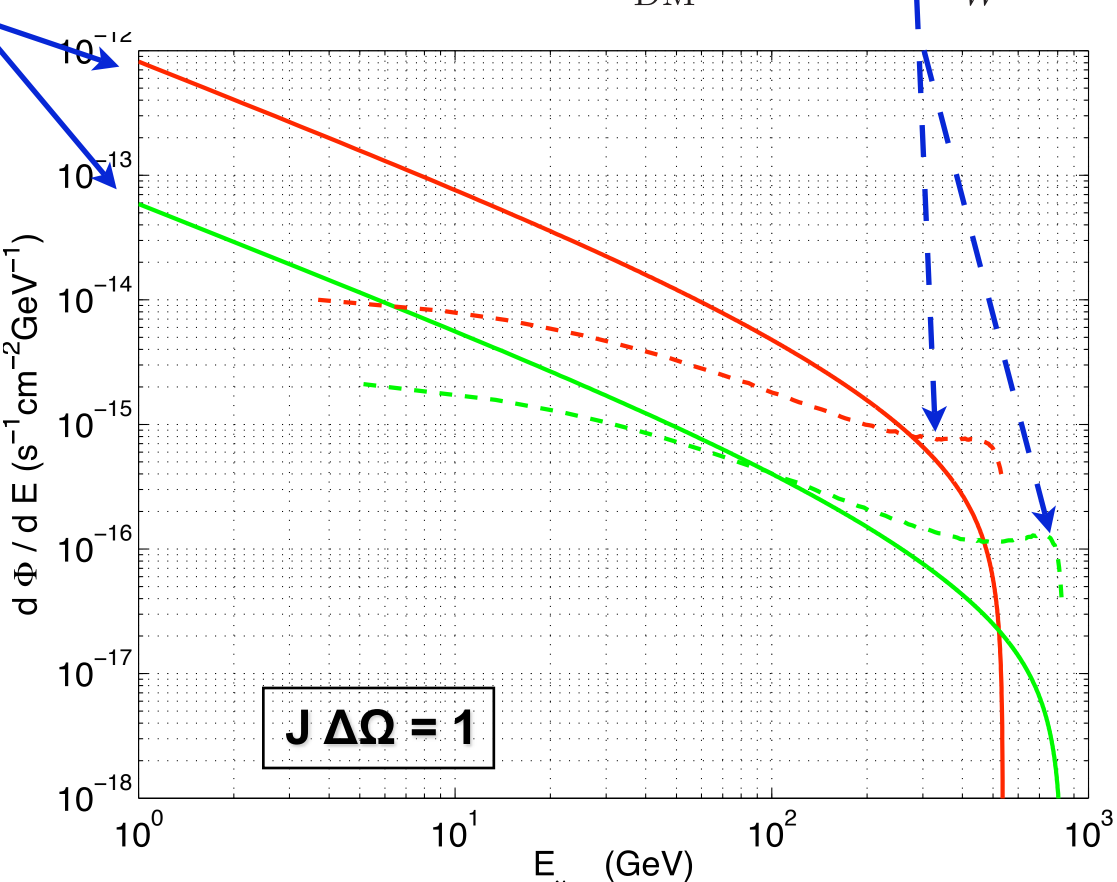
Final State Radiation Photon







Difficult!

S. Su

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
- H_2^0 (S or A) could be a good DM candidate
- Future work
  - * Identify twin Higgs mechanism
  - * Comparison with other models, e.g., little higgs