Discovering heavy colored vectors at the LHC

Natascia Vignaroli

SAPIENZA Università di Roma & INFN

IFAE 2011, Perugia

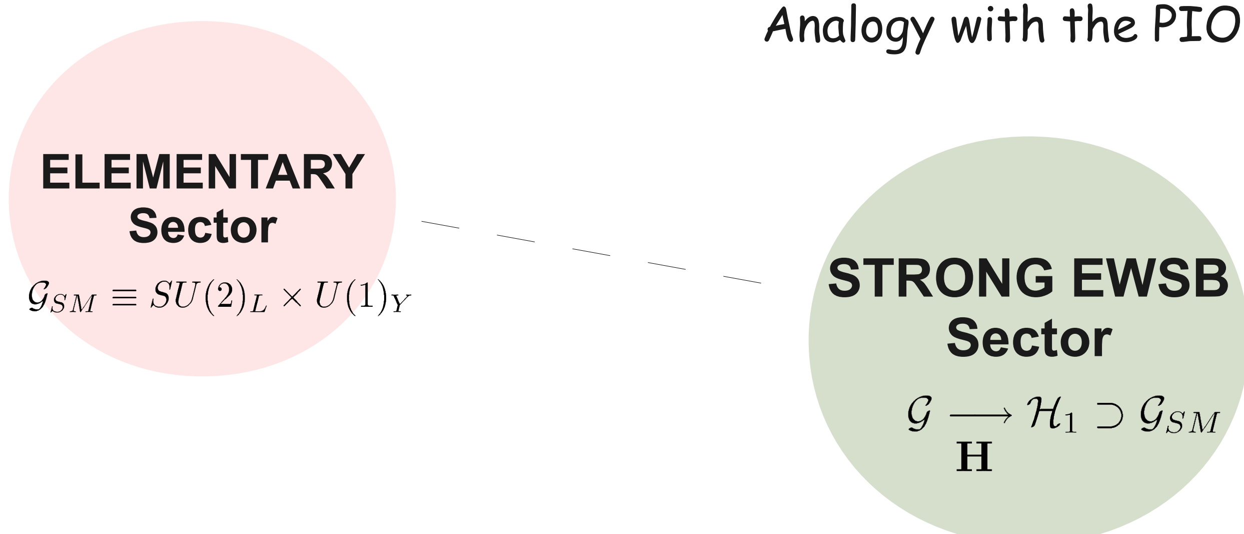
Work in progress with Roberto Contino

Composite Higgs from a New Strong dynamics

SOLUTION TO THE HIERARCHY PROBLEM

Higgs mass not sensitive to radiative corrections above the compositeness scale (o(TeV))

Analogy with the PION mass in QCD

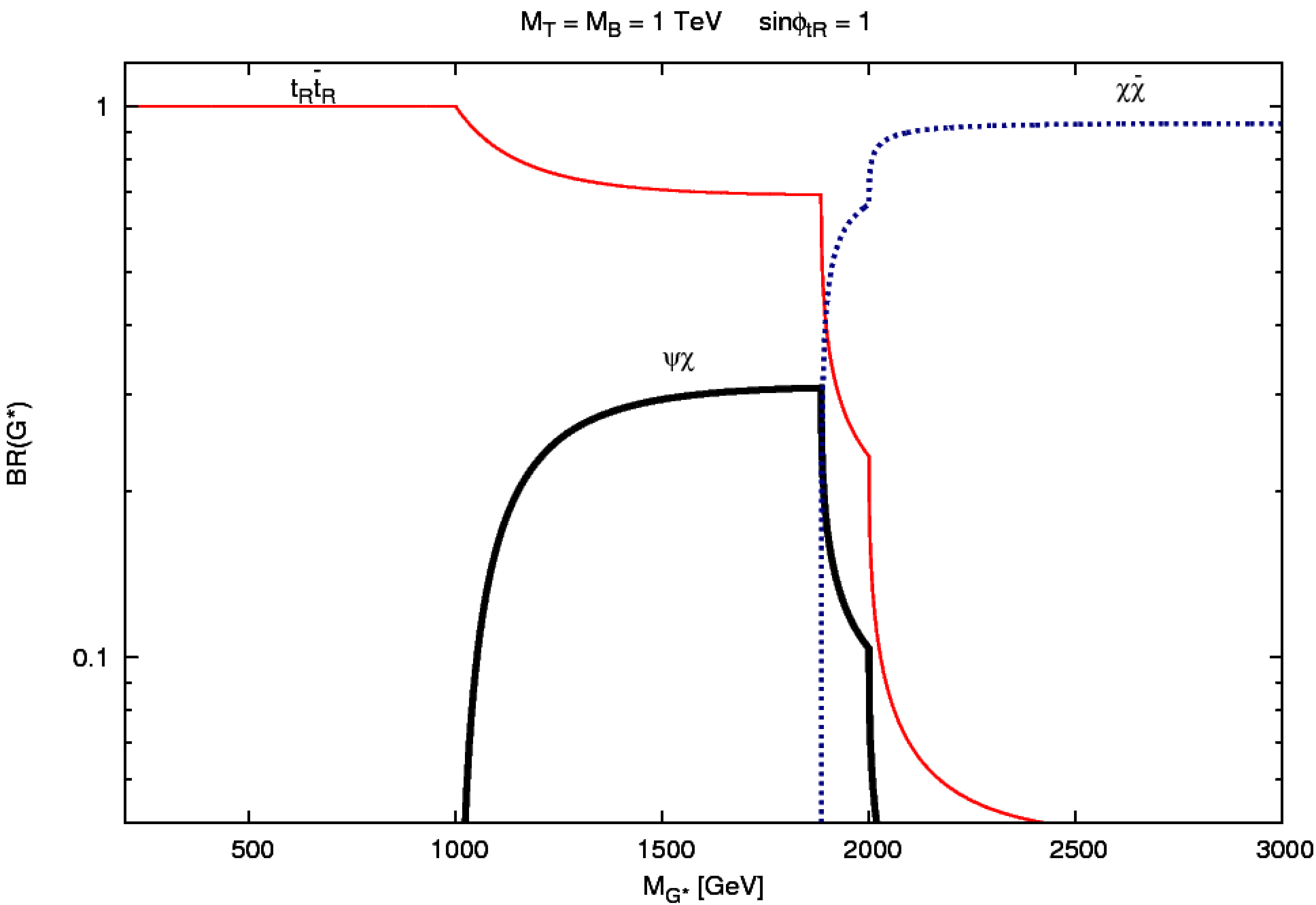


elementary/composite → light (SM) / heavy (NP)   t, b, g, ... / T, B, G*, ...

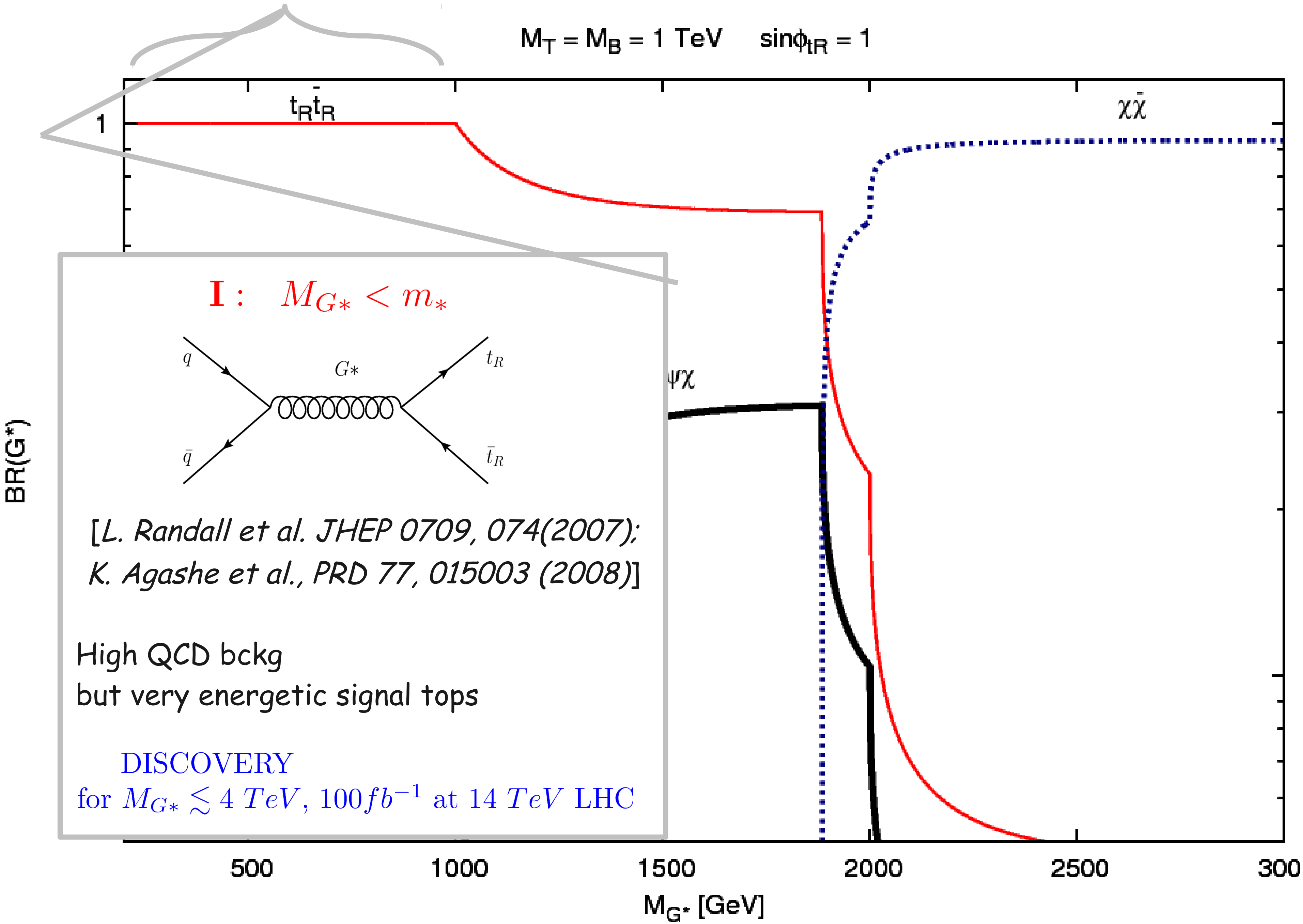
Heavier particles have larger degrees of compositeness

$\xrightarrow[\text{AdS/CFT}]{}$ *RS warped extra dimension*

BR(G*) .... scenarios for the G* search:



BR(G*) .... scenarios for the G* search:



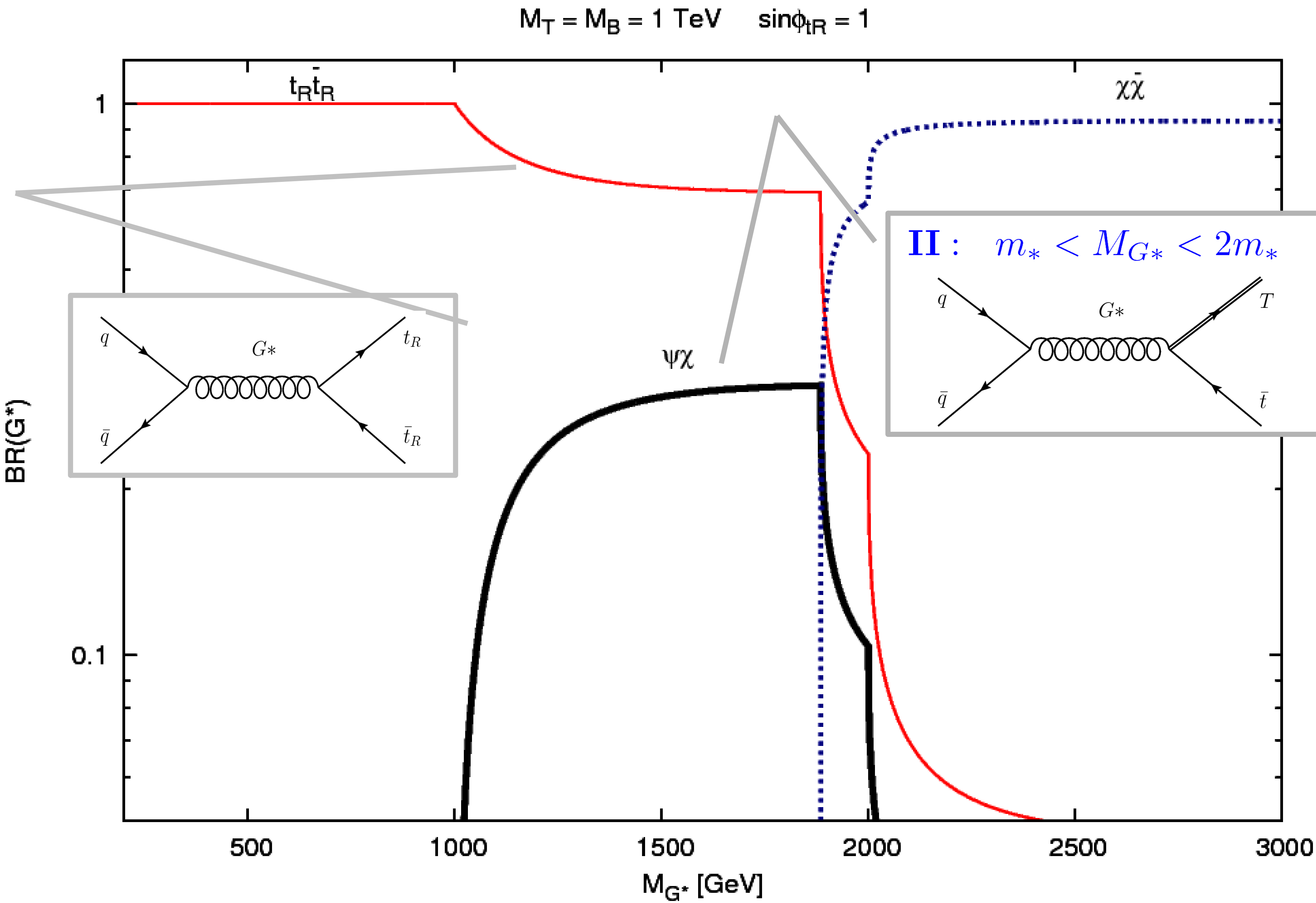
$\mathbf{I}:\quad M_{G*} < m_*$

[*L. Randall et al. JHEP 0709, 074(2007); K. Agashe et al., PRD 77, 015003 (2008)*]

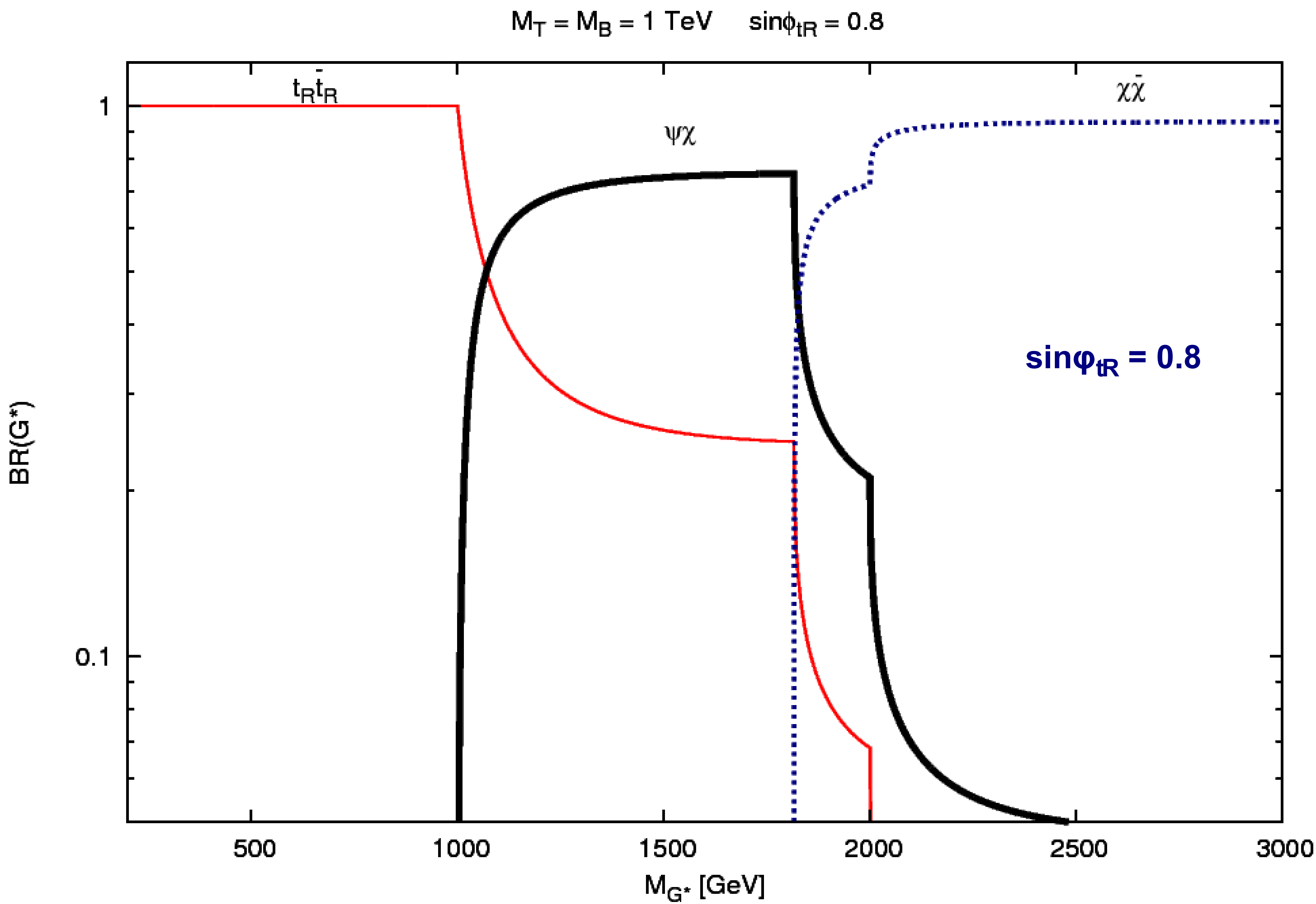
High QCD bckg
but very energetic signal tops

DISCOVERY
for $M_{G*} \lesssim 4\ TeV$, $100 fb^{-1}$ at 14 TeV LHC

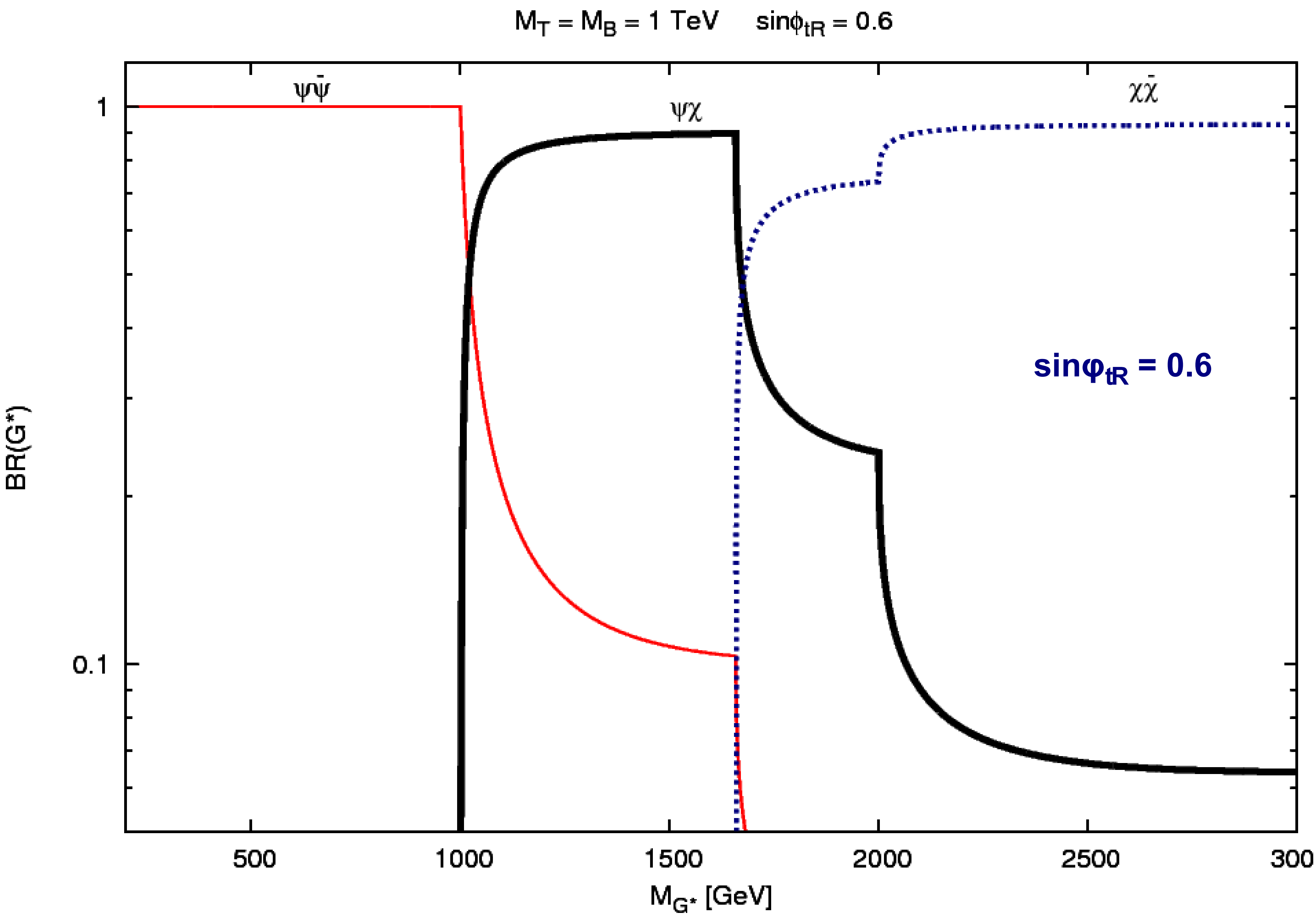
BR(G*) .... scenarios for the G* search:



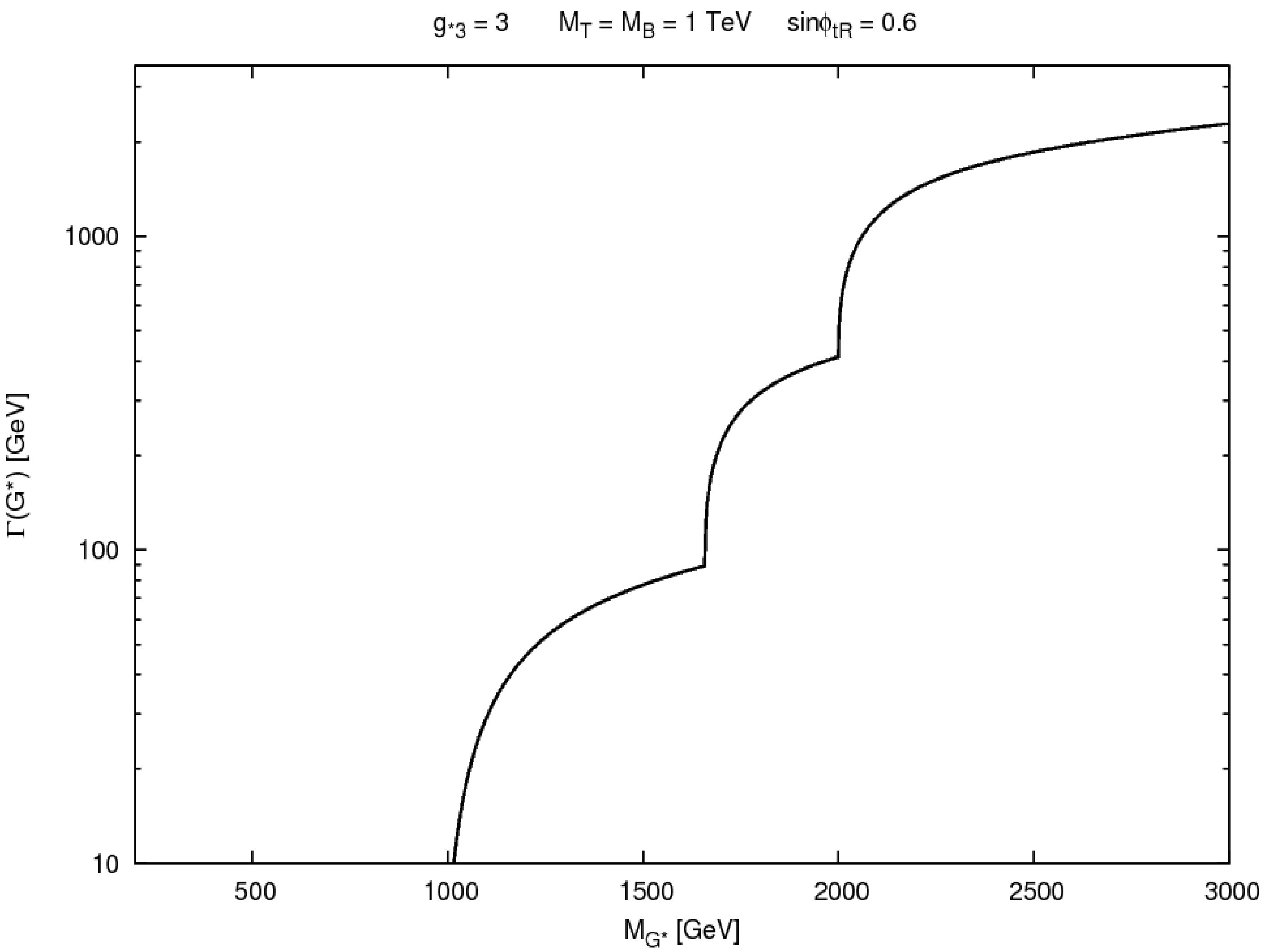
BR(G*) ....scenarios for the G* search:



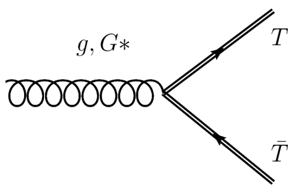
BR(G*) ....scenarios for the G* search:



G* width ....scenarios for the G* search:



Very large width (o(TeV))
In the case $M_{G^*}>2m_*$



⇓

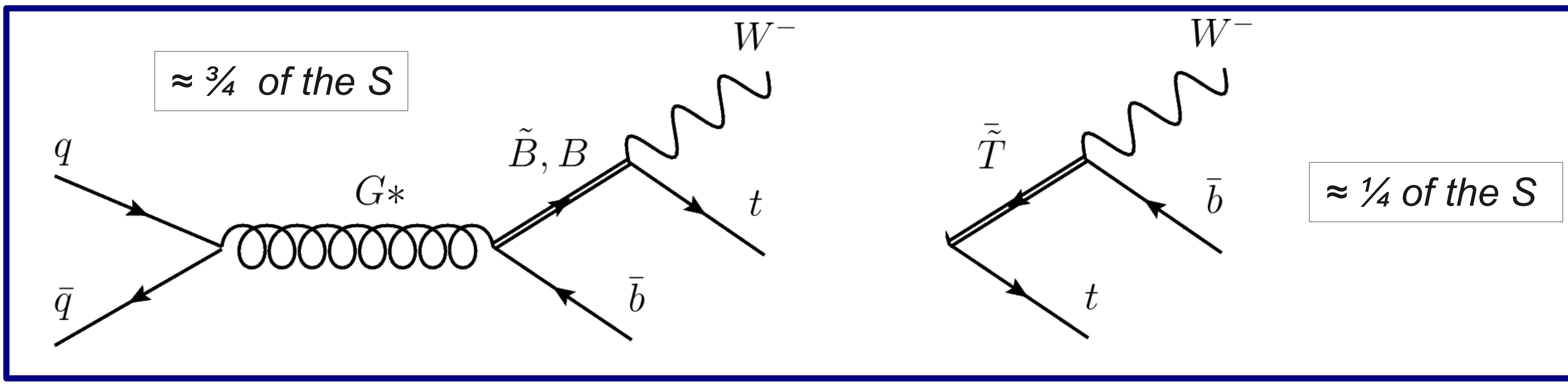
LHC cannot discover a G* in this case

G* search in the $\Psi\chi$ channel

- SEARCH CHANNELS

(heavy fermions decay into longitudinal weak bosons or into the Higgs)

$Z/h\ b\bar{b}$ $Z/h\ t\bar{t}$ Wtb

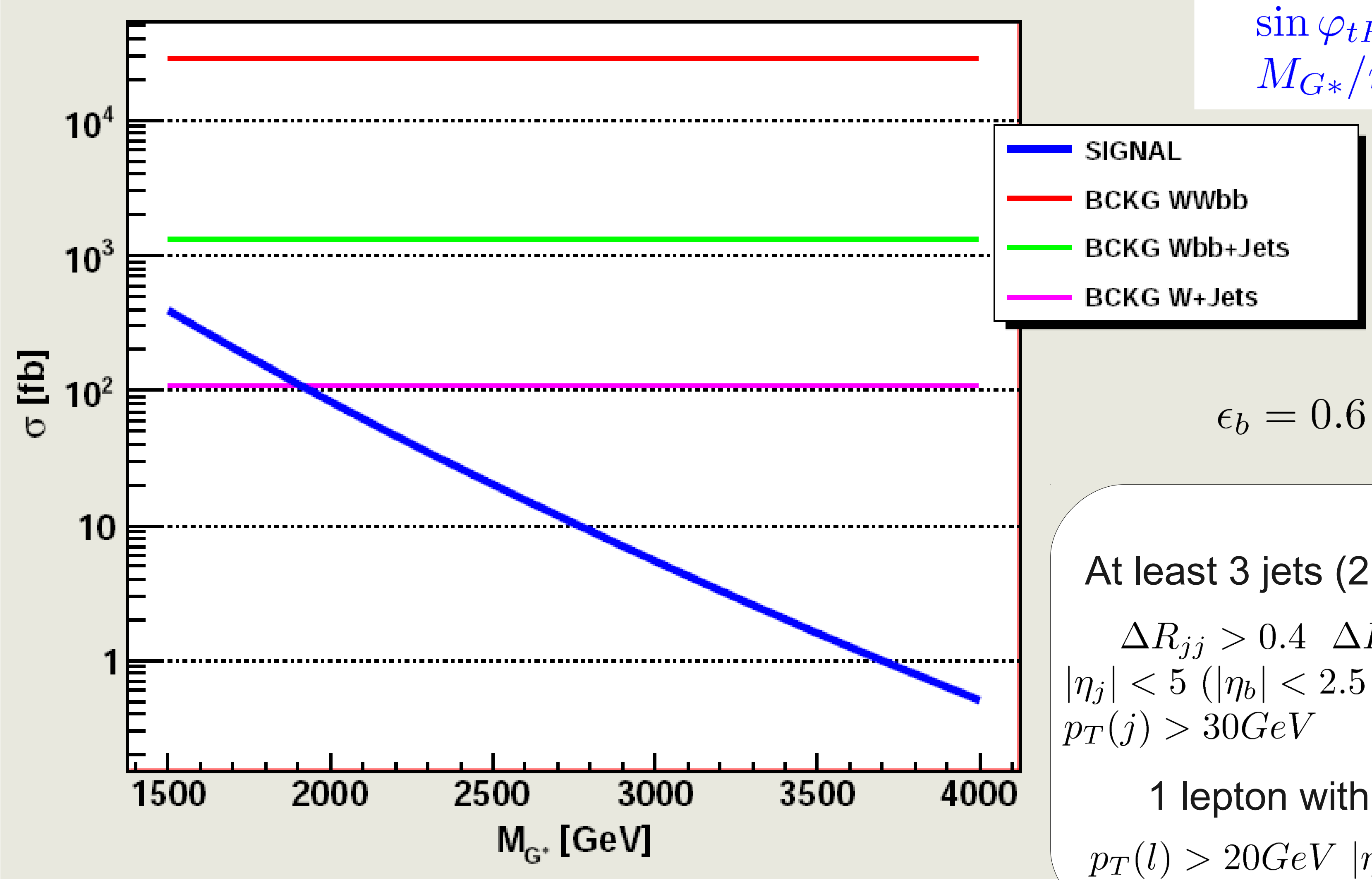


We fix $\frac{M_{G*}}{m_*} = 1.5$

And we look for G* (and heavy fermions) Signal in the $W(\to l\nu)W(\to jj)b\bar{b}$ channel

S and Bckg Cross sections after Acceptance Cuts and b-TAG

$\sqrt{s} = 14\ TeV$



$g_{*3} = Y_* = 3$
$\sin\varphi_{tR} = 0.6$
$M_{G*}/m_* = 1.5$

$\epsilon_b = 0.6\ r.f. = 0.01$

At least 3 jets (2 b) with:

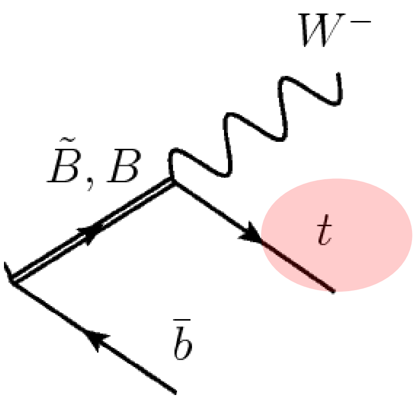
$\Delta R_{jj} > 0.4 \quad \Delta R_{lj} > 0.4$
$|\eta_j| < 5$ ($|\eta_b| < 2.5$ for the b-TAG)
$p_T(j) > 30GeV$

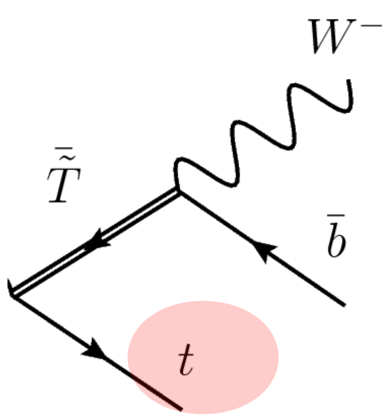
1 lepton with:

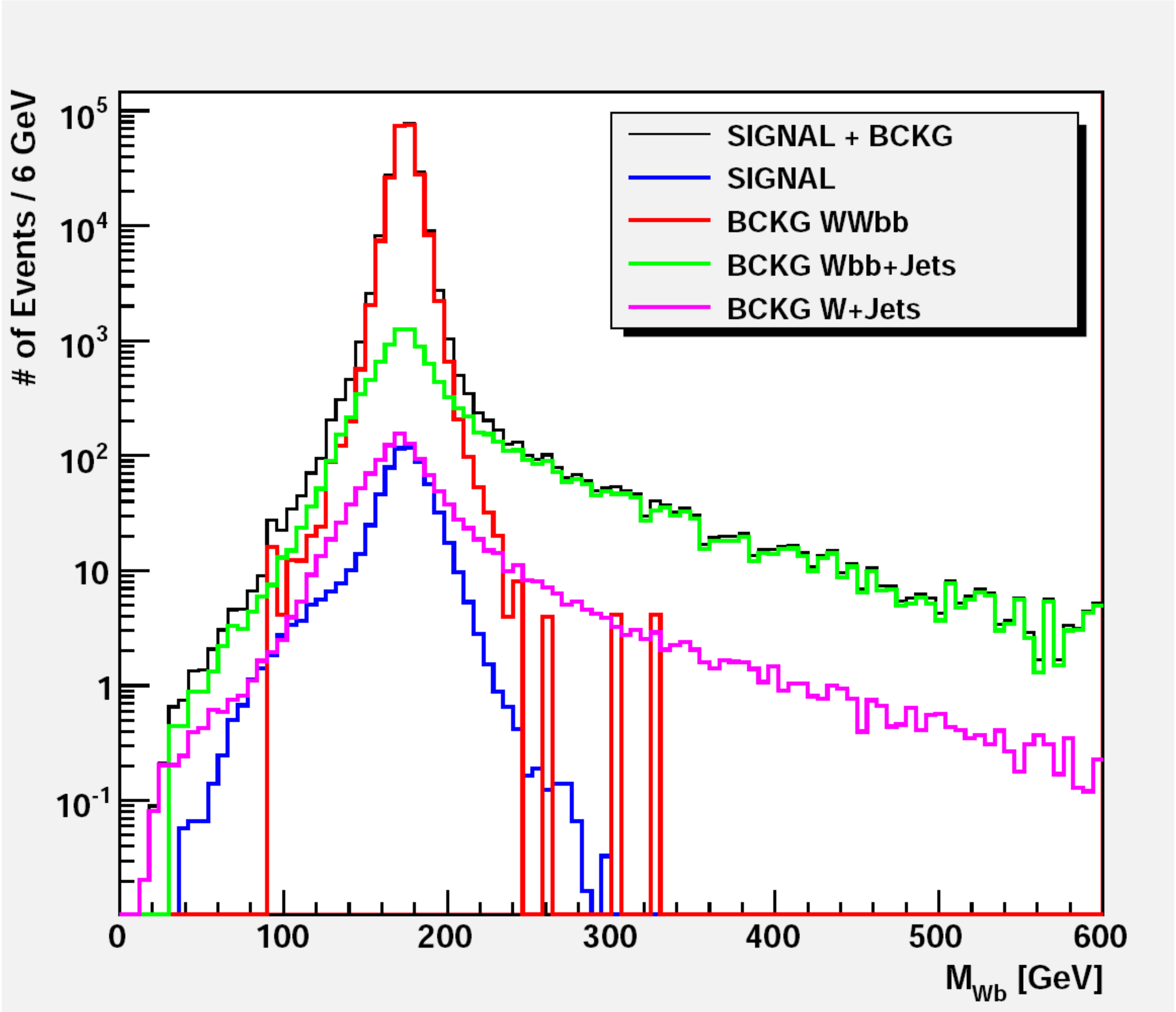
$p_T(l) > 20GeV \quad |\eta_l| < 2.5$

Top Reconstruction

After Neutrino Reconstruction ($\epsilon_{NR} \approx 0.8$)





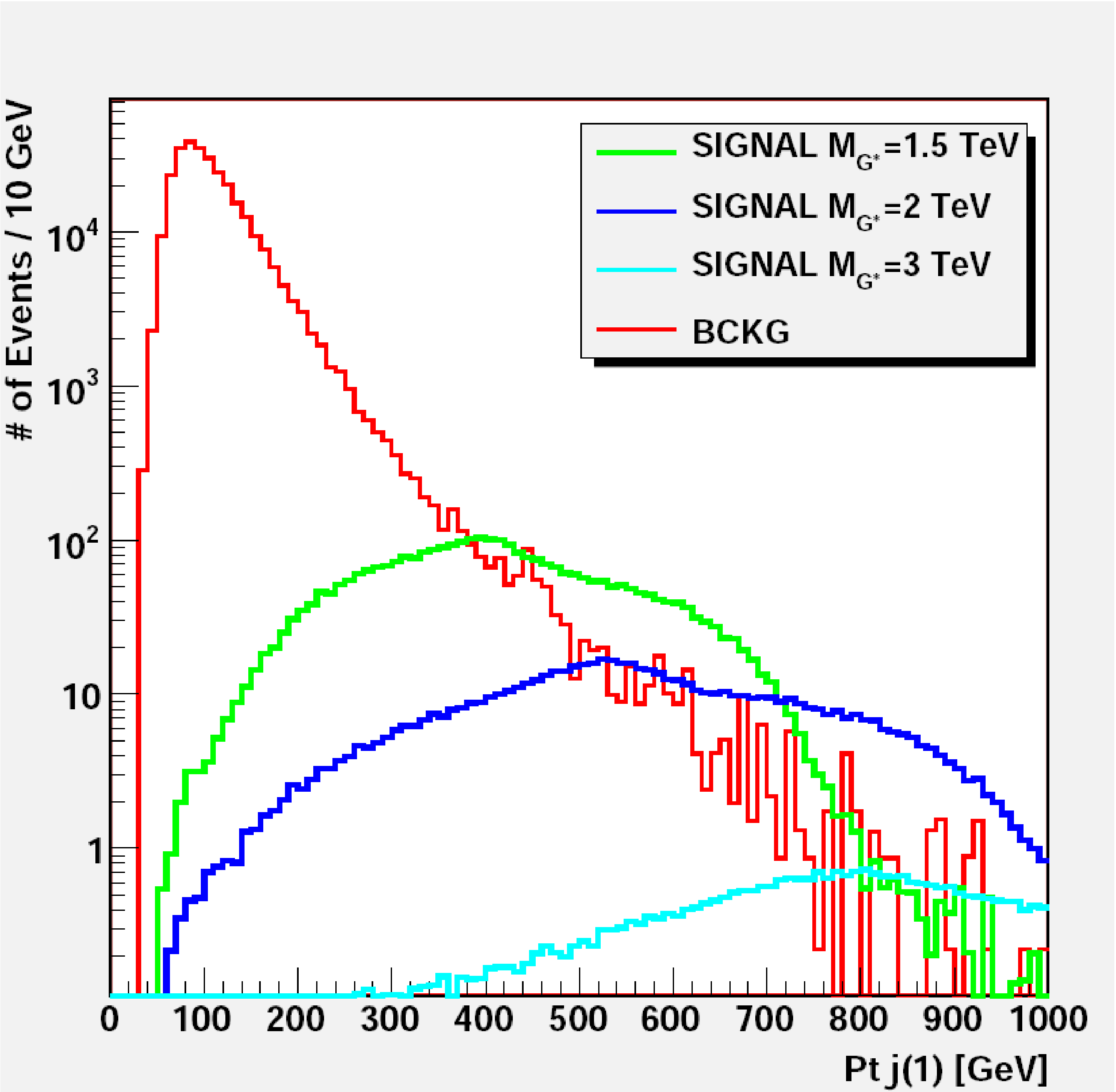


Conservative Cuts

Very energetic final states for the Signal

We apply cuts that reject less than 3% of the Signal (corresponding to M_{G^*}=1.5 TeV, which is the 'less energetic' case)

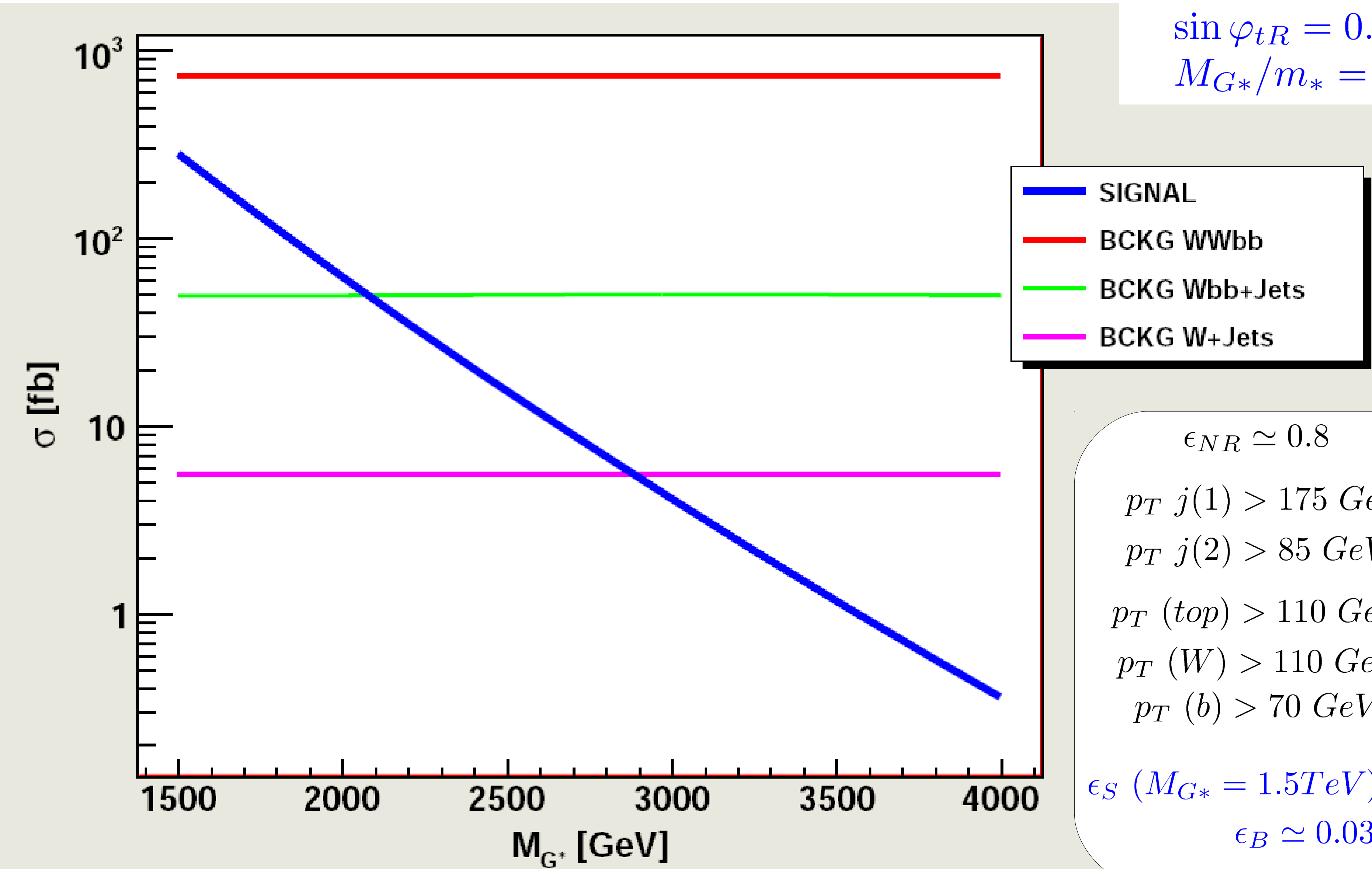
$$p_T\ j(1) > 175\ GeV$$
$$\epsilon_S\ (M_{G*} = 1.5TeV) = 0.97$$
$$\epsilon_B = 0.08$$



S and Bckg Cross sections after Neutrino and Top Reconstruction and the Pt Cuts

$\sqrt{s} = 14\ TeV$

$g_{*3} = Y_* = 3$
$\sin\varphi_{tR} = 0.6$
$M_{G*}/m_* = 1.5$



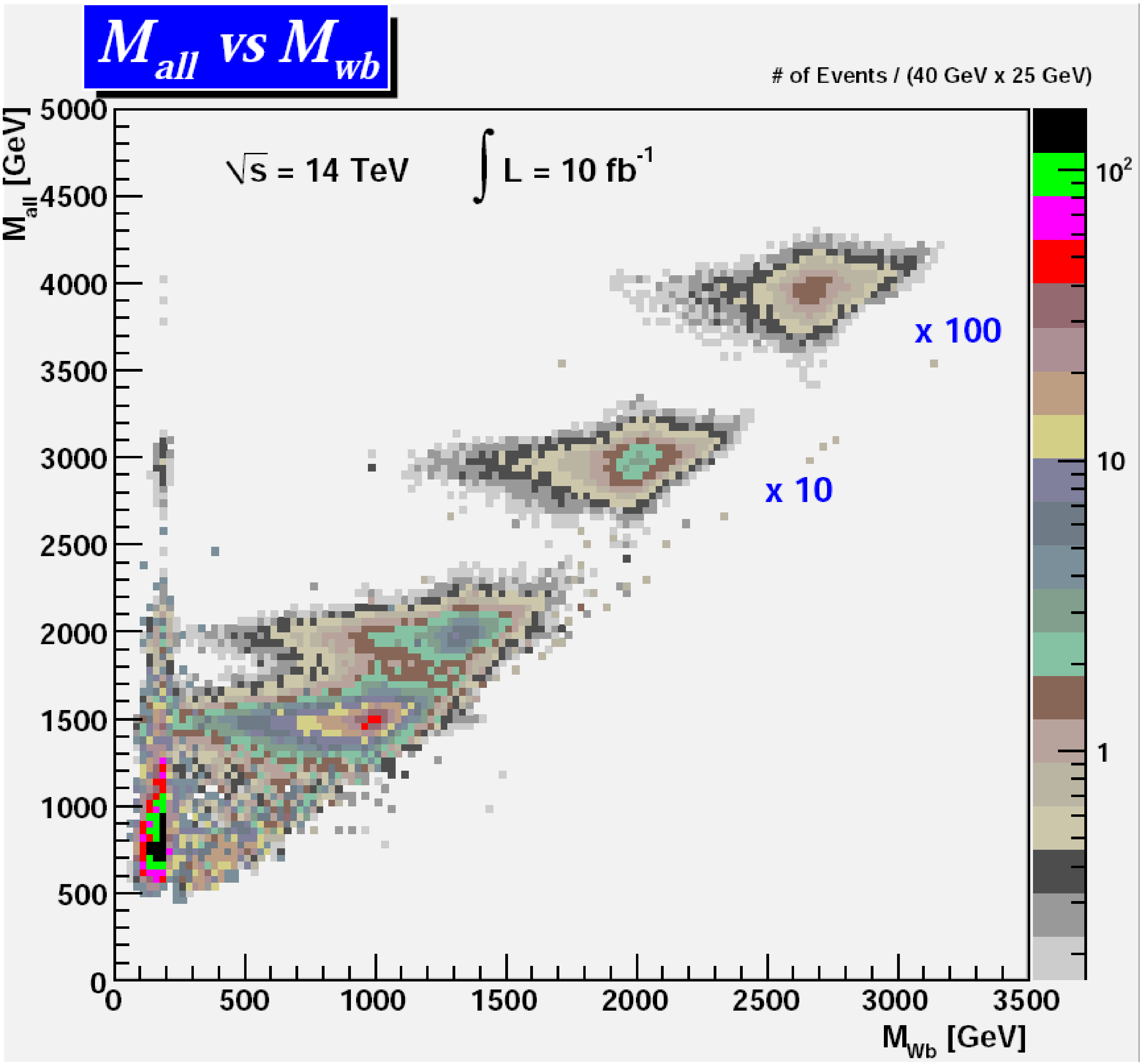
$\epsilon_{NR} \simeq 0.8$

$p_T\ j(1) > 175\ GeV$
$p_T\ j(2) > 85\ GeV$

$p_T\ (top) > 110\ GeV$
$p_T\ (W) > 110\ GeV$
$p_T\ (b) > 70\ GeV$

$\epsilon_S\ (M_{G*} = 1.5TeV) = 0.72$
$\epsilon_B \simeq 0.03$

Signal
$M_{G^*} = 1.5$ TeV
$M_{G^*} = 2$ TeV
$M_{G^*} = 3$ TeV
$M_{G^*} = 4$ TeV
+ BCKG



Invariant Mass Regions

M_{all} vs M_{wb}

Signal

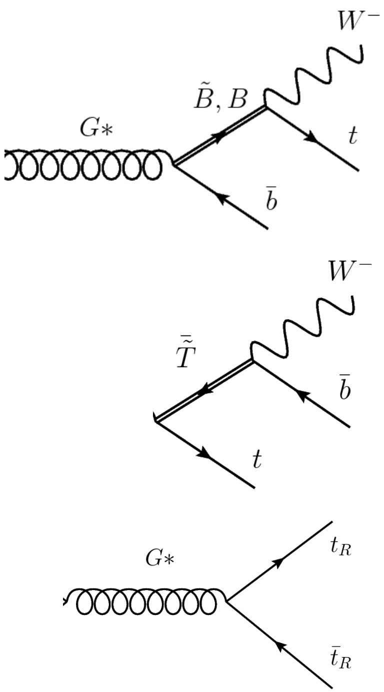
M_{G^*} = 1.5 TeV

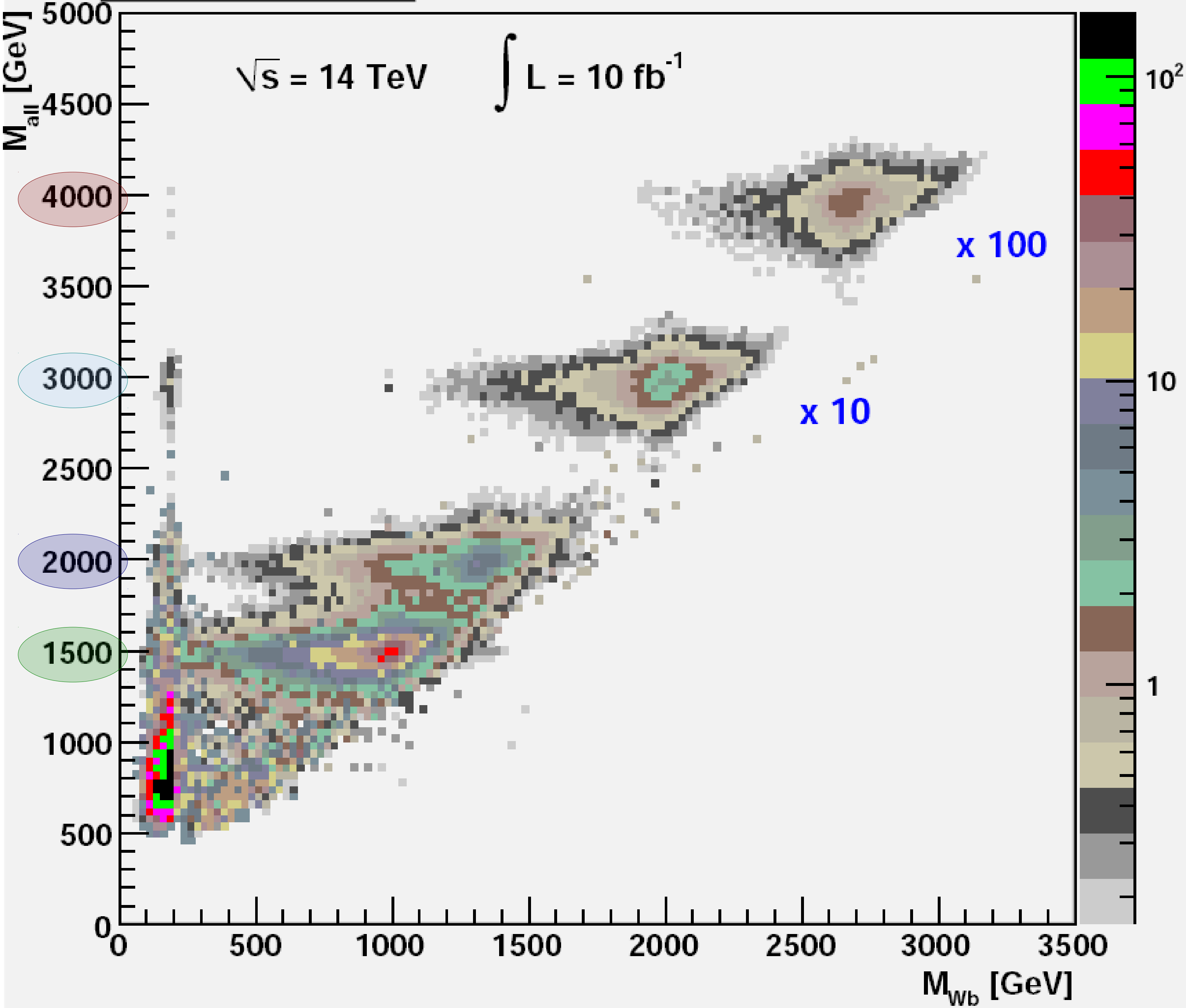
M_{G^*} = 2 TeV

M_{G^*} = 3 TeV

M_{G^*} = 4 TeV

+ BCKG

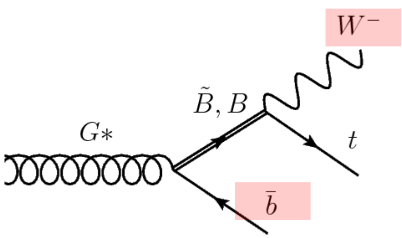


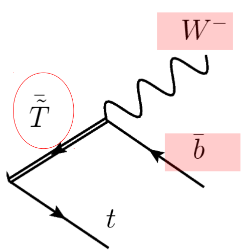


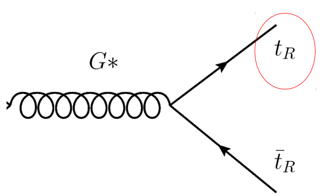
Invariant Mass Regions

M_{all} vs M_{wb}

Signal
M_{G*} = 1.5 TeV
M_{G*} = 2 TeV
M_{G*} = 3 TeV
M_{G*} = 4 TeV
+ BCKG

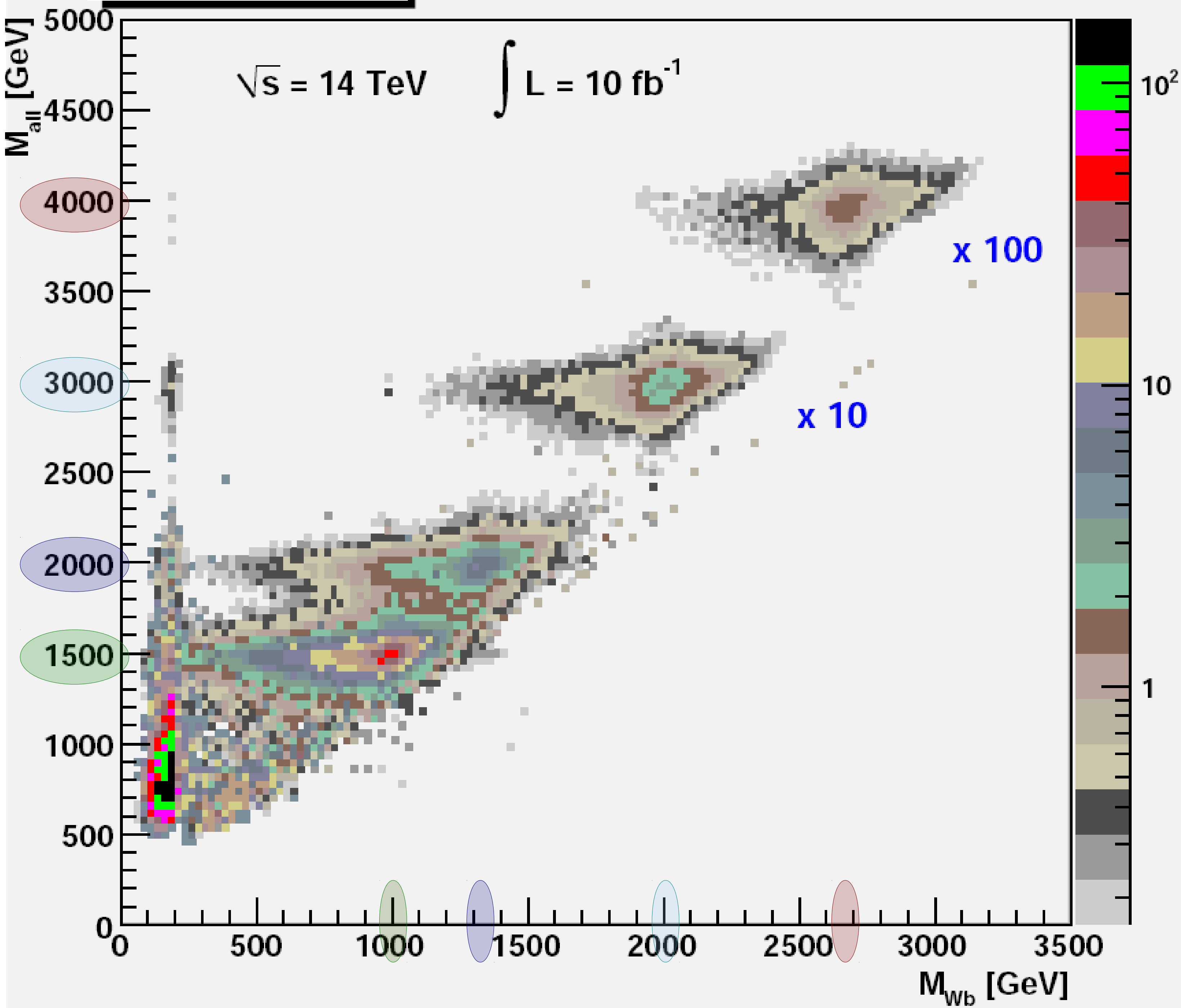






$$M_T = M_{G*}/1.5$$

Invariant Mass Regions



M_{all} vs M_{Wt}

Signal

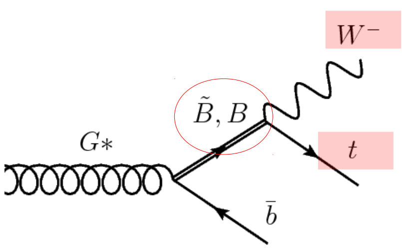
$M_{G*} = 1.5$ TeV

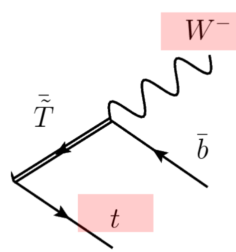
$M_{G*} = 2$ TeV

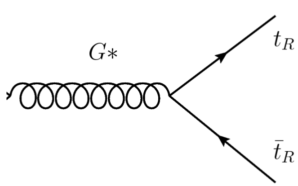
$M_{G*} = 3$ TeV

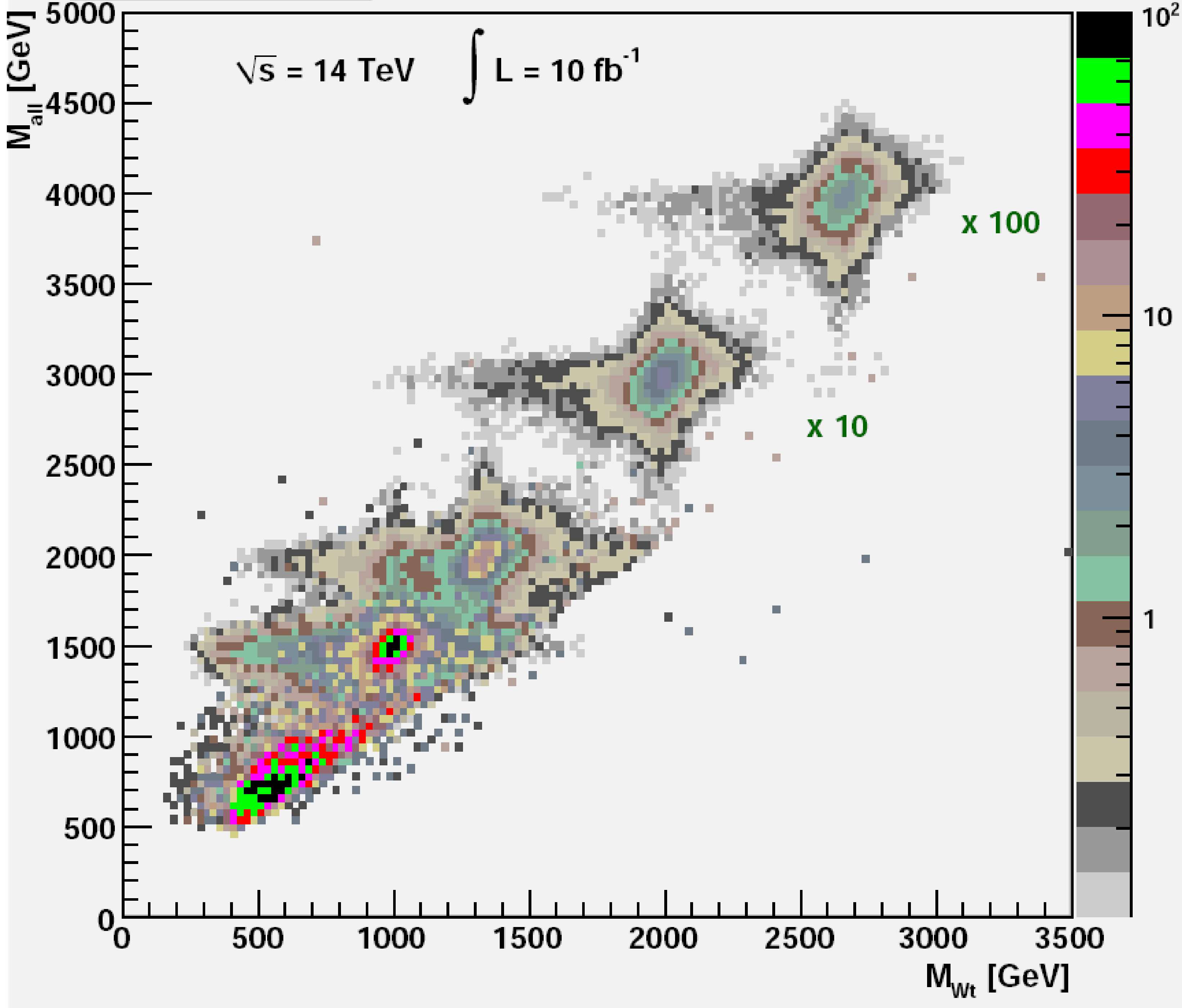
$M_{G*} = 4$ TeV

+ BCKG





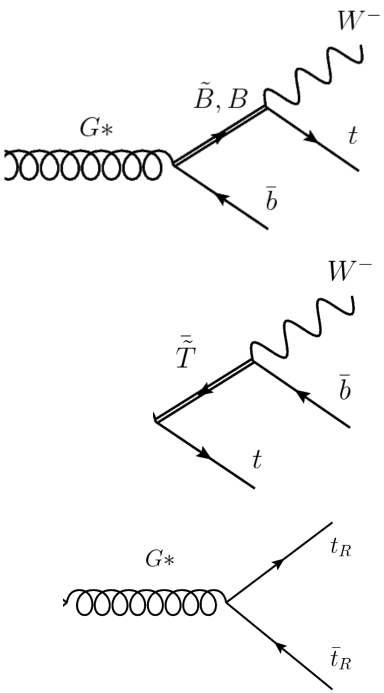


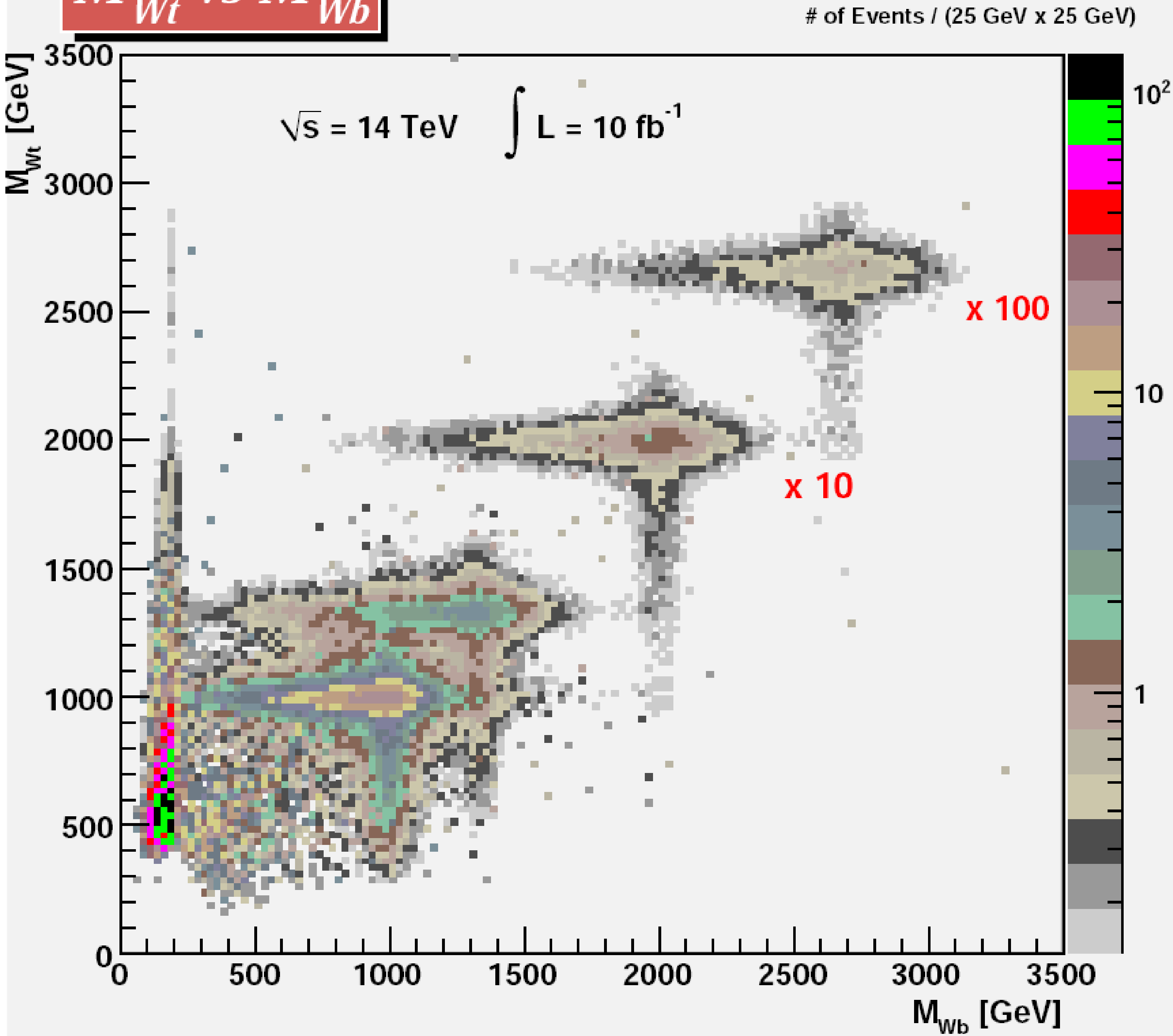


Invariant Mass Regions

M_{Wt} vs M_{Wb}

Signal
M_{G^*} = 1.5 TeV
M_{G^*} = 2 TeV
M_{G^*} = 3 TeV
M_{G^*} = 4 TeV
+ BCKG

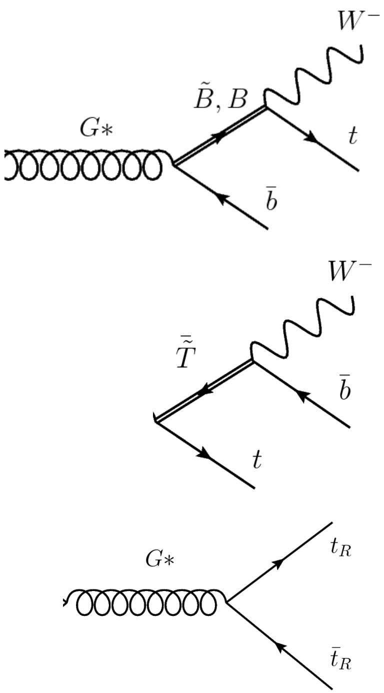


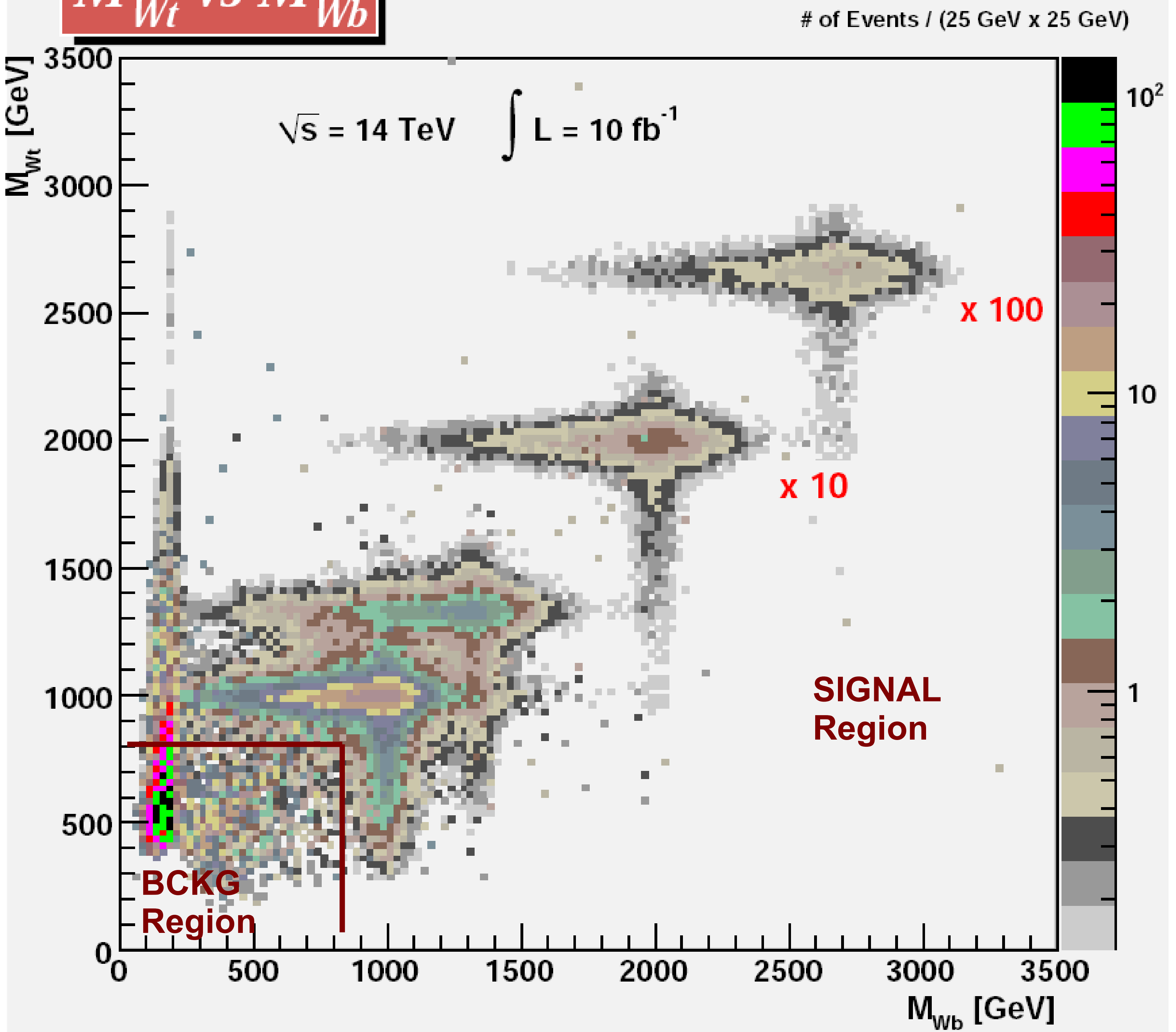


Invariant Mass Regions

M_{Wt} vs M_{Wb}

Signal
M_{G^*} = 1.5 TeV
M_{G^*} = 2 TeV
M_{G^*} = 3 TeV
M_{G^*} = 4 TeV
+ BCKG

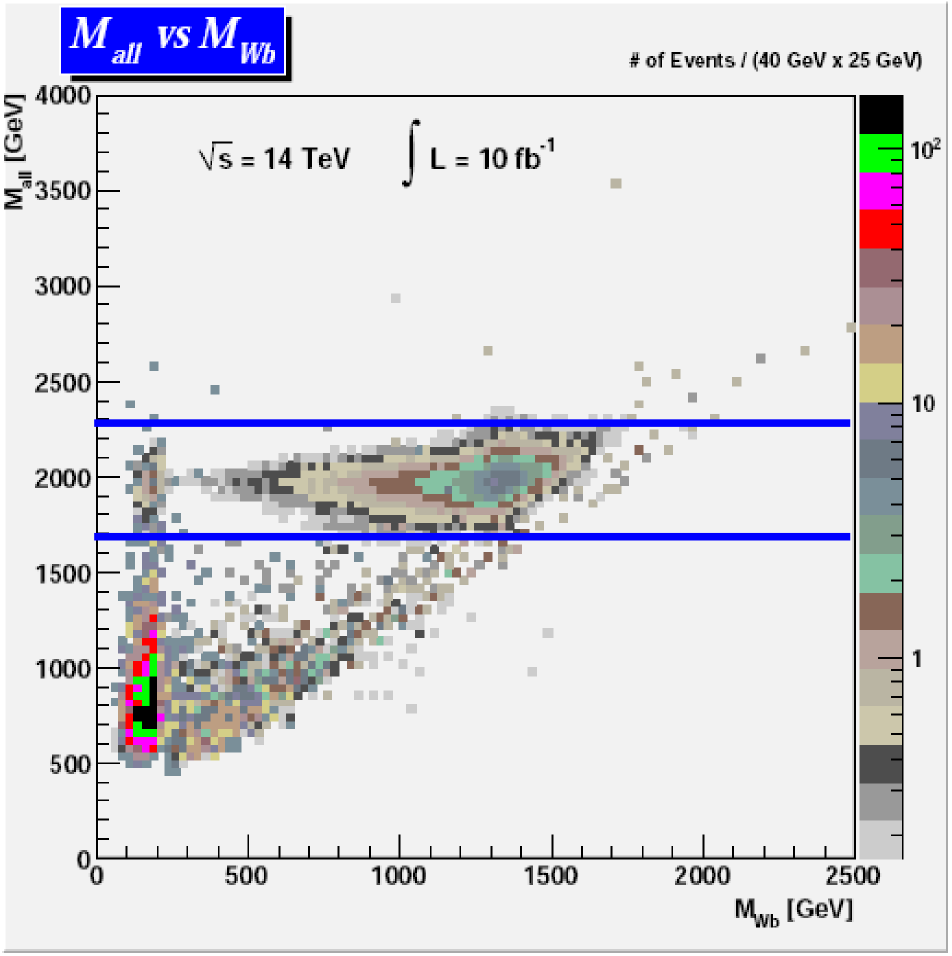


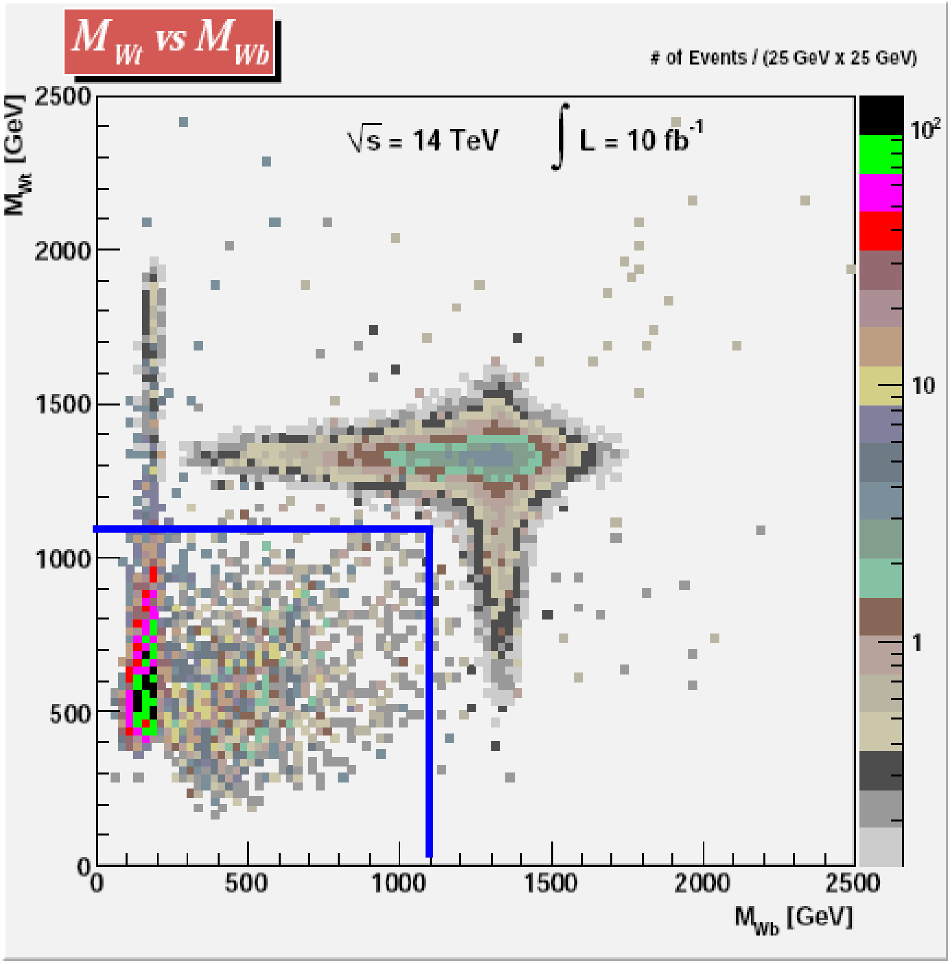


Invariant Mass Regions

Signal M_{G^*} = 2 TeV + BCKG

$$M_{Wb} > 1.1\ TeV\ ||\ M_{Wt} > 1.1\ TeV$$
$$1.7\ TeV\ <\ M_{all}\ <\ 2.3\ TeV$$

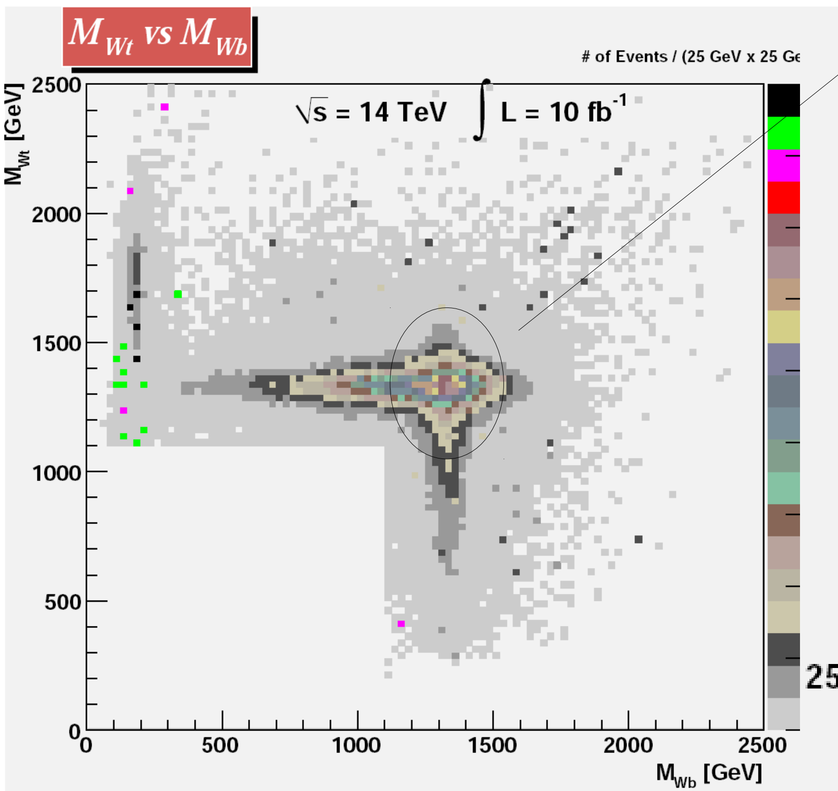


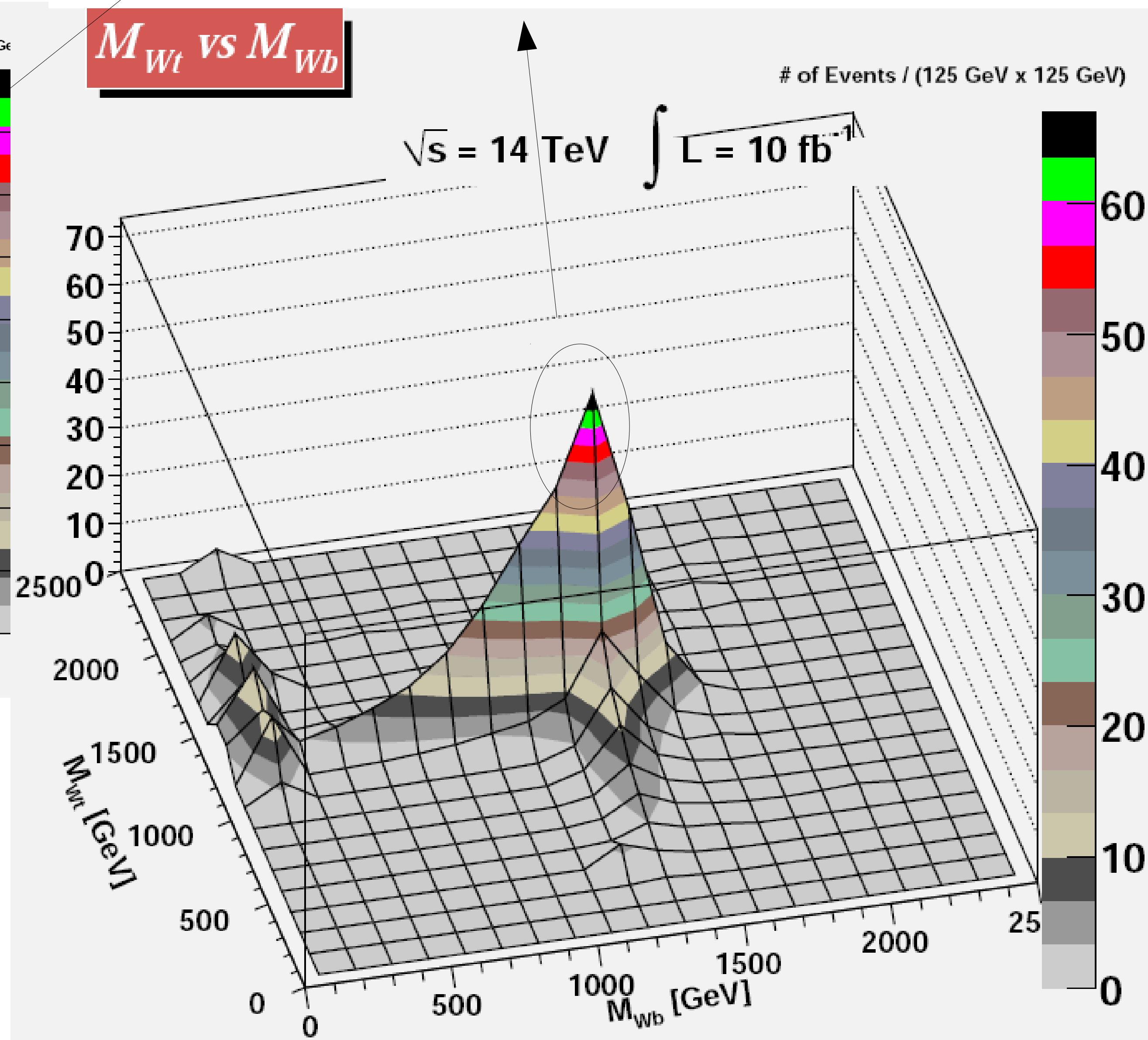


Signal M_{G^*} = 2 TeV + BCKG   After ALL Cuts

Heavy Fermions Invariant Mass peak

We set for simplicity $M_B = M_{\tilde{B}} = M_{\tilde{T}}$
but this is not necessarly the case





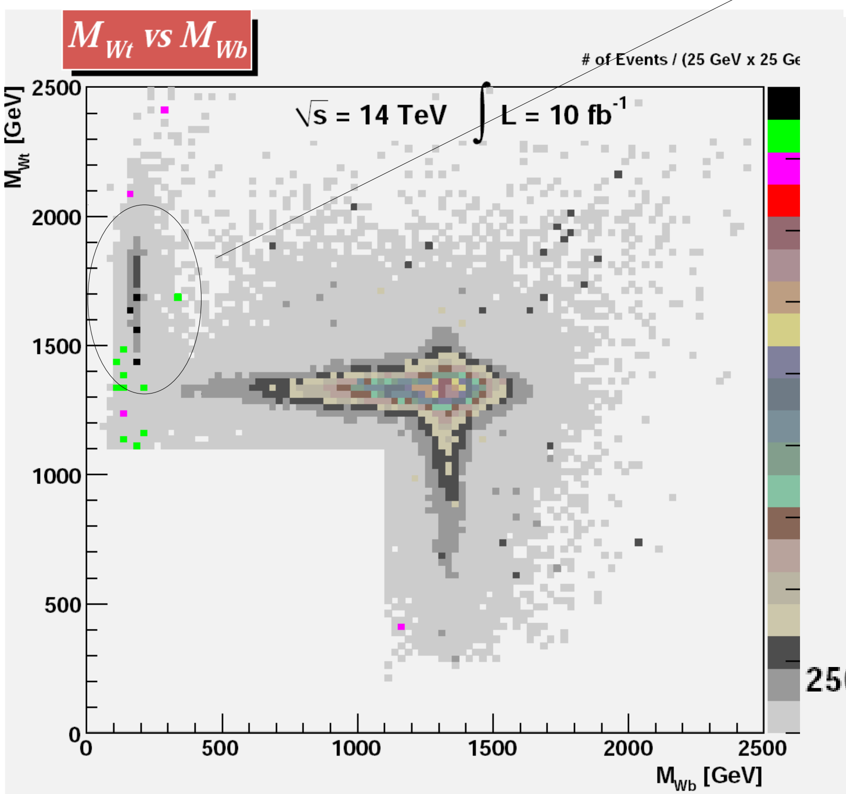
$M_{Wb} > 1.1\ TeV \ || \ M_{Wt} > 1.1\ TeV$

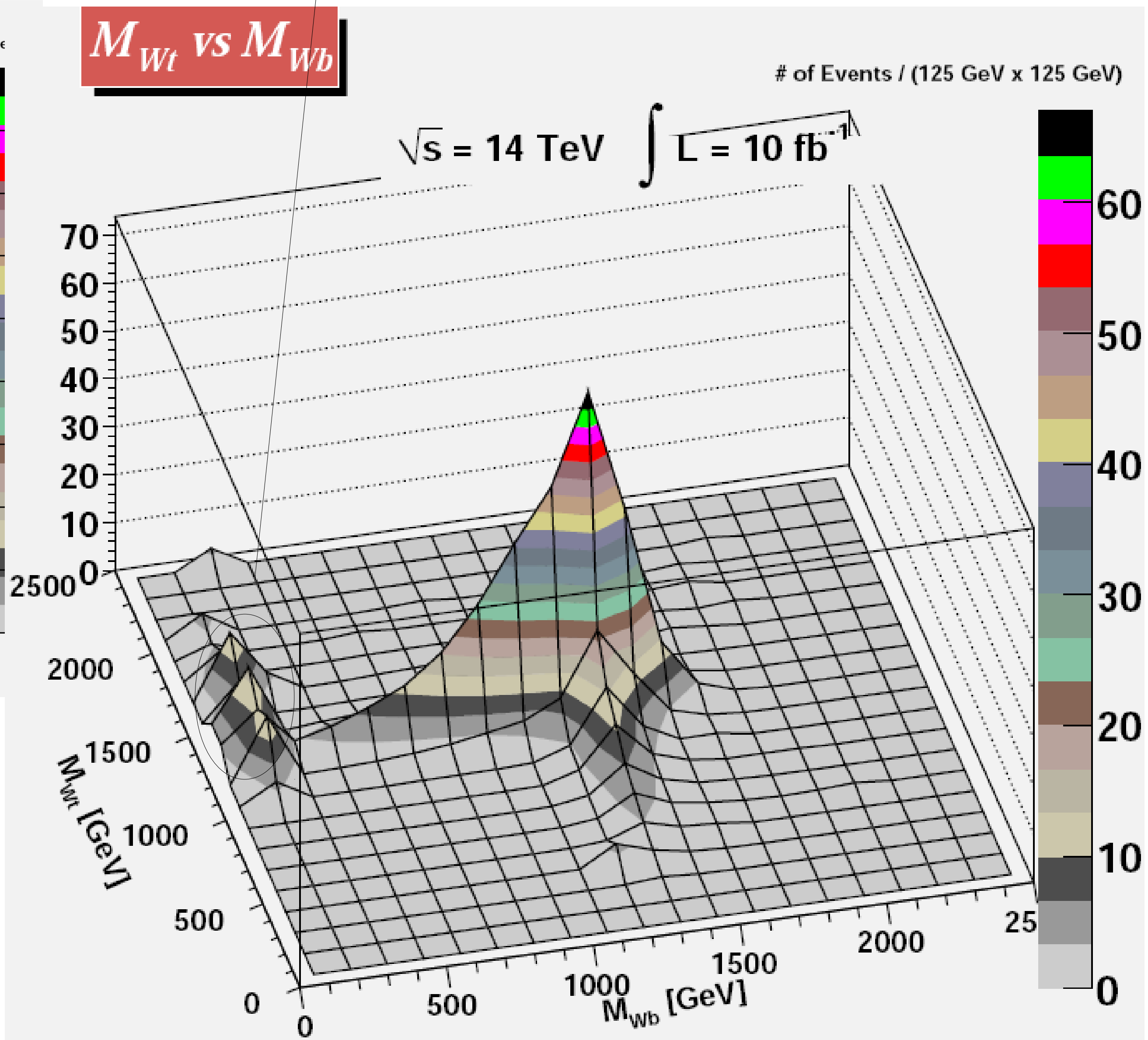
$1.7\ TeV < M_{all} < 2.3\ TeV$

Signal M_{G^*} = 2 TeV + BCKG After ALL Cuts

$t\bar{t}$ component of the Signal

We could extract hints on the top degree of compositeness



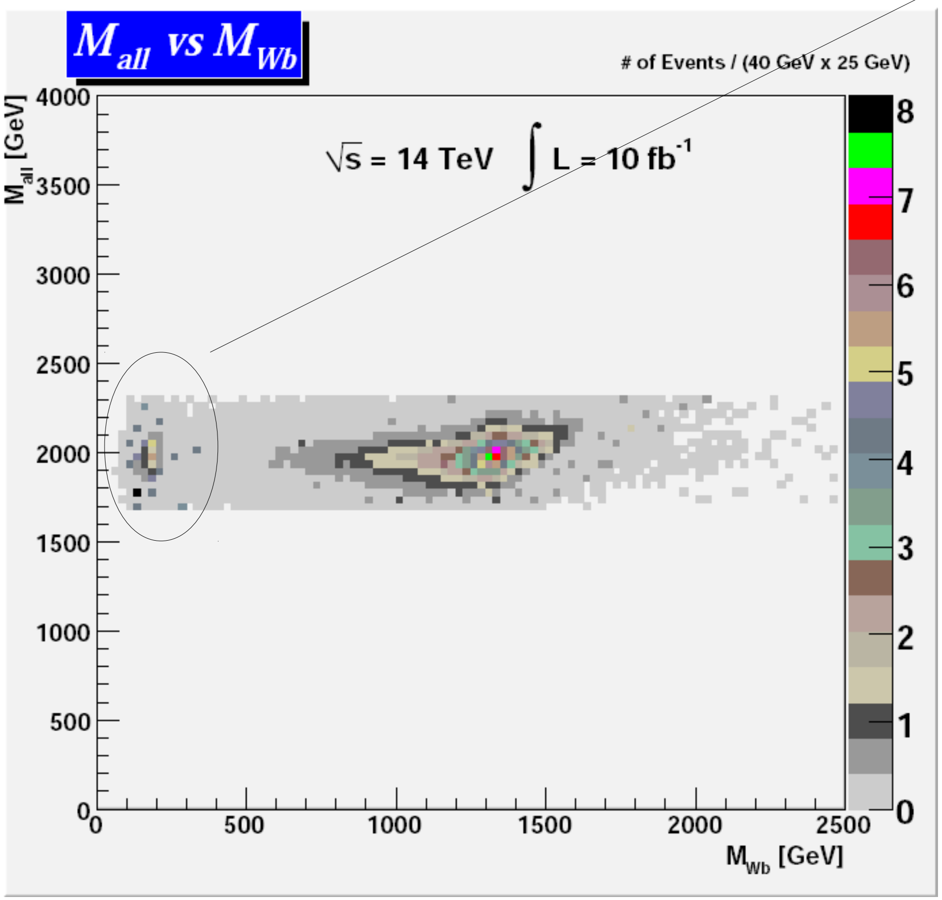


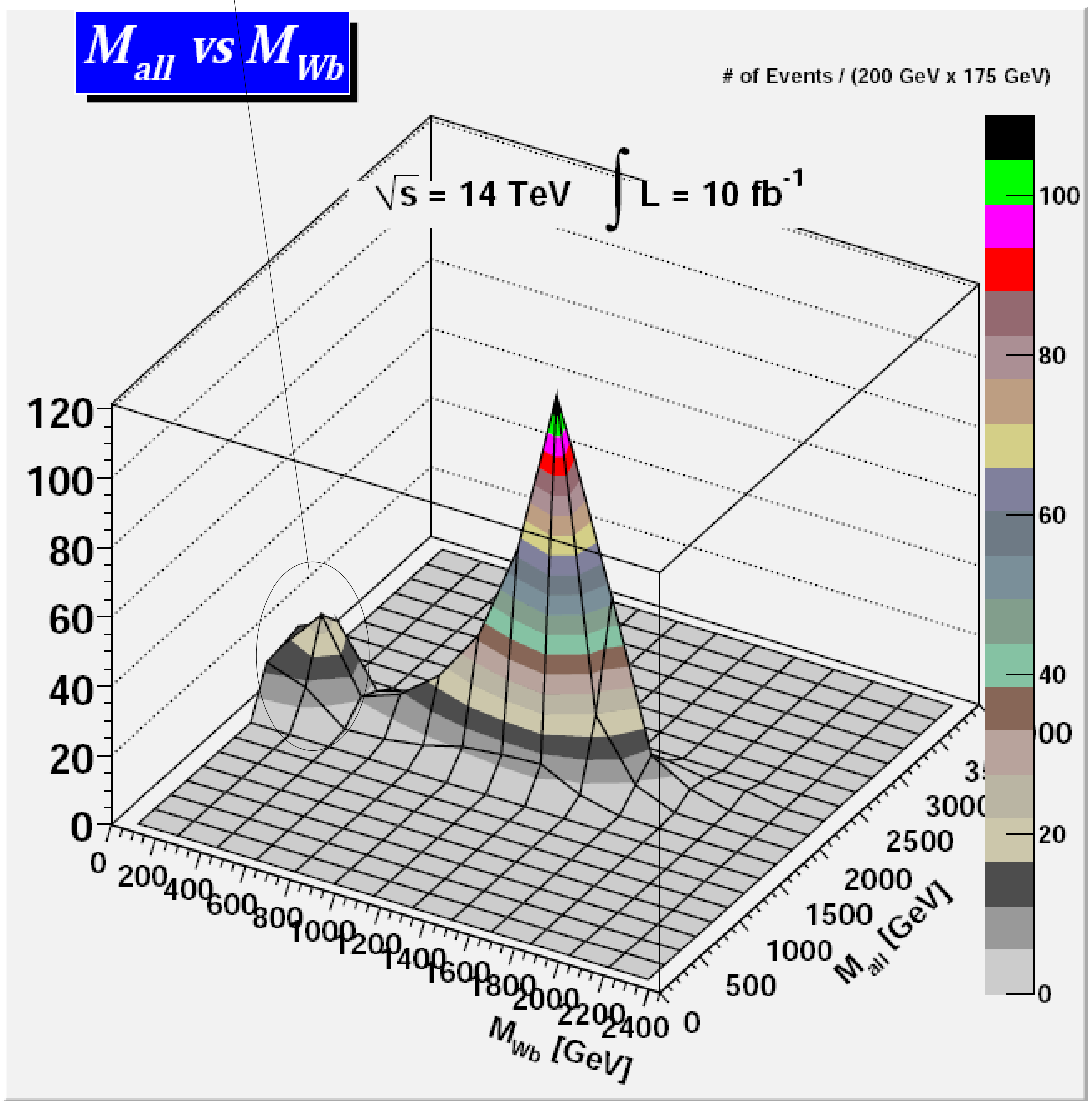
$$M_{Wb} > 1.1\ TeV \ || \ M_{Wt} > 1.1\ TeV$$
$$1.7\ TeV < M_{all} < 2.3\ TeV$$

Signal $M_{G^*} = 2$ TeV + BCKG   After ALL Cuts

$t\bar{t}$ component of the Signal

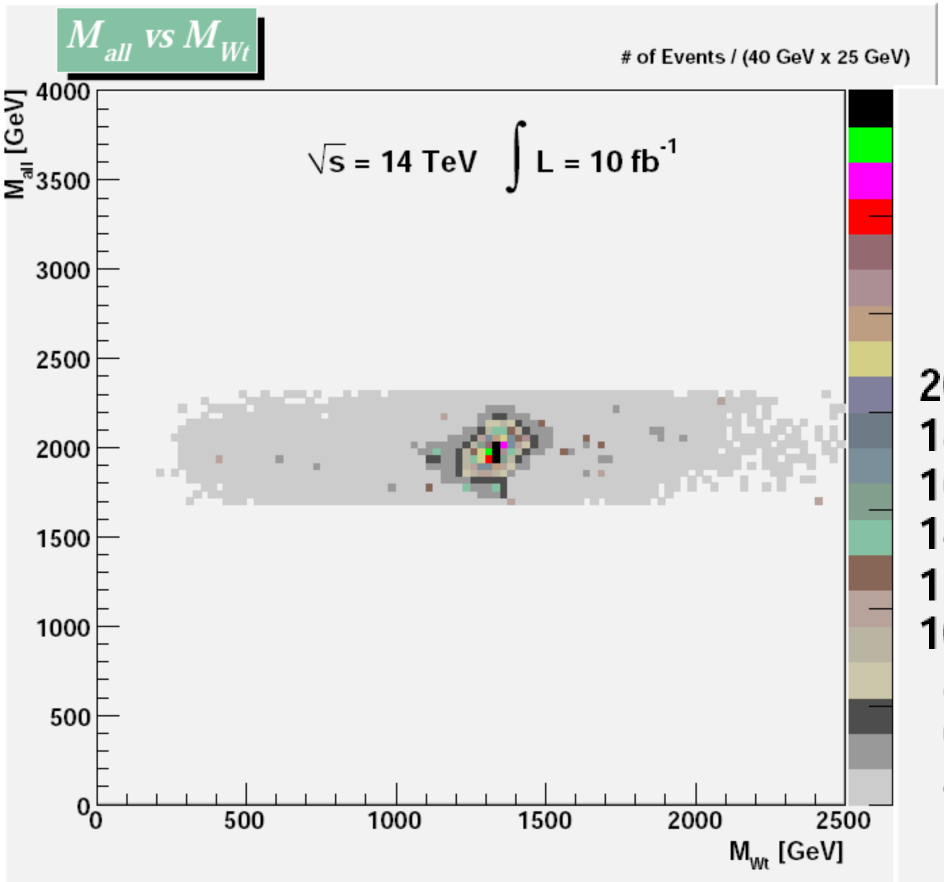
We could extract hints on the top degree of compositeness

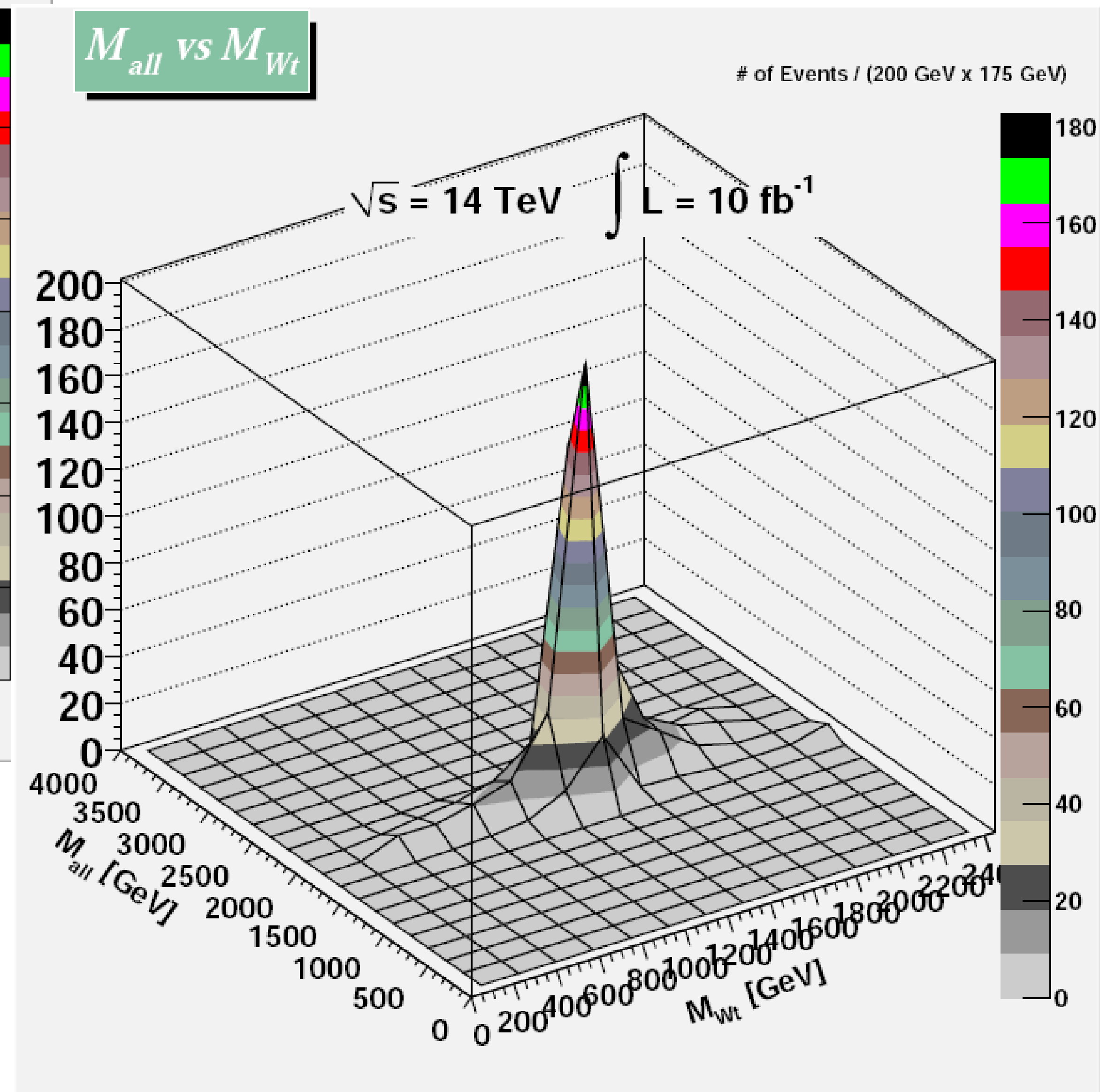




$$M_{Wb} > 1.1\ TeV\ ||\ M_{Wt} > 1.1\ TeV$$
$$1.7\ TeV\ <\ M_{all}\ <\ 2.3\ TeV$$

Signal $M_{G^*} = 2$ TeV + BCKG After ALL Cuts



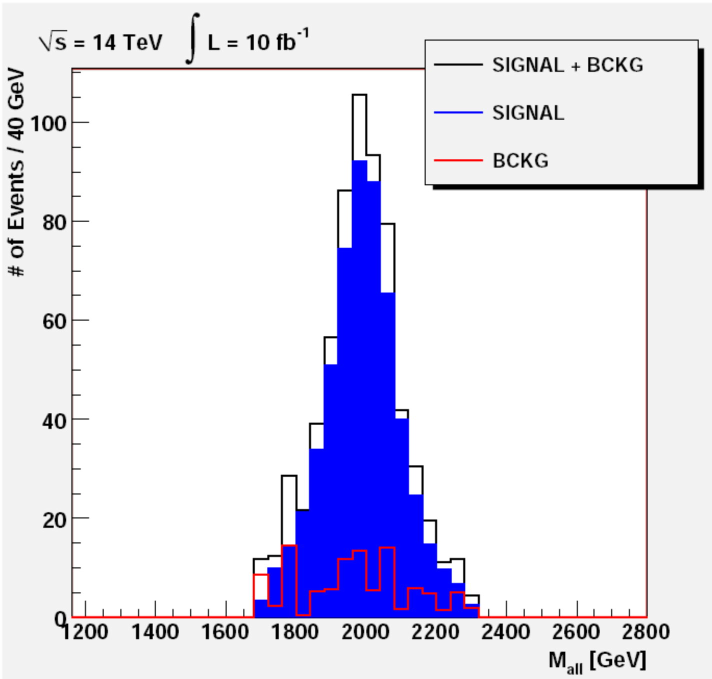


$$M_{Wb} > 1.1\ TeV \ || \ M_{Wt} > 1.1\ TeV$$

$$1.7\ TeV < M_{all} < 2.3\ TeV$$

Signal M_{G^*} = 2 TeV vs BCKG After ALL Cuts

$$M_{Wb} > 1.1\ TeV \ ||\ M_{Wt} > 1.1\ TeV$$
$$1.7\ TeV\ <\ M_{all}\ <\ 2.3\ TeV$$

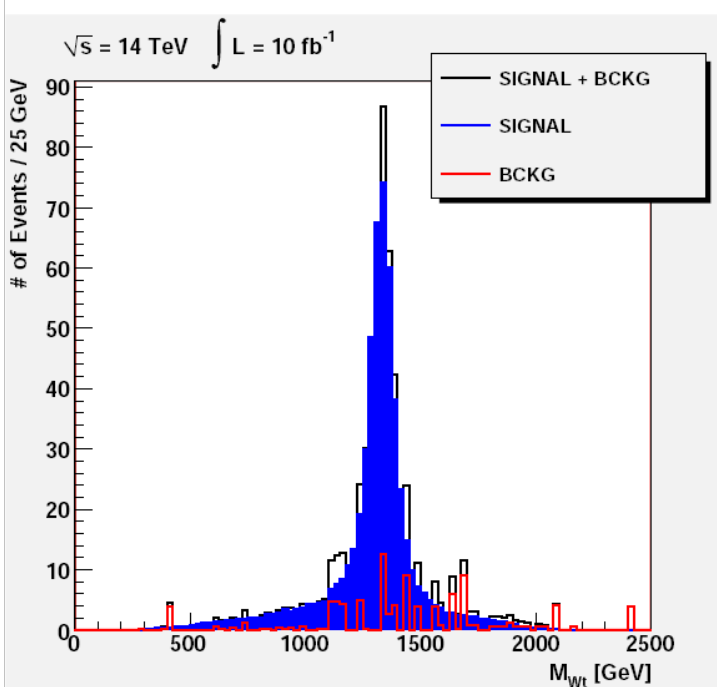


G^*

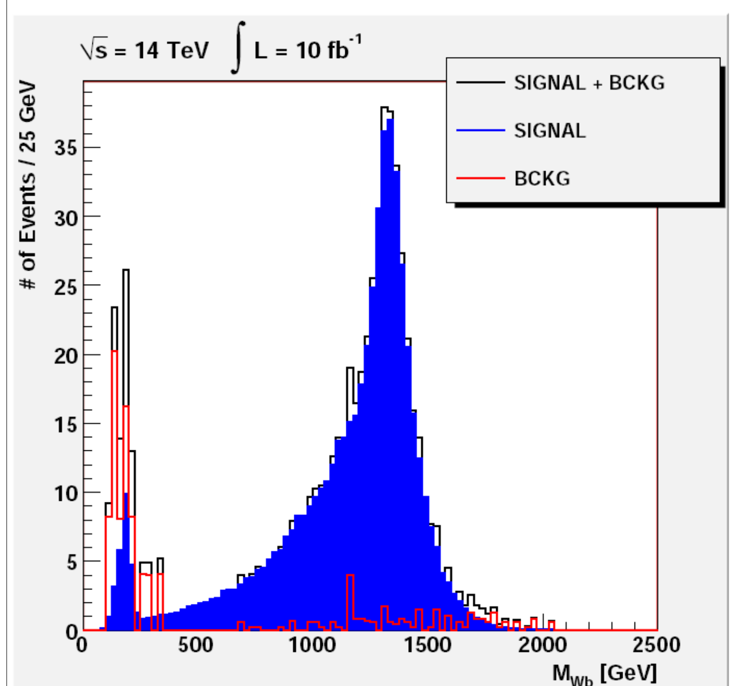
S/√B > 5 and at least 10 Signal Events:

$$\int \mathcal{L} \simeq 180\ pb^{-1}$$

$$S = 10 \quad S/B \simeq 5 \quad S/\sqrt{B} \simeq 7.3$$



$\tilde{B}, B$



$\tilde{T}$

14 TeV LHC Discovery Reach on G* and Heavy Fermions

$S/\sqrt{B} > 5$ and at least 10 Signal Events:

M_{G^*} = 1.5 TeV

$$\int \mathcal{L} \simeq 41\ pb^{-1}$$

$$S/B \simeq 6 \quad S/\sqrt{B} \simeq 8$$

$$M_{Wb} > 0.8\ TeV \ || \ M_{Wt} > 0.8\ TeV$$
$$1.3\ TeV < M_{all} < 1.7\ TeV$$

M_{G^*} = 2 TeV

$$\int \mathcal{L} \simeq 180\ pb^{-1}$$

$$S/B \simeq 5 \quad S/\sqrt{B} \simeq 7.3$$

$$M_{Wb} > 1.1\ TeV \ || \ M_{Wt} > 1.1\ TeV$$
$$1.7\ TeV < M_{all} < 2.3\ TeV$$

M_{G^*} = 3 TeV

$$\int \mathcal{L} \simeq 3\ fb^{-1}$$

$$S/B \simeq 8 \quad S/\sqrt{B} \simeq 9$$

$$M_{all} > 2.7\ TeV \quad M_{Wt} > 1.4\ TeV$$

M_{G^*} = 4 TeV

$$\int \mathcal{L} \simeq 38\ fb^{-1}$$

$$S/B \simeq 4 \quad S/\sqrt{B} \simeq 6.4$$

$$M_{all} > 3.6\ TeV \quad M_{Wt} > 2.1\ TeV$$

Conclusions

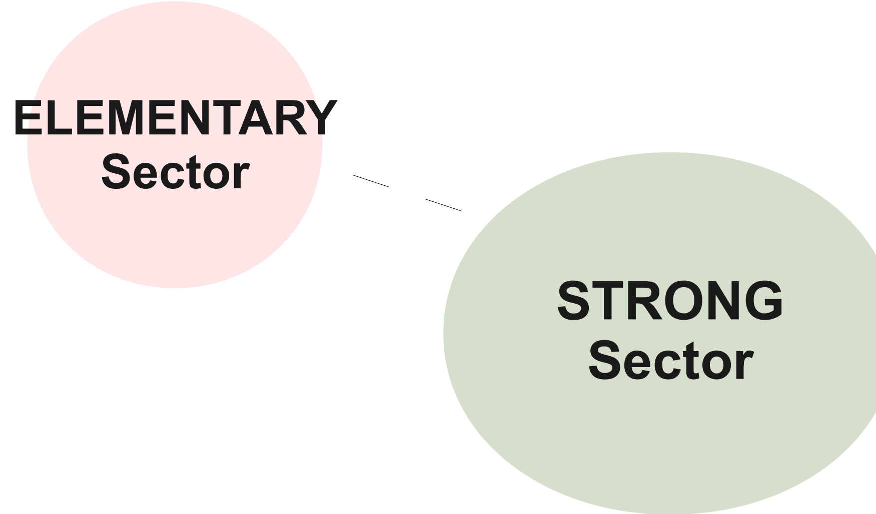
- G^* phenomenology strongly depends on the ratio M_{G^*}/m_*
- The case where $M_{G^*} < m_*$ is the only one studied in the literature on the G^* search at the LHC but it does not seem to be the preferred one by the hints from electroweak data and flavor observables (strong constraint on G^* mass from $K\bar{K}$ mixing)
- If $M_{G^*} > m_*$ (but not $M_{G^*} > 2m_*$)

  the search in the $\psi\chi$ channel is very promising for both the G^* and the heavy fermions search.

  It can also be important to extract hints on model parameters (as the top degree of compositeness)

Extra Slides

PARTIAL COMPOSITENESS



[D.B. Kaplan, Nucl. Phys. B 365, 259 (1991)]

Λ_{UV} Linear coupling between SM fermions and composite operators:

elementary/composite mixing

$\Lambda < \Lambda_{comp} < \Lambda_{UV}$

$$\mathcal{L}_{mix} = \sum_n \Delta_n \left(\bar{\psi}\chi_n + h.c.\right)$$

- *n=1* elementary/composite → light (SM) / heavy (NP)

Analogous rotation for bosons: $\tan\theta = g_{el}/g_*$

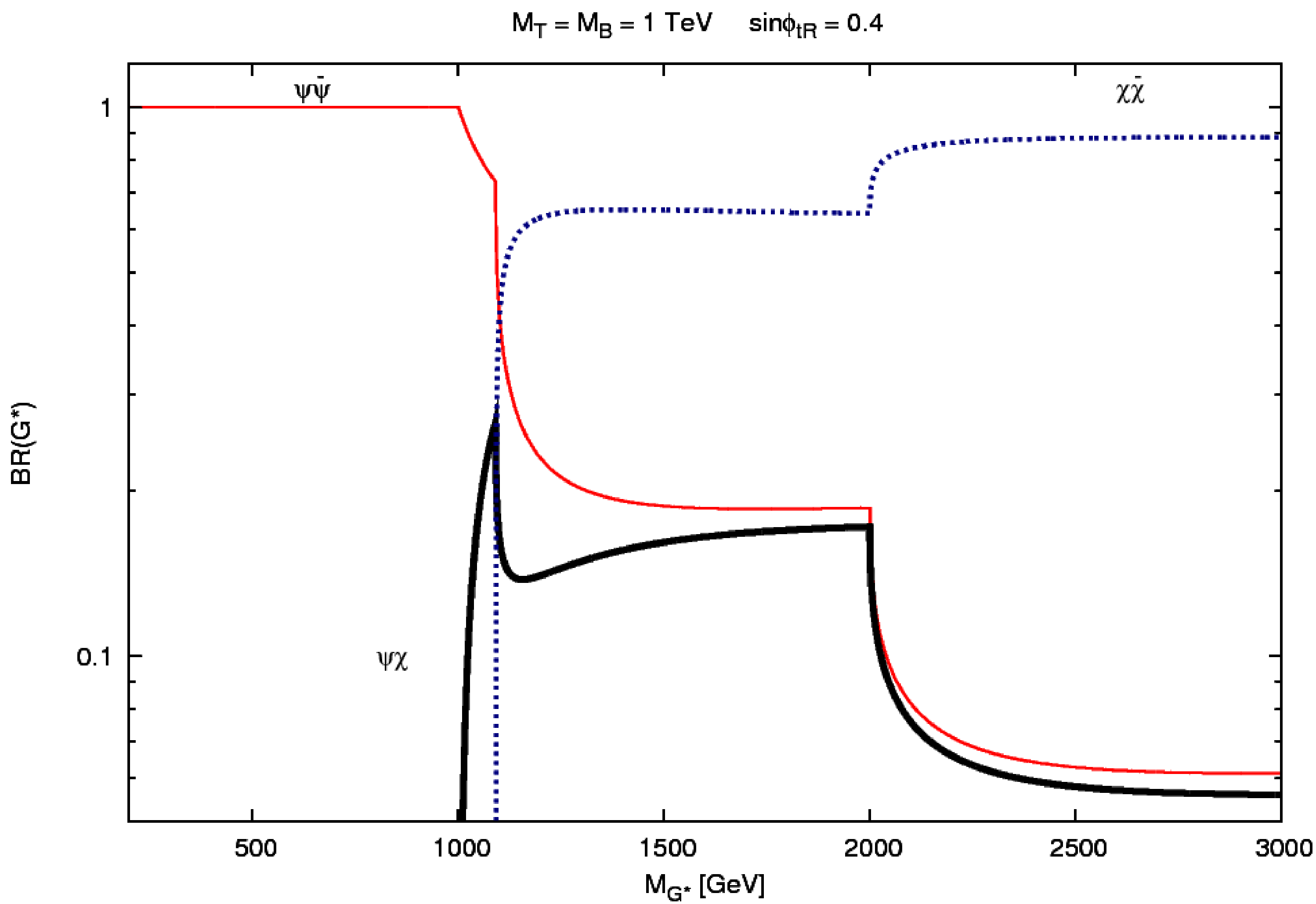
t, b, g, ...

T, B, G*, ...

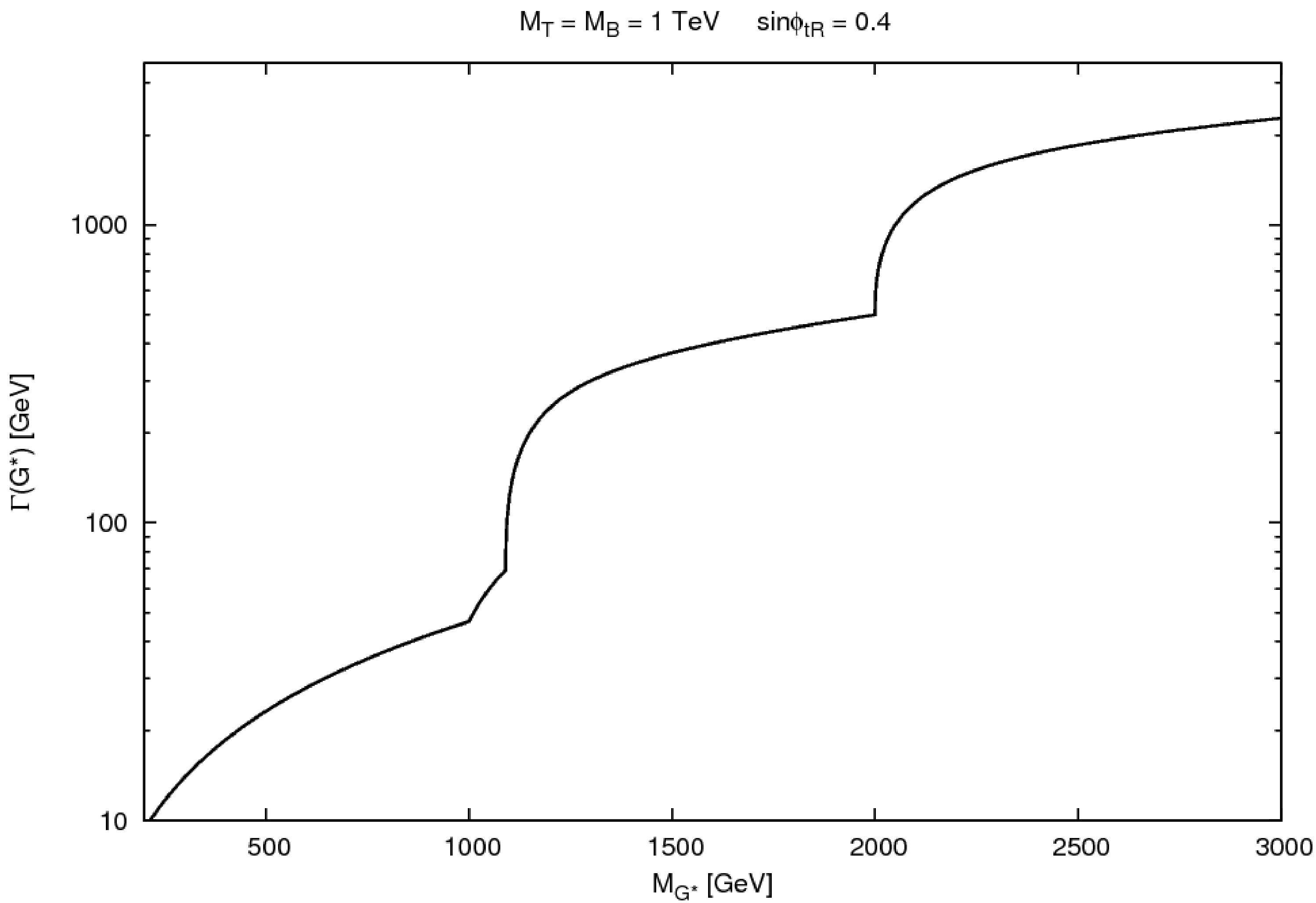
$$\begin{cases} |light\rangle = \cos\varphi|\psi\rangle + \sin\varphi|\chi\rangle \\ |heavy\rangle = -\sin\varphi|\psi\rangle + \cos\varphi|\chi\rangle \end{cases}$$

$$\tan\varphi = \frac{\Delta}{m_*}$$

Heavier particles have larger degrees of compositeness

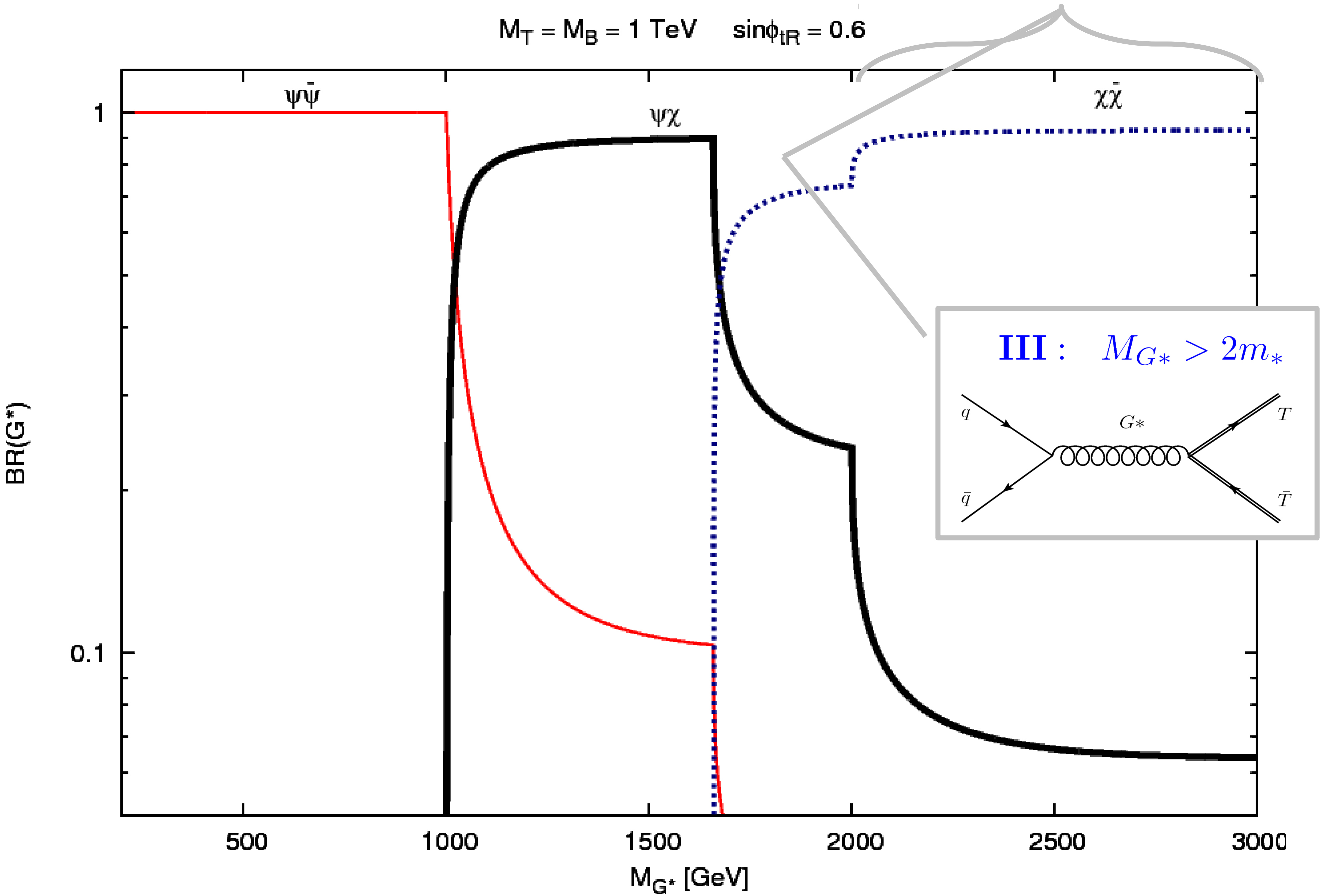


M_T = M_B = 1 TeV sinφ_tR = 0.4
ψψ̄
χχ̄
ψχ
1
0.1
BR(G*)
500
1000
1500
2000
2500
3000
M_G* [GeV]

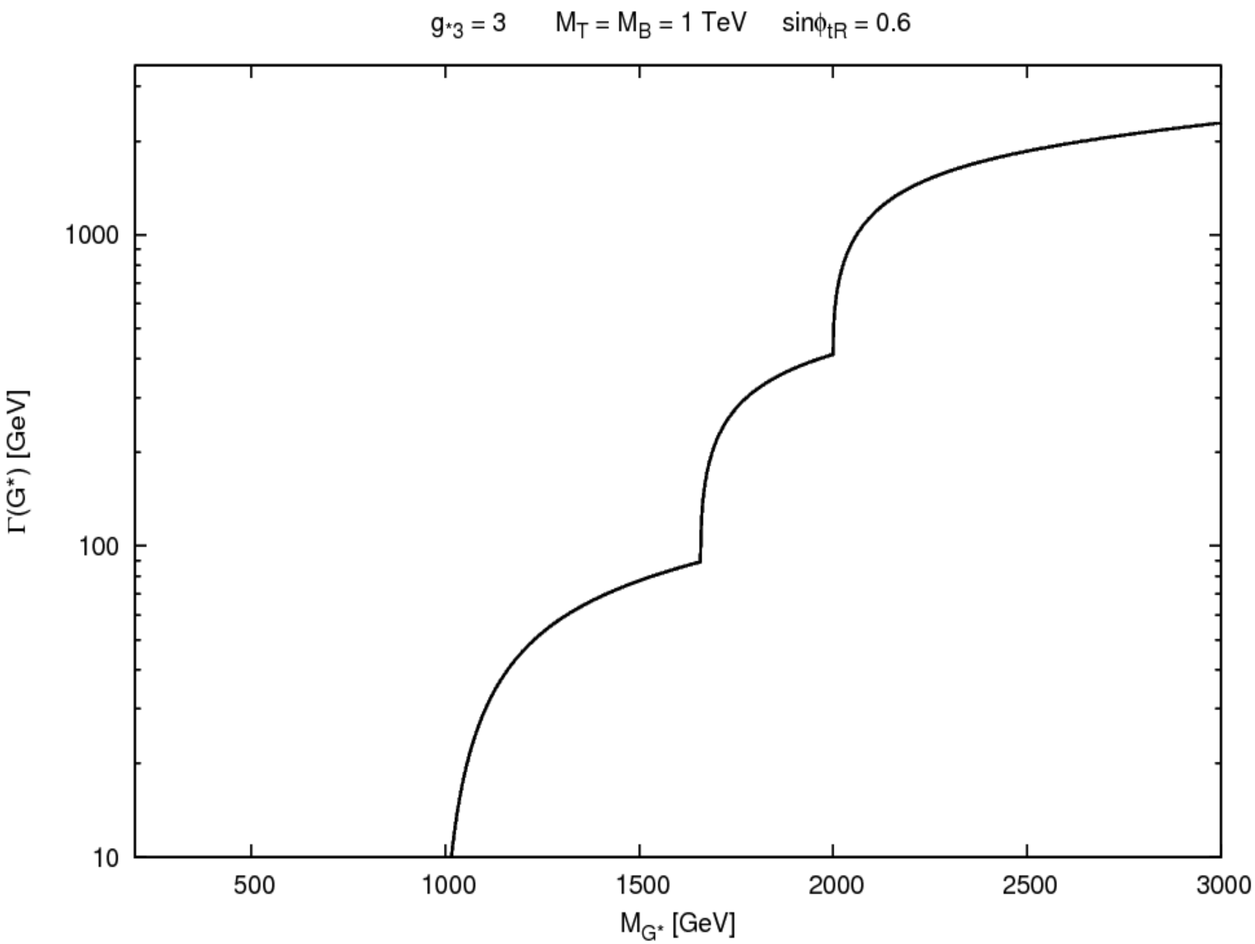


$M_T = M_B = 1$ TeV $\sin\phi_{tR} = 0.4$
$\Gamma(G^*)$ [GeV]
1000
100
10
500
1000
1500
2000
2500
3000
M_{G^*} [GeV]

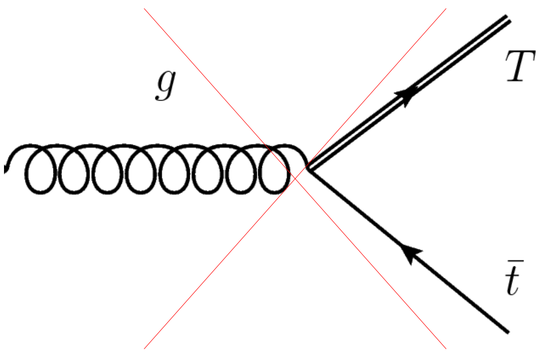
BR(G*) ....three scenarios for the G* search:



G* width



G* width not larger than o(100 GeV)
In the case
$m_* < M_{G^*} < 2m_*$



Anyway the G* discover through the **Ψχ channe**l could be still possible also in the case of larger G* width ,because of the **presence of heavy fermions (with quite narrow width) only in the signal**

DeltaRjj>0,7

SR=0,6
MG*=1,5 TeV

2j+2b	11,6%		
1j+2b	49%	1Mj+2b	42%
1j+1b	19%		

SR=0,6
MG*=2 TeV

2j+2b	6%		
1j+2b	49%	1Mj+2b	45%
1j+1b	27%		

SR=0,6
MG*=3 TeV

2j+2b	2,7%		
1j+2b	47%	1Mj+2b	45%
1j+1b	37%		

DeltaRjj>0,4

SR=0,6
MG*=1,5 TeV

2j+2b	45%		
1j+2b	34%	1Mj+2b	21%
1j+1b	6%		

SR=0,6
MG*=2 TeV

2j+2b	31%		
1j+2b	45%	1Mj+2b	36%
1j+1b	9,1%		

SR=0,6
MG*=3 TeV

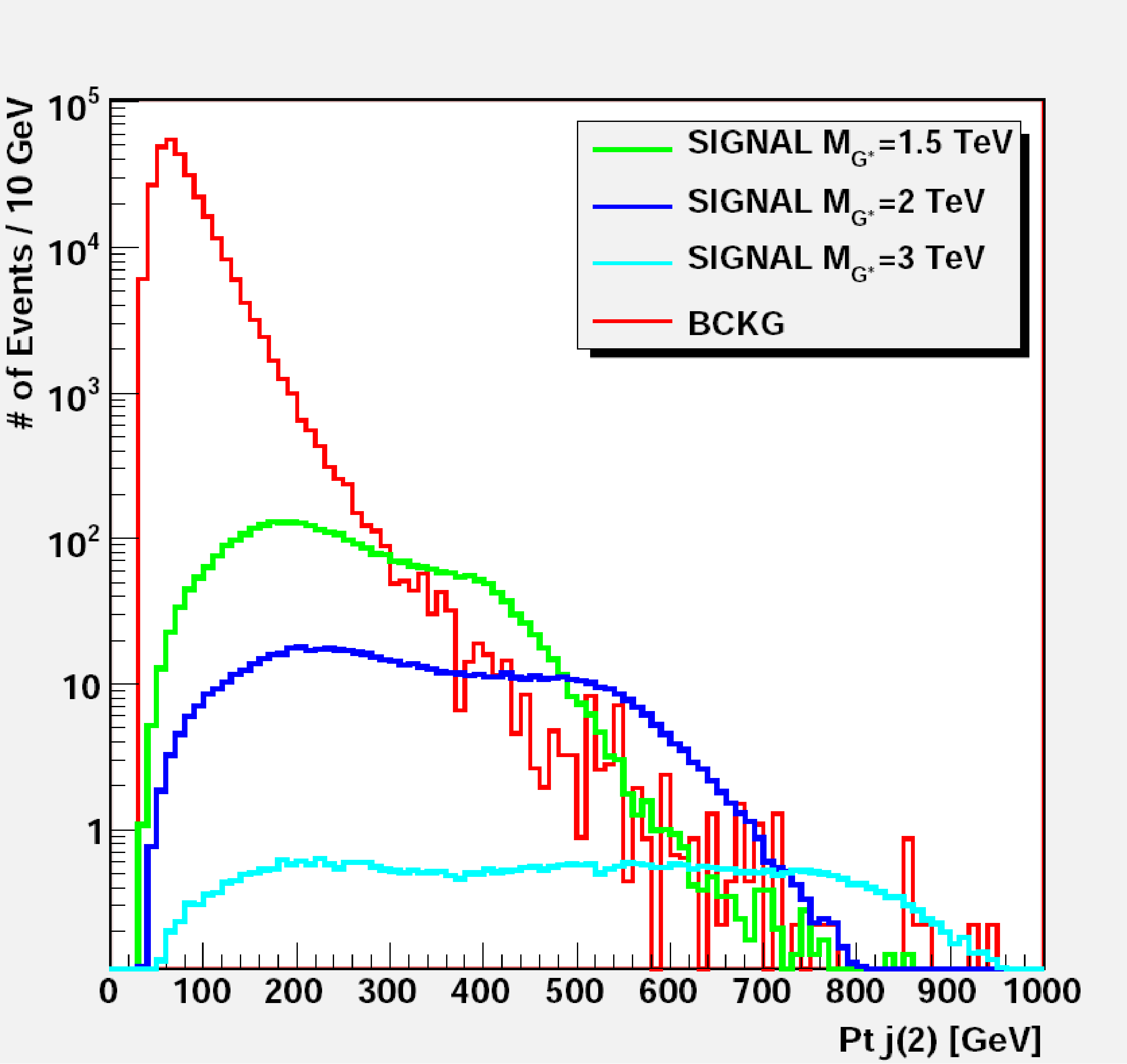
2j+2b	14%		
1j+2b	53%	1Mj+2b	49%
1j+1b	17%		

Conservative Cuts

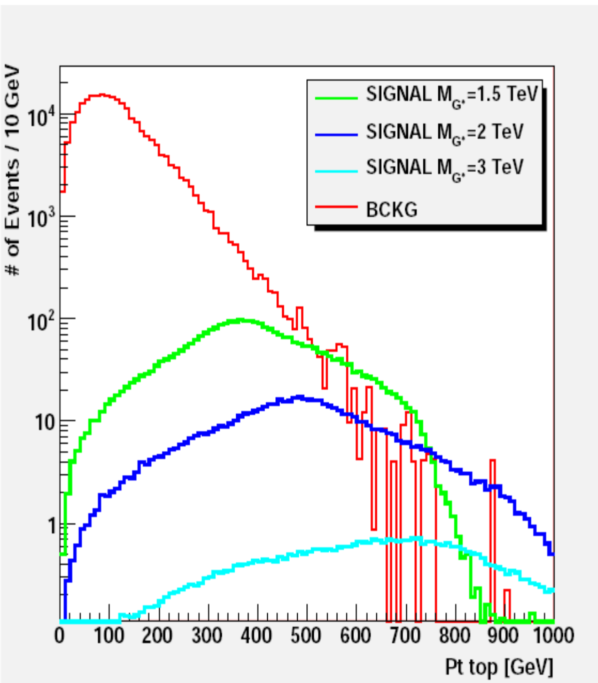
- Very energetic final states for the Signal

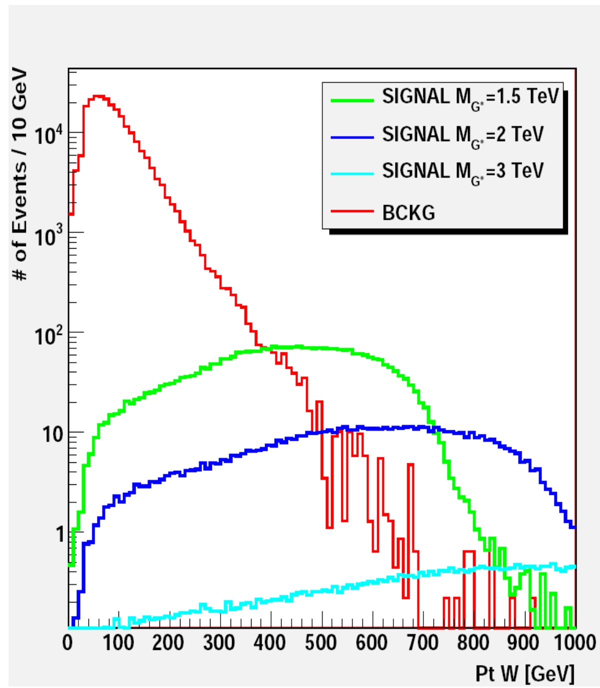
- We apply cuts that reject less than 3% of the Signal (corresponding to M_{G^*} =1.5 TeV, which is the 'less energetic' case)

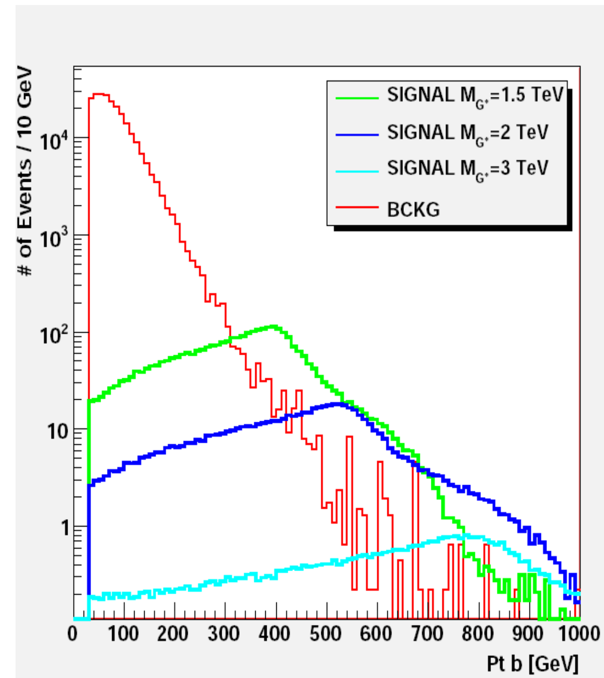
$$p_T\ j(2) > 85\ GeV$$
$$\epsilon_S\ (M_{G*} = 1.5TeV) = 0.97$$
$$\epsilon_B = 0.32$$

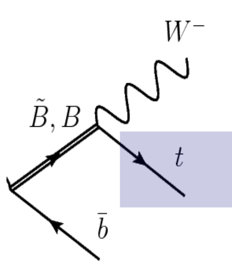


Conservative Cuts



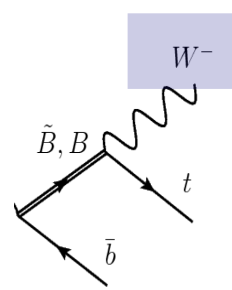






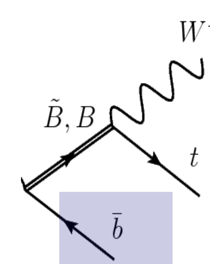
$p_T\ (top) > 110\ GeV$

$\epsilon_B = 0.54$



$p_T\ (W) > 110\ GeV$

$\epsilon_B = 0.28$



$p_T\ (b) > 70\ GeV$

$\epsilon_B = 0.46$

Signal

$M_{G^*} = 1.5$ TeV

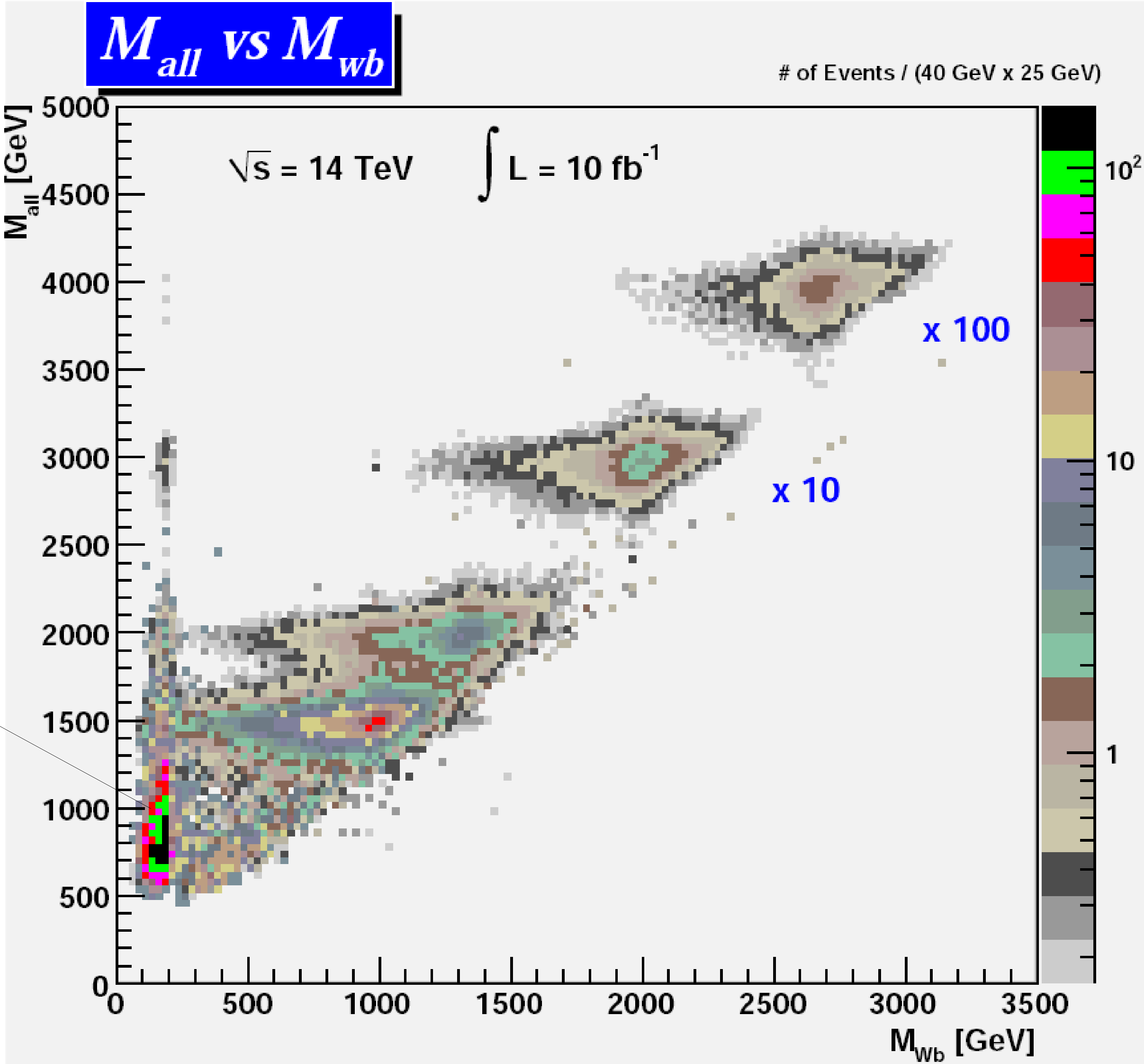
$M_{G^*} = 2$ TeV

$M_{G^*} = 3$ TeV

$M_{G^*} = 4$ TeV

+ BCKG

$t\bar{t}$ $BCKG$



Invariant Mass Regions

SO(5)xU(1)x → SO(4)xU(1)x
TS-5

- $$\mathcal{Q}_{2/3} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix} = (2,2)_{2/3}\,, \quad \tilde{T} = (1,1)_{2/3}$$
  $$\mathcal{Q}'_{-1/3} = \begin{bmatrix} B_{-1/3} & T' \\ B_{-4/3} & B' \end{bmatrix} = (2,2)_{-1/3}\,, \quad \tilde{B} = (1,1)_{-1/3}$$
  $$\mathcal{H} = (2,2)_0$$
- $$\mathcal{L}_{mix} = -\Delta_{L1}\bar{q}_L\,(T,B) - \Delta_{R1}\bar{t}_R\tilde{T} - \Delta_{L2}\bar{q}_L\,(T',B') - \Delta_{R2}\bar{b}_R\tilde{B} + h.c.$$
- $\Delta_{L2} \ll \Delta_{L1}$ $$m_b = \frac{v}{\sqrt{2}} Y_{*D} s_2 s_{bR} \quad m_t = \frac{v}{\sqrt{2}} Y_{*U} s_1 s_R\,, \quad s_2 = \frac{\Delta_{L2}}{M_{Q'}} c_1$$

b_L P_{LR} eigenstate for $\Delta_{L2} = 0$ $(T_{3L}(B) = T_{3R}(B),\ \underbrace{T_{3L}(B') \neq T_{3R}}_{\Delta_{L2}}(B'))$

$$\delta g_{Lb} \sim \frac{1}{2}\frac{m_t^2}{M_Q^2 s_R^2}\left[s_2^2 + \frac{M_Z^2}{M_Q^2}\right]$$

t_R and b_R P_C eigenstates

SO(5)xU(1)x → SO(4)xU(1)x
TS-5

- $$\mathcal{Q}_{2/3} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix} = (2,2)_{2/3}\,,\ \tilde{T} = (1,1)_{2/3}$$
  $$\mathcal{Q}'_{-1/3} = \begin{bmatrix} B_{-1/3} & T' \\ B_{-4/3} & B' \end{bmatrix} = (2,2)_{-1/3}\,,\ \tilde{B} = (1,1)_{-1/3}$$
  $$\mathcal{H} = (2,2)_0$$
- $$\mathcal{L}_{mix} = -\Delta_{L1}\bar{q}_L\,(T,B) - \Delta_{R1}\bar{t}_R\tilde{T} - \Delta_{L2}\bar{q}_L\,(T',B') - \Delta_{R2}\bar{b}_R\tilde{B} + h.c.$$
- $\Delta_{L2} \ll \Delta_{L1}$ $$m_b = \frac{v}{\sqrt{2}}Y_{*D}s_2 s_{bR} \quad m_t = \frac{v}{\sqrt{2}}Y_{*U}s_1 s_R\,, \quad s_2 = \frac{\Delta_{L2}}{M_{Q'}}c_1$$

$m_b \ll m_t$ do not require
an almost fully elementary b_R

SO(5)xU(1)x → SO(4)xU(1)x TS-10

- $$\mathcal{Q}_{2/3} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix} = (2,2)_{2/3}$$

$$\tilde{\mathcal{Q}}_{2/3} = \begin{pmatrix} \tilde{T}_{5/3} \\ \tilde{T} \\ \tilde{B} \end{pmatrix} = (1,3)_{2/3} \ , \ \mathcal{Q}'_{2/3} = \begin{pmatrix} T'_{5/3} \\ T' \\ B' \end{pmatrix} = (3,1)_{2/3}$$

- $$\mathcal{L}_{mix} = -\Delta_{L1}\bar{q}_L\,(T,B) - \Delta_{R1}\bar{t}_R\tilde{T} - \Delta_{R2}\bar{b}_R\tilde{B} + h.c.$$

$$m_t = \frac{v}{\sqrt{2}}Y_* s_1 s_R \quad m_b = \frac{v}{\sqrt{2}}Y_* s_1 s_{bR} \ , \quad s_1 = \frac{\Delta_{L1}}{M'_Q} \ s_R = \frac{\Delta_{R1}}{M_{\tilde{T}}} \ s_{bR} = \frac{\Delta_{R2}}{M_{\tilde{B}}}$$

b_L P_{LR} eigenstate

$$\delta g_{Lb} \sim \frac{1}{2}\frac{m_t^2}{M_Q^2 s_R^2}\left[\frac{M_Z^2}{M_Q^2}\right] + o\left(\frac{m_b^2}{M_Q^2}\right)$$

t_R P_C eigenstate ($T_{3L} = T_{3R} = 0$), b_R not ($T_{3R} \neq 0$)

SO(5)xU(1)x → SO(4)xU(1)x
TS-10

- $$\mathcal{Q}_{2/3} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix} = (2,2)_{2/3}$$

$$\tilde{\mathcal{Q}}_{2/3} = \begin{pmatrix} \tilde{T}_{5/3} \\ \tilde{T} \\ \tilde{B} \end{pmatrix} = (1,3)_{2/3} \;, \quad \mathcal{Q}'_{2/3} = \begin{pmatrix} T'_{5/3} \\ T' \\ B' \end{pmatrix} = (3,1)_{2/3}$$

- $$\mathcal{L}_{mix} = -\Delta_{L1}\bar{q}_L\,(T,B) - \Delta_{R1}\bar{t}_R\tilde{T} - \Delta_{R2}\bar{b}_R\tilde{B} + h.c.$$

$$m_t = \frac{v}{\sqrt{2}}Y_* s_1 s_R \quad m_b = \frac{v}{\sqrt{2}}Y_* s_1 s_{bR} \;, \quad s_1 = \frac{\Delta_{L1}}{M'_Q} \; s_R = \frac{\Delta_{R1}}{M_{\tilde{T}}} \; s_{bR} = \frac{\Delta_{R2}}{M_{\tilde{B}}}$$

$$m_b \ll m_t \longrightarrow s_{bR} \ll s_R$$

b_R almost fully elementary

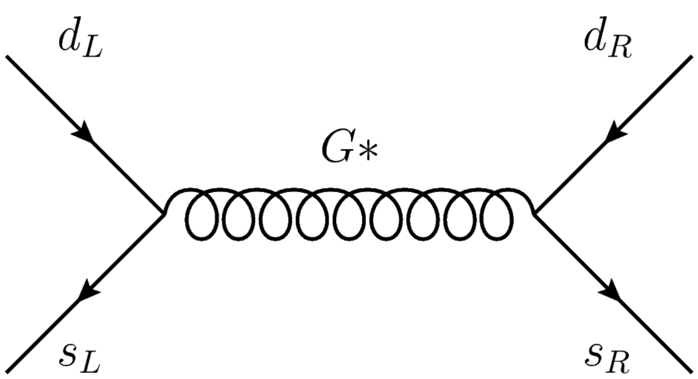
M_{G*}/m_* ?? ...what from data?

- $\mathbf{m}_* \gtrsim 1\ TeV$ MFV bound from $b \to s\gamma$

  [$\mathbf{m}_* \lesssim (3 \div 4)\ TeV$ (naturalness)] $f.t. \approx 1\%$

- $\mathbf{M}_{\mathbf{G}*} \gtrsim\ 11 \left(\frac{g_{*3}}{Y_*}\right) TeV$ NMFV bound from ϵ_K

  [in the TS-5: $\mathbf{M}_{\mathbf{G}*} \gtrsim\ \frac{s_1}{s_2}\ 11 \left(\frac{g_{*3}}{Y_*}\right) TeV$]



$$\mathcal{O}_4 = \bar{d}_R^\alpha s_L^\alpha \bar{d}_L^\beta s_R^\beta$$

Contribution from the mixing via 3rd generation:

$$\mathcal{C}_4 \sim \frac{g_{*3}^2}{M_{G*}^2}(D_L^\dagger)_{13}(D_L)_{23}s_1^2(D_R)_{23}(D_R^\dagger)_{13}s_{bR}^2$$

$$\sim s_1^2 s_{bR}^2 \frac{g_{*3}^2}{M_{G*}^2}\frac{m_s m_d}{m_b^2}$$

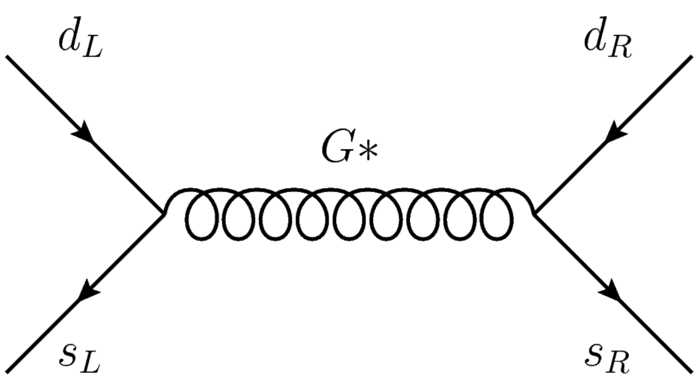
M_{G*}/m_* ?? ...what from data?

- $\mathbf{m}_* \gtrsim 1\ TeV$ MFV bound from $b \to s\gamma$

  [$\mathbf{m}_* \lesssim (3 \div 4)\ TeV$ (naturalness)] $f.t. \approx 1\%$

- $\mathbf{M}_{\mathbf{G}*} \gtrsim\ 11 \left(\frac{g_{*3}}{Y_*}\right) TeV$ NMFV bound from ϵ_K

  [in the TS-5: $\mathbf{M}_{\mathbf{G}*} \gtrsim\ \frac{s_1}{s_2}\ 11 \left(\frac{g_{*3}}{Y_*}\right) TeV$]



$\mathcal{O}_4 = \bar{d}^\alpha_R s^\alpha_L \bar{d}^\beta_L s^\beta_R$

Bound evaluated with the **assumptions**:

- Anarchical Y_*
- $(D_{L,R})_{ij} \sim \frac{(s_{L,R})_i}{(s_{L,R})_j}$ $D^\dagger_L D_L = U^\dagger_L D_L \equiv V_{CKM}$