Discovering the composite Higgs through the decay of a heavy fermion

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*a*rXiv: 1204.0468

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Composite Higgs from a New Strong dynamics

SOLUTION TO THE HIERARCHY PROBLEM

Georgi, Kaplan, 1984

• Higgs mass not sensitive to radiative corrections above the compositeness scale (O(TeV)) [*Analogy with the PION mass in QCD*]
• Further protection if it is also the pGB of a global symmetry in the strong sector

ELEMENTARY Sector

$\mathcal{G}_{SM} \equiv SU(2)_L \times U(1)_Y$

STRONG EWSB Sector

$\mathcal{G} \underset{\mathbf{H}}{\longrightarrow} \mathcal{H}_1 \supset \mathcal{G}_{SM}$

elementary/composite mixing

small rotation ↓

light (SM) / heavy (NP)

t, b, g, ... / T, B, G*, ...

Strong couplings among composites

$g_{1*}, g_{2*}, g_{3*}, Y_* \gg g_1, g_2, g_3, Y$

$1 < Y_* \ll 4\pi$

Heavier particles have larger degrees of compositeness

$$\mathcal{L} = \mathcal{L}_{\mathrm{elementary}} + \mathcal{L}_{\mathrm{composite}} + \mathcal{L}_{\mathrm{mixing}}$$

$$\mathcal{H} = (\mathbf{2},\mathbf{2})_0 = \begin{bmatrix} \phi_0^\dagger & \phi^+ \\ -\phi^- & \phi_0 \end{bmatrix}$$

$$\mathcal{L}_{composite} = + Tr\left\{\bar{\mathcal{Q}}\left(i\,\not\partial - M_{Q*}\right)\mathcal{Q}\right\} + \dots$$
$$+ \frac{1}{2}\,\mathrm{Tr}\left\{\partial_\mu \mathcal{H}^\dagger \partial^\mu \mathcal{H}\right\} - V(\mathcal{H}^\dagger\mathcal{H})$$
$$+ Y_* Tr\left\{\bar{\mathcal{Q}}\mathcal{H}\tilde{\mathcal{Q}}\right\} + \dots$$

$$1 < Y_* \ll 4\pi$$

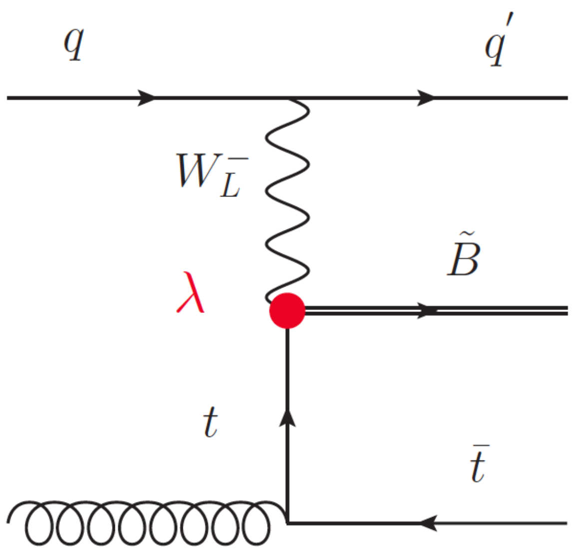
elementary/composite
mixing
+
EWSB

$$m_\psi = \frac{v}{\sqrt{2}} Y_* \sin\varphi_L \sin\varphi_{\psi R}$$

$$Y_* \sin\varphi\cos\varphi\ \bar{\chi}\psi h/W_L/Z_L$$

INTERACTIONS
Heavy fermion – SM fermion – EW bosons

Single production of a heavy-bottom



$$\mathcal{H} = (\mathbf{2},\mathbf{2})_0 = \begin{bmatrix} \phi_0^\dagger & \phi^+ \\ -\phi^- & \phi_0 \end{bmatrix}$$

$$\begin{aligned} \mathcal{L}_{\tilde{B},h} = & \frac{1}{2}\mathrm{Tr}\left\{\partial_\mu \mathcal{H}^\dagger \partial^\mu \mathcal{H}\right\} - V(\mathcal{H}^\dagger \mathcal{H}) \\ & + \bar{\tilde{B}}\left(i \not{\partial} - m_{\tilde{B}}\right)\tilde{B} \\ & - \lambda\left(\bar{b}_L \phi_0 \tilde{B}_R + \bar{t}_L \phi^+ \tilde{B}_R\right) + h.c. \end{aligned}$$

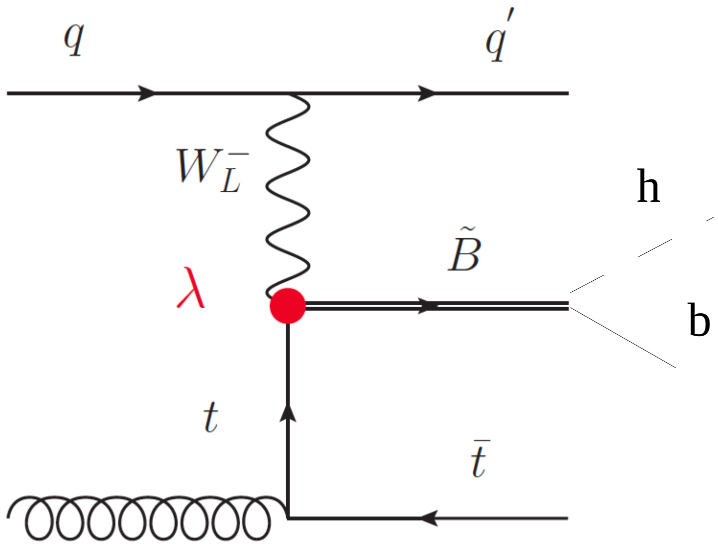
$$\lambda = Y_* \sin\varphi_L \cos\varphi_{bR} \simeq Y_* \sin\varphi_L \gtrsim 1$$

Sizable contribution to the Higgs production

Heavy-bottom BRs are fixed by the equivalence theorem:

$$BR(\tilde{B} \to W_L t) \simeq 50\% \qquad BR(\tilde{B} \to Z_L b) \simeq BR(\tilde{B} \to hb) \simeq 25\%$$

Higgs production from a Singly-produced heavy-bottom



$$\mathcal{L}_{\tilde{B},h} = \frac{1}{2}\,\mathrm{Tr}\left\{\partial_\mu \mathcal{H}^\dagger \partial^\mu \mathcal{H}\right\} - V(\mathcal{H}^\dagger \mathcal{H})$$
$$+ \bar{\tilde{B}}\,(i\not\partial - m_{\tilde{B}})\,\tilde{B}$$
$$- \lambda \left(\bar{b}_L \phi_0 \tilde{B}_R + \bar{t}_L \phi^+ \tilde{B}_R\right) + h.c.$$

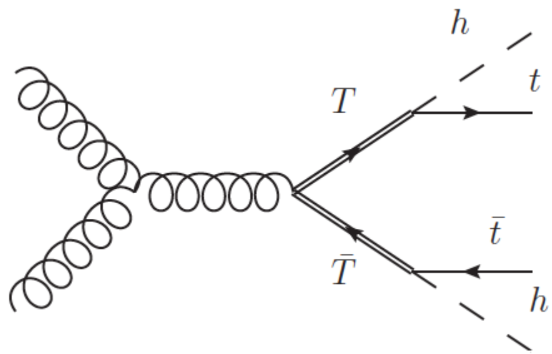
$$\lambda = Y_* \sin\varphi_L \cos\varphi_{bR} \simeq Y_* \sin\varphi_L \gtrsim 1$$

- Sizable cross section
- Dependence on few parameters: λ, m_B
- Possibility to measure the λ coupling

Other interesting Heavy-quark-mediated Higgs production mechanisms:

- Double production

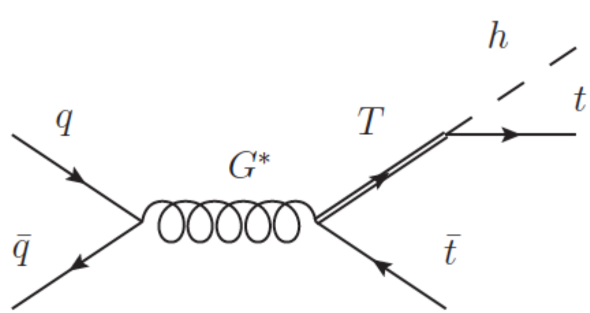
Azatov et al.
arxiv:1204.0455



Less powerful than single production for highest values of the heavy fermion mass

- Single production from a heavy gluon

Carmona, Chala, Santiago
arxiv:1203.1488

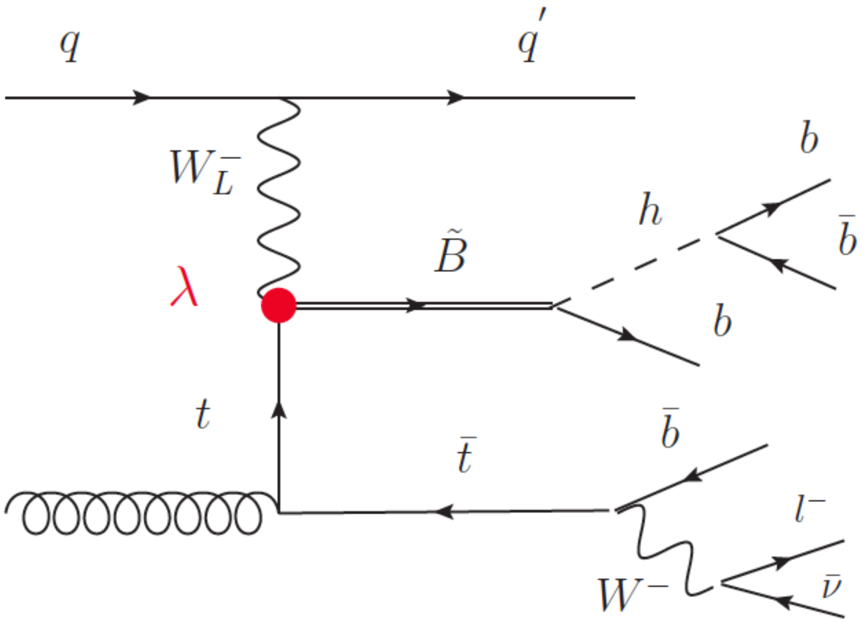


Very interesting channel for the discovery of a heavy gluon (arxiv:1107.4558; 1110.6058; 1110.5914)

Could be very powerful but it is much more model dependent

They do not allow for a measure of the λ coupling

Discovery analysis of the single production



Final state: $pp \to l^{\pm} + n\, jets + \not{E}_T$

Main backgrounds

- wwbb+jets (mainly tt+jets events)
- wbb+jets
- w+jets

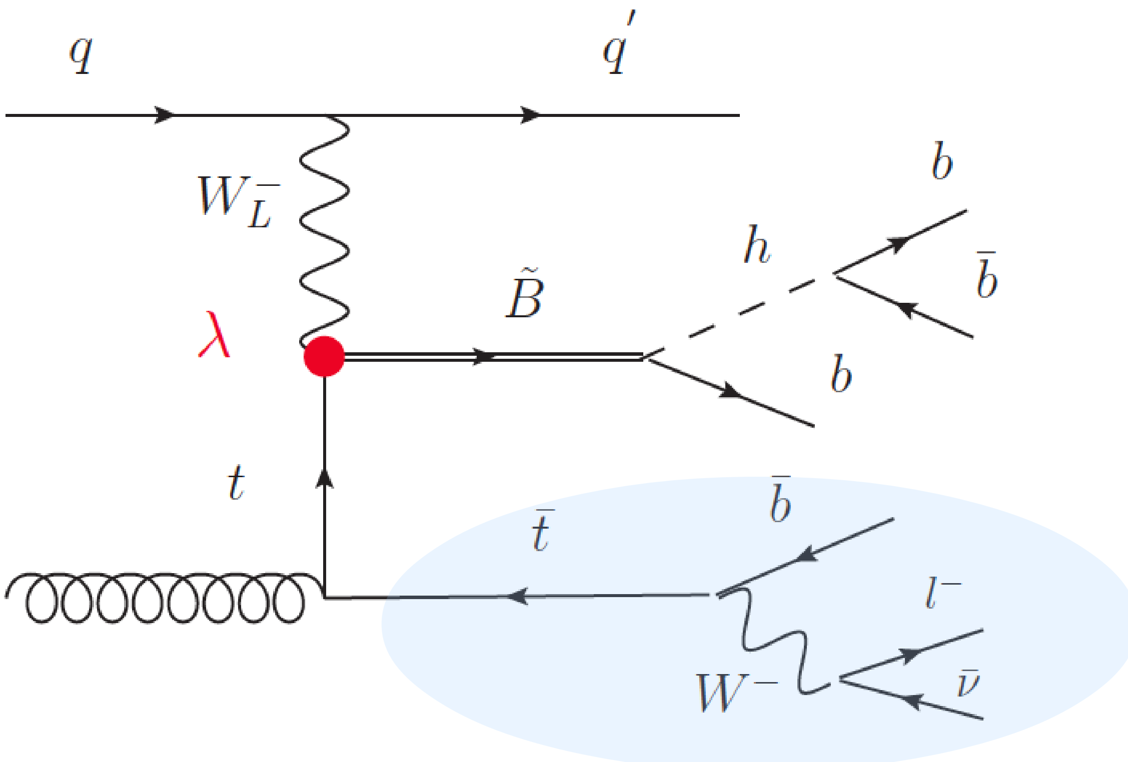
We impose: $n \geq 4\,,\quad$ At least 2 b-tag

With jets and leptons satisfying the acceptance cuts:

$$p_T\ j \geq 30\,\text{GeV} \qquad |\eta_j| \leq 5 \qquad \Delta R_{jj} \geq 0.4$$

$$p_T\ l \geq 20\,\text{GeV} \qquad |\eta_l| \leq 2.5 \qquad \Delta R_{jl} \geq 0.4$$

Heavy-bottom and Higgs reconstruction

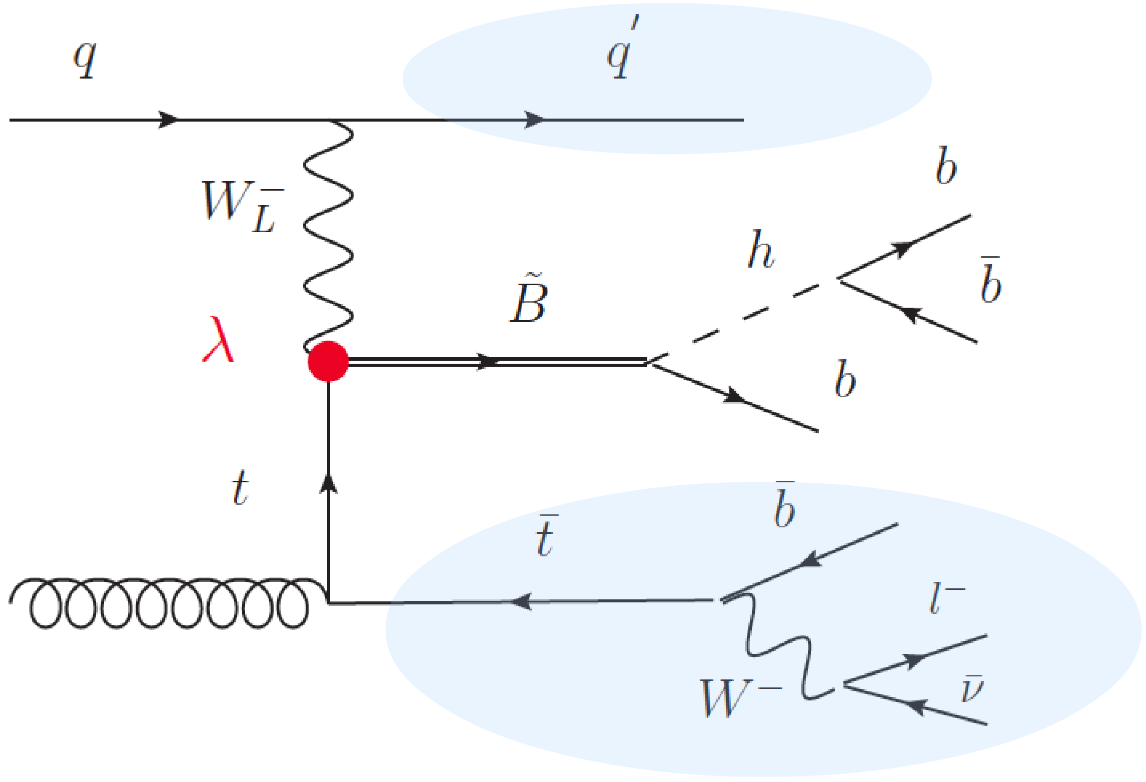


1) Top Reconstruction

After the neutrino reconstruction, we select among all the possible Wj combinations the one with the inv. mass closest to the top mass

Heavy-bottom and Higgs reconstruction

q' is emitted at very high rapidity



2) Light-jet tag

The final light-jet is the jet (not coming from the top) with the highest rapidity in almost the 90% of the events

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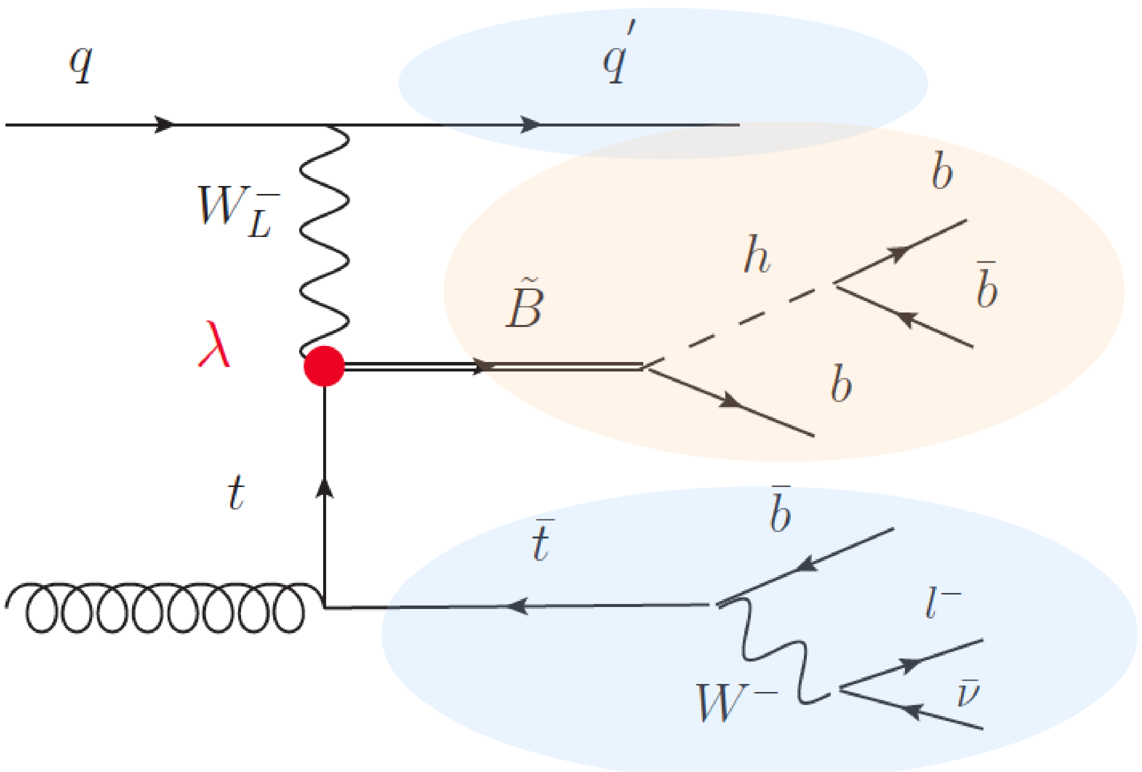

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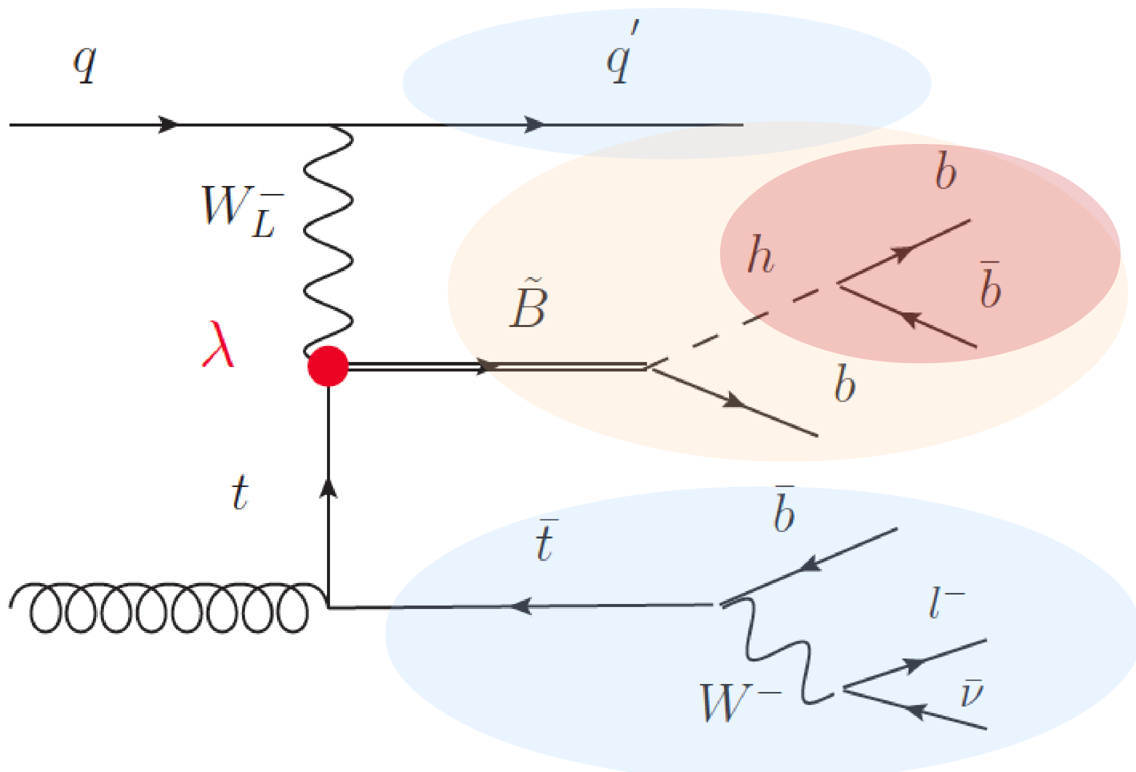

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The b directy-produced from the heavy-bottom is harder than the b's from the Higgs

1) Top Reconstruction

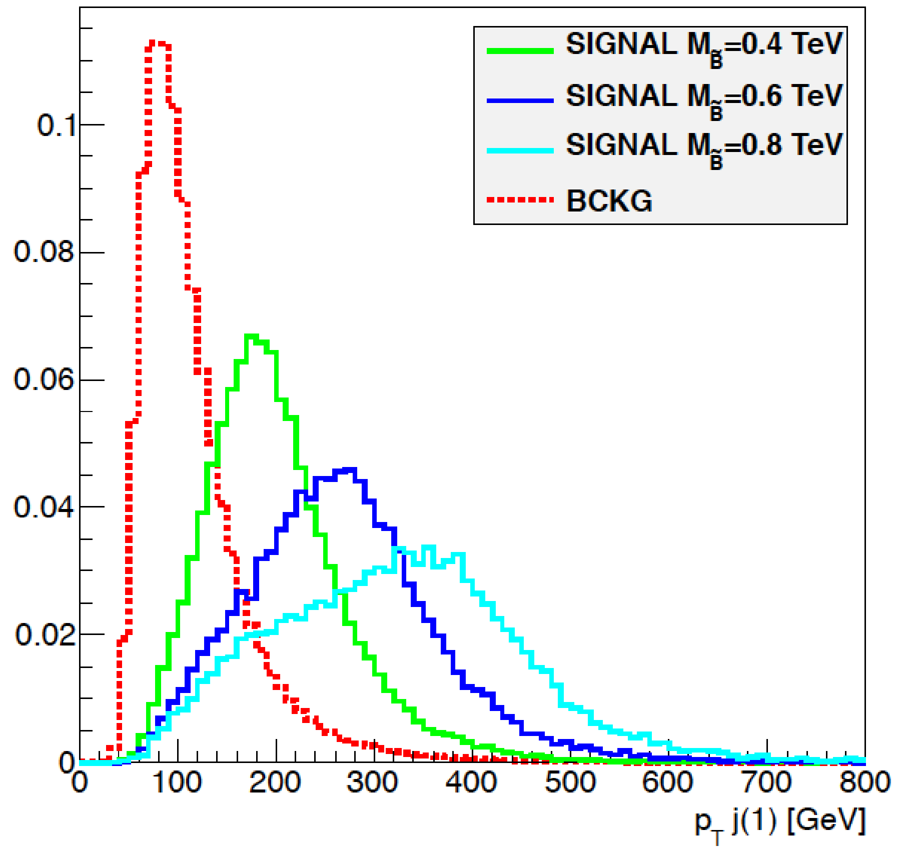
After the neutrino reconstruction, we select among all the possible Wj combinations the one with the inv. mass closest to the top mass

The *Higgs* resonance is reconstructed discarding from the heavy-bottom decay products the hardest jet among them

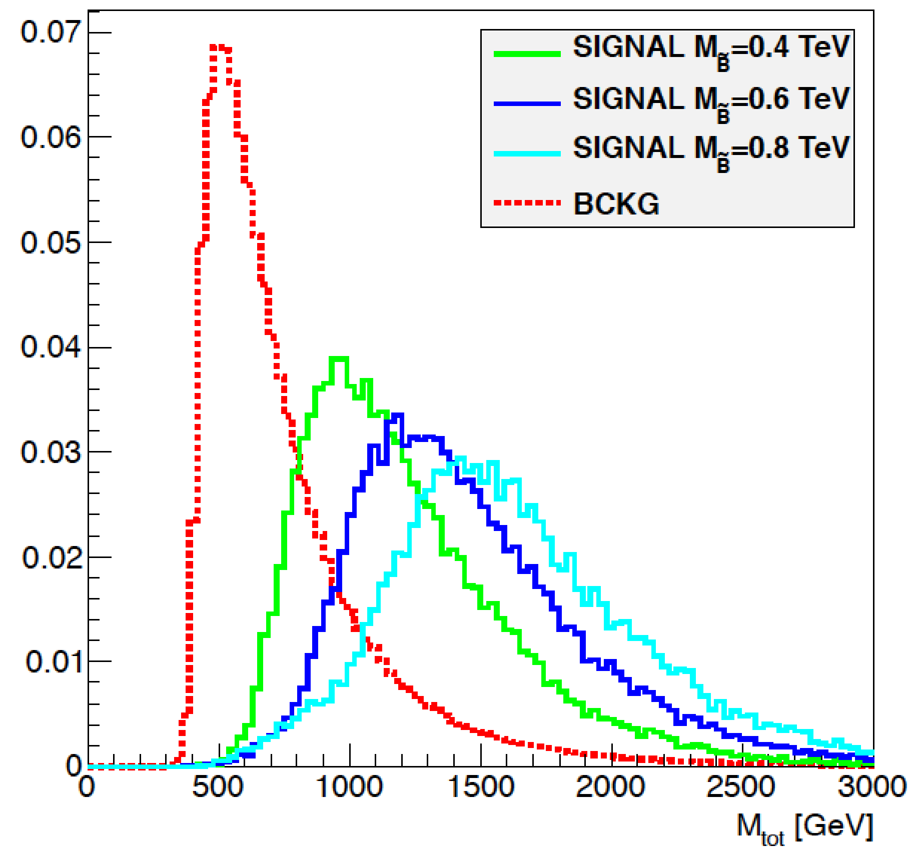
Main Cuts

We exploit the signal peculiarities:

- Exchange of a heavy resonance → energetic final state
- Final light-jet at very high rapidity



$p_T\ j(1) > 170$ GeV



$M_{\tilde{B}tj} > 1200$ GeV

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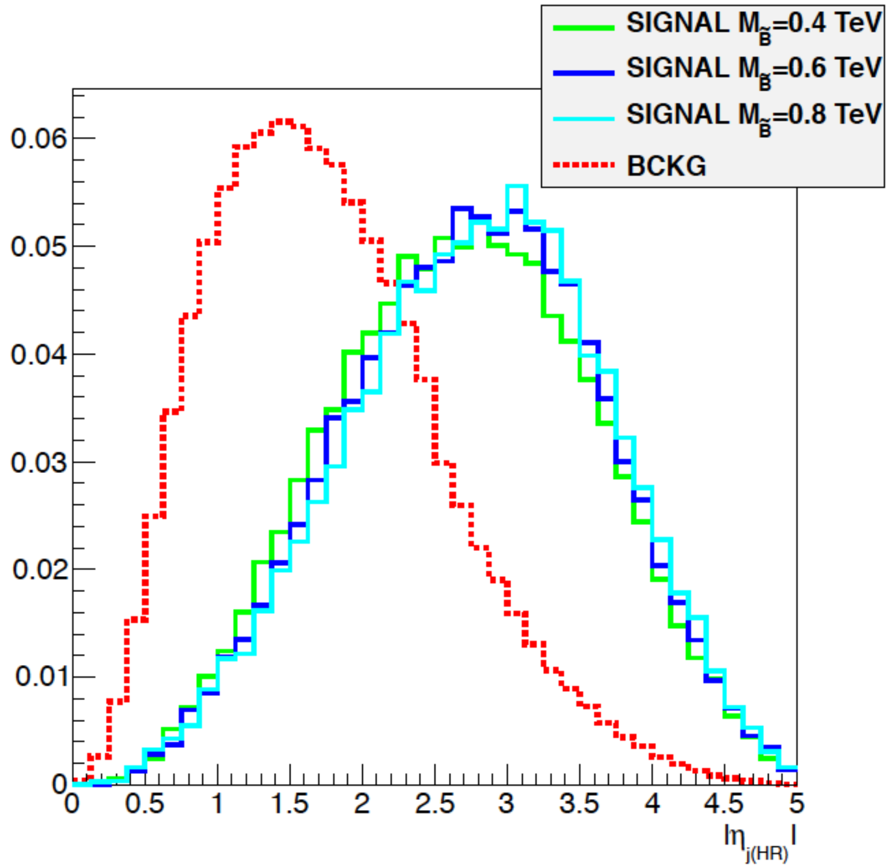


$$M_{\tilde{B}tj} > 1200 \text{ GeV}$$

$$p_T \; j(1) > 170 \text{ GeV}$$

$$p_T \; j(2) > 100 \text{ GeV}$$

$$\eta_{j(HR)} > 2.5$$

$$p_T \; top > 100 \text{ GeV}$$

$$\gamma(h) > 1.4$$

$$|\eta_h| < 1.8$$

$$p_T \; j(HR) > 30 \text{ GeV}$$

$$M_{h-j} < 70 \text{ GeV}$$

Optimized to minimize the discovery luminosity of the signal with a heavy-bottom of 400 GeV. They will be refined in a second step for the cases of heaviest bottom-prime

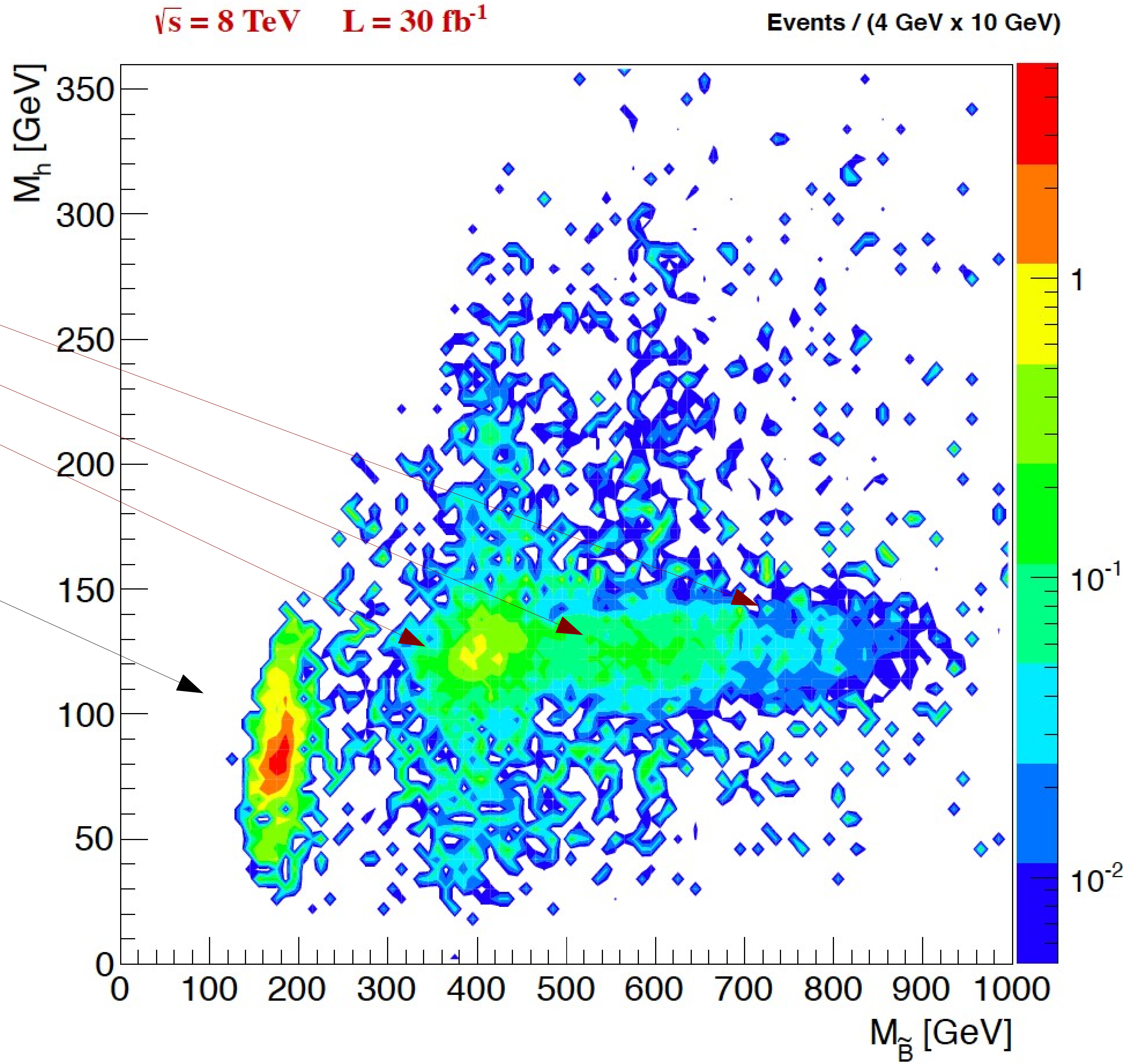
M_h vs M_B

Signal
λ=3
mh=125 GeV

m_B= 800 GeV
m_B= 600 GeV
m_B =400 GeV

+ BCKG

Bckg is mainly constituted by tt+jets events. Instead of the heavy bottom, in this case, we select a top and instead of the Higgs, the W from this top.



M_h vs M_B

Signal
λ=3
mh=125 GeV

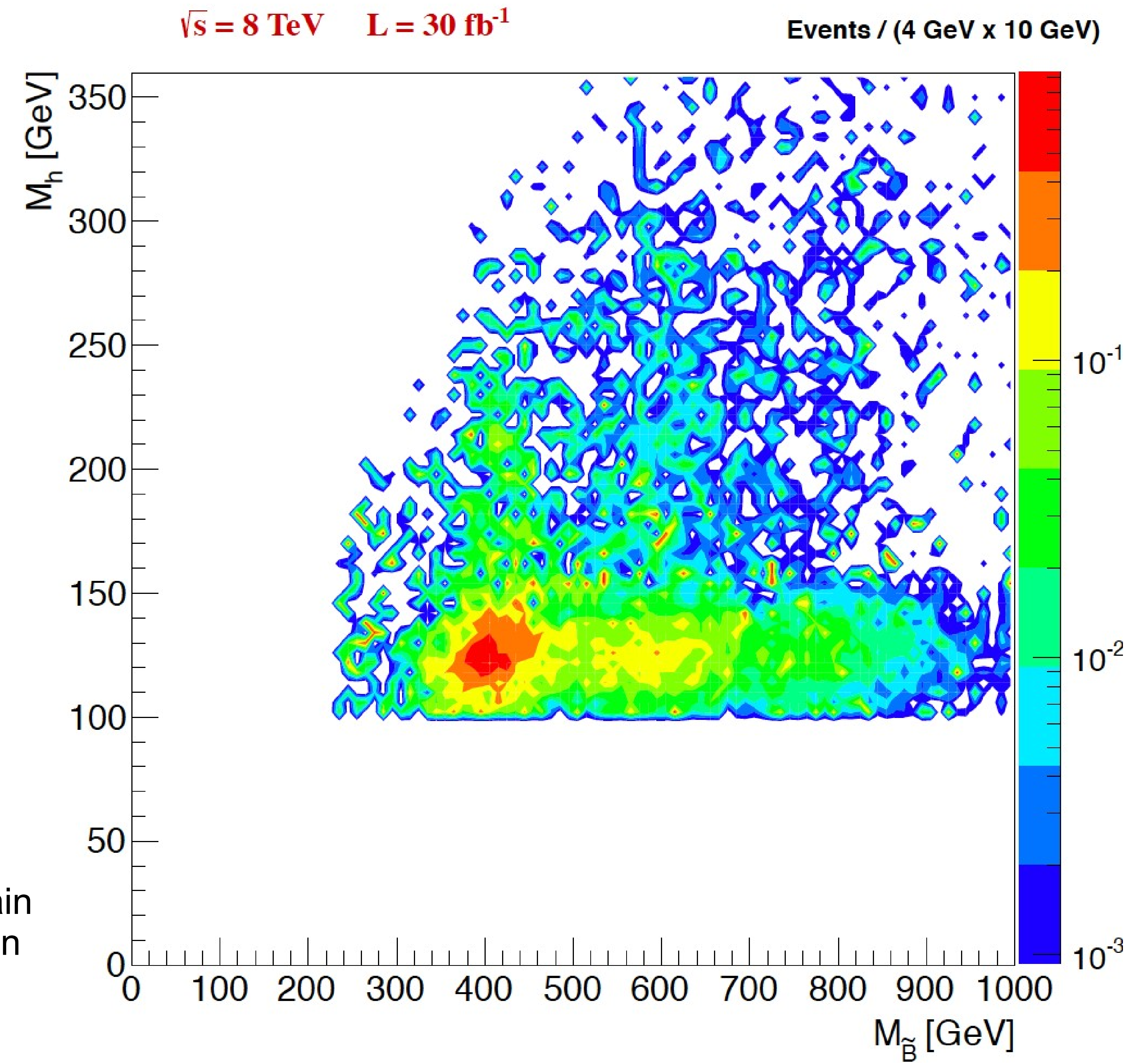
m_B= 800 GeV
m_B= 600 GeV
m_B =400 GeV

+ BCKG

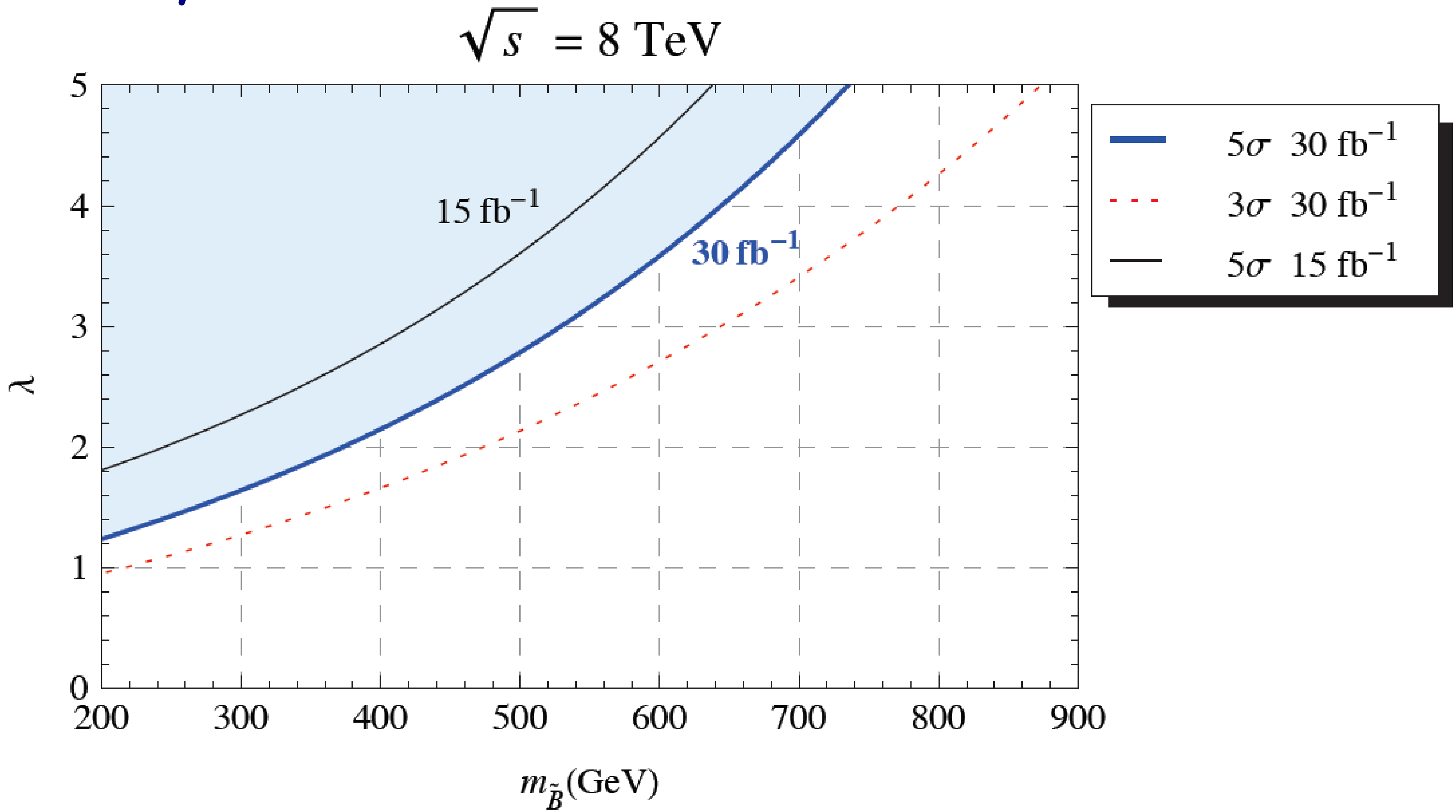
We cut away the region < (mt, mW)

↓

Signal excess clearly observable:
We can refine the main cuts and apply cuts on M_B , M_h

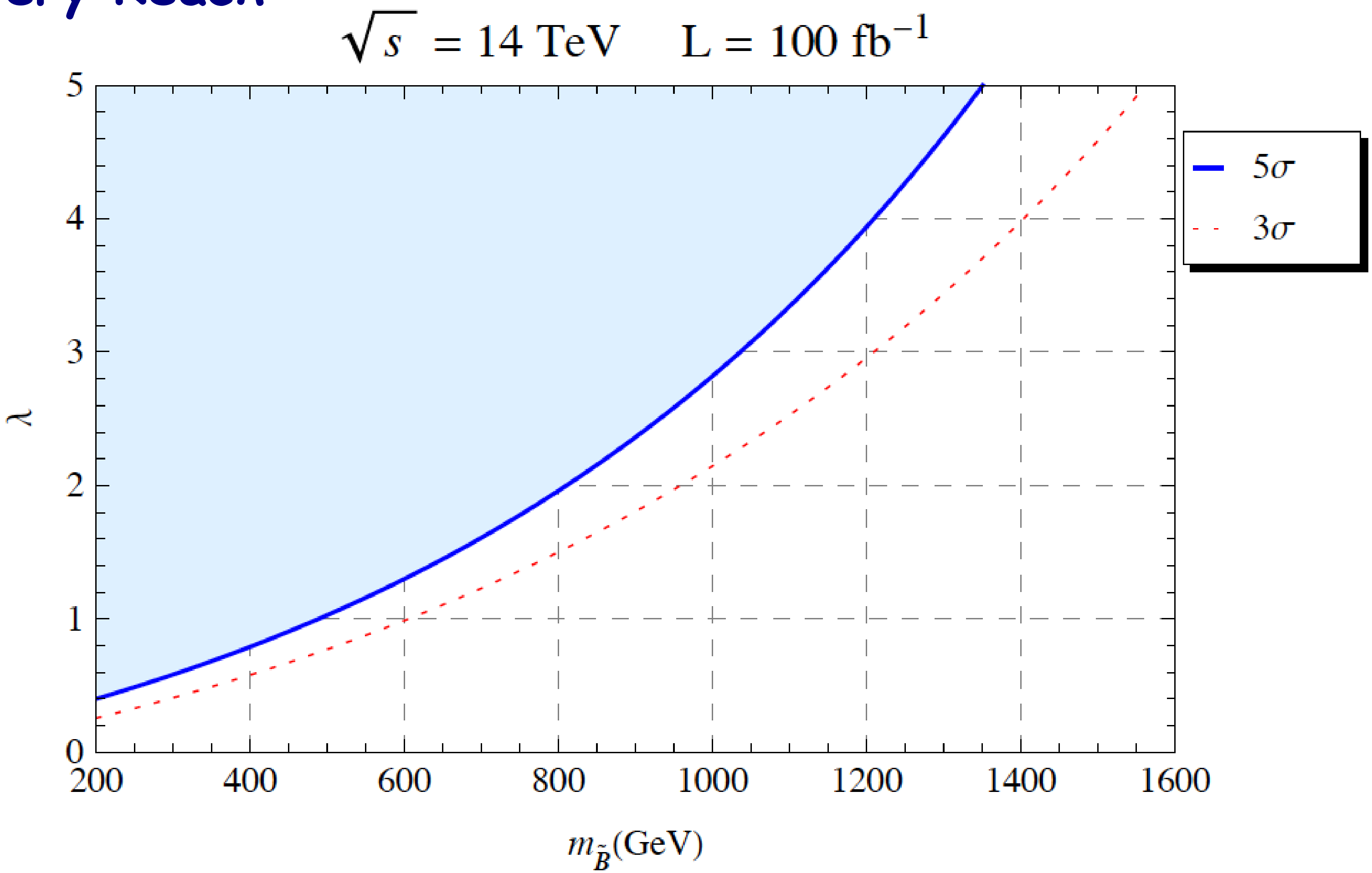


LHC Discovery Reach



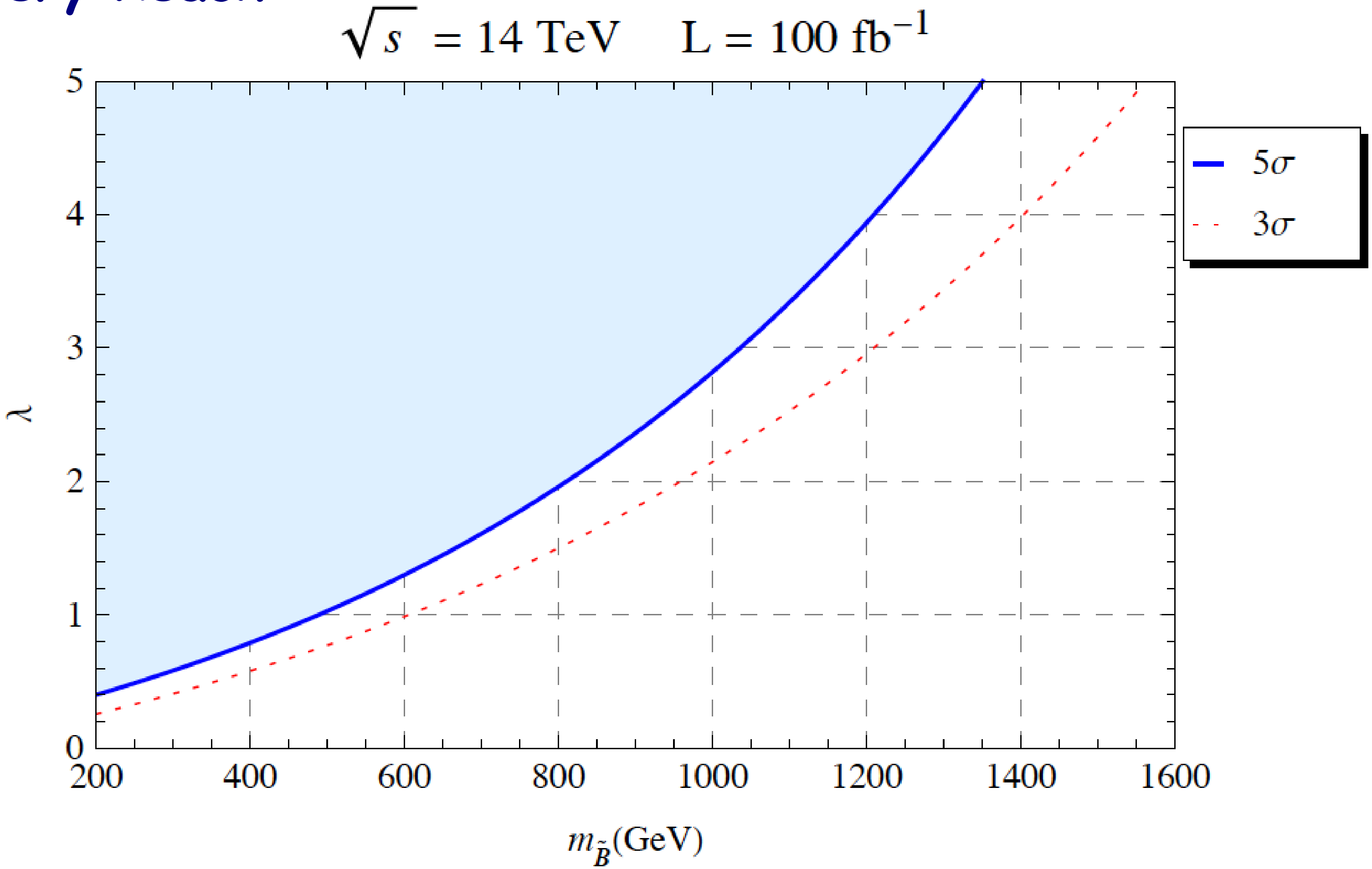
For a reference value **λ=3** With **30 fb-1** → Discovery (observation) for heavy bottom with mass up to **530 (650) GeV**

LHC Discovery Reach



- Wide discovery reach
- In the case of a heavy bottom as light as **~500 GeV** the 14 TeV LHC would be sensitive to the measure of the λ coupling in basically the full range, **λ >1**, predicted by the theory

LHC Discovery Reach



A ~500 GeV heavy bottom is allowed → theoretically

In the specific case considered (TS10 model with custodial symmetry, arxiv:1204.0478) the heavy bottom is a ***custodian***, it could be much lighter than other resonances

↓

(Up to now and to my knowledge) experimentally

$M_{\tilde{B}} \gtrsim 420$ GeV derived from ATLAS collaboration, arxiv:1202.6540

Channels of Higgs production from singly-produced heavy fermions

The LHC Discovery reach in the plane (Λ_B, m_B) could be directly translated into a reach in the plane (Λ_T, m_T)

Final state		Mediating heavy fermion		light for
$\mathbf{hbt + jets}$	(W_L exchange)	$\tilde{B}$	$BR(\tilde{B} \to hb) \simeq 25\%$	composite t_R
		$\tilde{T}$	$BR(\tilde{T} \to ht) \simeq 25\%$	
		$\tilde{T}'$	$BR(\tilde{T}' \to ht) \simeq 25\%$	composite t_R
$\mathbf{ht\bar{t} + jets}$	(Z_L/h exchange)	T	$BR(T \to ht) \simeq 50\%$	
		$T_{2/3}$	$BR(T_{2/3} \to ht) \simeq 50\%$	composite t_L
		$\tilde{T}$	$BR(\tilde{T} \to ht) \simeq 25\%$	
		$\tilde{T}'$	$BR(\tilde{T}' \to ht) \simeq 25\%$	composite t_R
$\mathbf{hb\bar{b} + jets}$	(Z_L/h exchange)	$\tilde{B}$	$BR(\tilde{B} \to hb) \simeq 25\%$	composite t_R
		$\tilde{B}'$	$BR(\tilde{B}' \to hb) \simeq 50\%$	composite t_R

In the TS10. Similar contributions are expected in different CHM with custodial symmetry

- **Comparative analyses of these channels, by measuring different Λ couplings, could shed light on the theory and on the EWSB mechanism**

Conclusions

The Higgs production from a singly-produced heavy fermion is a powerful channel to **TEST the Higgs properties and understand its nature**
(An analysis of the strong scattering of Higgs and W_L/Z_L would require for this a much larger amount of integrated luminosity, about 300 fb-1 at 14 TeV LHC [arxiv:1002.1011])

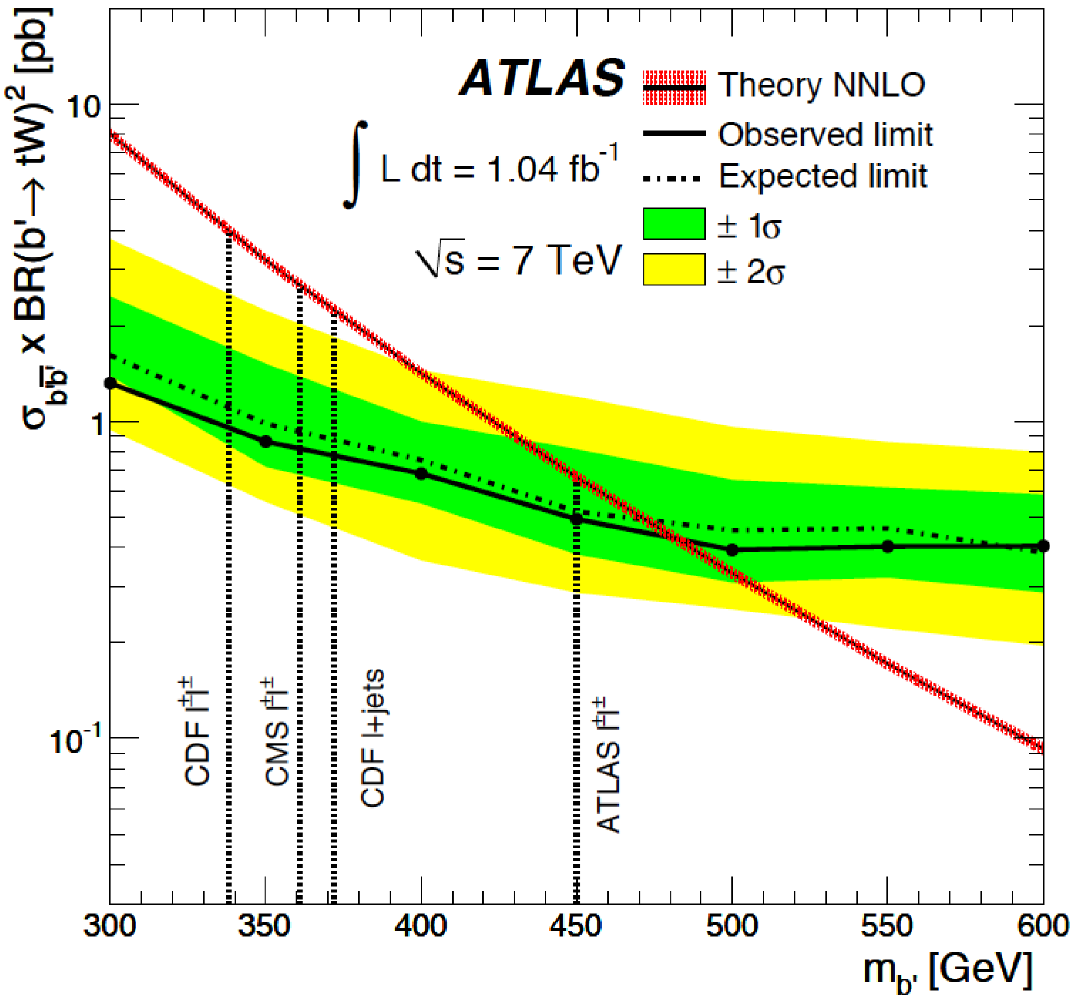
Also promising for the **DISCOVERY of the heavy fermion**

Important to **shed light on the theory behind the EWSB mechanism**, since it allows the measurement of the λ coupling among SM fermions, heavy fermions and electro-weak bosons

Extra Slides

Search for down-type fourth generation quarks

arxiv:1202.6540



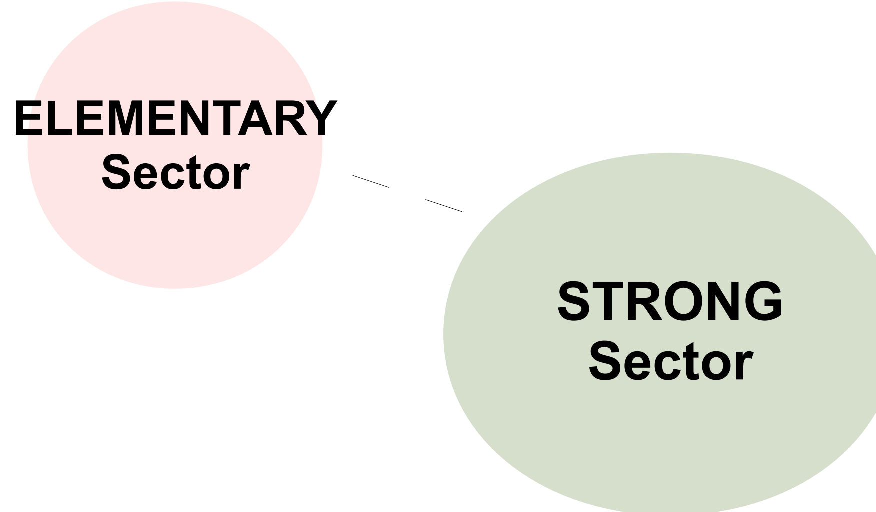
$$BR(b' \to Wt) = 1$$

$$m_{b'} > 480 \text{ GeV [95\% C.L.]}$$

$$BR(b' \to Wt) = 0.5$$

$$m_{b'} \gtrsim 420 \text{ GeV [95\% C.L.]}$$

PARTIAL COMPOSITENESS



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

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

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 $\rightarrow$ light (SM) / heavy (NP)

Two-Site models

t, b, ...

T, B, ...

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

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

Heavier particles have larger degrees of compositeness

LHC Discovery Reach

$\lambda = 3$

8 TeV

m_B =400 GeV

$$\int \mathcal{L} \simeq 14 \ fb^{-1} \qquad S/B \simeq 5.6$$

m_B= 600 GeV

$$\int \mathcal{L} \simeq 50 \ fb^{-1} \qquad S/B \simeq 4.6$$

m_B= 800 GeV

$$\int \mathcal{L} \simeq 340 \ fb^{-1} \qquad S/B \simeq 1.5$$

14 TeV

m_B =400 GeV

$$\int \mathcal{L} \simeq 1.5 \ fb^{-1} \qquad S/B \simeq 6.1$$

m_B= 600 GeV

$$\int \mathcal{L} \simeq 4.8 \ fb^{-1} \qquad S/B \simeq 6.0$$

m_B= 800 GeV

$$\int \mathcal{L} \simeq 23 \ fb^{-1} \qquad S/B \simeq 2.4$$

m_B= 1000 GeV

$$\int \mathcal{L} \simeq 78 \ fb^{-1} \qquad S/B \simeq 2.1$$

m_B= 1200 GeV

$$\int \mathcal{L} \simeq 260 \ fb^{-1} \qquad S/B \simeq 1.2$$

EWPT

- $$\rho = \frac{M_W^2}{M_Z^2 \cos\theta_W^2} = 1 \quad \text{[tree level]} \qquad \Delta\rho \propto (v/f)^2 \quad \text{[loop]}$$

  Custodial Symmetry in the Strong Sector:

$$SU(2)_L \times SU(2)_R \times U(1)_X \rightarrow SU(2)_V \times U(1)_X$$

- $\mathbf{Z b_L \bar{b}_L} \rightarrow$ Protection from custodial symmetry subgroup:

[Agashe, DaRold, Contino, Pomarol, PLB 641 (2006) 62]

$$g_{Lb}^{SM}|_{tree} = (Q_{3L} - Q \sin^2\theta_w)$$

$\mathbf{U(1)_V \times P_{LR}}$	$\mathbf{P_C}$
$SU(2)_L \leftrightarrow SU(2)_R$	$\vert T_L\ T_R;\ T_{3L}\ T_{3R}\rangle \rightarrow \vert T_L\ T_R;\ -T_{3L}\ -T_{3R}\rangle$
$inv \rightarrow T_L = T_R,\ T_{3L} = T_{3R}$	$SO(3)$ vectors: $P_C = diag(1,-1,-1)$
	$inv \rightarrow T_{3L} = T_{3R} = 0$

We derive a simple Two-Site Model (low-energy limit of MCHM10) which incorporates a custodial symmetry and a P_{LR} parity: TS10

SO(5)xU(1)x → SO(4)xU(1)x TS-10

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

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

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

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

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

b_R almost fully elementary