Teoria e fenomenologia dei modelli di Higgs composto

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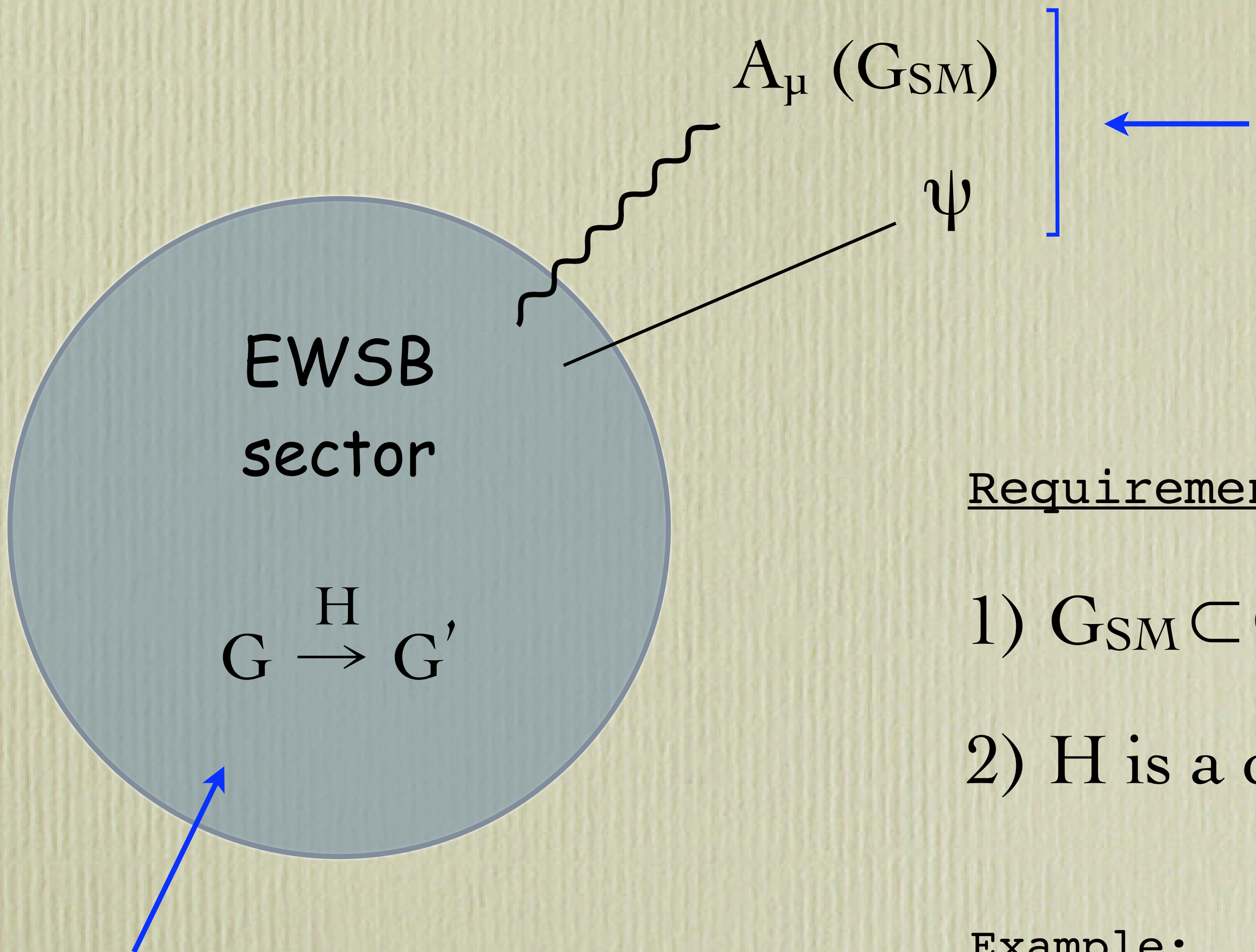
Part I:

Quick review of the Composite Higgs

Composite Higgs models

[Georgi & Kaplan, `80s]



SM (elementary) sector

EWSB sector characterized by:

$m_\rho \qquad g_{SM} \lesssim g_\rho \lesssim 4\pi$

(derived scale: $f = m_\rho / g_\rho$)

Requirements:

1) $G_{SM} \subset G'$

2) H is a doublet of $SU(2)_L$

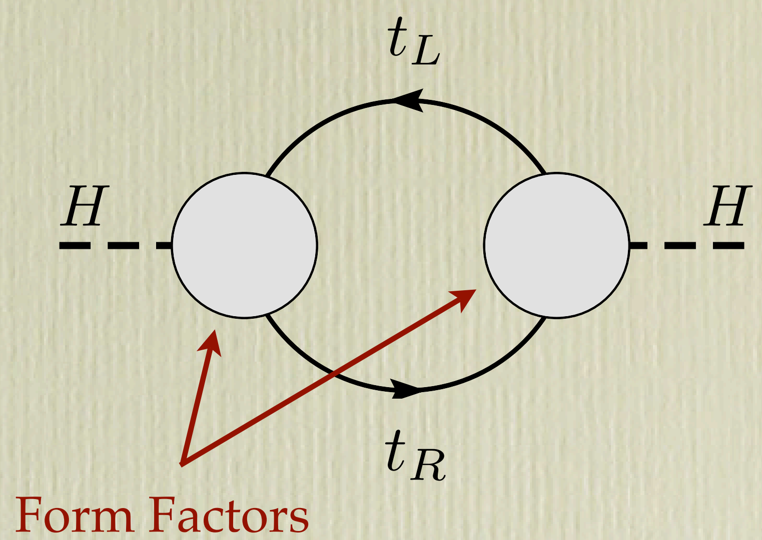
Example:

$SO(5) \rightarrow SO(4) \sim SU(2)_L \times SU(2)_R$

gives 4 real Goldstones: one $SU(2)_L$ doublet H

1-loop potential for the pseudo-Goldstone Higgs

- only loops with virtual elementary fields generate a potential
- Higgs couplings switch off at large momenta ➞ finiteness

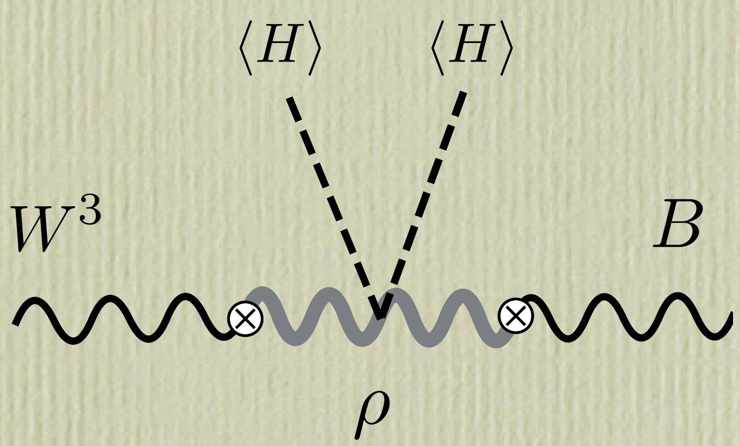


periodic function $(H \in G/G')$

$$V(h) \approx \frac{3\, y_t^2}{16\pi^2}\, m_\rho^2\, f^2\, \zeta(h/f) \qquad \lambda_4 \sim \frac{3}{16\pi^2}\, y_t^2\, g_\rho^2$$

$$\xi = \left(\frac{v}{f}\right)^2$$

← new parameter compared to TC (fixed by the dynamics)



$$m_\rho \sim \frac{4\pi f}{\sqrt{N}}$$

$$S \sim 16\pi \left(\frac{v}{m_\rho}\right)^2 \sim \xi \, \frac{N}{\pi}$$

$$\xi \to 0$$
$$[\, f \to \infty \,]$$

decoupling limit: All ρ's become heavy and one re-obtains the SM

Constraint on the strong sector from the LEP precision tests :

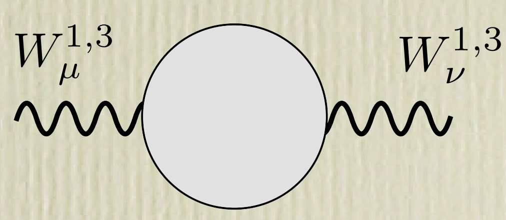
Custodial Symmetry

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \qquad \Delta\rho \equiv (\rho - 1) = \frac{4}{v^2}\left[\Pi_{11}(0) - \Pi_{33}(0)\right]$$

- The bound from LEP $\Delta\rho \lesssim 2\times 10^{-3}$ strongly constrains tree-level corrections

- If the residual symmetry after EWSB is just $U(1)_Q$ there will be tree-level corrections from the strong sector to $\Delta\rho$

$$\langle J^1_\mu J^1_\nu\rangle \neq \langle J^3_\mu J^3_\nu\rangle$$

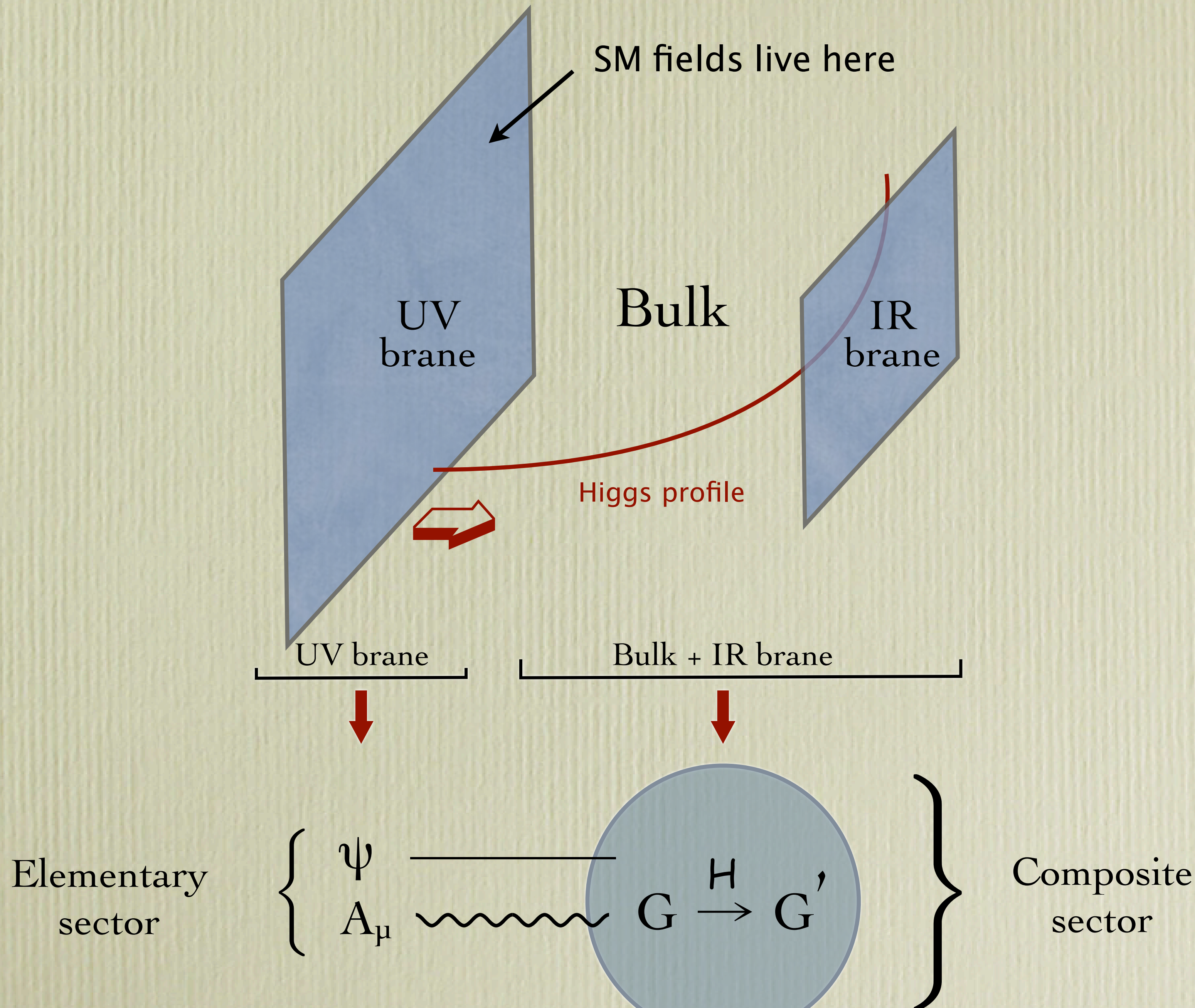


- A larger preserved "custodial" symmetry $SU(2)_C$ under which J^i_μ transforms like a triplet can protect $\Delta\rho$

[Sikivie et al. NPB 173 (1980) 189]

$$SU(2)_L \times SU(2)_R \to SU(2)_C \quad \Rightarrow \quad \langle J^1_\mu J^1_\nu\rangle = \langle J^3_\mu J^3_\nu\rangle$$

Equivalence with 5D warped field theories:



Part II:

Implications for the LHC

1. How to tell whether the Higgs is composite
2. Direct production of new states

An effective Lagrangian for the Strongly Interacting Light Higgs

built along the rules of the chiral expansion:

Giudice, Grojean, Pomarol, Rattazzi
JHEP 0706:045 (2007)

1. each extra Goldstone leg is weighted by a factor $1/f$
2. each derivative is weighted by a factor $1/m_\rho$
3. higher dimensional operators that violate the symmetry of the σ-model must be suppressed by g_{SM}

at the level of dimension-6 operators:

strong constraint from LEP

$\Delta\rho = c_T\xi$

$$\mathcal{L}_{\mathrm{SILH}} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$
$$- \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \mathrm{h.c.}\right)$$

probe strong coupling

$$+ \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$

1-loop suppressed →

$$+ \frac{i c_{HW} g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W^i_{\mu\nu} + \frac{i c_{HB} g'}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\left(D^\mu H\right)^\dagger\left(D^\nu H\right) B_{\mu\nu}$$

more than 1-loop suppressed →

$$+ \frac{c_\gamma g'^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g g_S^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}$$

form factors

dominant effect:

shift in the Higgs couplings

subdominant role in scattering amplitudes

one combination constrained by LEP: $\hat{S} = (c_W + c_B)\frac{m_W^2}{m_\rho^2}$

$$\mathcal{L}_{\rm SILH} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$
$$- \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right)$$
$$+ \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$
$$+ \frac{i c_{HW} g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{i c_{HB} g'}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$+ \frac{c_\gamma g'^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g g_S^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}$$

directly affect Higgs gluon production and Higgs decay to photons

(subdominant compared to c_H)

shifts in the Higgs couplings:

$$\Gamma\left(h\to f\bar{f}\right)_{\rm SILH}=\Gamma\left(h\to f\bar{f}\right)_{\rm SM}\left[1-\xi\left(2c_y+c_H\right)\right]$$

$$\Gamma\left(h\to W^+W^-\right)_{\rm SILH}=\Gamma\left(h\to W^+W^{(*)-}\right)_{\rm SM}\left[1-\xi\left(c_H-\frac{g^2}{g_\rho^2}\hat{c}_W\right)\right]$$

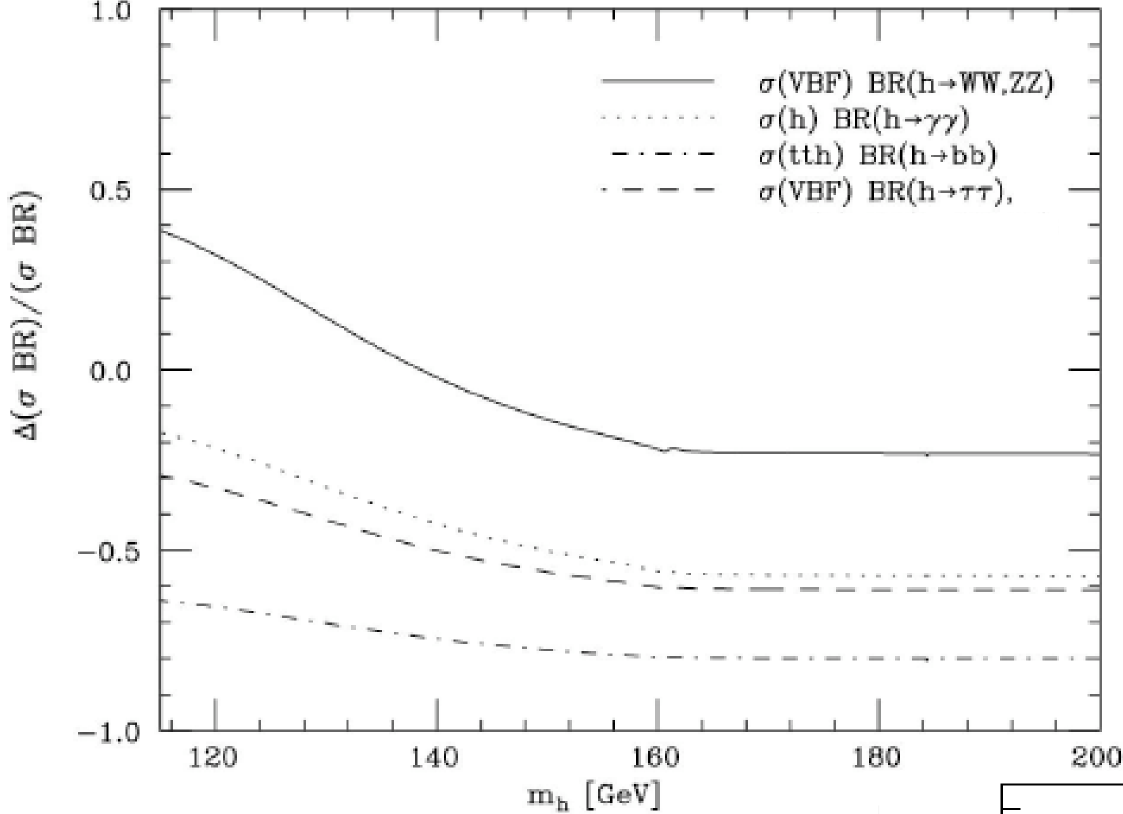
$$\Gamma\left(h\to ZZ\right)_{\rm SILH}=\Gamma\left(h\to ZZ^{(*)}\right)_{\rm SM}\left[1-\xi\left(c_H-\frac{g^2}{g_\rho^2}\hat{c}_Z\right)\right]$$

$$\Gamma\left(h\to gg\right)_{\rm SILH}=\Gamma\left(h\to gg\right)_{\rm SM}\left[1-\xi\,{\rm Re}\left(2c_y+c_H+\frac{4y_t^2c_g}{g_\rho^2I_g}\right)\right]$$

$$\Gamma\left(h\to\gamma\gamma\right)_{\rm SILH}=\Gamma\left(h\to\gamma\gamma\right)_{\rm SM}\left[1-\xi\,{\rm Re}\left(\frac{2c_y+c_H}{1+J_\gamma/I_\gamma}+\frac{c_H-\frac{g^2}{g_\rho^2}\hat{c}_W}{1+I_\gamma/J_\gamma}+\frac{\frac{4g^2}{g_\rho^2}c_\gamma}{I_\gamma+J_\gamma}\right)\right]$$

$$\Gamma\left(h\to\gamma Z\right)_{\rm SILH}=\Gamma\left(h\to\gamma Z\right)_{\rm SM}\left[1-\xi\,{\rm Re}\left(\frac{2c_y+c_H}{1+J_Z/I_Z}+\frac{c_H-\frac{g^2}{g_\rho^2}\hat{c}_W}{1+I_Z/J_Z}+\frac{4c_{\gamma Z}}{I_Z+J_Z}\right)\right]$$

$$\left[\hat{c}_W=c_W+\left(\frac{g_\rho}{4\pi}\right)^2c_{HW}\,,\quad \hat{c}_Z=\hat{c}_W+\tan^2\theta_W\left[c_B+\left(\frac{g_\rho}{4\pi}\right)^2c_{HB}\right],\quad c_{\gamma Z}=\frac{c_{HB}-c_{HW}}{4\sin2\theta_W}\right]$$



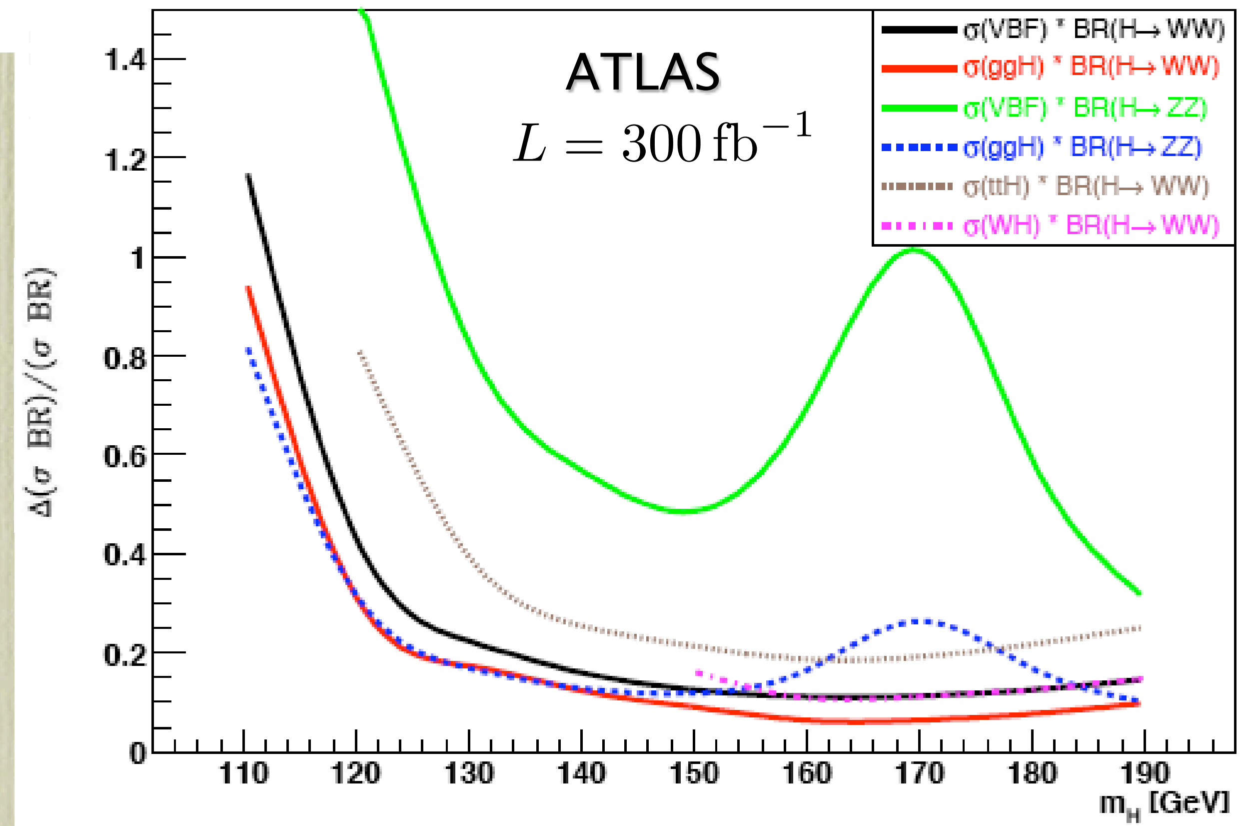
prediction of the SO(5)/SO(4) model [$c_y/c_H = 1$] for $c_H\xi = 0.25$

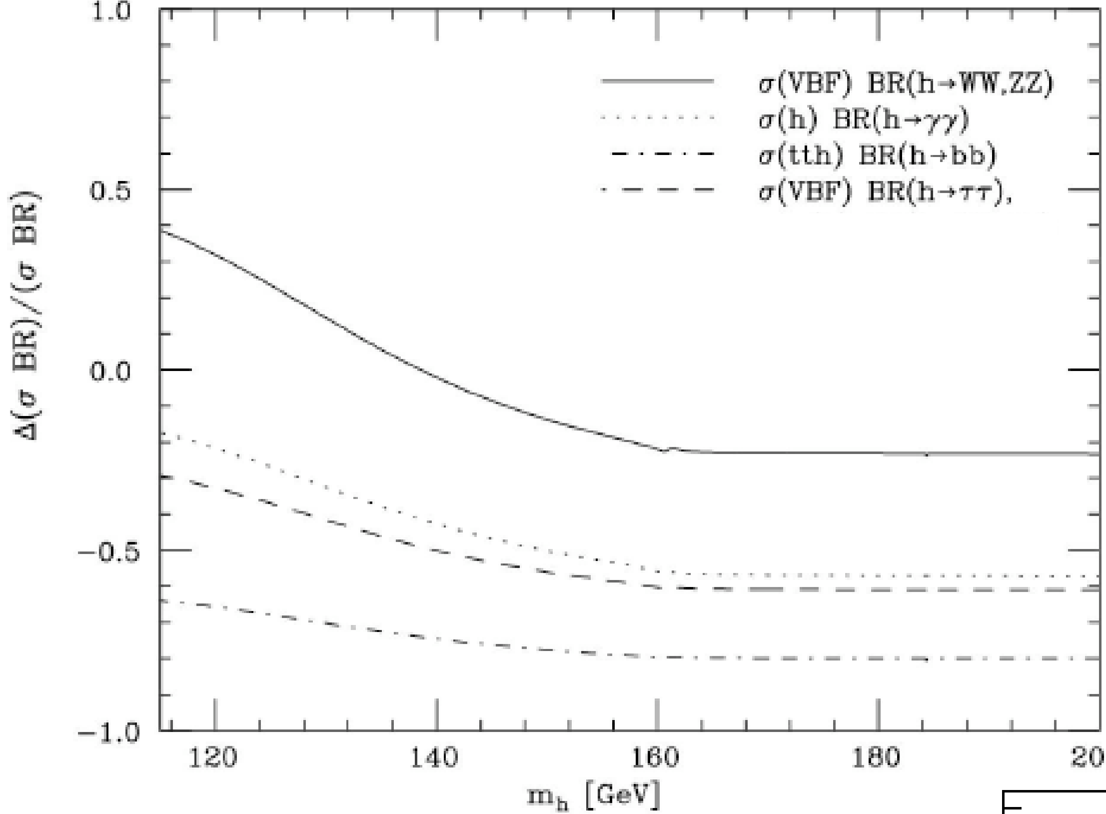
[Giudice et al. JHEP 0706:045, 2007]

LHC sensitive up to

$c_H\xi = 0.2 - 0.4$

[Duhrssen ATL-PHYS-2003-030]





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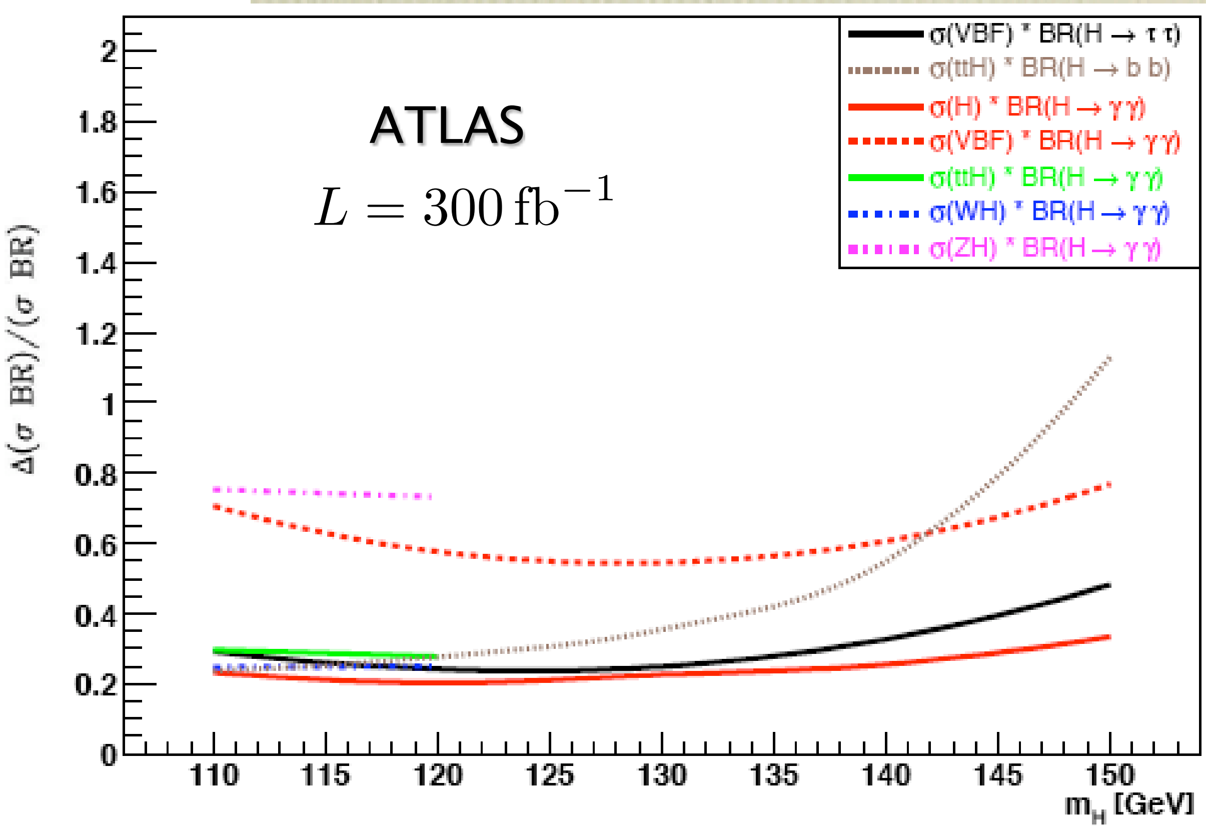
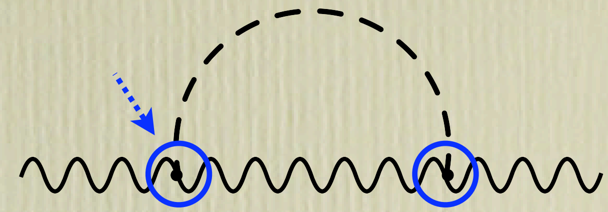


☞ as stressed in: Barbieri et al. PRD 76 (2007) 115008



the shifts in the Higgs couplings induce an IR correction to the precision parameters $\epsilon_{1,3}$

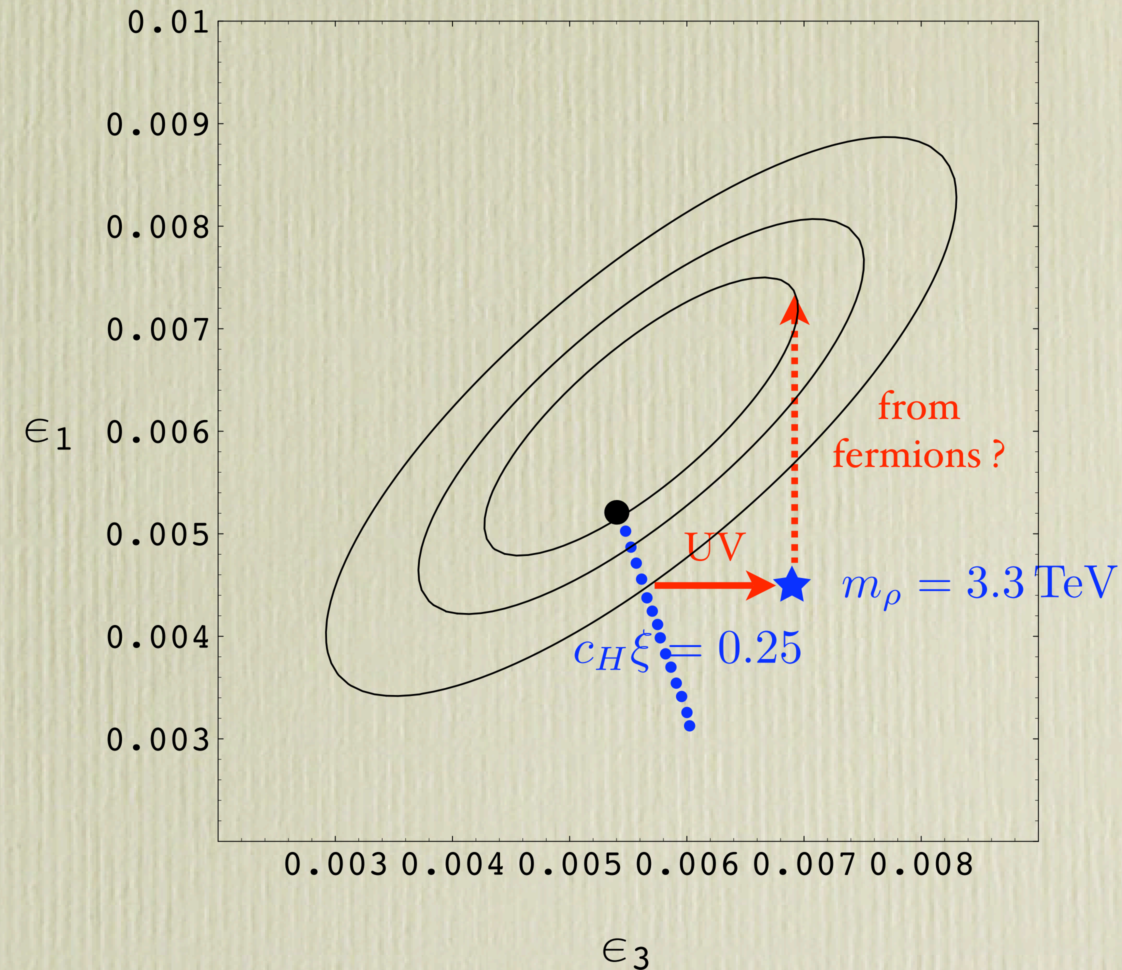
$$\epsilon_{1,3} = a_{1,3}\,\log\left(\frac{M_Z^2}{\mu^2}\right) - a_{1,3}\,(1-c_H\xi)\log\left(\frac{m_h^2}{\mu^2}\right) - a_{1,3}\,(c_H\xi)\log\left(\frac{m_\rho^2}{\mu^2}\right) + \text{finite terms}$$

$$a_1 = +\,\frac{3}{16\pi}\,\frac{\alpha(M_Z)}{\cos^2\theta_W}$$

$$a_3 = -\,\frac{1}{12\pi}\,\frac{\alpha(M_Z)}{4\sin^2\theta_W}$$

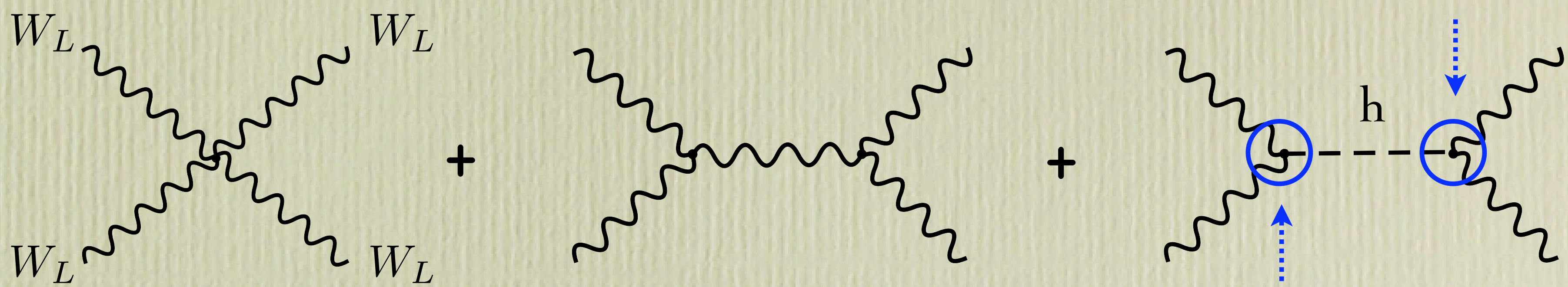
$$\Delta\epsilon_1 = a_1\,(c_H\xi)\log\left(\frac{m_h^2}{m_\rho^2}\right)$$

$$\Delta\epsilon_3 = a_3\,(c_H\xi)\log\left(\frac{m_h^2}{m_\rho^2}\right)$$



WW scattering

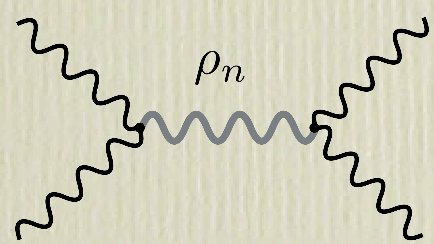
- The Higgs compositeness implies a partial unitarization of the WW scattering:



$$A\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{g_2^2}{4M_W^2}\left[s - \frac{s^2\left(1 - c_H\xi\right)}{s - m_h^2} + t - \frac{t^2\left(1 - c_H\xi\right)}{t - m_h^2}\right]$$

Unitarity is lost at a scale: $\Lambda = \Lambda_0 / \sqrt{c_H \xi}$ $\quad \Lambda_0 = 1.2\,\mathrm{TeV}$

[Full unitarity is recovered thanks to the exchange of the heavy vectorial resonances $\sum_n$



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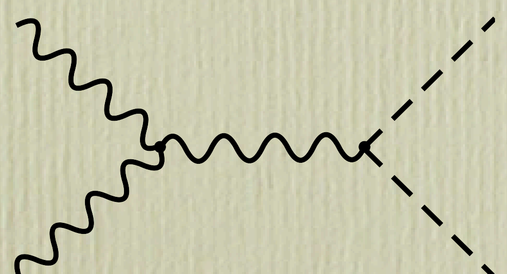
- At large invariant (WW) masses one case thus rescale:

$$\sigma(pp \to V_L V_L' X)_{c_H \xi} \simeq (c_H \xi)^2 \, \sigma(pp \to V_L V_L' X)_{\text{no Higgs}}$$

with $L = 200\,\text{fb}^{-1}$ the LHC should be sensitive up to $c_H \xi = 0.5 - 0.7$

[Giudice et al. JHEP 0706:045, 2007]

- Strong vector boson scattering is accompanied by strong Higgs production:



$$A\left(Z_L Z_L \to hh\right) = A\left(W_L^+ W_L^- \to hh\right) = \frac{s}{v^2}\,(c_H \xi)$$

WORK IN PROGRESS

with C. Grojean, M. Moretti, F. Piccinini, R. Rattazzi

Part II:

Implications for the LHC

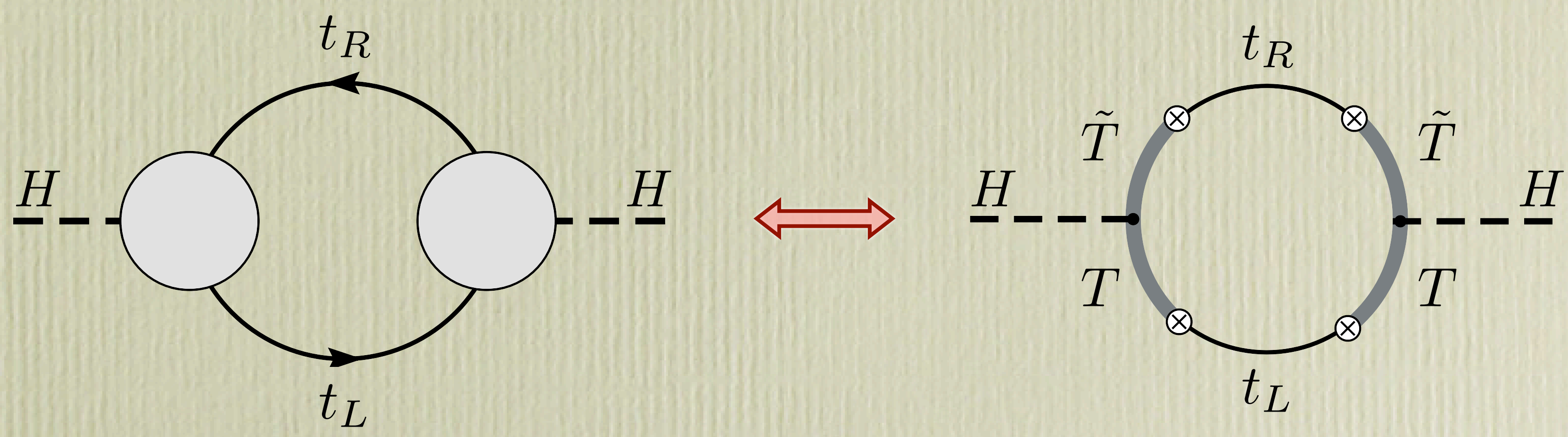
1. How to tell whether the Higgs is composite

2. Direct production of new states

The Top Partners

A light Higgs requires:

New vector-like quarks with $M \sim 500\,\text{GeV}$
in multiplets of $SU(2)_L \times SU(2)_R \times U(1)_X$



⭐ Two simple $SU(2)_L \times SU(2)_R \times U(1)_X$ assignments: $[\ Y = T_{3_R} + X\ ]$

Model A

$$(\mathbf{2},\mathbf{1})_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix} \qquad (\mathbf{1},\mathbf{2})_{1/6} = \begin{pmatrix} \tilde{T} \\ \tilde{B} \end{pmatrix}$$

$[\ X = (B-L)/2\ ]$

electric charge +5/3

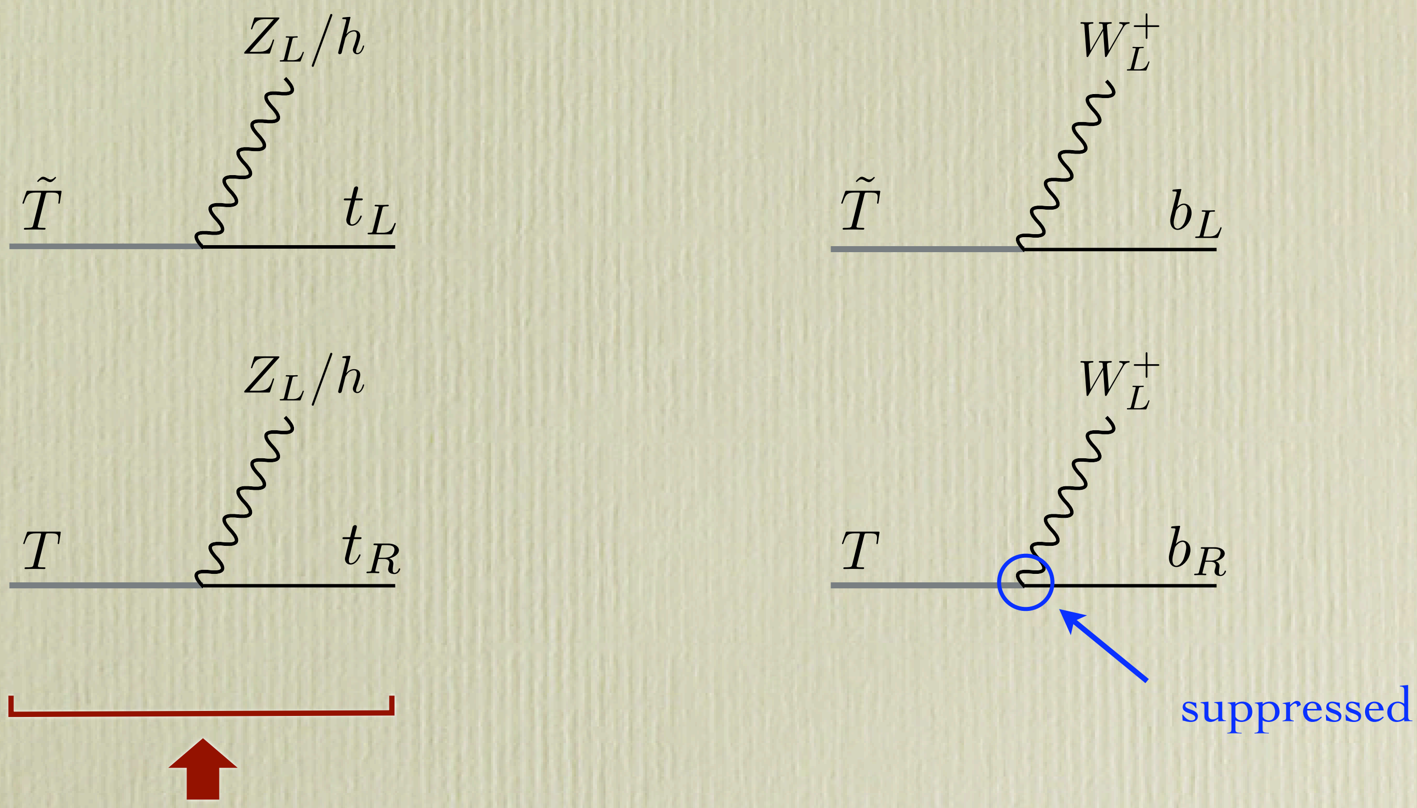
Model B

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

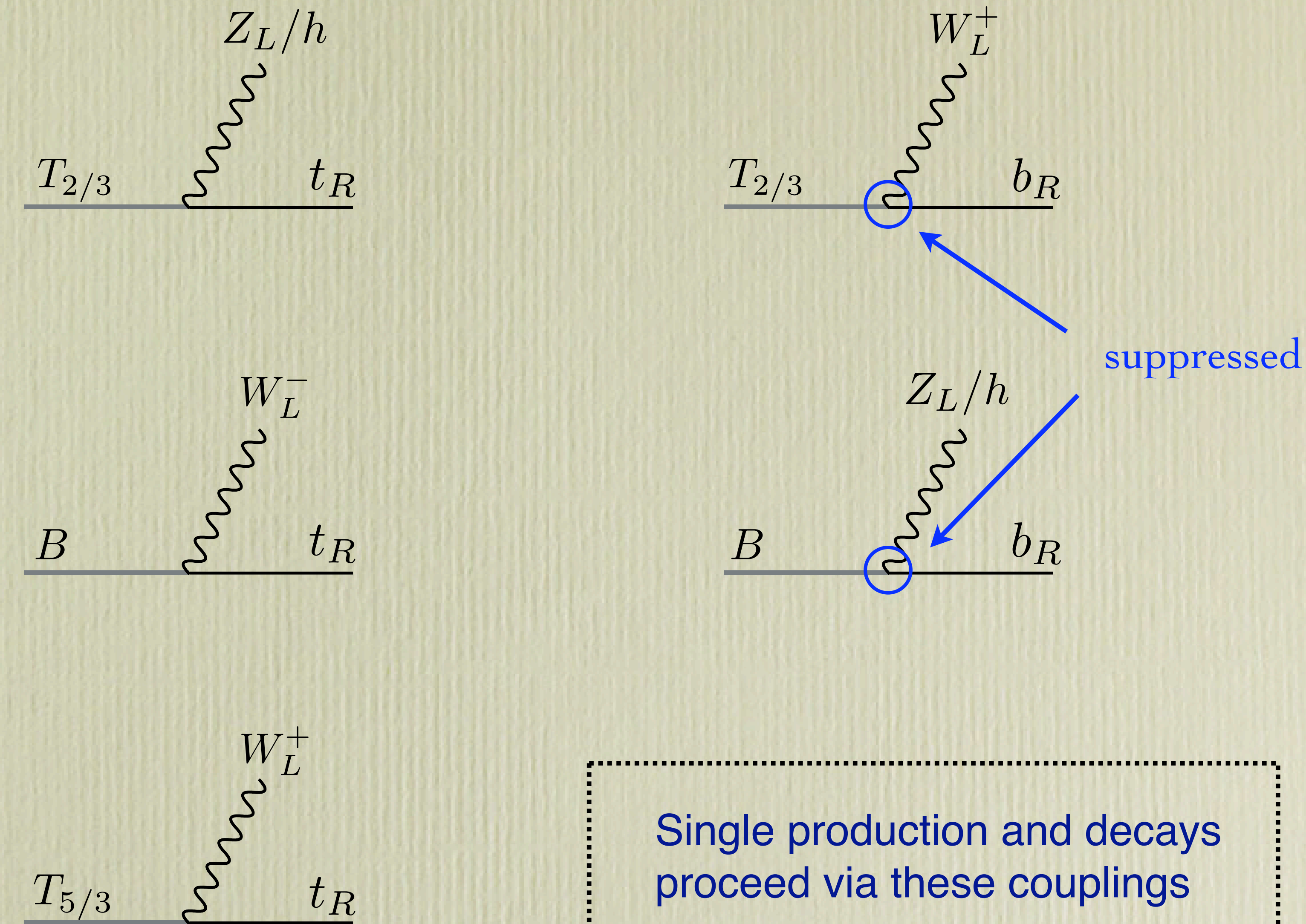
$[\ X = 2(B-L)]$

- largest coupling of the heavy fermions to the Higgs degrees of freedom (W_L, Z_L, h) and to the SM third quark generation

- couplings to well defined SM quark chiralities   [Yukawa couplings]



FCNC : absent for a 4th generation !



Single production and decays proceed via these couplings

Pair production proceeds via the usual QCD coupling

Production of the heavy tops ($\tilde{T}, T, T_{2/3}$) has been studied in the literature:

- Single production via bW fusion ➡ best channel: $\tilde{T} \to W^+ b \to l^+ \nu b$

LHC reach with $L = 300\ \mathrm{fb}^{-1}$: $M = 2\,(2.5)$ TeV for $\lambda_T = 1\,(2)$

see: Azuelos et al. Eur.Phys.J. C39S2 (2005) 13 [hep-ph/0402037]

- Pair production ➡ best channels: $\tilde{T}\bar{\tilde{T}} \to \begin{cases} W^+ b\, W^- \bar{b} \\ W^+ b\, h\bar{t} \\ W^+ b\, Z\bar{t} \end{cases} \to$ final states with 1 charged lepton

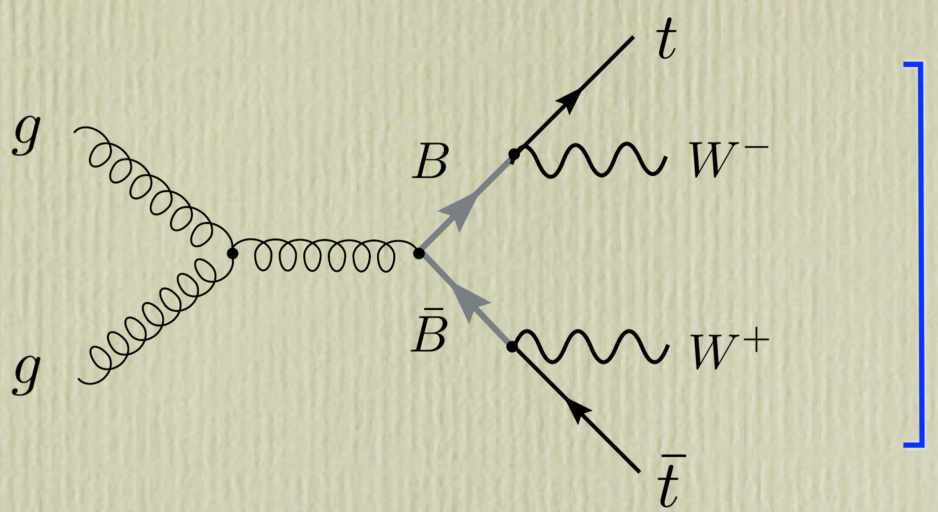
$L_{disc} = 2.1(90)\ \mathrm{fb}^{-1}$ for $M_{\tilde{T}} = 0.5(1)$ TeV

see: J.A. Aguilar-Saavedra PoS TOP2006:003,2006 [hep-ph/0603199] and refs. therein

Pair production of the heavy bottom (B) has also been investigated recently:

Skiba and Tucker-Smith PRD 75 (2007) 115010

C. Dennis et al. hep-ph/0701158



⬅ Spectacular Final State

- channels investigated: $l^\pm + jets + \not{E}_T$ and $l^+ l^- + jets + \not{E}_T$

  ➡ Challenge: $t\bar{t} + jets$ huge background ➡ hard cuts on M_{eff} needed

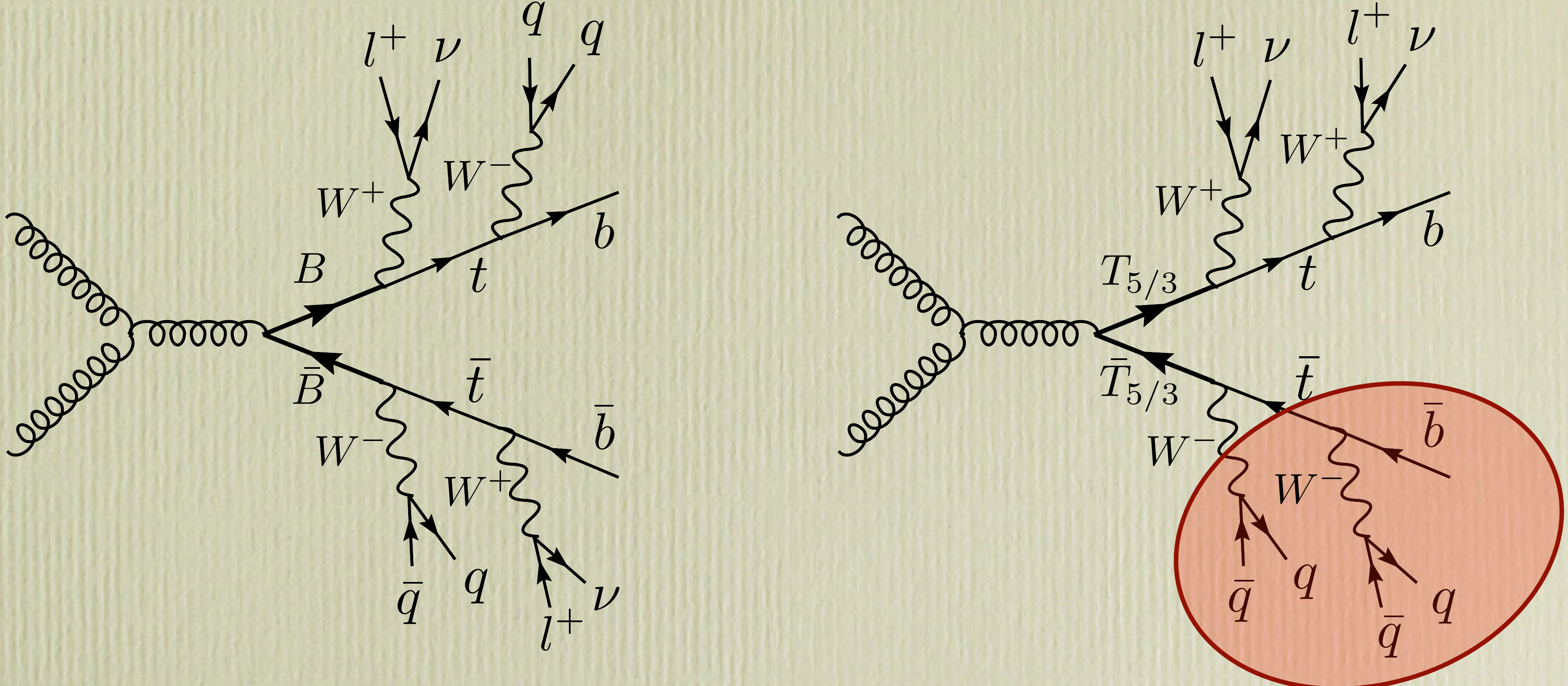
- additional strategy proposed by Skiba and Tucker-Smith : look for highly boosted tops and Ws and cut on single jet invariant mass

  ⦿ works only for heavy masses $M_B \gtrsim 1$ TeV

  ⦿ results depend on the jet energy algorithm used

☞ look for $B\bar{B}$ and $T_{5/3}\bar{T}_{5/3}$ in same-sign dilepton final states

[R.C., G.Servant arXiv:0801.1679]



✓ $t\bar{t} + jets$ is not a background anymore [except for charge mis-ID]

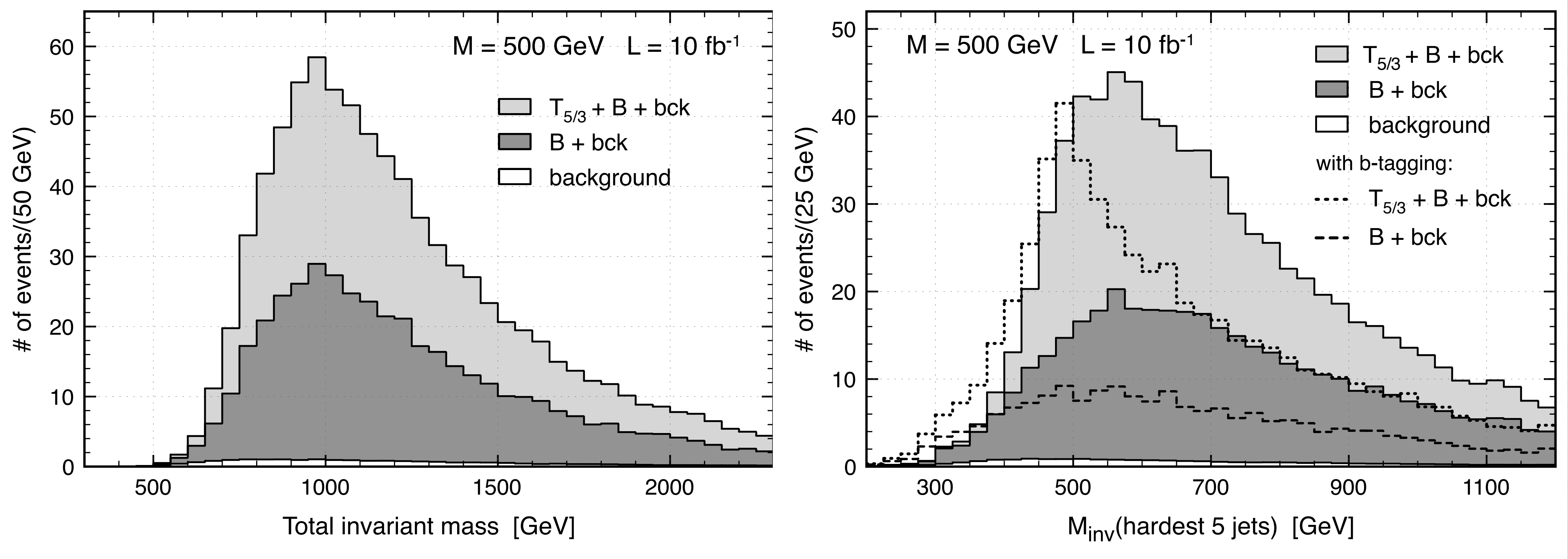
✓ For the $T_{5/3}$ case one can reconstruct the resonant (tW) invariant mass

Cuts:

jets : $\begin{cases} p_T(\text{1st}) \geq 100 \text{ GeV} \\ p_T(\text{2nd}) \geq 80 \text{ GeV} \\ n_{jet} \geq 5, \quad |\eta_j| \leq 5 \end{cases}$

leptons : $\begin{cases} p_T(\text{1st}) \geq 50 \text{ GeV} \\ p_T(\text{2nd}) \geq 25 \text{ GeV} \\ |\eta_l| \leq 2.4, \quad \Delta R_{lj} \geq 0.4 \end{cases}$

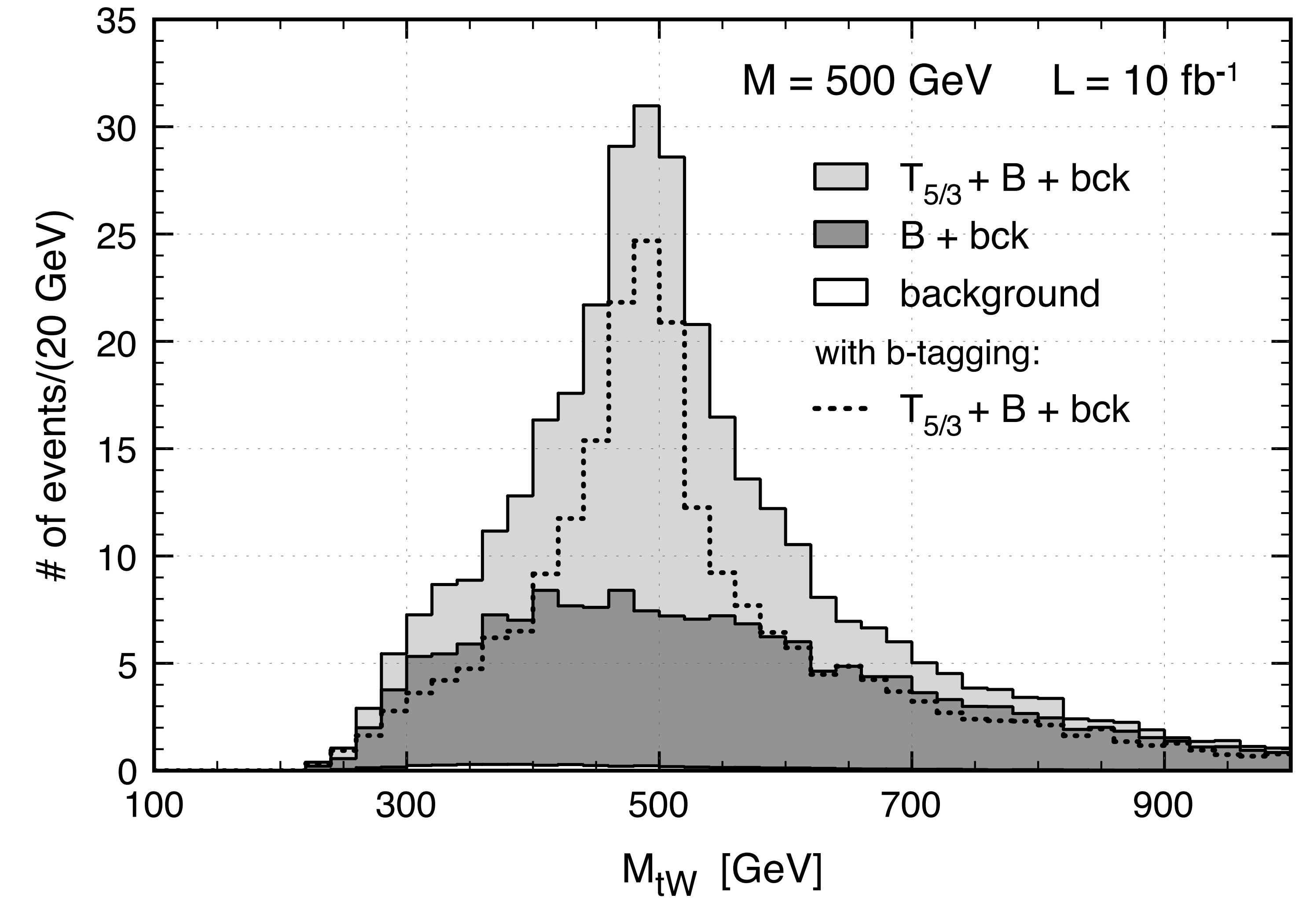
$\not{E}_T \geq 20$ GeV



Discovery Potential:

		L_{disc}
$M = 500$ GeV	$T_{5/3} + B$	$56\,\text{pb}^{-1}$
	B only	$147\,\text{pb}^{-1}$

less than $100\,\text{pb}^{-1}$



M = 500 GeV L = 10 fb-1
T5/3 + B + bck
B + bck
background
with b-tagging:
T5/3 + B + bck
# of events/(20 GeV)
MtW [GeV]
0
5
10
15
20
25
30
35
100
300
500
700
900

Backup slides

Signal and Background Simulation

Signal and SM background have been simulated using:

- MadGraph/MadEvent [MatrixElement] + Pythia [Showering - no hadronization or und.event]
- Quark/Jet matching a la MLM
- Jets reconstructed with a cone algorithm (GetJet) with $\Delta R = 0.4\ ,\ E_T^{min} = 30\,\mathrm{GeV}$
- Jet energy and momentum smeared by $100\%/\sqrt{E}$ to simulate the detector resolution

		σ [fb]	$\sigma \times BR(l^\pm l^\pm)$ [fb]
	$T_{5/3}\overline{T}_{5/3}/B\overline{B} + jets \ \ (M = 500\ \mathrm{GeV})$	2.5×10^3	104
	$T_{5/3}\overline{T}_{5/3}/B\overline{B} + jets \ \ (M = 1\ \mathrm{TeV})$	37	1.6
SM bckg $[m_h = 180\ \mathrm{GeV}]$	$t\bar{t}W^+W^- + jets \ \ (\supset t\bar{t}h + jets)$	121	5.1
SM bckg $[m_h = 180\ \mathrm{GeV}]$	$t\bar{t}W^\pm + jets$	595	18.4
SM bckg $[m_h = 180\ \mathrm{GeV}]$	$W^+W^-W^\pm + jets\ (\supset hW^\pm + jets)$	603	18.7
SM bckg $[m_h = 180\ \mathrm{GeV}]$	$W^\pm W^\pm + jets$	340	15.5

other backgrounds:

★ Events where one lepton comes from a b-decay

these leptons are soft: completely removed by our cut $p_T(l) \geq 25\,\mathrm{GeV}$

★ $t\bar{t} + jets$ events where the charge of one lepton is mis-identified

charge mis-ID probability ϵ_{mis} strongly depends on the lepton's p_T and η

for $t\bar{t} + jets$ the hardest lepton has $p_T(l) \sim 100\,\mathrm{GeV}$

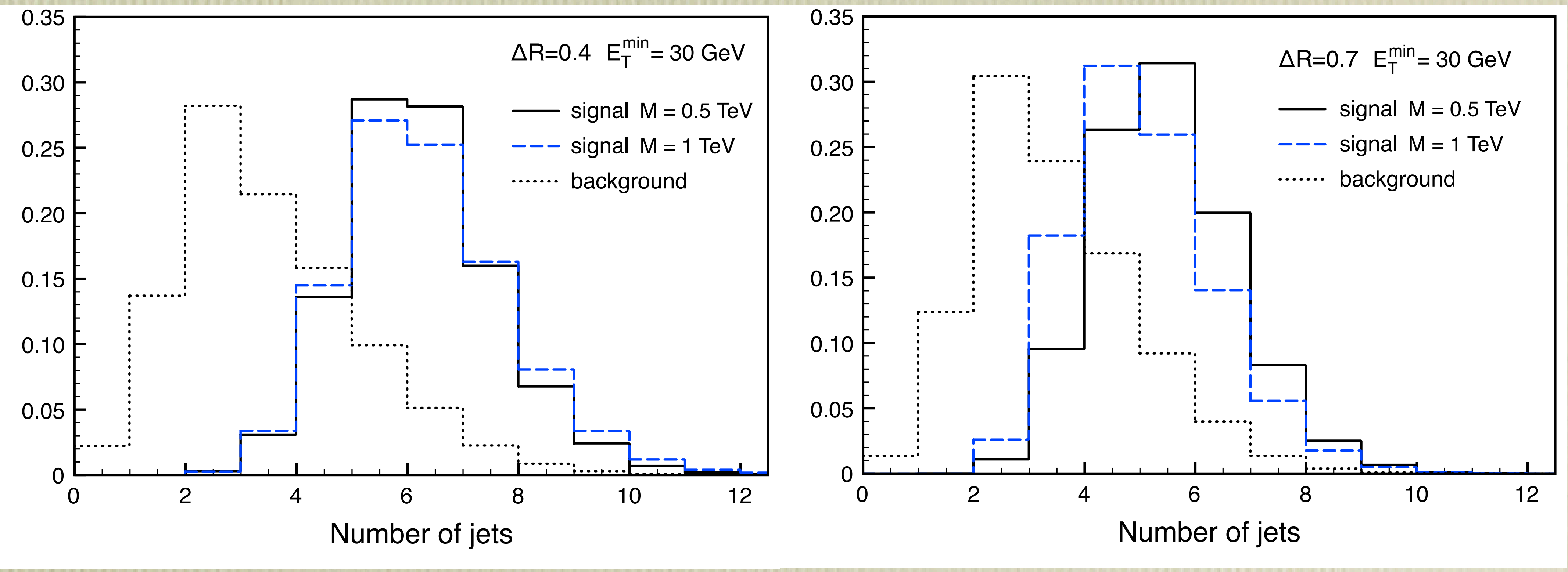
➡ $\epsilon_{mis} \sim 10^{-4}$ seems possible ➡ $t\bar{t} + jets$ negligible

★ $Wl^+l^- + jets$ events where one lepton is lost

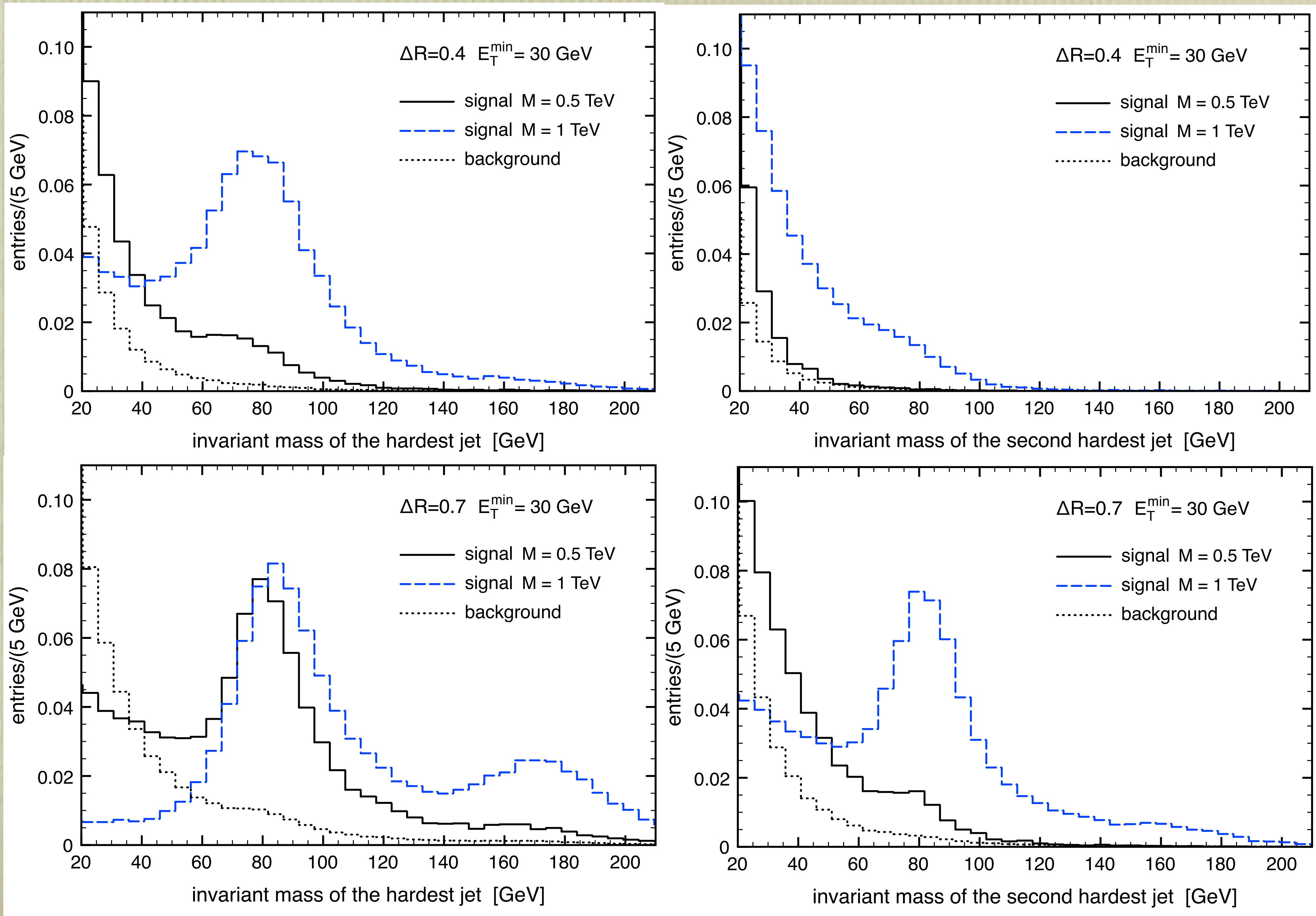
technically difficult to simulate with all the needed jets

➡ we estimate it to be $\lesssim 30\%$ of the sum of the included backgrounds

jets - with two different cone sizes



jet invariant mass
with two different cone sizes



Strategy and main cuts

★ For $\Delta R = 0.4$ only the M=1 TeV signal has one "double" jet from boosted W's

★ We demand at least 5 hard jets ($p_T \geq 30$ GeV) : $l^{\pm} l^{\pm} + n\ jets + \not{E}_T \ \ (n \geq 5)$

★ Reference luminosities: $10\ \text{fb}^{-1}$ for $M = 500$ GeV
$100\ \text{fb}^{-1}$ for $M = 1$ TeV

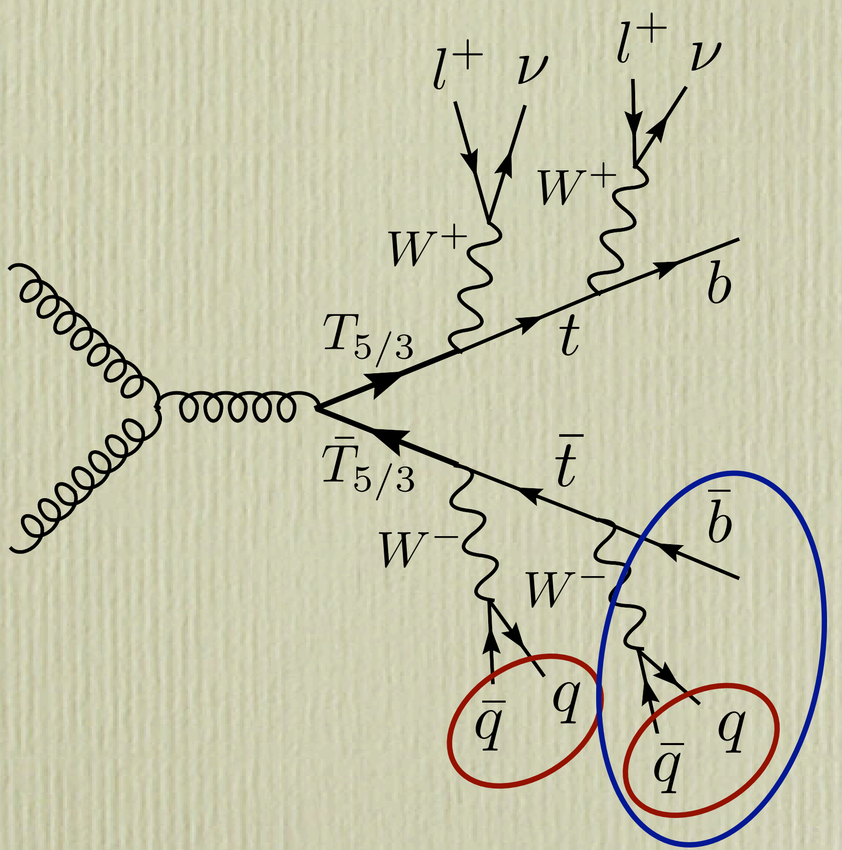
Main Cuts:

$$\underline{\text{jets}} : \begin{cases} p_T(\text{1st}) \geq 100\ \text{GeV} \\ p_T(\text{2nd}) \geq 80\ \text{GeV} \\ n_{jet} \geq 5, \quad |\eta_j| \leq 5 \end{cases} \qquad \underline{\text{leptons}} : \begin{cases} p_T(\text{1st}) \geq 50\ \text{GeV} \\ p_T(\text{2nd}) \geq 25\ \text{GeV} \\ |\eta_l| \leq 2.4\,, \quad \Delta R_{lj} \geq 0.4 \end{cases} \qquad \not{E}_T \geq 20\ \text{GeV}$$

	signal ($M = 500$ GeV)	signal ($M = 1$ TeV)	$t\bar{t}W$	$t\bar{t}WW$	WWW	$W^{\pm}W^{\pm}$
Efficiencies (ϵ_{main})	0.42	0.43	0.074	0.12	0.008	0.01
σ [fb] $\times BR \times \epsilon_{main}$	44.2	0.67	1.4	0.62	0.15	0.16

Mass Reconstruction

M=500 GeV



1. Reconstruct 2 W's

$$|M(jj) - m_W| \leq 20 \text{ GeV}$$

$$\Delta R_{jj}(\text{1st pair}) \leq 1.5$$
$$|\vec{p}_T(\text{1st pair})| \geq 100 \text{ GeV}$$

$$\Delta R_{jj}(\text{2nd pair}) \leq 2.0$$
$$|\vec{p}_T(\text{2nd pair})| \geq 30 \text{ GeV}$$

2. Reconstruct 1 top (t=Wj)

$$|M(Wj) - m_t| \leq 25 \text{ GeV}$$

	signal ($M = 500$ GeV)	$t\bar{t}W$	$t\bar{t}WW$	WWW	WW
ϵ_{2W}	0.62	0.36	0.49	0.29	0.15
ϵ_{top}	0.65	0.56	0.64	0.35	0.35