Discovering the Top Partners

in Same-Sign Dilepton Events at the LHC

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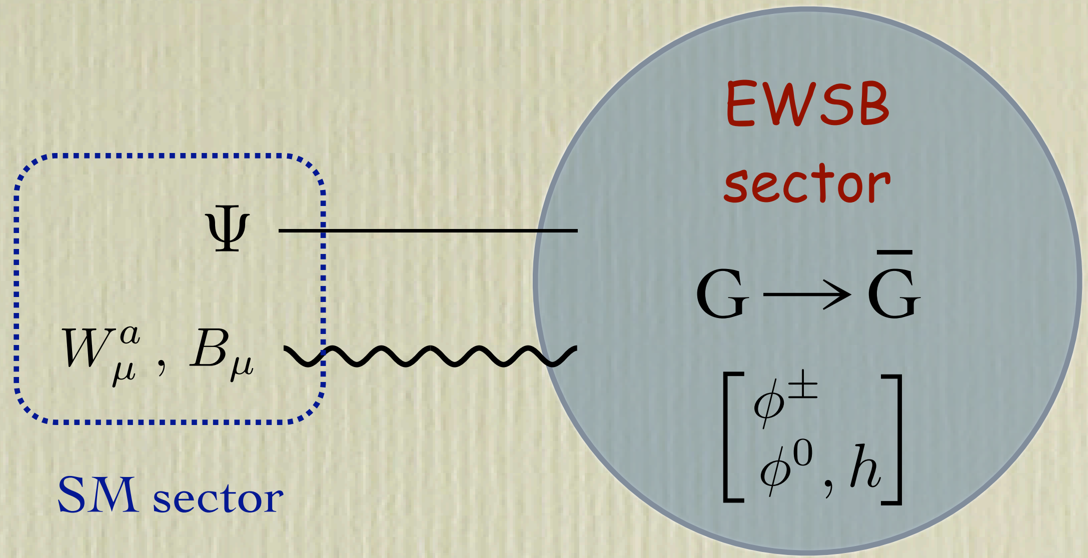
R.C., G. Servant JHEP 0806:026 (2008)

The theoretical framework

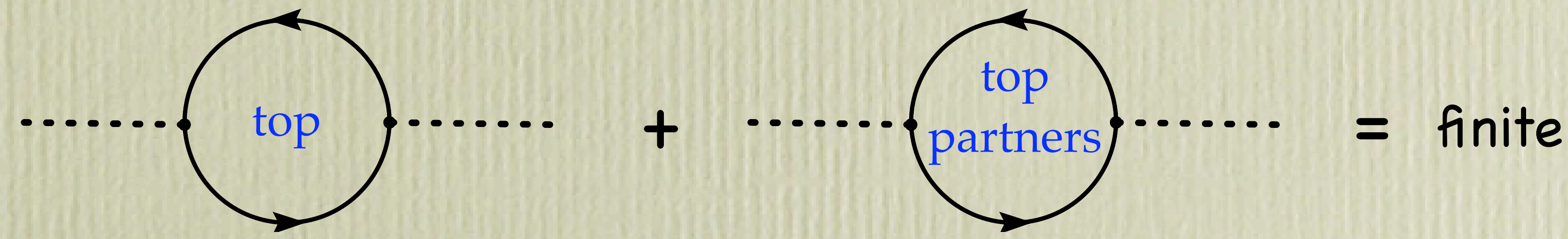
We focus on models where:

- the Higgs is a composite pseudo-Goldstone boson of a new strongly-interacting sector



ex: $SO(5) \rightarrow SO(4)$

- UV finiteness of the Higgs mass term is enforced by the exchange of the heavy fermionic Top Partners



- the SM fermions mix linearly with the composite heavy fermions (partial compositeness)

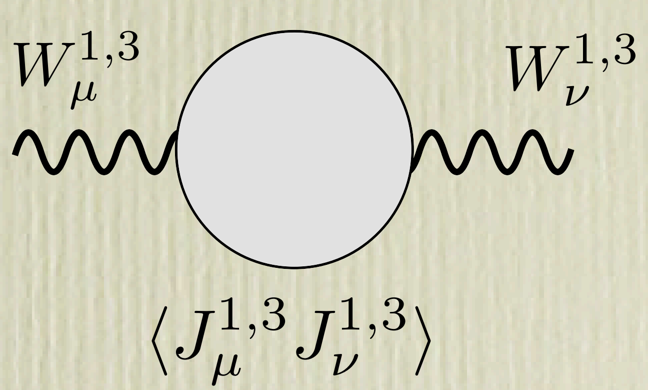
Constraints on the strong sector from the LEP precision tests : 1. Custodial Symmetry

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

- 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]

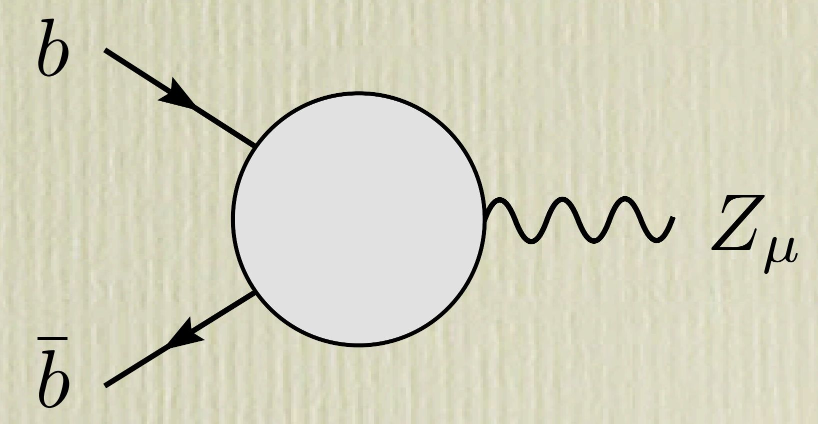
$$SU(2)_L \times SU(2)_R \to SU(2)_C \quad \Rightarrow \quad \boxed{\langle J^1_\mu J^1_\nu \rangle = \langle J^3_\mu J^3_\nu \rangle}$$

Constraints on the strong sector from the LEP precision tests : 2. Custodial Parity

$$g_{Lb}\, \frac{g}{\cos\theta_W}\, Z_\mu \bar{b}_L \gamma^\mu b_L$$

$$g_{Lb} = g_{Lb}^{SM} + \delta g_{Lb}$$

$$g_{Lb}^{SM}|_{tree} = \left(T_L^3 - Q \sin^2\theta_W\right)$$



- The bound from LEP $\delta g_{Lb}/|g_{Lb}^{SM}| \lesssim 0.25\%$ strongly constraints tree-level corrections

- A LR parity can protect g_{Lb} :

  [Agashe, DaRold, R.C., Pomarol PLB 641 (2006) 62]

$$SU(2)_L \times SU(2)_R \times P_{LR} \rightarrow SU(2)_C \times P_{LR}$$

Assumptions:

1. The global symmetry of the strong sector is:

$$O(4) \times U(1)_X \to O(3) \times U(1)_X \qquad Y = T_R^3 + X$$

2. SM fields are linearly coupled to composite operators:

$$\mathcal{L}_{int} = \Phi^\dagger \mathcal{O}_\Phi + h.c.$$

then:

i) One can always rotate to a basis in which each operator $\mathcal{O}_\Phi$ has definite quantum numbers $T_{L,R}$, $T^3_{L,R}$

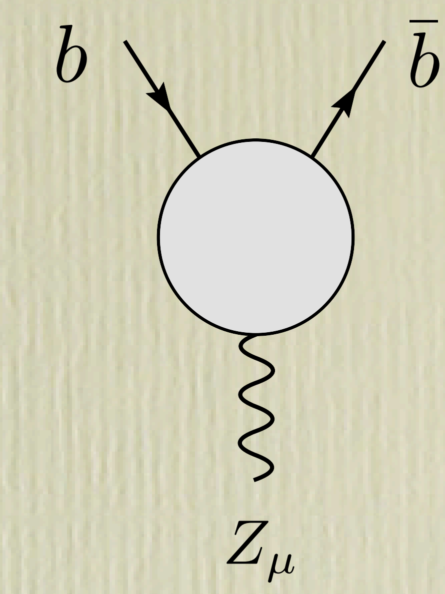
ii) One can univocally assign to each SM field Φ definite quantum numbers $T_{L,R}$, $T^3_{L,R}$ corresponding to those of the operator $\mathcal{O}_\Phi$

3. We demand b_L to be an eigenstate of P_{LR} :

$$T_L = T_R \, , \qquad T_L^3 = T_R^3$$

so that $\mathcal{L}_{int} = \bar{b}_L \mathcal{O}_b + h.c.$ is invariant under P_{LR}

Notice:



- At zero momentum the coupling to the Z is given by:

$$\frac{g}{\cos\theta_W}\left(Q_L^3 - Q\sin^2\theta_W\right) Z_\mu \bar{\psi}\gamma^\mu\psi$$

the electric charge is conserved

possible modifications to g_{Lb} can only arise from corrections to Q_L^3

- We can treat the SM field W_L^3 as an external source that probes Q_L^3

It follows: $\delta g_{Lb} = 0$ by $U(1)_V \times P_{LR}$ invariance $[U(1)_V \subset SU(2)_C]$

proof:

from $U(1)_V$ invariance it follows: $0 = \delta Q_V^3 = \delta Q_L^3 + \delta Q_R^3$

from P_{LR} invariance it follows: $\delta Q_L^3 = \delta Q_R^3$

$\Rightarrow$ $\delta Q_L^3 = 0$

A simple Two-site model:

Exotic top partner with charge +5/3

$$\mathcal{Q} = (\mathbf{2},\mathbf{2})_{2/3} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix}, \qquad \tilde{T} = (\mathbf{1},\mathbf{1})_{2/3}\,, \qquad \mathcal{H} = (\mathbf{2},\mathbf{2})_0 = \begin{bmatrix} \phi_0^\dagger & \phi^+ \\ -\phi^- & \phi_0 \end{bmatrix}$$

b_L mixes with B which has: $T^3_L = T^3_R = -\frac{1}{2}$

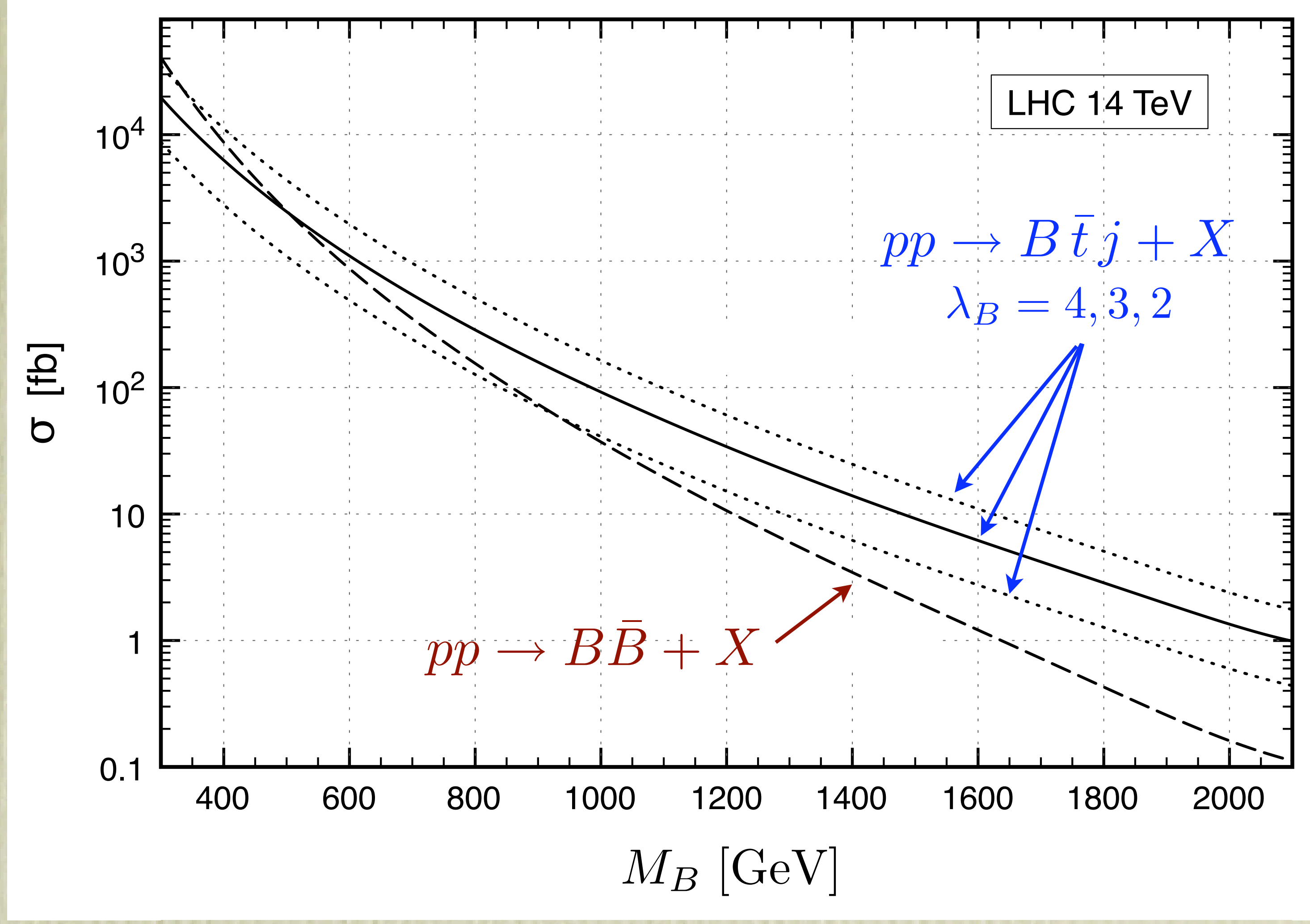
✔ Assumption #3 fulfilled → Zbb protection at work

$$\begin{aligned}\mathcal{L} =& \bar{q}_L \partial\!\!\!/\, q_L + \bar{t}_R \partial\!\!\!/\, t_R \\ &+ \mathrm{Tr}\left\{\bar{\mathcal{Q}}\left(\partial\!\!\!/ - M_Q\right)\mathcal{Q}\right\} + \bar{\tilde{T}}\left(\partial\!\!\!/ - M_{\tilde{T}}\right)\tilde{T} + Y_*\,\mathrm{Tr}\{\bar{\mathcal{Q}}\,\mathcal{H}\}\,\tilde{T} + h.c \\ &+ \Delta_L\,\bar{q}_L\,(T,B) + \Delta_R\,\bar{t}_R\tilde{T} + h.c.\end{aligned}$$

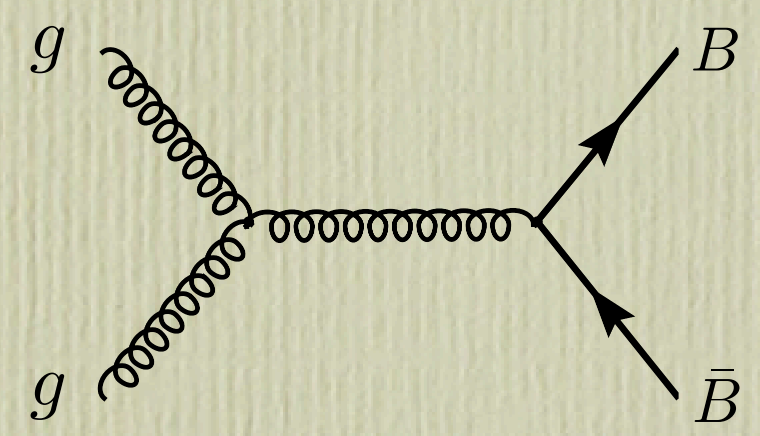
After rotating to the mass eigenbasis $\tan\varphi_L = \frac{\Delta_L}{M_Q}, \quad \tan\varphi_R = \frac{\Delta_L}{M_{\tilde{T}}}$

$$\begin{aligned}\mathcal{L}_{yuk} =& Y_*\sin\varphi_L\sin\varphi_R\left(\bar{t}_L\phi_0^\dagger t_R - \bar{b}_L\phi^- t_R\right) + Y_*\cos\varphi_L\sin\varphi_R\left(\bar{T}\phi_0^\dagger t_R - \bar{B}\phi^- t_R\right) \\ &+ Y_*\sin\varphi_L\cos\varphi_R\left(\bar{t}_L\phi_0^\dagger\tilde{T} - \bar{b}_L\phi^-\tilde{T}\right) + Y_*\sin\varphi_R\left(\bar{T}_{5/3}\phi^+ t_R + \bar{T}_{2/3}\phi_0 t_R\right) + \dots\end{aligned}$$

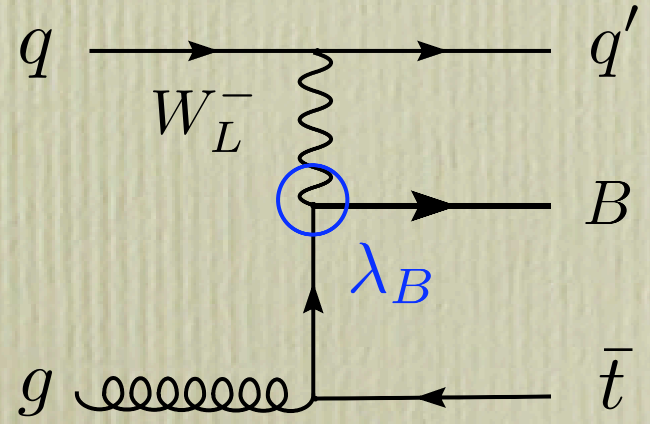
Discovering the top partners at the LHC



Pair production

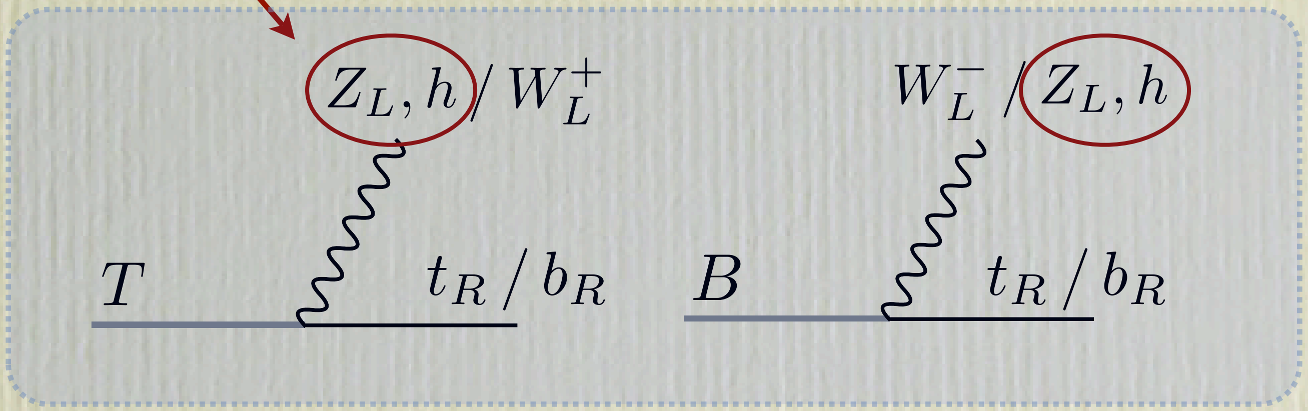


Single production



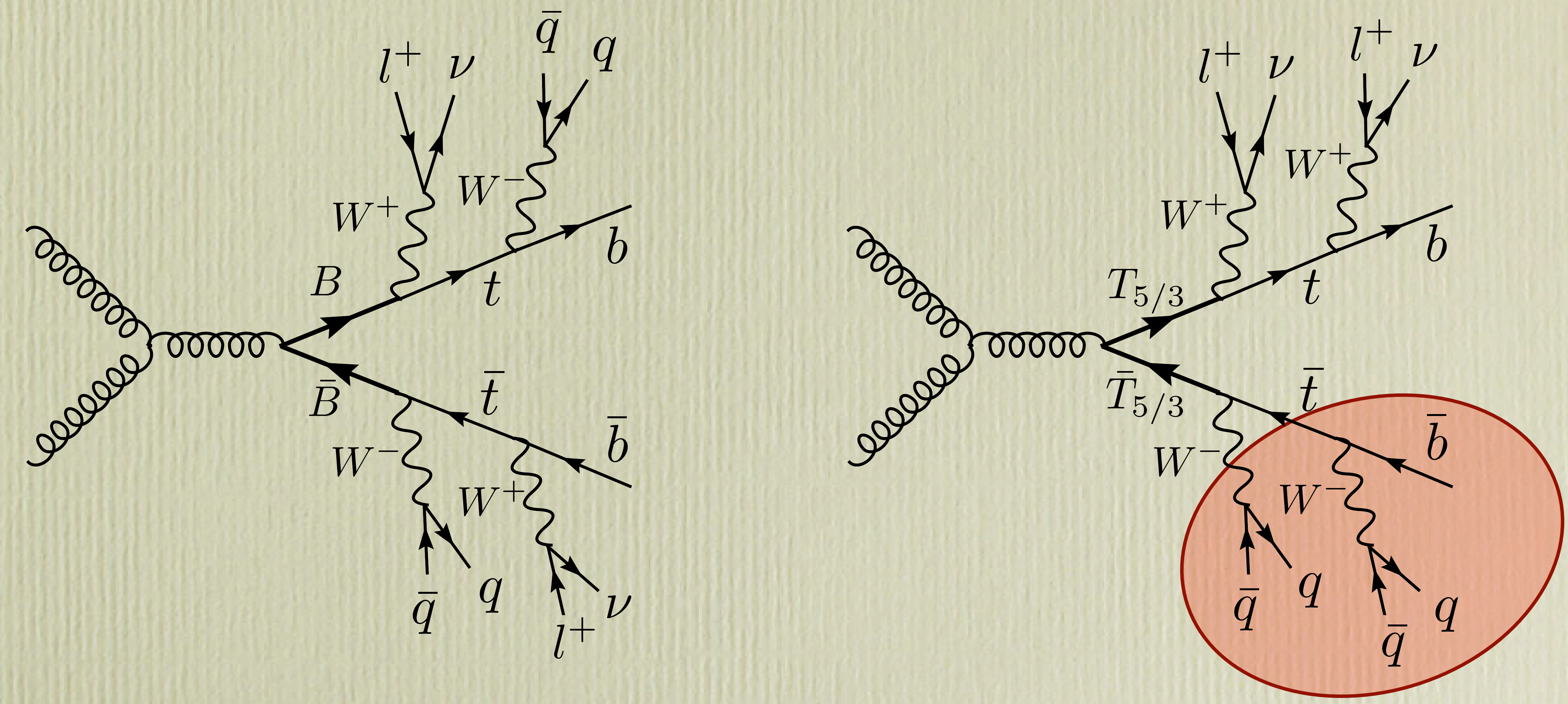
Decay modes

FCNC : absent for a 4th generation !



Discovering the B, $T_{5/3}$ heavy partners in same-sign di-lepton events

[R.C. and G.Servant JHEP 0806:026 (2008)]



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

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

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]
$T_{5/3}\overline{T}_{5/3}/B\overline{B} + jets$ ($M = 500$ GeV)	2.5×10^3	104
$T_{5/3}\overline{T}_{5/3}/B\overline{B} + jets$ ($M = 1$ TeV)	37	1.6
$t\bar{t}W^+W^- + jets$ ($\supset t\bar{t}h + jets$)	121	5.1
$t\bar{t}W^\pm + jets$	595	18.4
$W^+W^-W^\pm + jets$ ($\supset hW^\pm + jets$)	603	18.7
$W^\pm W^\pm + jets$	340	15.5

SM bckg [$m_h = 180$ GeV] (applies to the last four rows)

other backgrounds:

★ Events where one lepton comes from a b-decay

removed by our cuts : $p_T(l) \geq 25\,\mathrm{GeV}$

$\Delta R(lj) \geq 0.4$

★ Fake leptons from light jets (from $W + jets$ and $t\bar{t} + jets$)

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

➡ $Z + jets$ strongly reduced by a cut on missing E_T

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

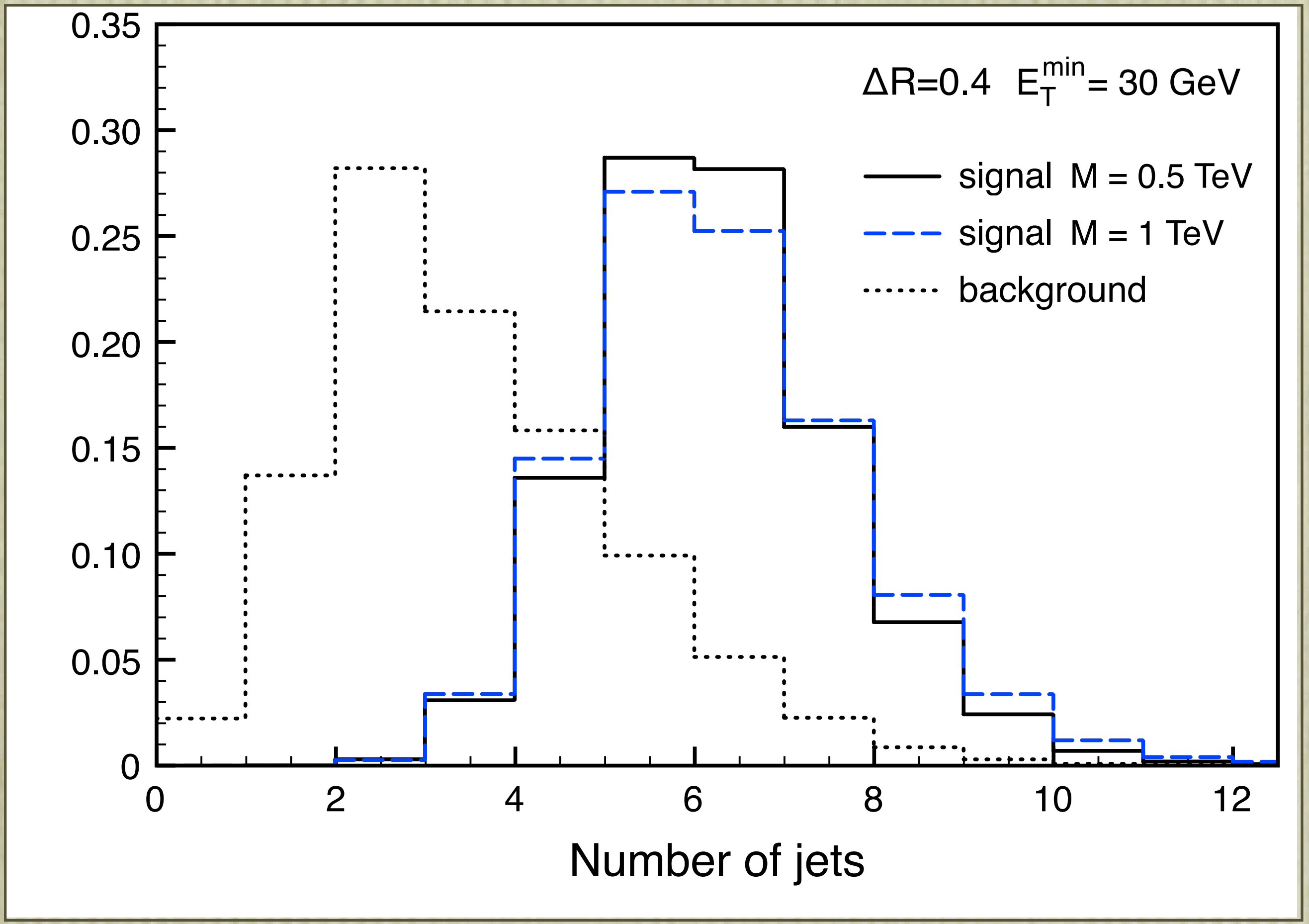
➡ for $\epsilon_{mis} \sim 10^{-4}$ $t\bar{t} + jets$ negligible

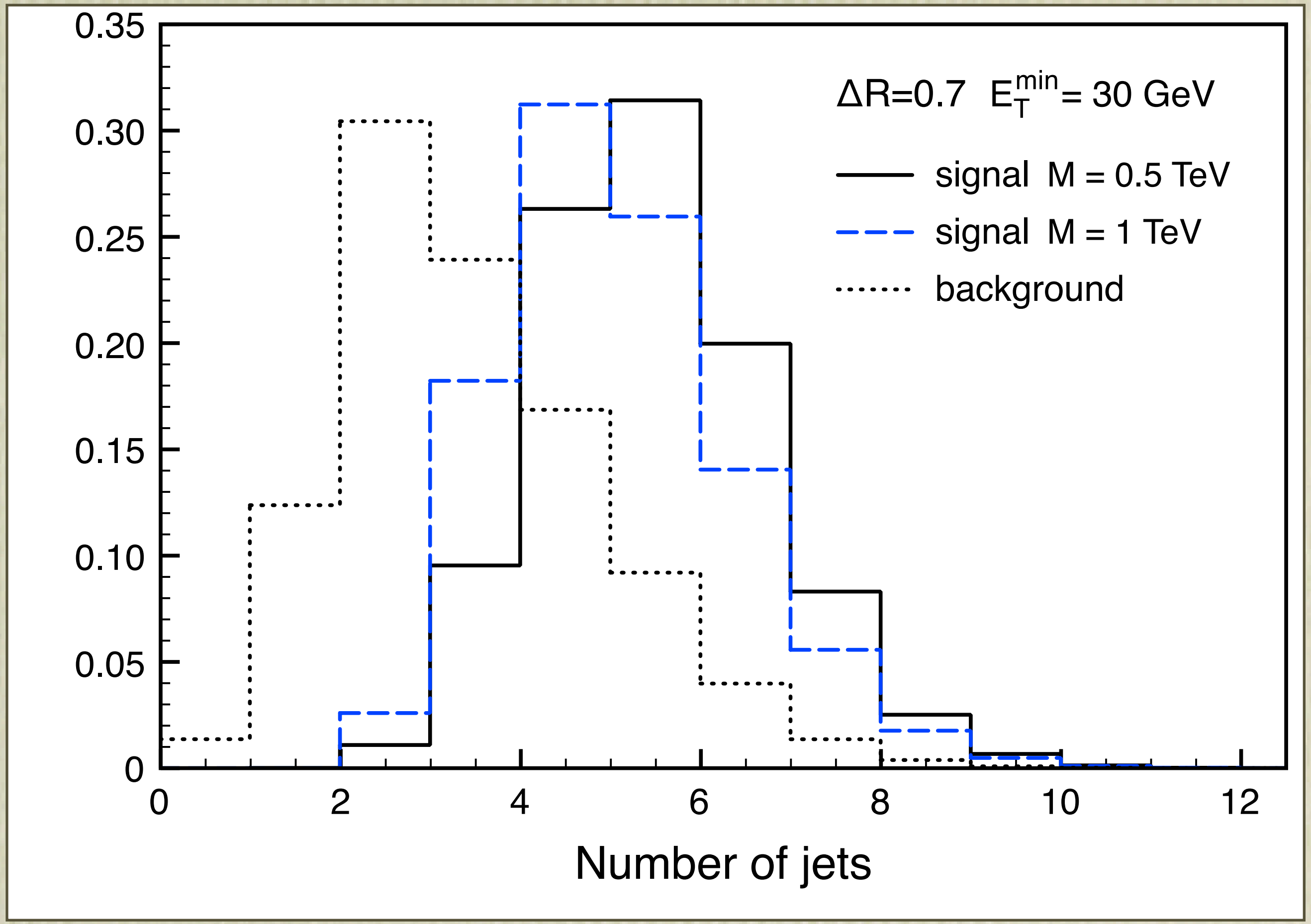
★ $Wl^+l^- + jets$ events where one lepton is lost

technically difficult to simulate (with Madgraph) with all the needed jets

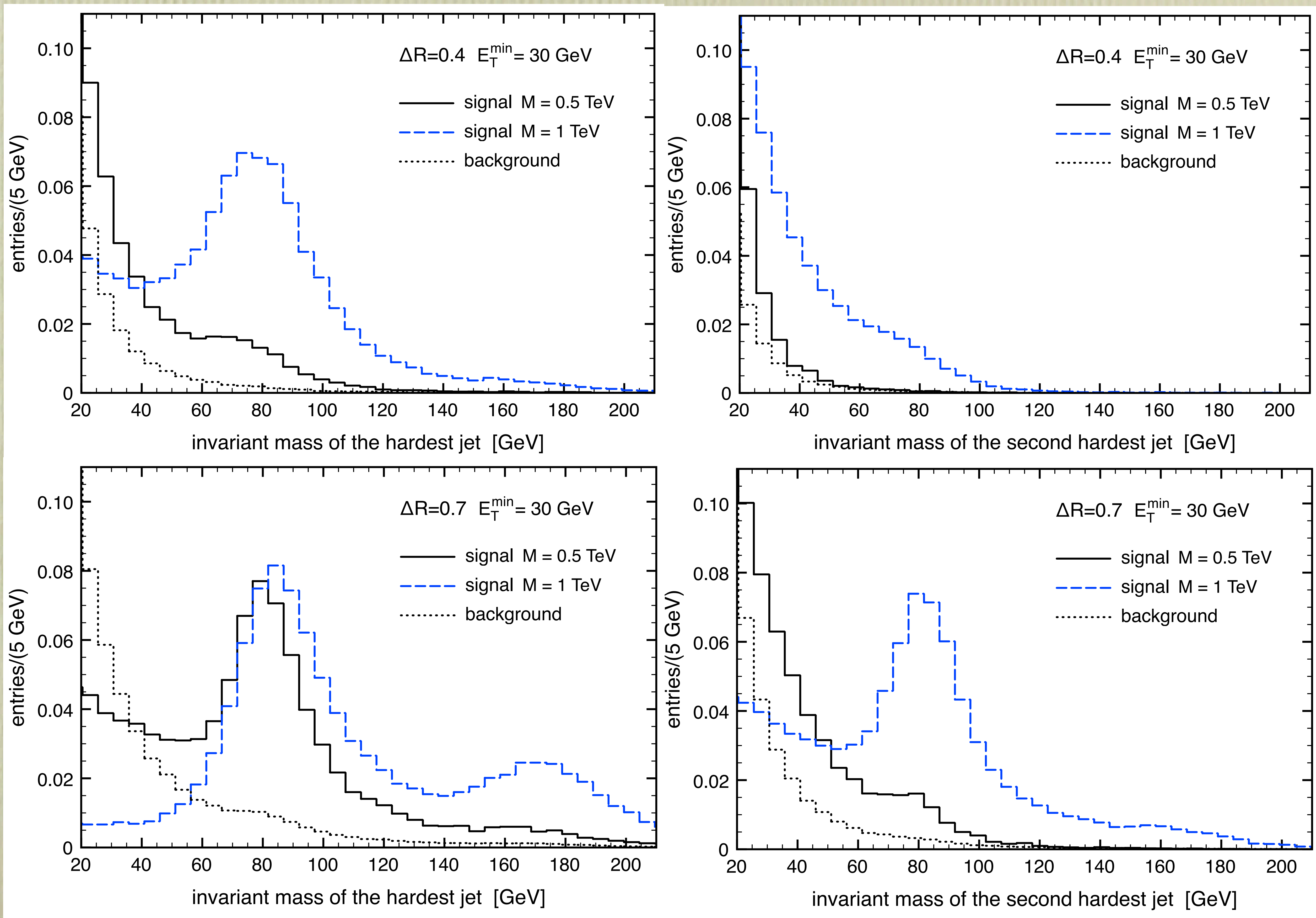
➡ we estimate it to be $\lesssim 30\%$ of the sum of the included backgrounds

jets – with two different cone sizes





jet invariant mass
with two different cone sizes



Strategy and 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) : $l^\pm l^\pm + n\ jets + \not{E}_T \ \ (n \geq 5)$

Cuts:

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

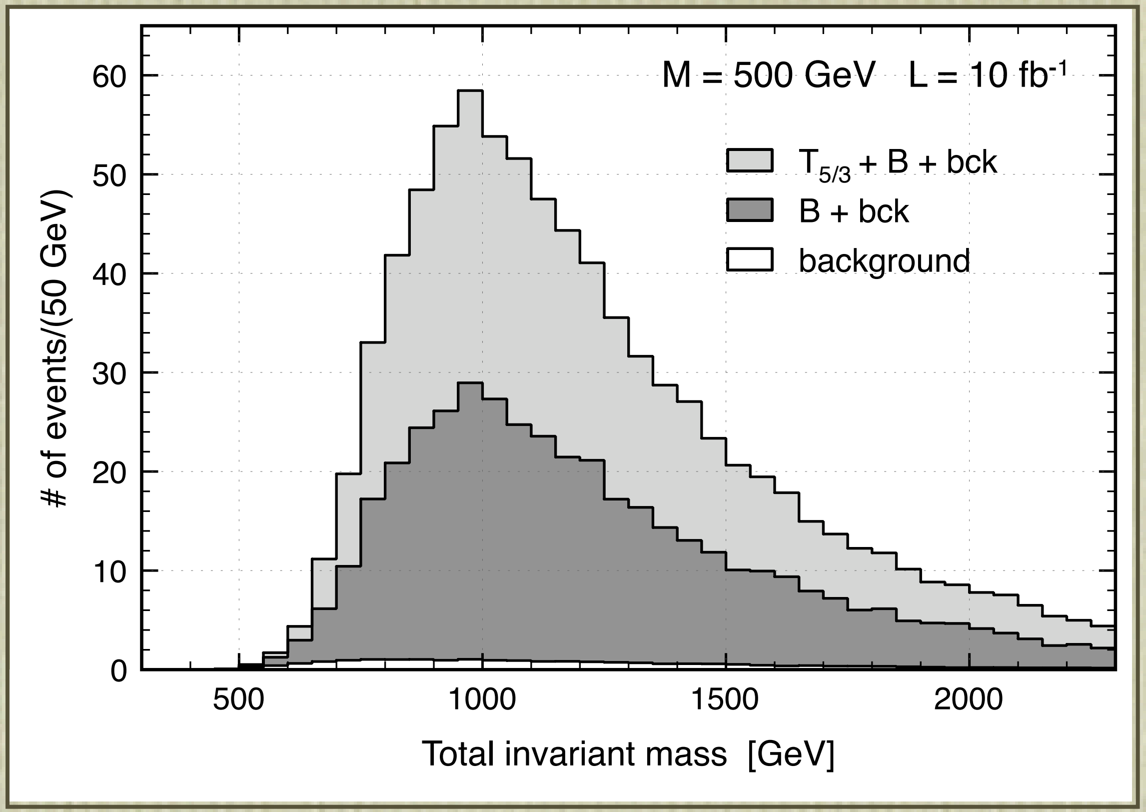
	signal ($M = 500$ GeV)	signal ($M = 1$ TeV)	$t\bar{t}W$	$t\bar{t}WW$	WWW	$W^\pm W^\pm$
Efficiencies (ϵ_{main})	0.42	0.43	0.074	0.12	0.008	0.01
σ [fb] $\times BR \times \epsilon_{main}$	44.2	0.67	1.4	0.62	0.15	0.16

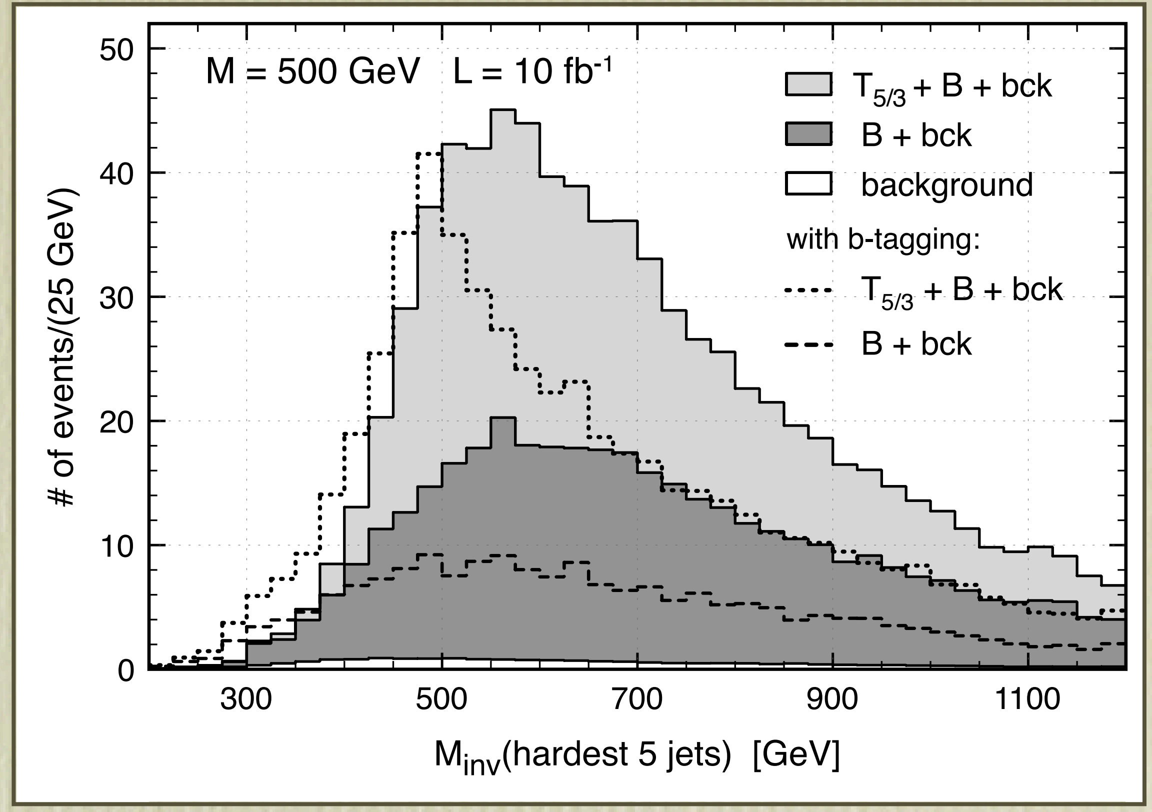
Extra Cuts for M=1TeV:

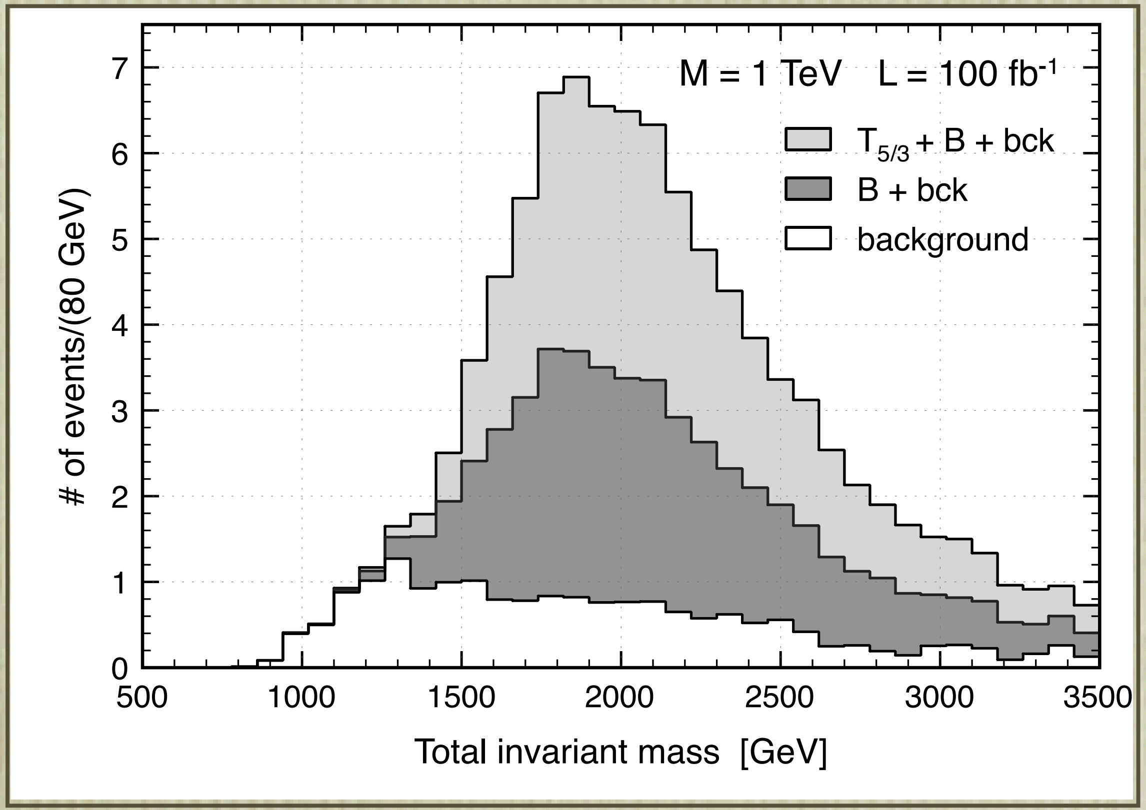
$p_T(\text{1st jet}) \geq 200$ GeV

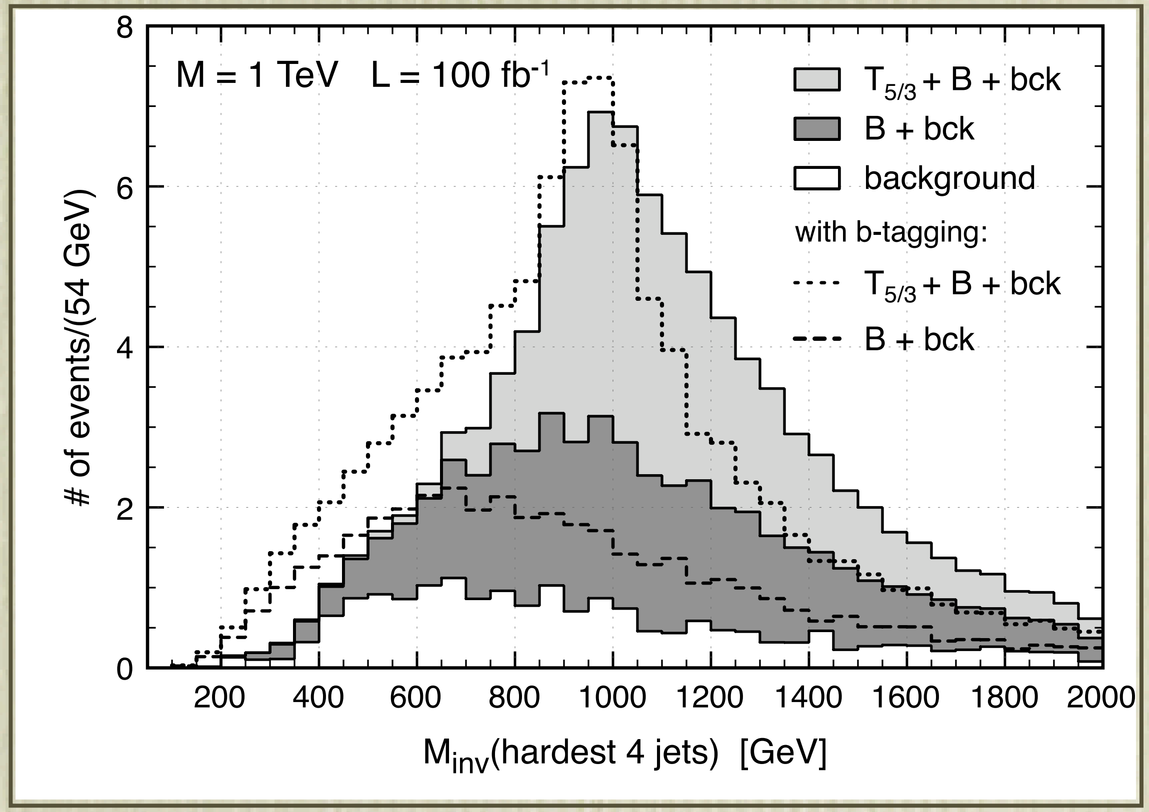
$\sum_i |\vec{p}_T(l_i)| \geq 300$ GeV

	signal ($M = 1$ TeV)	$t\bar{t}W$	$t\bar{t}WW$	WWW	WW
Efficiencies (ϵ_{disc})	0.65	0.091	0.032	0.16	0.18
σ [fb] $\times BR \times \epsilon_{main} \times \epsilon_{disc}$	0.43	0.12	0.02	0.02	0.03







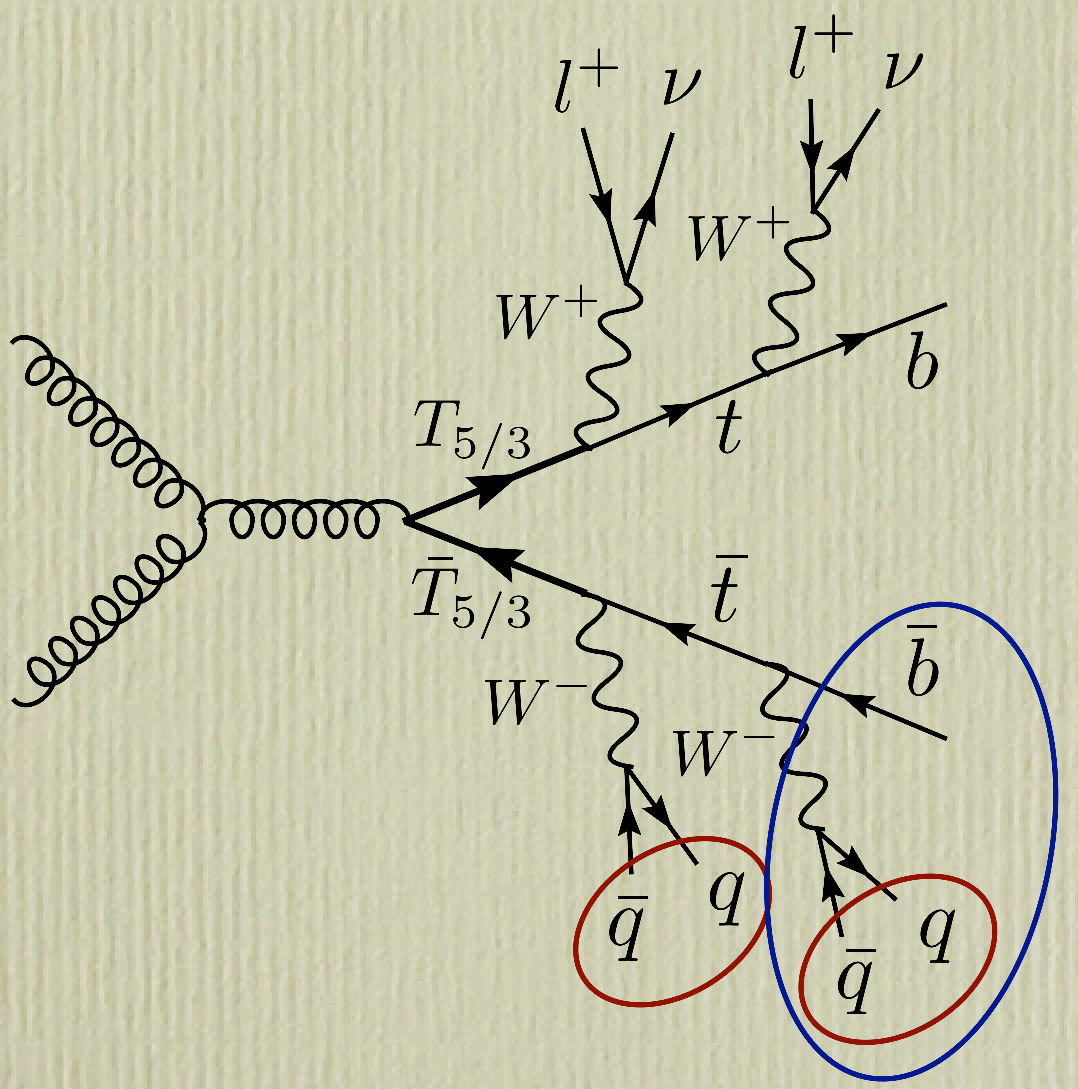


Discovery Potential:

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

		L_{disc}
$M = 1$ TeV	$T_{5/3} + B$	$15\,\mathrm{fb}^{-1}$
	B only	$48\,\mathrm{fb}^{-1}$

Mass Reconstruction
M=500 GeV



1. Reconstruct 2 W's

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

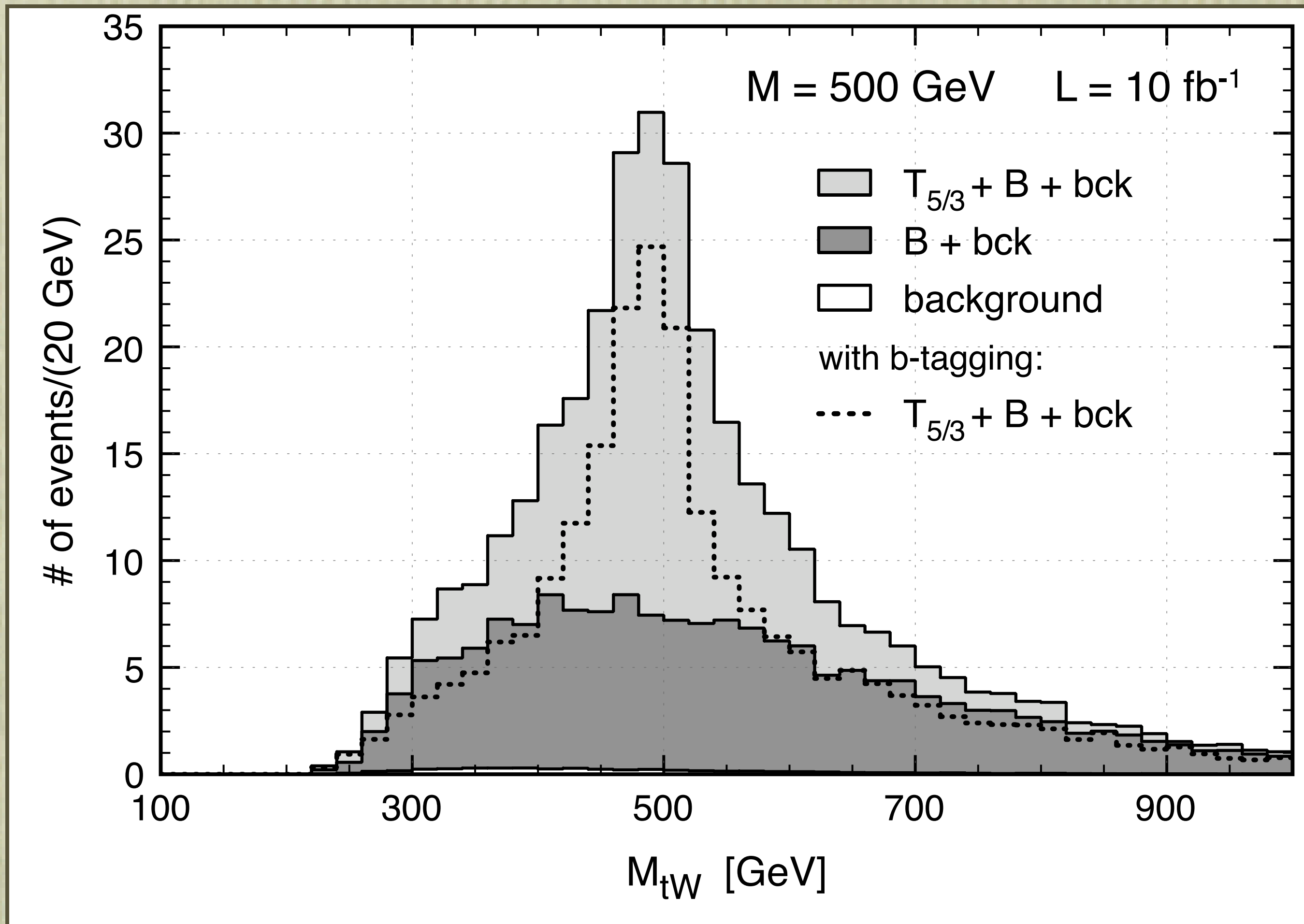
$$\Delta R_{jj}(\text{1st pair}) \leq 1.5$$
$$|\vec{p}_T(\text{1st pair})| \geq 100 \text{ GeV}$$

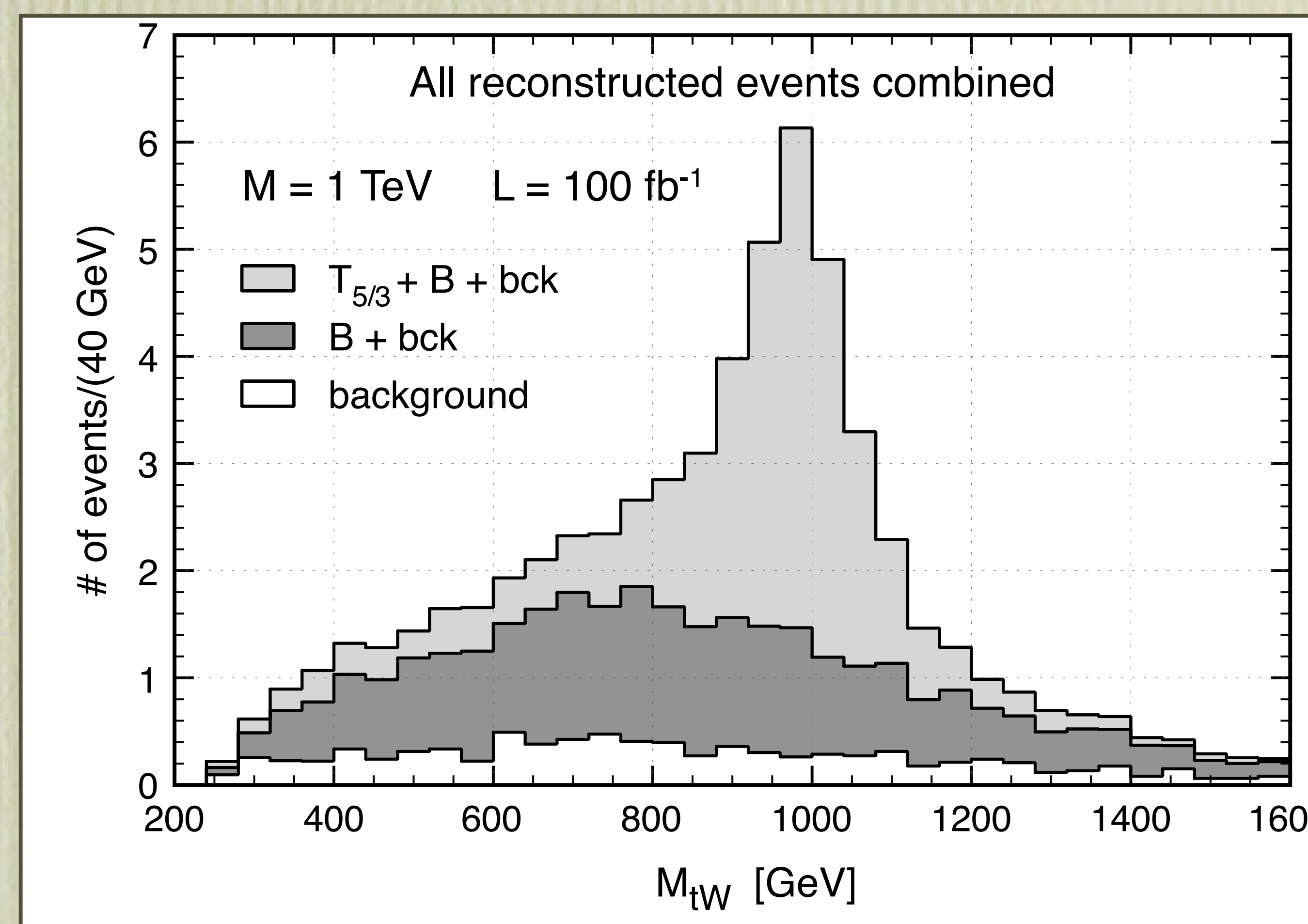
$$\Delta R_{jj}(\text{2nd pair}) \leq 2.0$$
$$|\vec{p}_T(\text{2nd pair})| \geq 30 \text{ GeV}$$

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


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


All reconstructed events combined
M = 1 TeV L = 100 fb-1
T5/3 + B + bck
B + bck
background
# of events/(40 GeV)
MtW [GeV]
0
1
2
3
4
5
6
7
200
400
600
800
1000
1200
1400
1600

CDF search and bounds

[M. Hickman, D. Whiteson, M. Wilson, D. Berge]

- 2.7 fb^-1 analyzed by CDF at 1.96 TeV

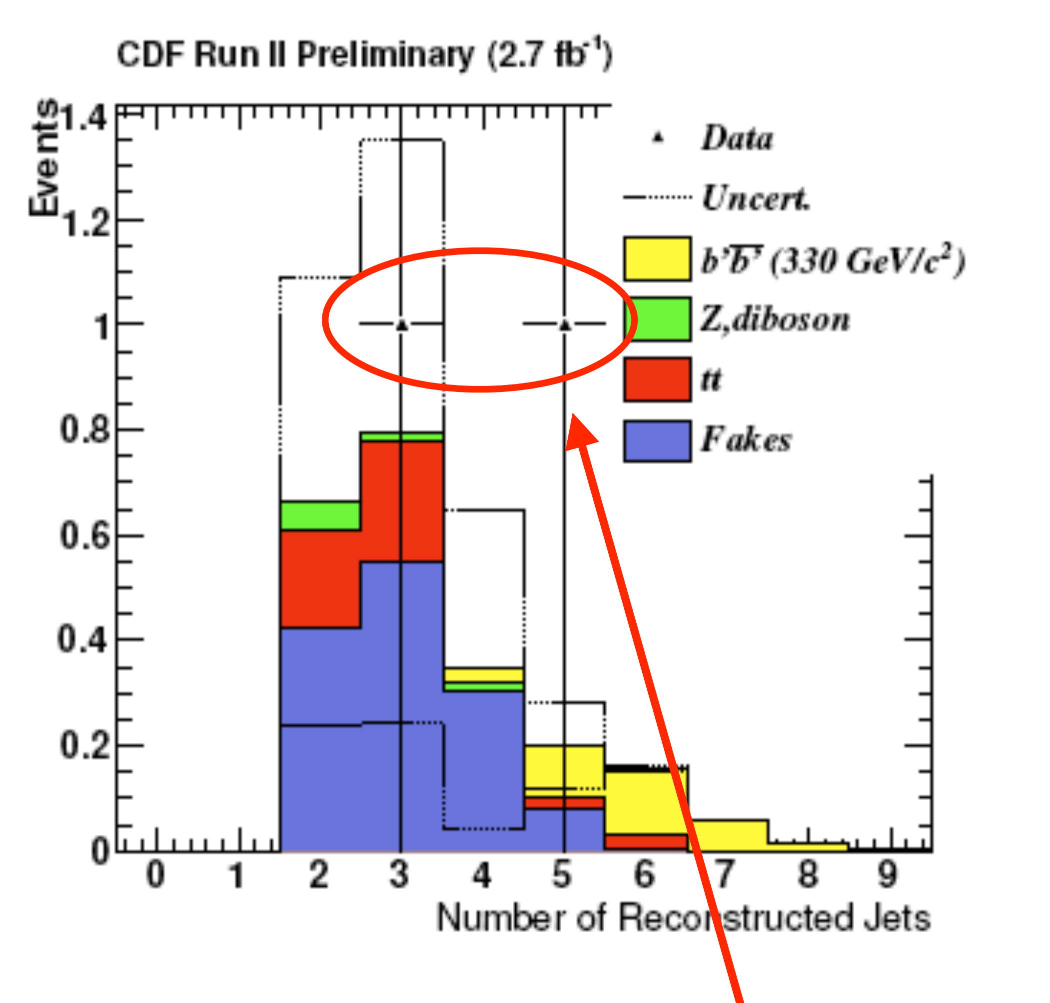
- Cuts:
  1. Two same-charge leptons with $|\eta| < 1.1$ and $p_T > 20\,\mathrm{GeV}$
  2. At least two jets with $|\eta| < 2.4$ and $p_T > 25\,\mathrm{GeV}$
  3. At least one b-tag
  4. At least 20 GeV of missing transverse energy

- Included backgrounds:

largest bckg after cuts

(majority of fakes from heavy quarks)

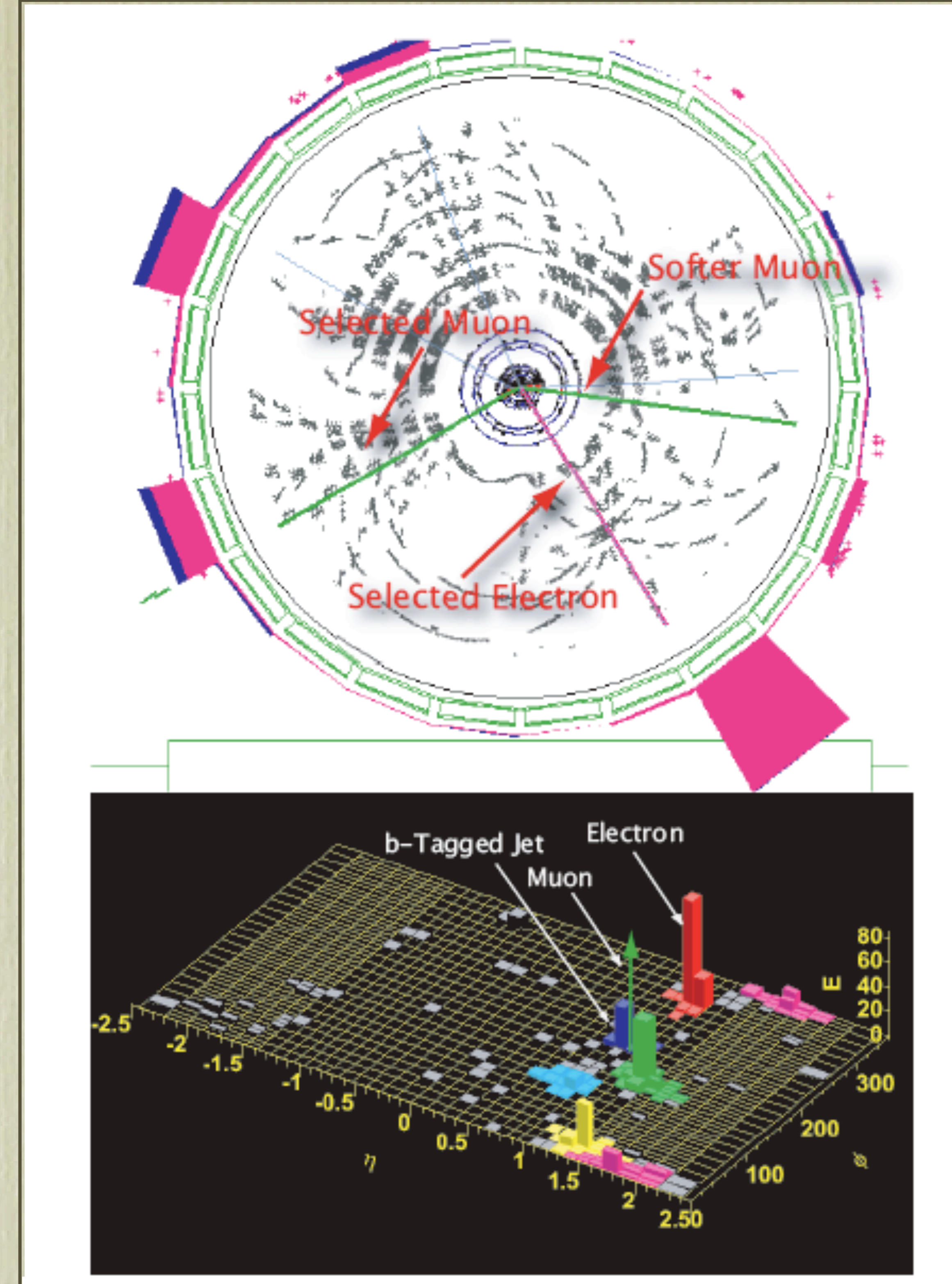
  - Fake leptons (from light or heavy jets) from $W + jets$ ($\supset Wb\bar{b},\ Wc\bar{c},\ t\bar{t} \to W + jets$)
  - Charge mis-ID electrons from $t\bar{t} + jets$, $Z + jets$ ← killed by miss ET cut



2 events survive the cuts

Source	ee	mm	em	ll
300 GeV/c^2 b'	1.97 ± .20	2.14 ± .21	4.88 ± .49	9.0 ± .90
300 GeV/c^2 $T_{5/3}+B$	4.17 ± .42	4.22 ± .42	9.56 ± .96	17.9 ± 1.8

Source	ee	$\mu\mu$	$e\mu$	ll
$Z, diboson$	0.03 ± 0.02	0.02 ± 0.01	0.04 ± 0.02	0.10 ± 0.05
tt	0.17 ± 0.02	0.06 ± 0.01	0.22 ± 0.02	0.50 ± 0.05
$W + jets$	0.56 ± 0.56	0.34 ± 0.34	0.47 ± 0.47	1.40 ± 1.40
Total	0.8 ± 0.6	0.4 ± 0.3	0.7 ± 0.5	1.9 ± 1.4
Data	0	1	1	2



Event display for $e\mu$ 5-jet event (run 198843 event 15281816)

Final bound at 95% CL :

$$m_{b'} \geq 325\,\mathrm{GeV}$$
$$m_{B,T_{5/3}} \geq 351\,\mathrm{GeV}$$

Conclusions

- Heavy partners of the top are a robust and motivated prediction of a large class of non-supersymmetric models

- Same-sign dilepton final states seem promising for an early discovery of B and $T_{5/3}$

- CDF already set an important bound: $m_{B,T_{5/3}} \geq 351\,\mathrm{GeV}$

- A fully-detailed analysis at the LHC is in progress by both ATLAS and CMS groups

Extra Slides

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

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

M. Perelstein, M. Peskin, A. Pierce Phys. Rev. D69 (2004) 075002

✦ 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

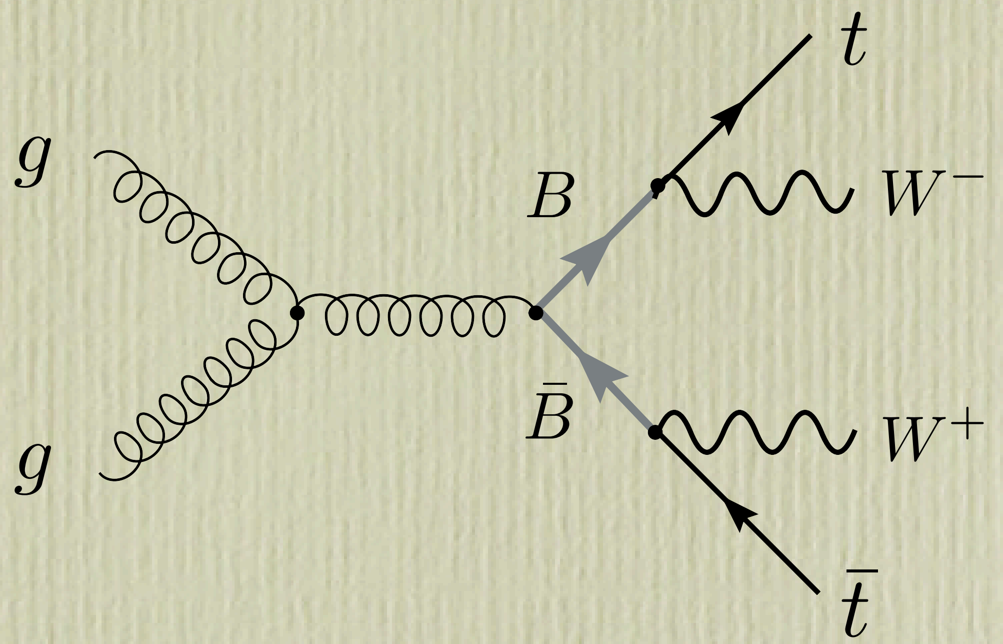
$L_{disc} = 2.1(90) \text{ fb}^{-1}$ for $M_{\tilde{T}} = 0.5(1)$ TeV

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



- 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

Mass Reconstruction
M=1 TeV

Extra Cuts
for reconstruction at
M=1TeV

(looser than extra cuts for discovery)

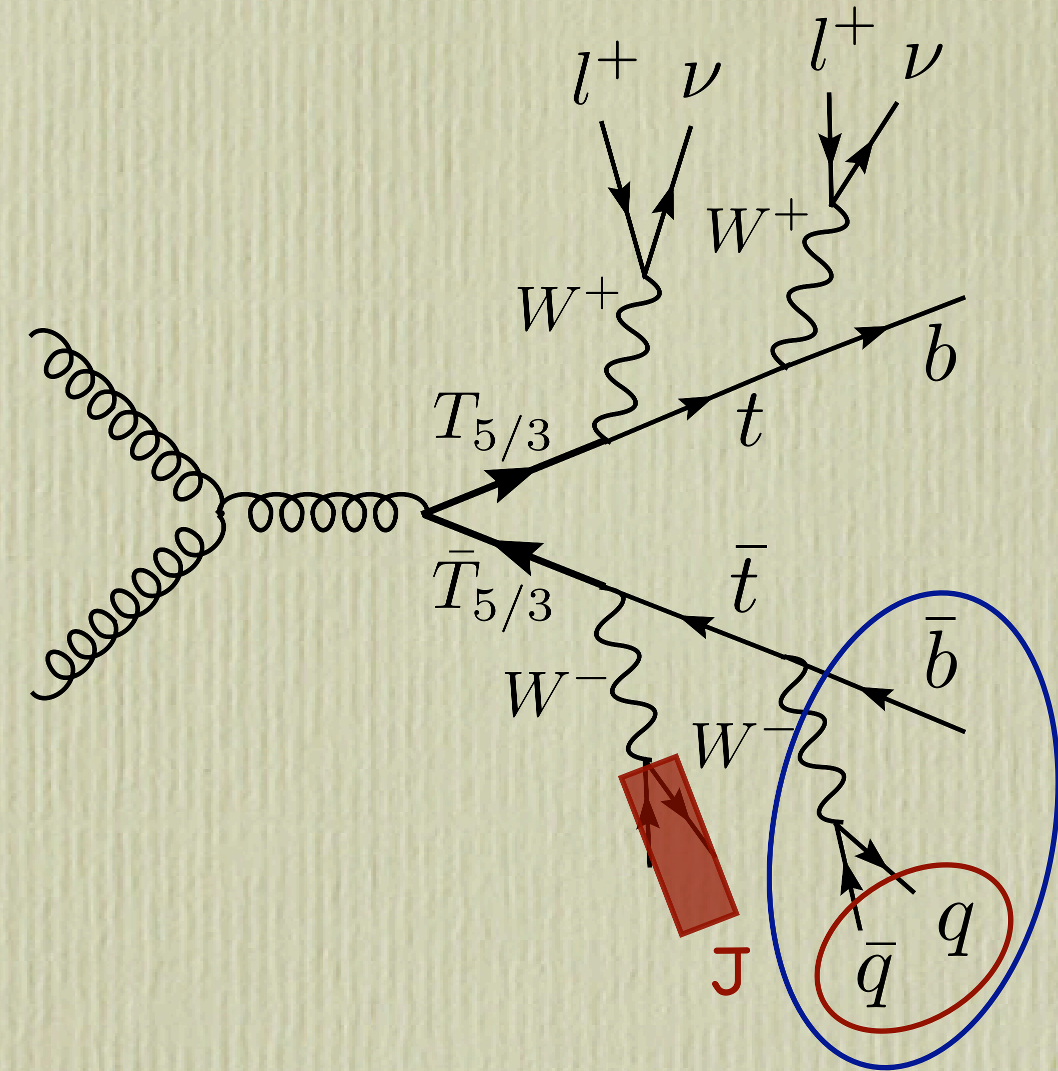
$M_{inv}(\text{tot}) \geq 1500$ GeV

$p_T(\text{1st jet}) \geq 200$ GeV

$p_T(\text{2nd jet}) \geq 100$ GeV

$p_T(\text{1st lepton}) \geq 100$ GeV

	signal ($M = 1$ TeV)	$t\bar{t}W$	$t\bar{t}WW$	WWW	WW
Efficiencies (ϵ_{rec})	0.83	0.18	0.07	0.22	0.38
σ [fb] $\times BR \times \epsilon_{main} \times \epsilon_{rec}$	0.55	0.24	0.04	0.03	0.06



1. Reconstruct 1 or 2 W's

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

$$\Delta R_{jj}(\text{1st pair}) \leq 0.7$$
$$|\vec{p}_T(\text{1st pair})| \geq 250 \text{ GeV}$$

$$\Delta R_{jj}(\text{2nd pair}) \leq 1.5$$
$$|\vec{p}_T(\text{2nd pair})| \geq 80 \text{ GeV}$$

	signal ($M = 1$ TeV)	$t\bar{t}W$	$t\bar{t}WW$	WWW	WW
ϵ_{2W}	0.31	0.15	0.23	0.16	0.071
ϵ_{1W}	0.57	0.62	0.59	0.58	0.49

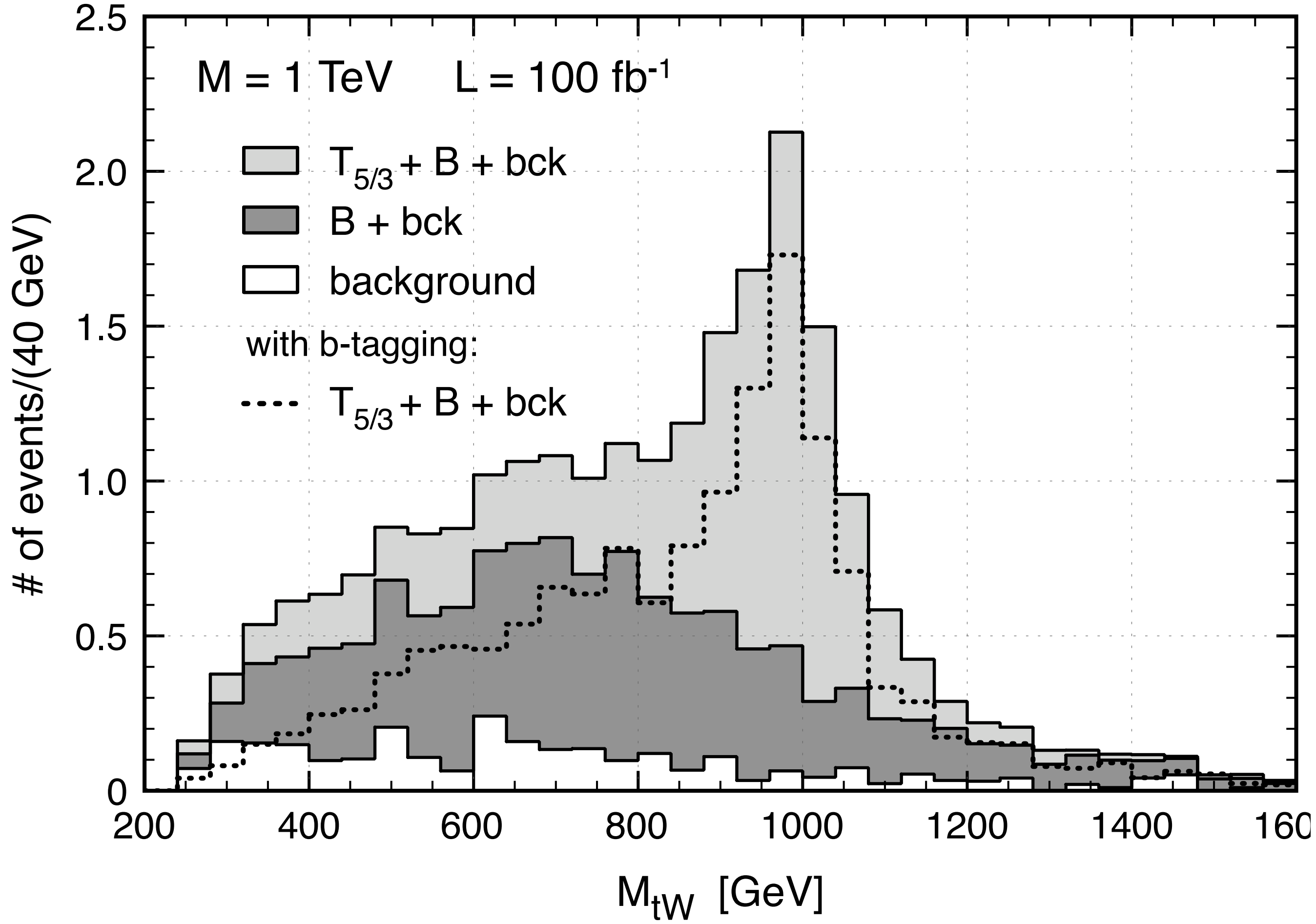
2. Reconstruct 1 top: (t=Wj)

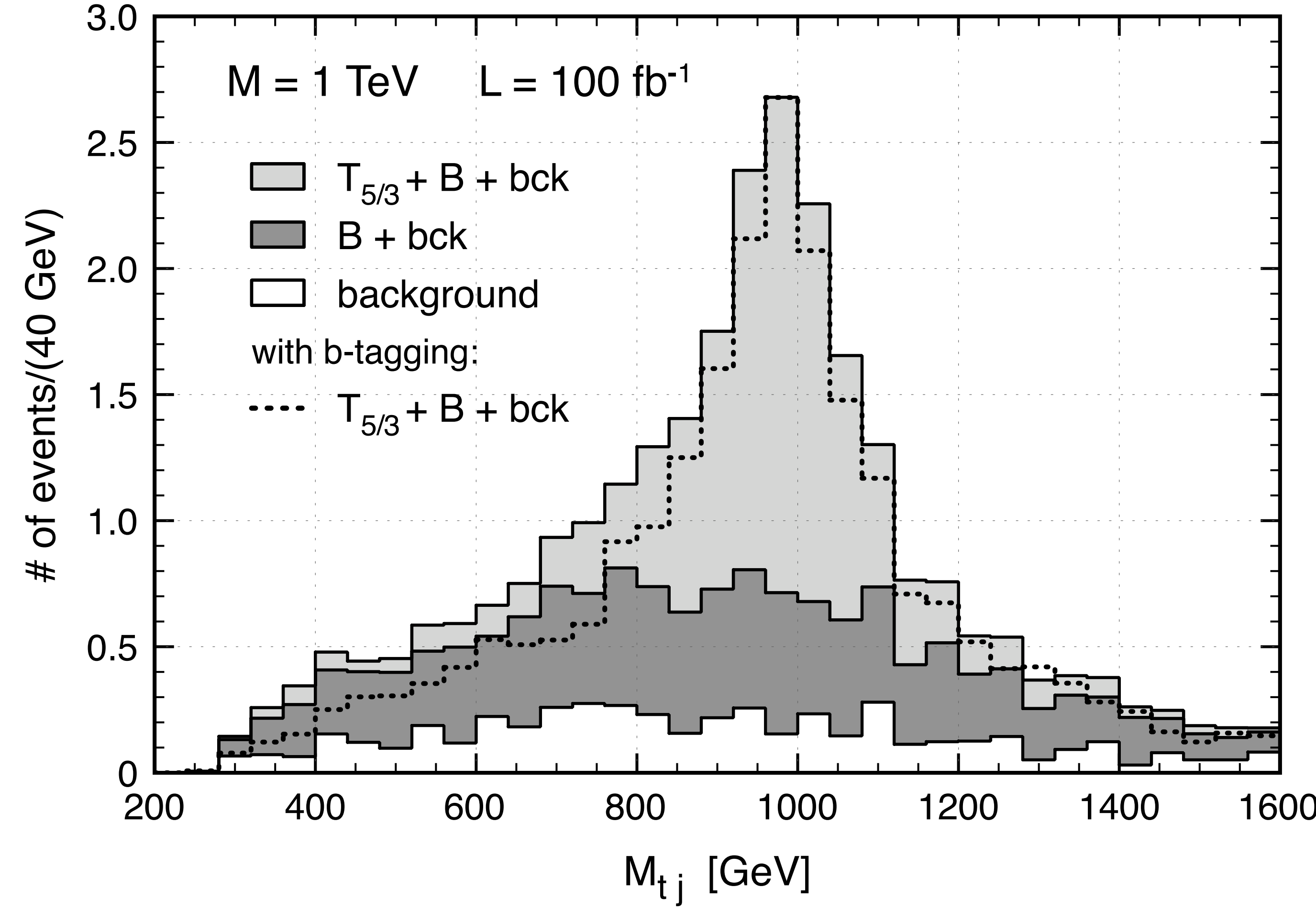
i) t=Wj using events with 2 W

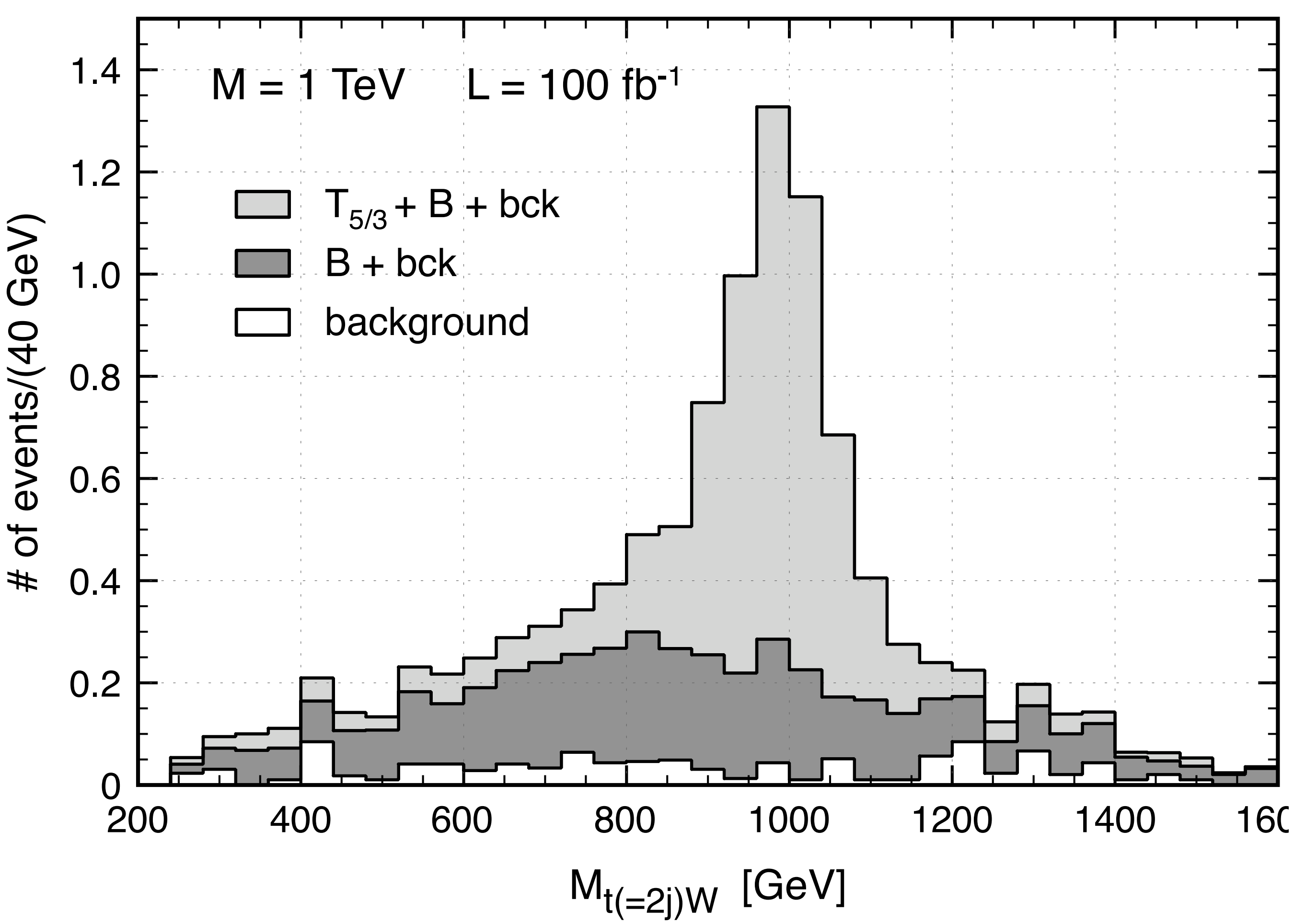
ii) t=Wj using events with 1 W

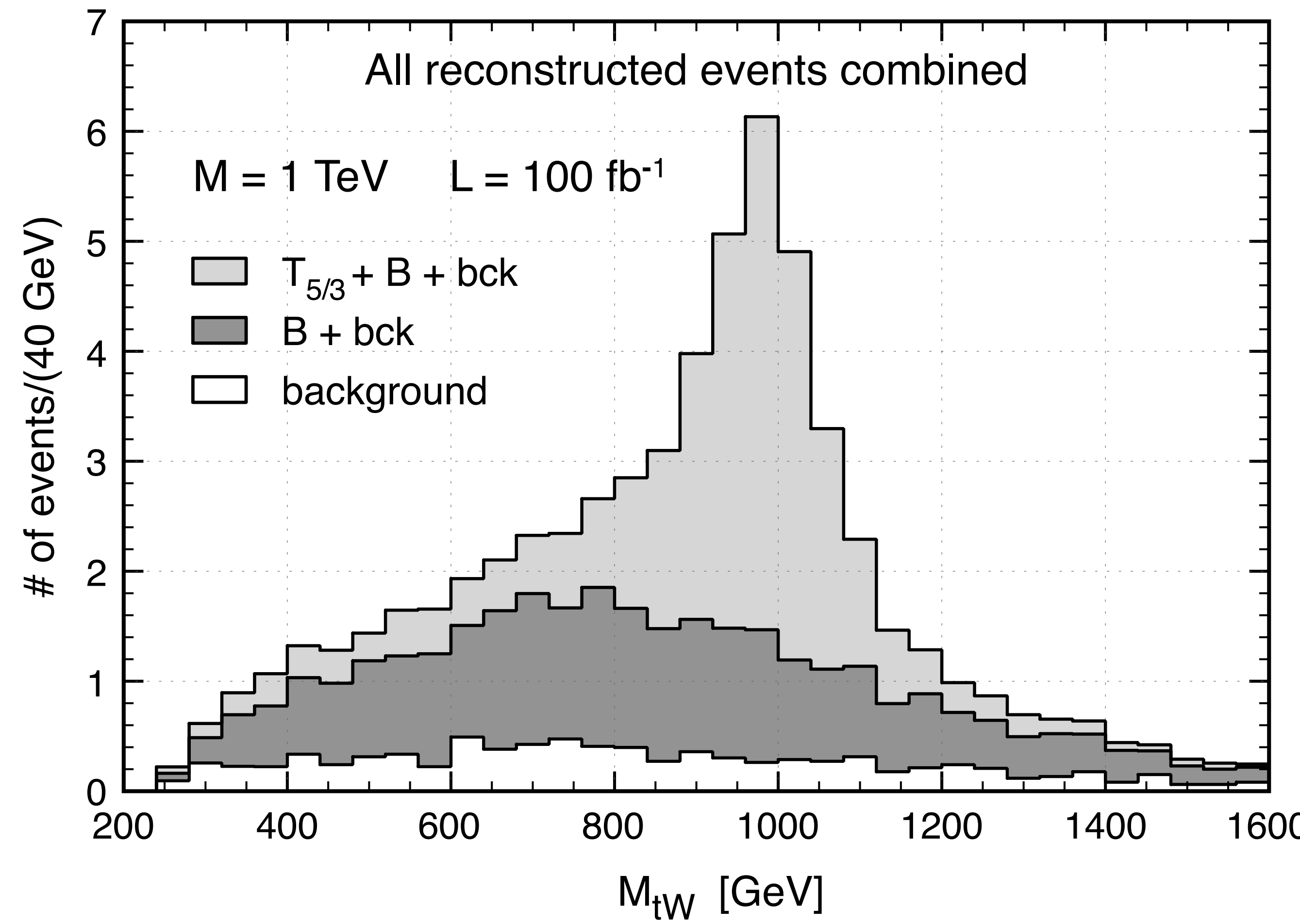
iii) t=jj using events with 1 W

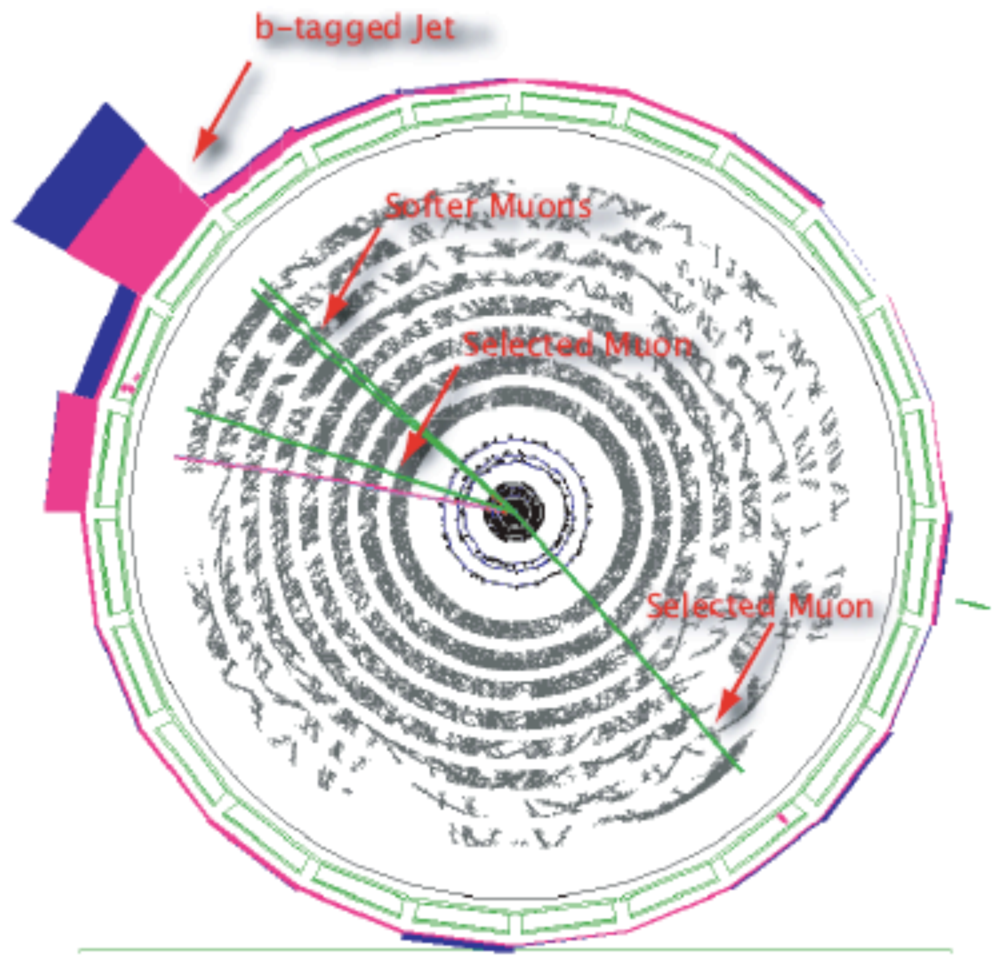
	signal ($M = 1$ TeV)	$t\bar{t}W$	$t\bar{t}WW$	WWW	WW
$\epsilon_{top}^{[2W]}(t = Wj)$	0.62	0.56	0.62	0.11	0.13
$\epsilon_{top}^{[1W]}(t = Wj)$	0.44	0.56	0.53	0.22	0.20
$\epsilon_{top}(t = jj)$	0.18	0.04	0.06	0.06	0.07


M = 1 TeV L = 100 fb^{-1}
$T_{5/3}$ + B + bck
B + bck
background
with b-tagging:
$T_{5/3}$ + B + bck
# of events/(40 GeV)
M_{tW} [GeV]


M = 1 TeV L = 100 fb^{-1}
$T_{5/3}$ + B + bck
B + bck
background
with b-tagging:
$T_{5/3}$ + B + bck
# of events/(40 GeV)
$M_{t\,j}$ [GeV]


M = 1 TeV L = 100 fb^{-1}
$T_{5/3}$ + B + bck
B + bck
background
# of events/(40 GeV)
$M_{t(=2j)W}$ [GeV]


All reconstructed events combined
M = 1 TeV L = 100 fb^{-1}
$T_{5/3}$ + B + bck
B + bck
background
# of events/(40 GeV)
M_{tW} [GeV]



Event display for $\mu\mu$ 3-jet event (run 185637 event 3178143)