Gauge-Higgs Unification

Theory and Phenomenological Consequences at the LHC

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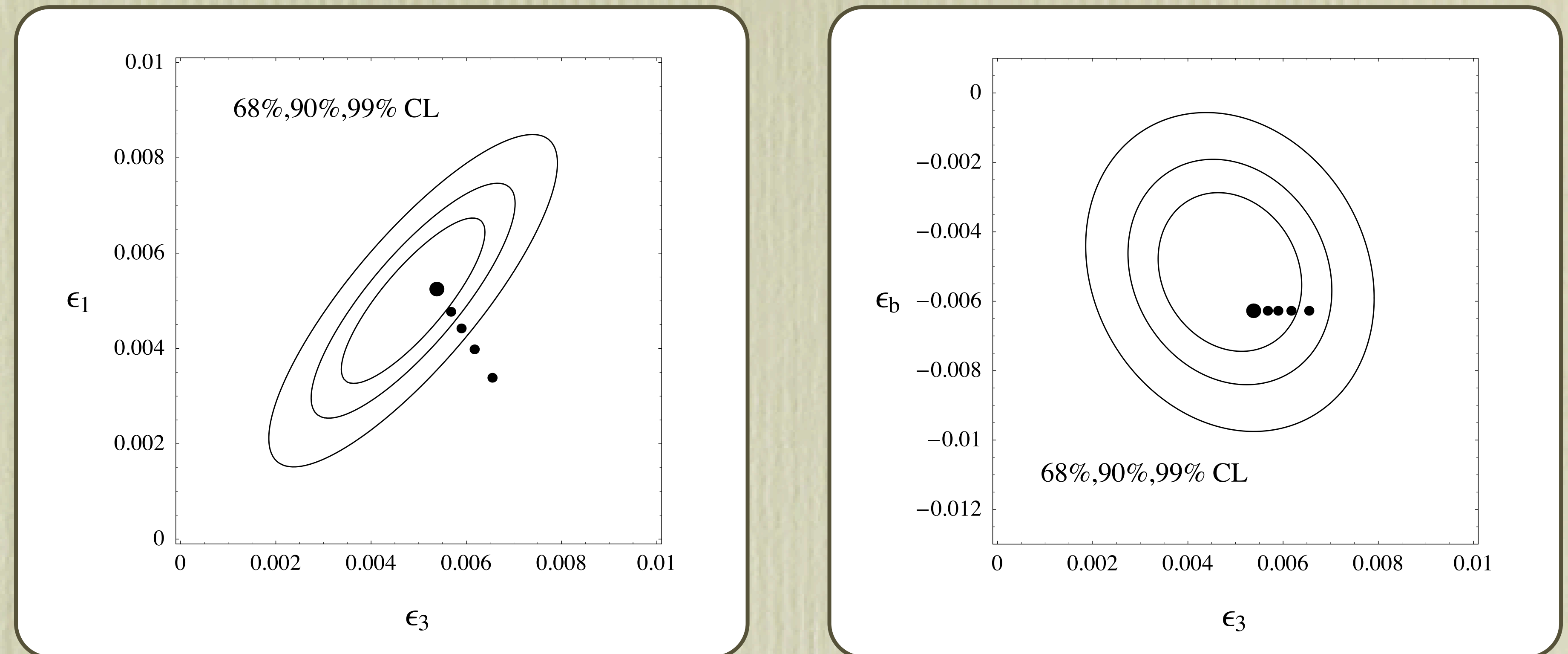
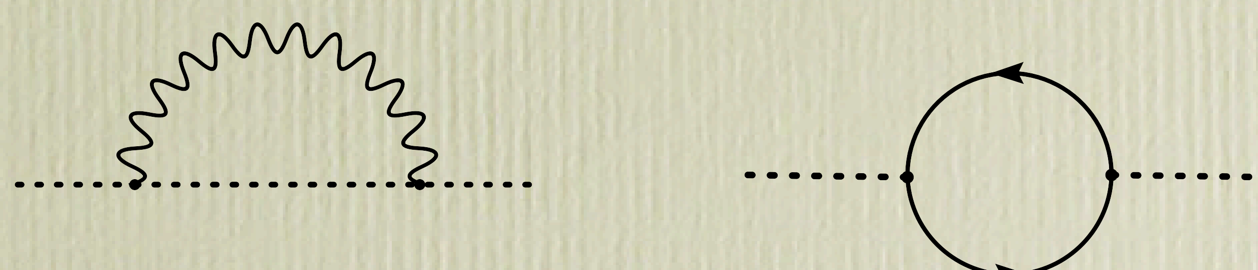
Fact #1 : LEP and SLD precision data strongly suggest the existence of a light Higgs boson, mH ~ 100-300 GeV



Fact #2 : The instability against radiative correction makes a light (elementary) scalar in the low-energy spectrum highly unnatural unless a symmetry protection is at work



$$\delta m_h^2 = \left[6\, y_t^2 - \frac{3}{4} \left(3\, g_2^2 + g_1^2 \right) - 6\, \lambda_4 \right] \frac{\Lambda^2}{8\pi^2}$$

Two examples of symmetry protections

mass of fermions and gauge bosons are UV-stable:
each protected by a symmetry

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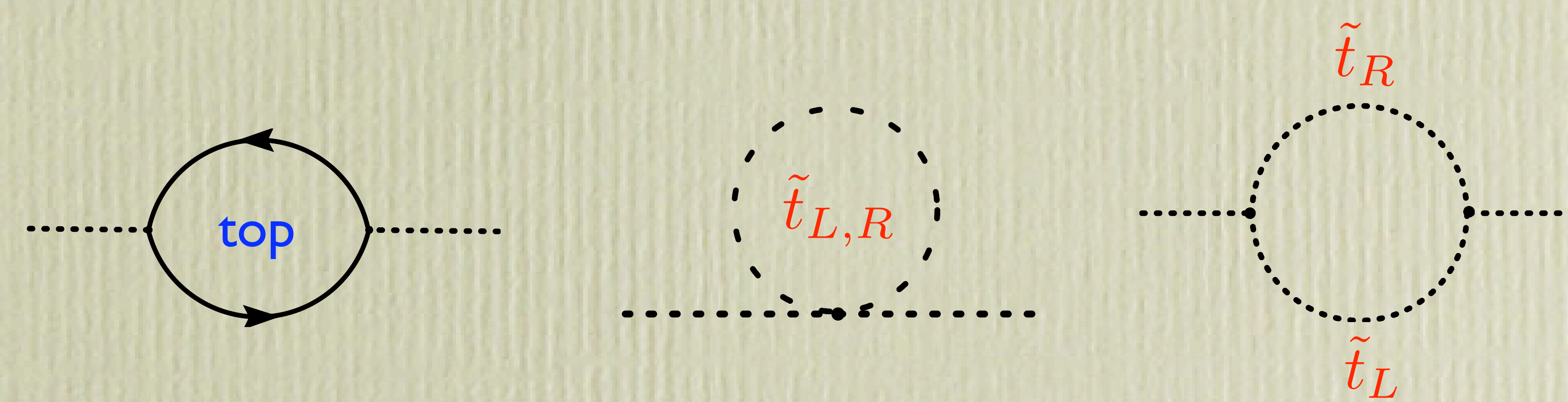

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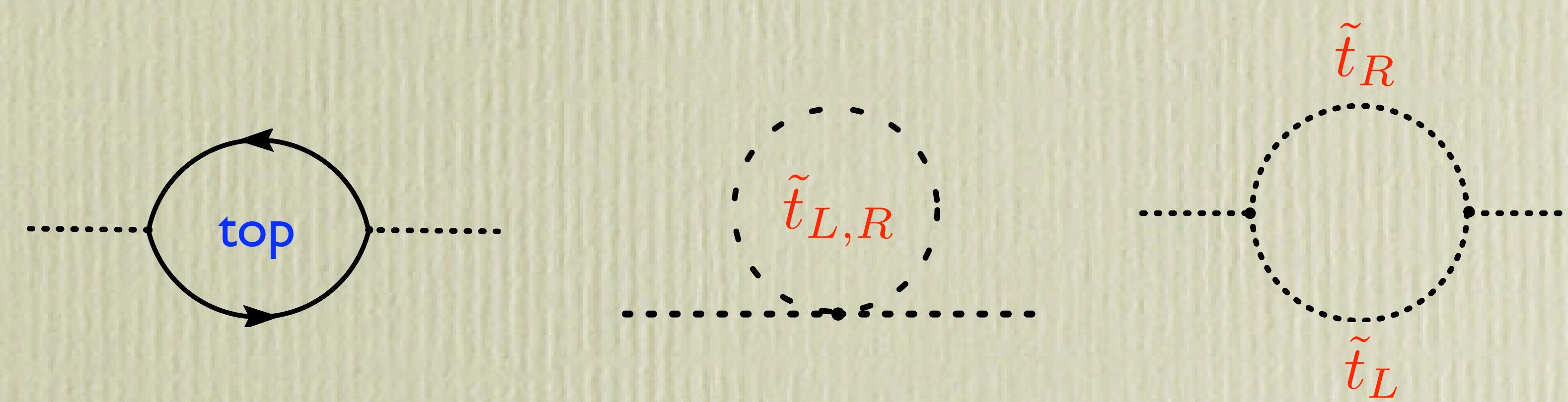

GAUGE SYMMETRY ⟶ GAUGE-HIGGS UNIFICATION $\qquad h = A_5$

(gauge protection)

[requires extra dimensions]

Quick introduction to Gauge-Higgs unification

- Suppose a fifth extra spatial dimension exists: $A_M = \{A_\mu, A_5\}$

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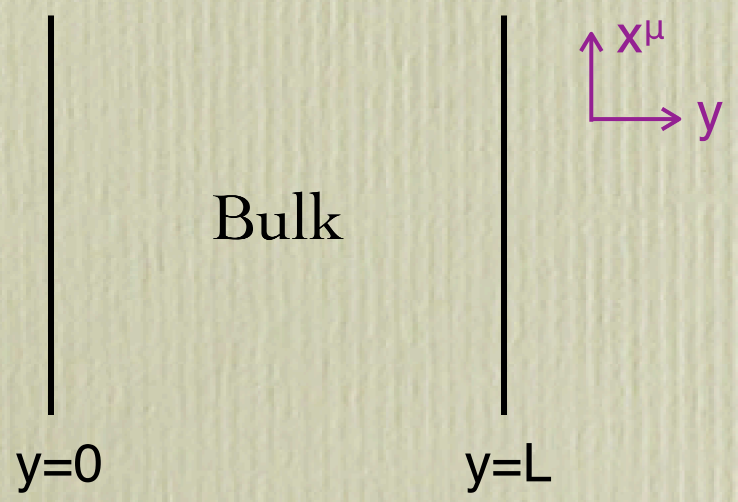
Consider a segment :



Any field propagating into the 5th dimension can be decomposed in Fourier armonics

$$\Phi(x,y) = \sum_n \zeta_n(y)\phi^{(n)}(x)$$

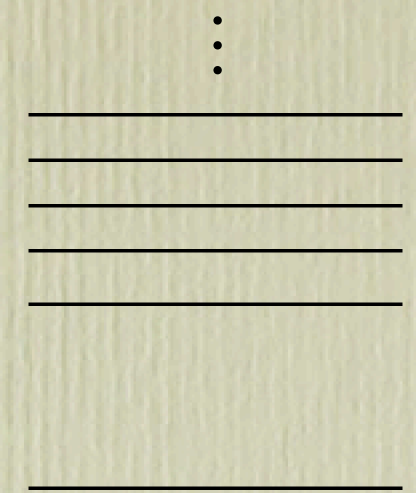
and must satisfy definite boundary conditions :

$$\partial_5\Phi(x,y_i) = 0 \qquad \text{Neumann} \qquad (+)$$

$$\Phi(x,y_i) = 0 \qquad \text{Dirichlet} \qquad (-)$$

Each Fourier mode behaves like a 4D field

with mass $m_n = \dfrac{n\,\pi}{L} \quad (n = 0, 1, 2, \dots)$



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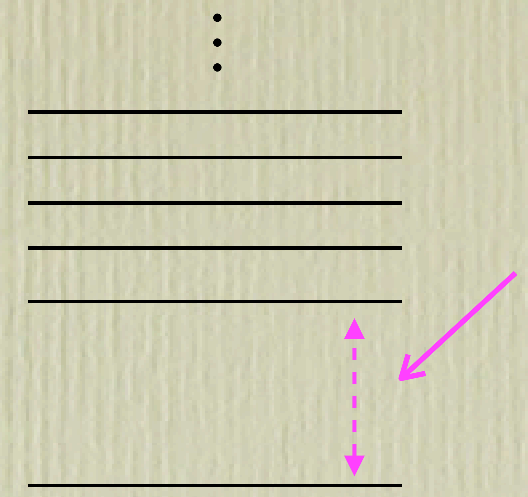

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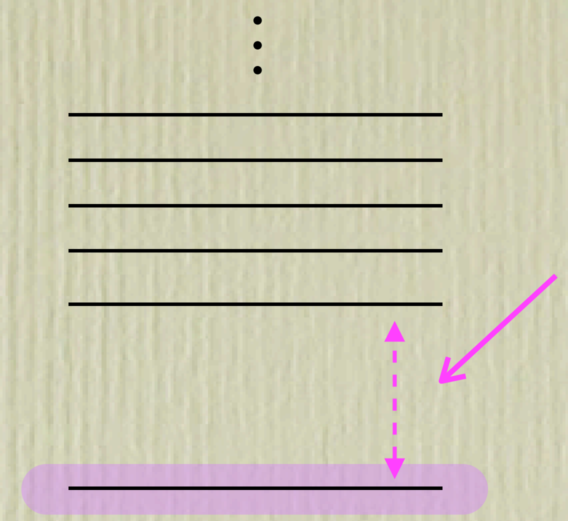

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only (++) fields have “zero-modes”

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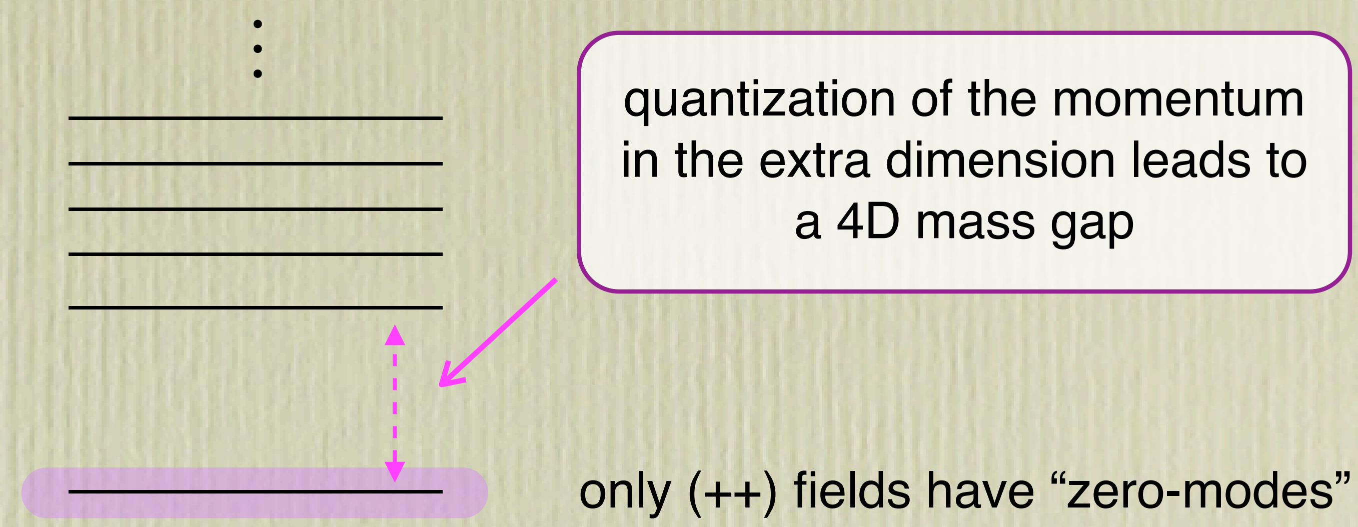

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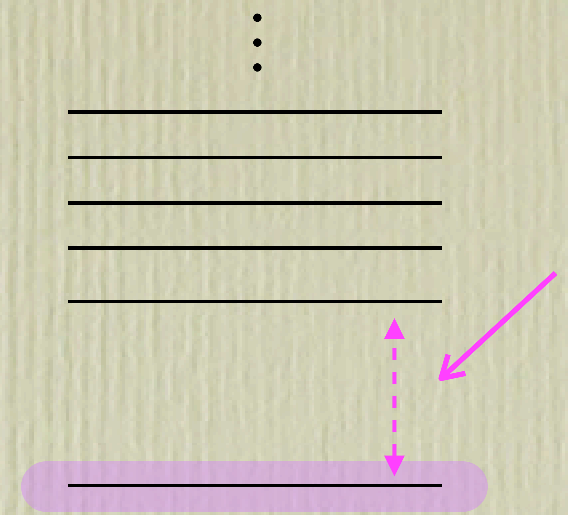

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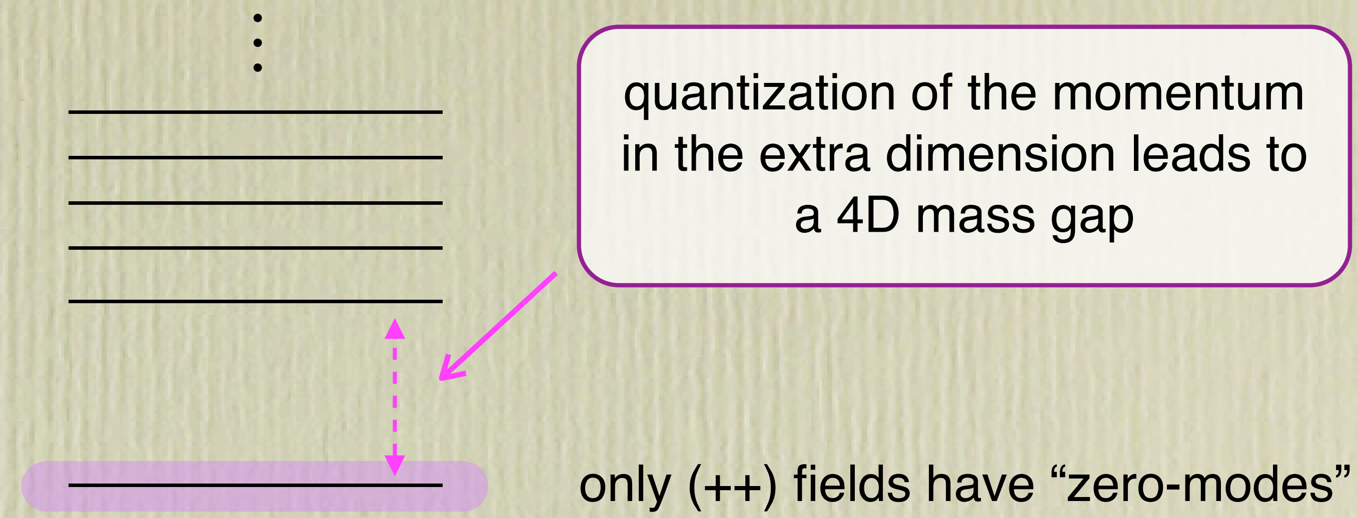

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2. A_5, being a gauge field, transforms as an adjoint representation ⟶ not an SU(2) doublet !

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with the following boundary conditions:

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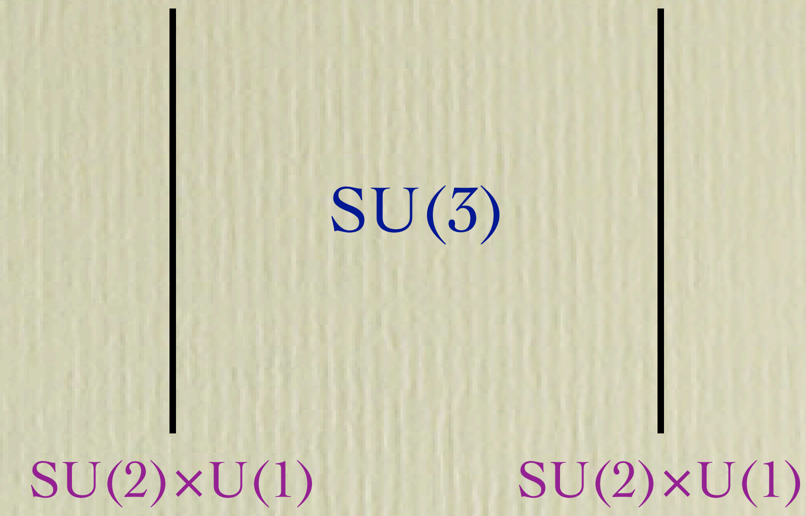

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A_5

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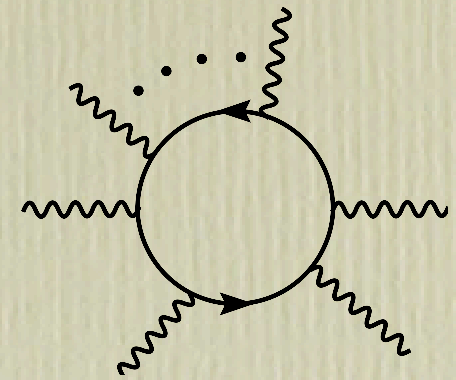
The Yukawa coupling between
doublet and singlet originates
from the covariant derivative :

$$\bar\Psi\, i\Gamma^M\,(\partial_M - iA_M)\,\Psi \supset \bar\Psi_L\gamma^5 T^{\hat a}\Psi_R\, A_5^{\hat a} + h.c.$$

The Higgs potential at 1-loop



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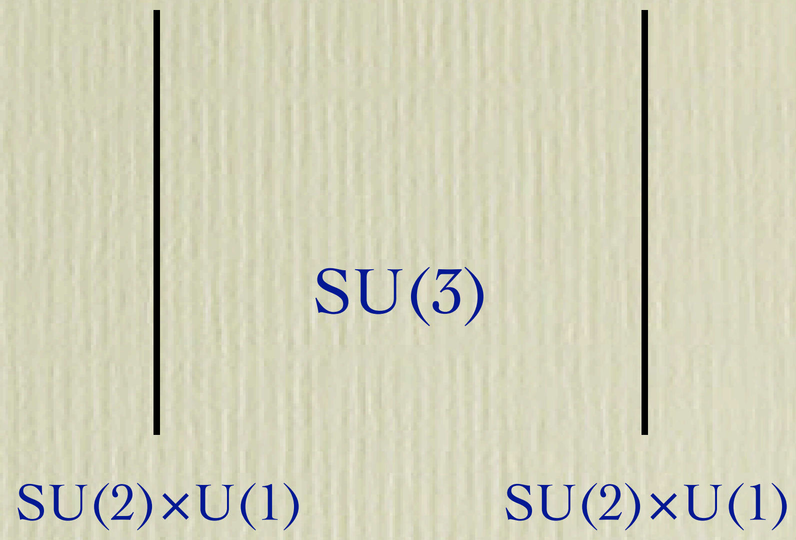

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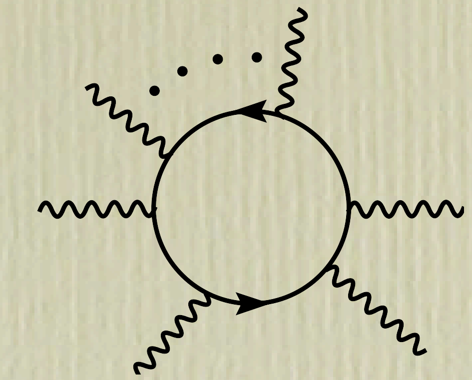

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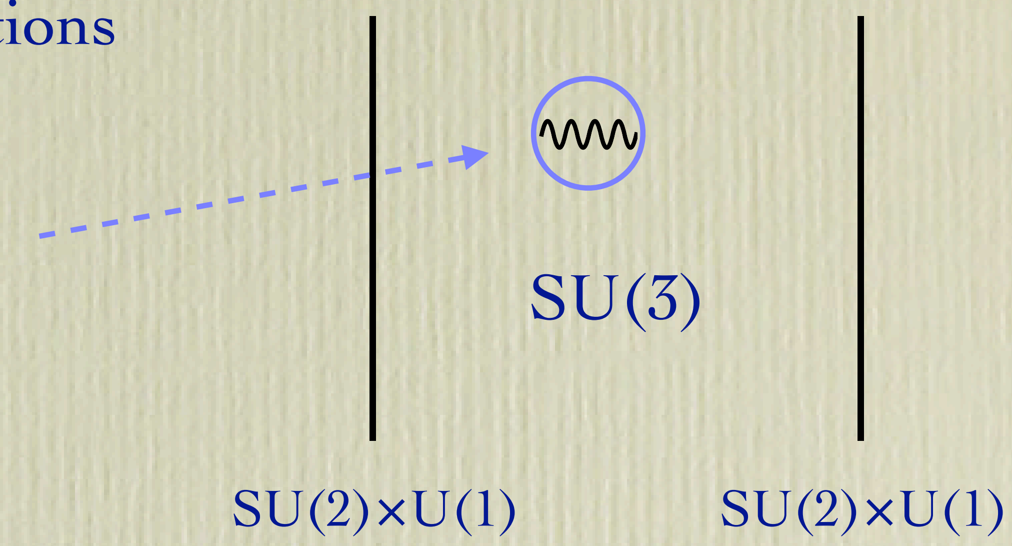

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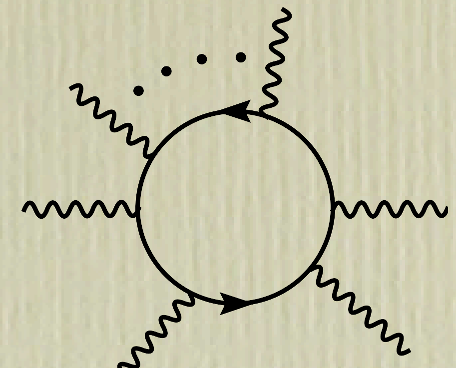

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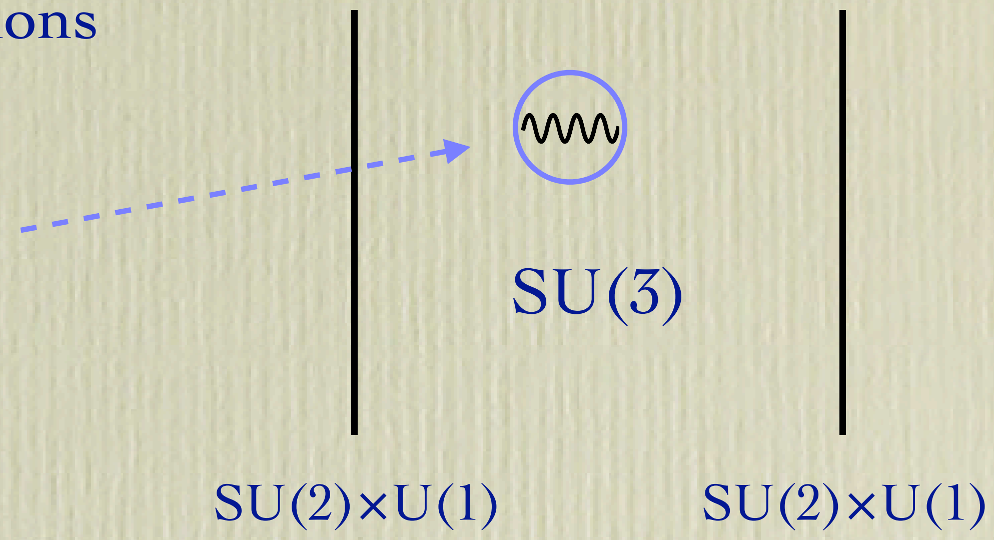

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- Being a finite-volume effect (like the Casimir energy) the potential can only depend on A_5 through the gauge-invariant Wilson line :

$$V = V(\Phi), \qquad \Phi(x) = \exp\left\{ i \int_0^L dx^5 A_5(x,y) \right\}$$

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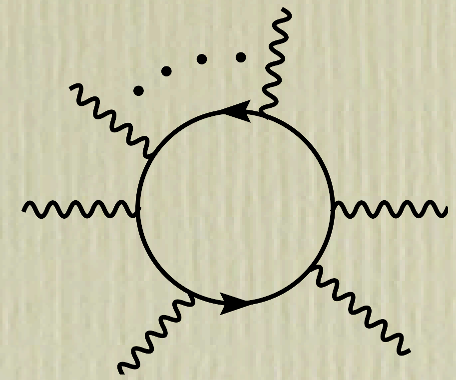

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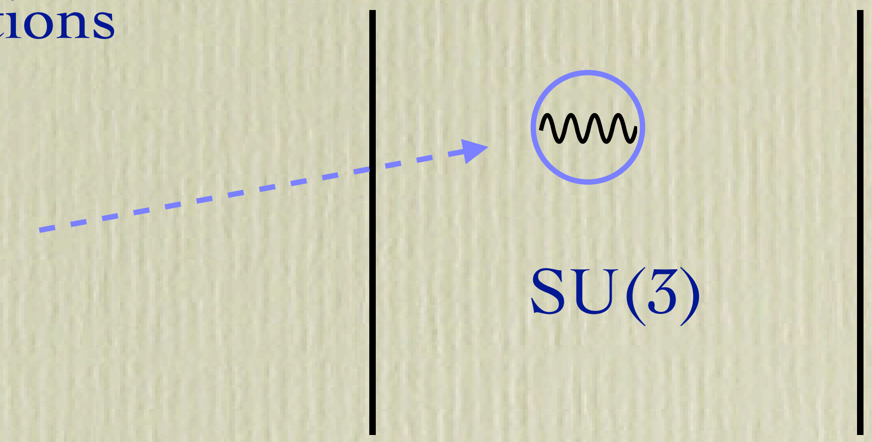

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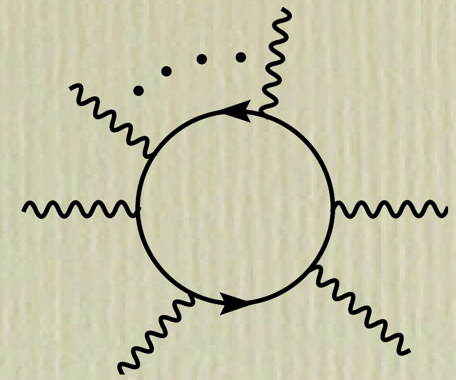

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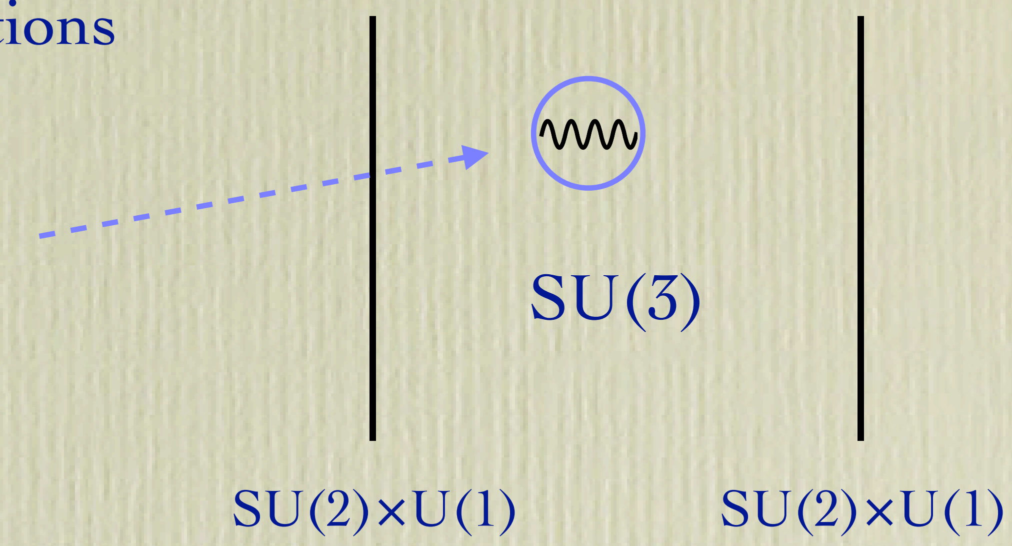

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← periodic function

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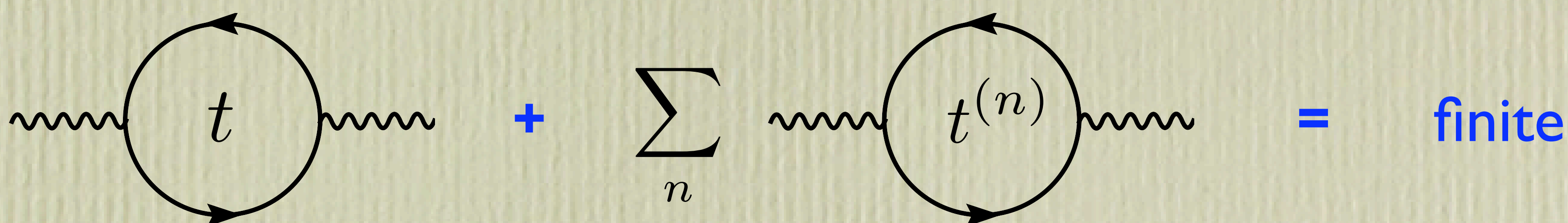

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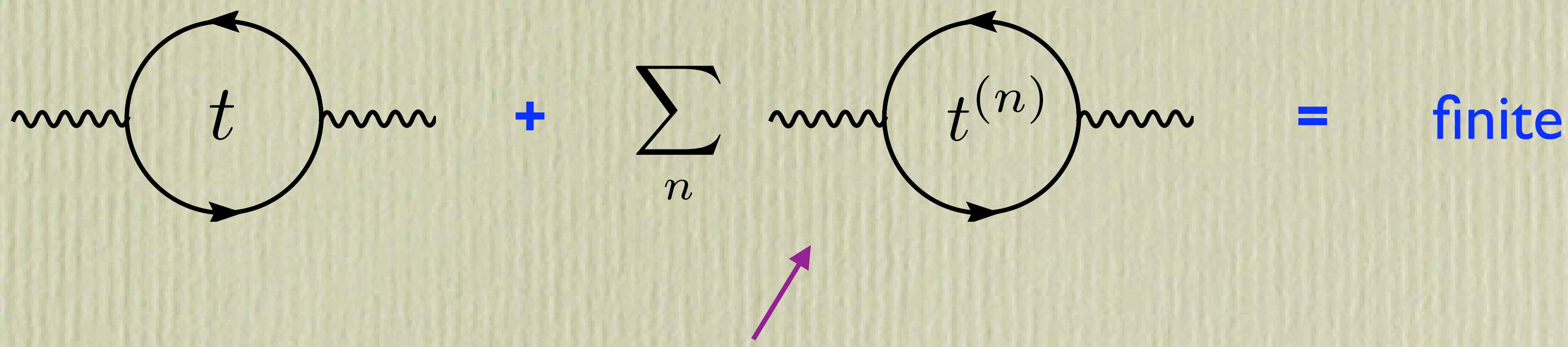

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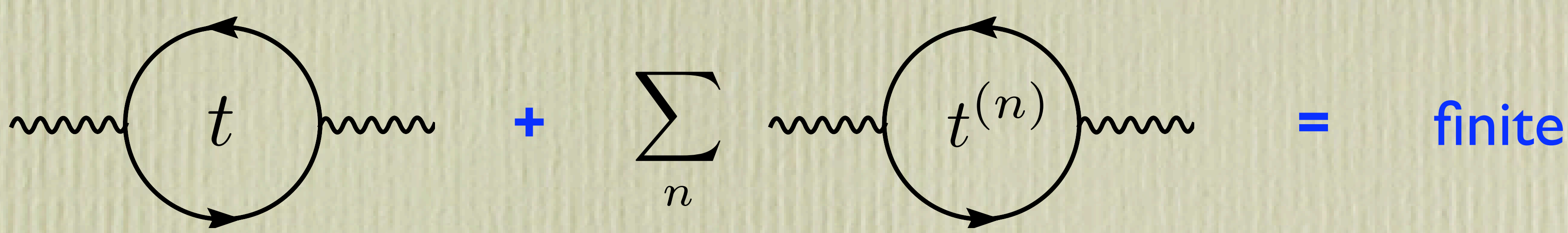

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Heavy Top partners come in complete multiplets of the bulk gauge symmetry

For a symmetry larger than SU(3) there can be fermions with exotic quantum numbers

For example: SO(5) ⟶ SO(4)

$$\Psi(= 5 \text{ of } SO(5)) = \begin{bmatrix} \mathbf{2_{7/6}} = \begin{pmatrix} T_{5/3} \\ T \end{pmatrix} \\ \mathbf{2_{1/6}} = \begin{pmatrix} t \\ b \end{pmatrix} \\ \mathbf{1_{2/3}} = t \end{bmatrix}$$

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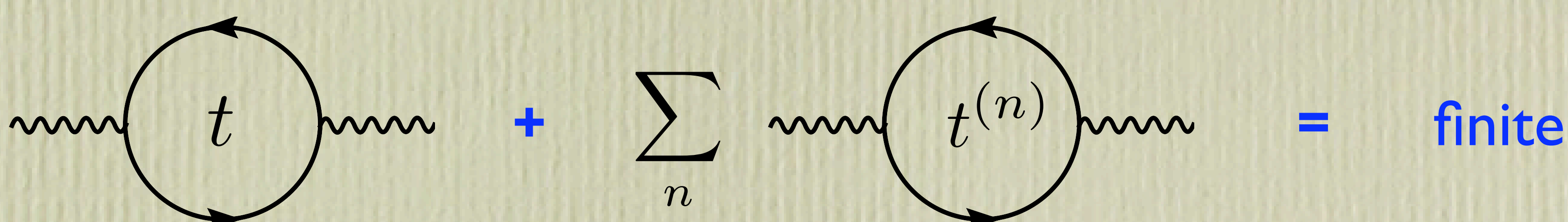

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Discovering the top partners at the LHC

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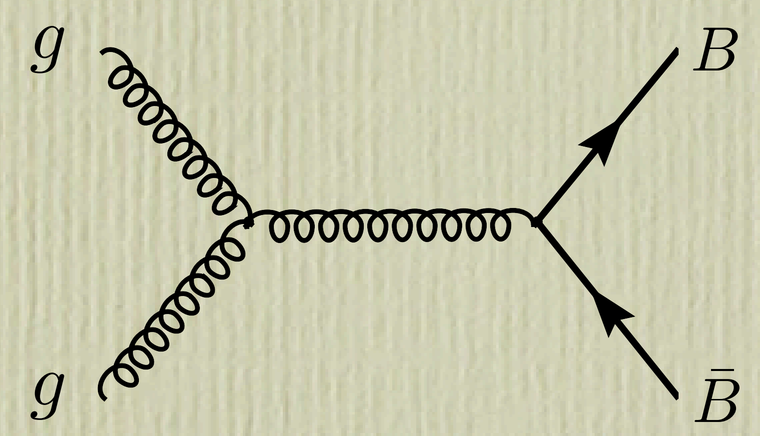

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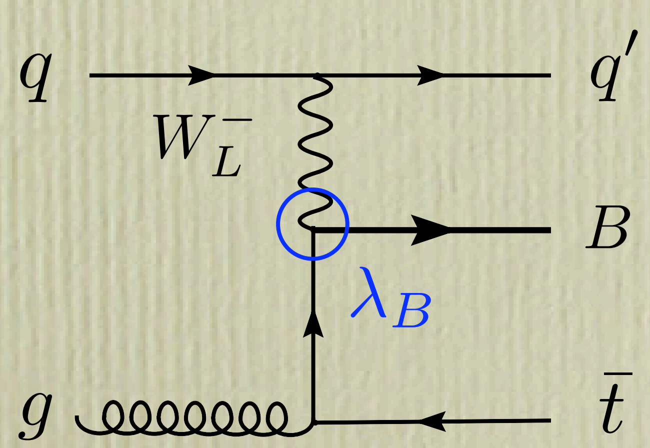

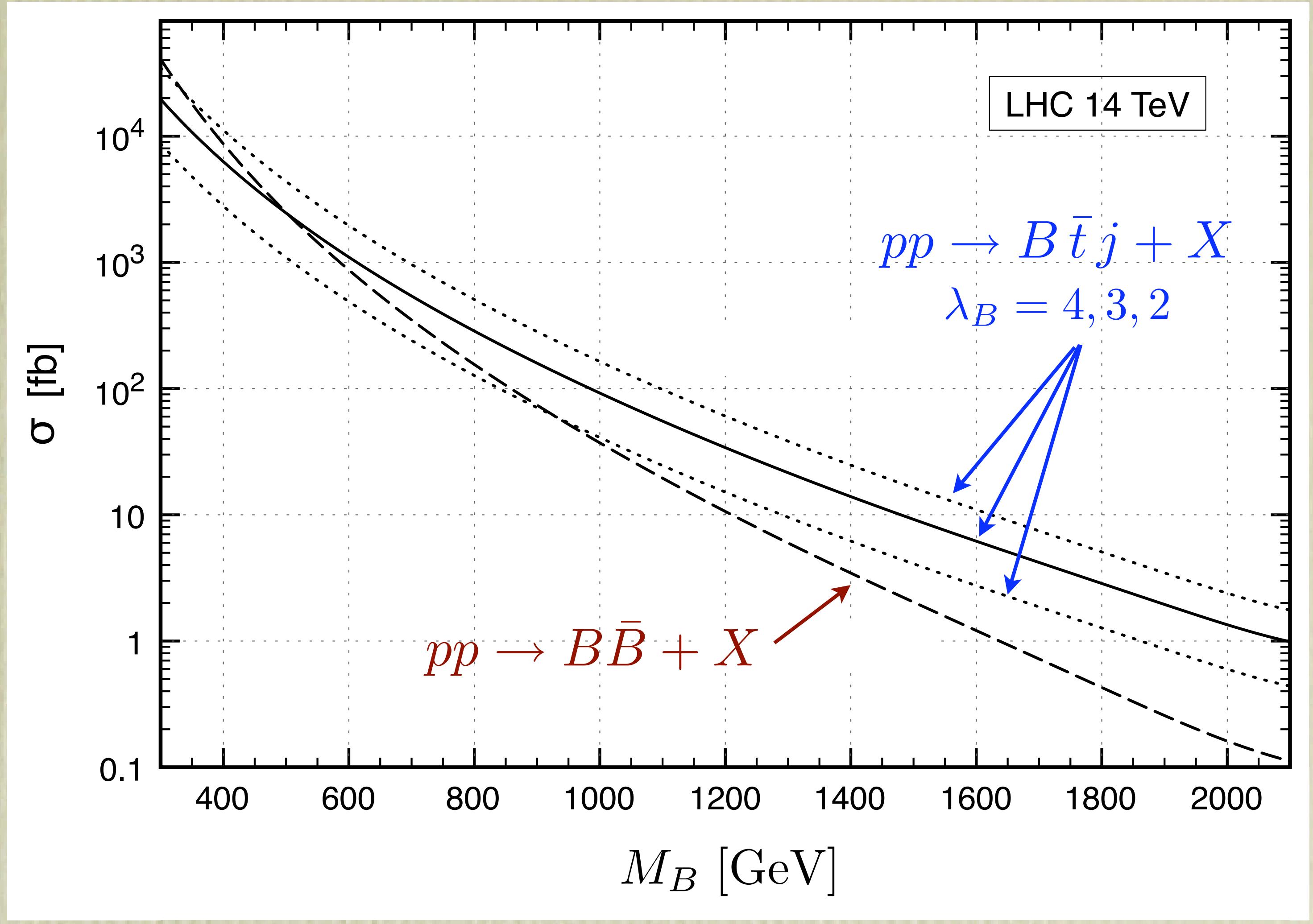

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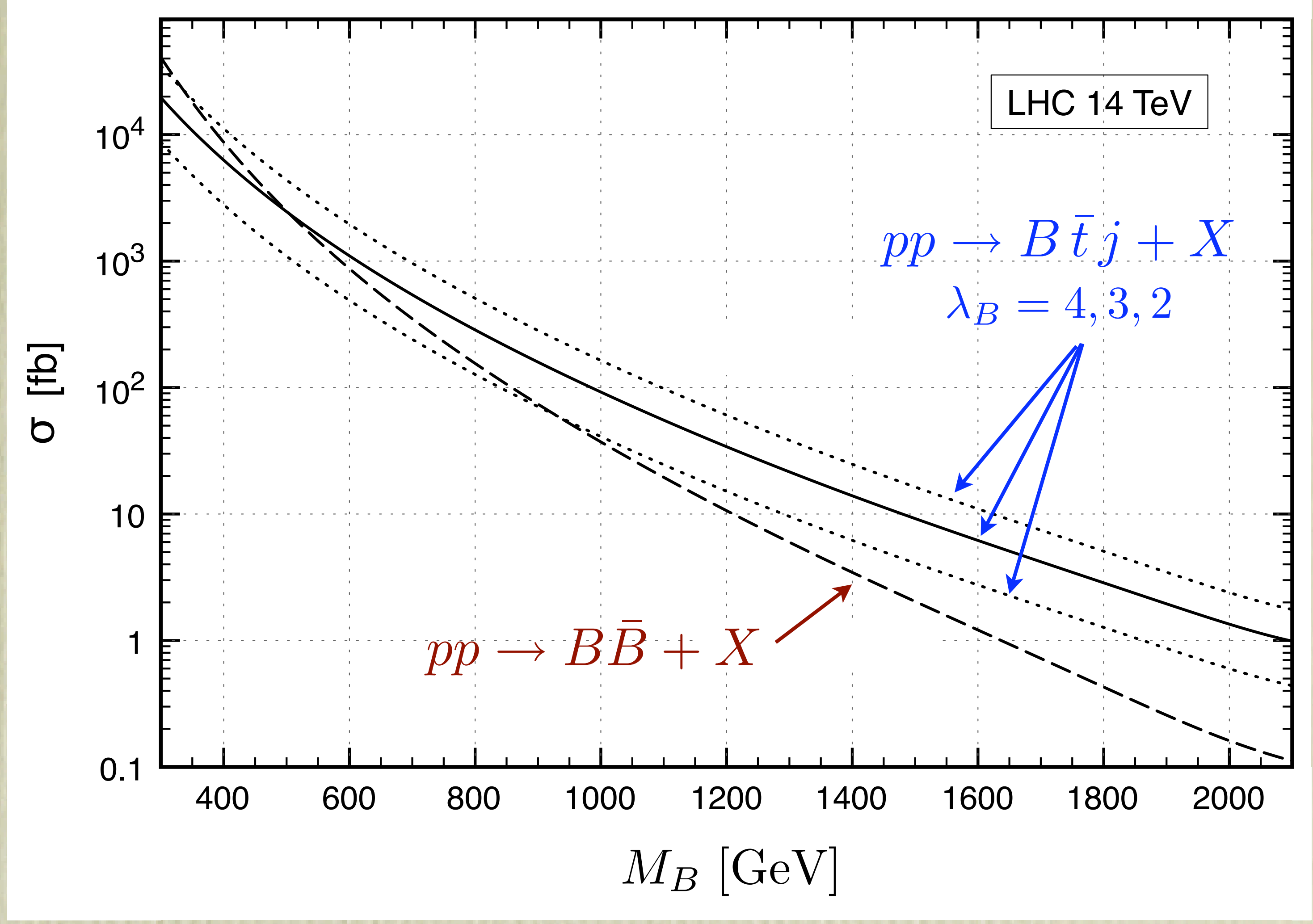

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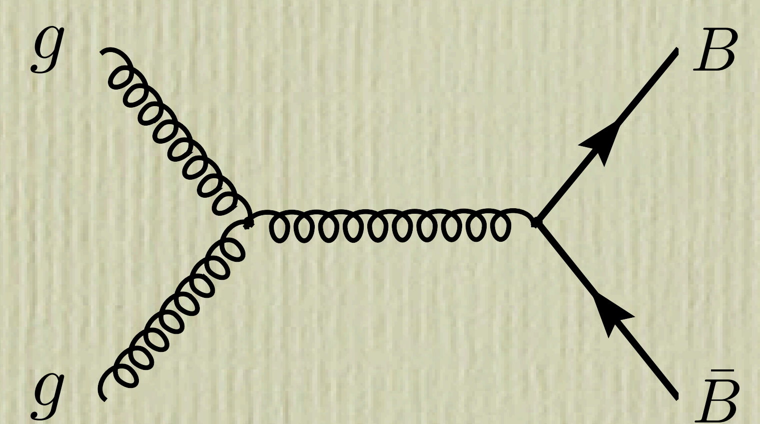

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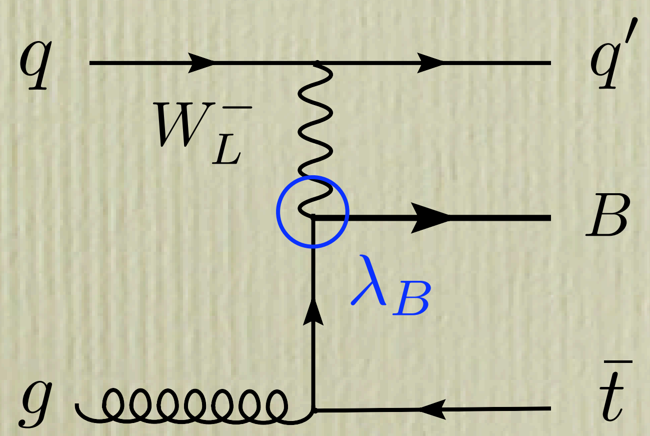
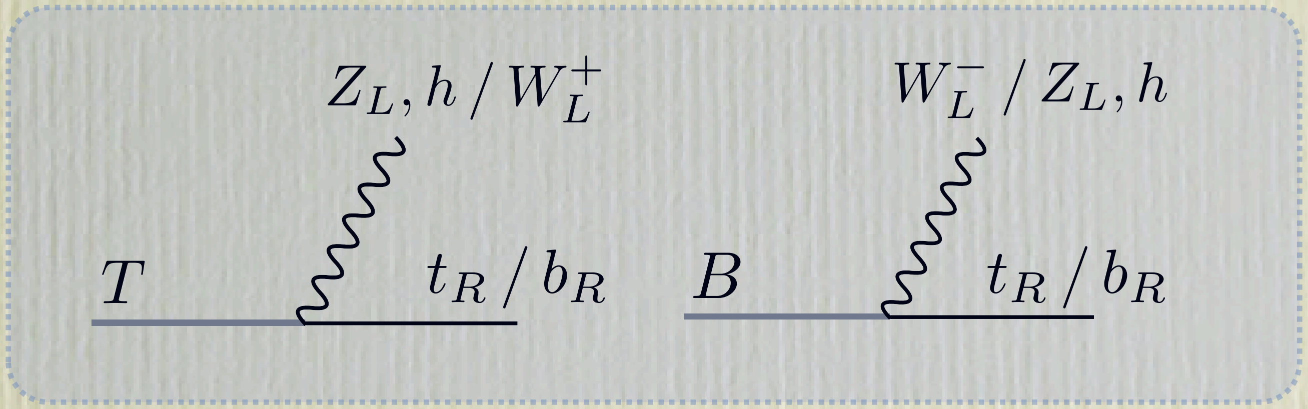


Decay modes



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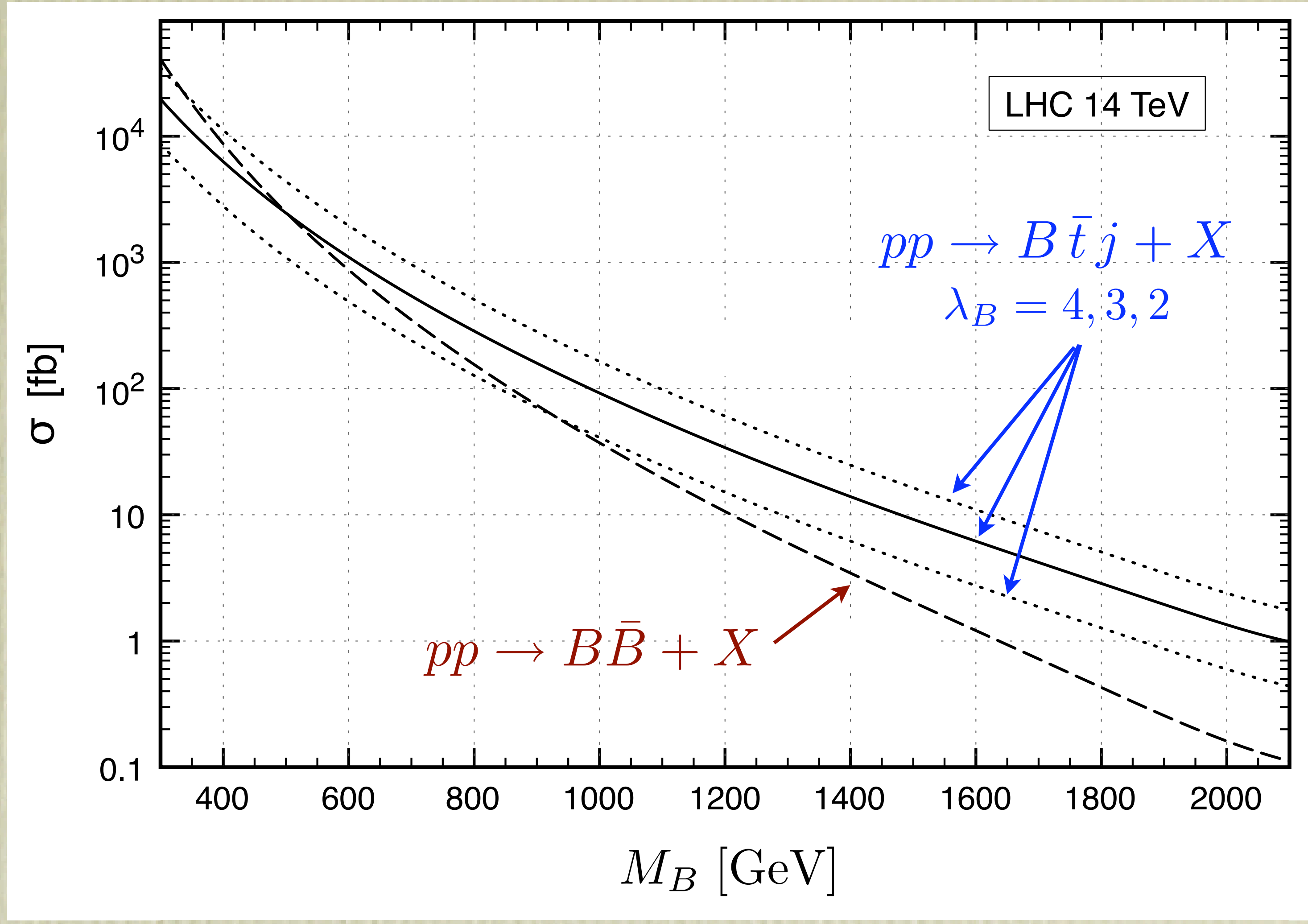
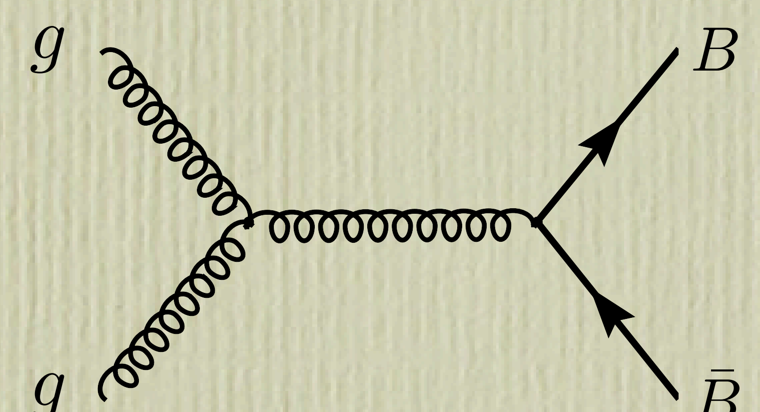
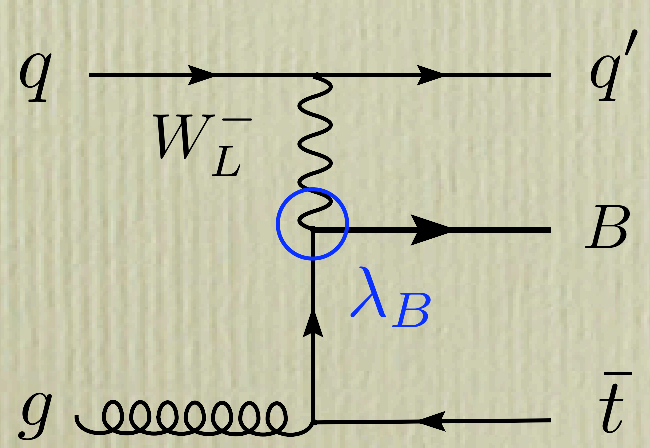


Pair production

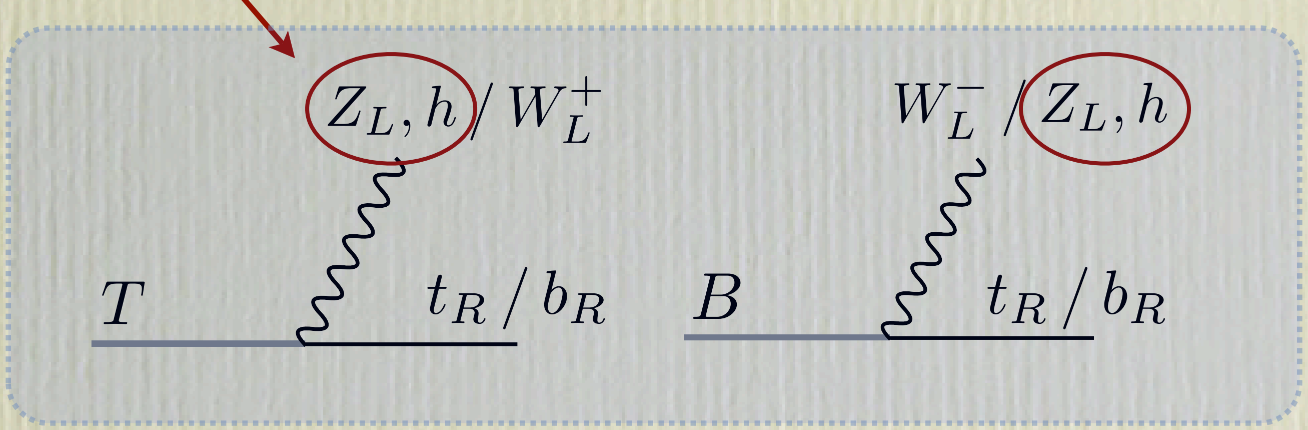


Single production



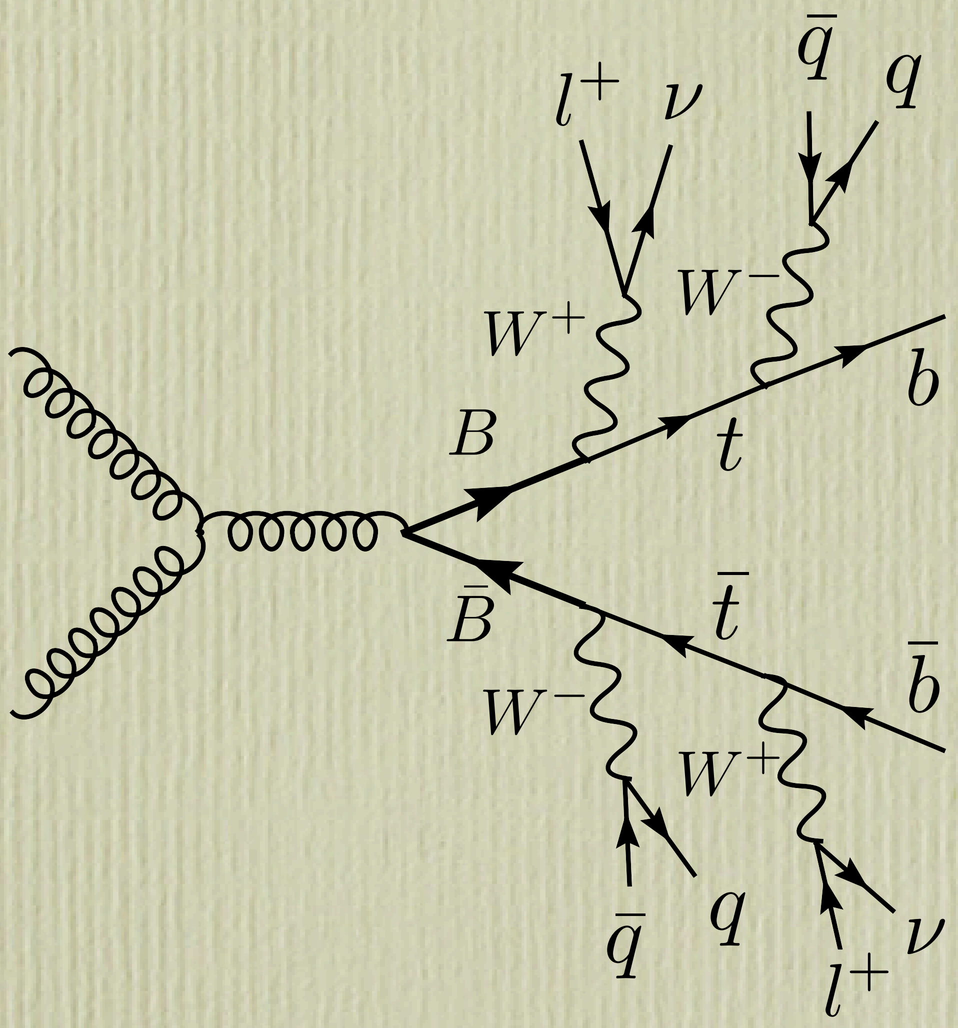
Decay modes

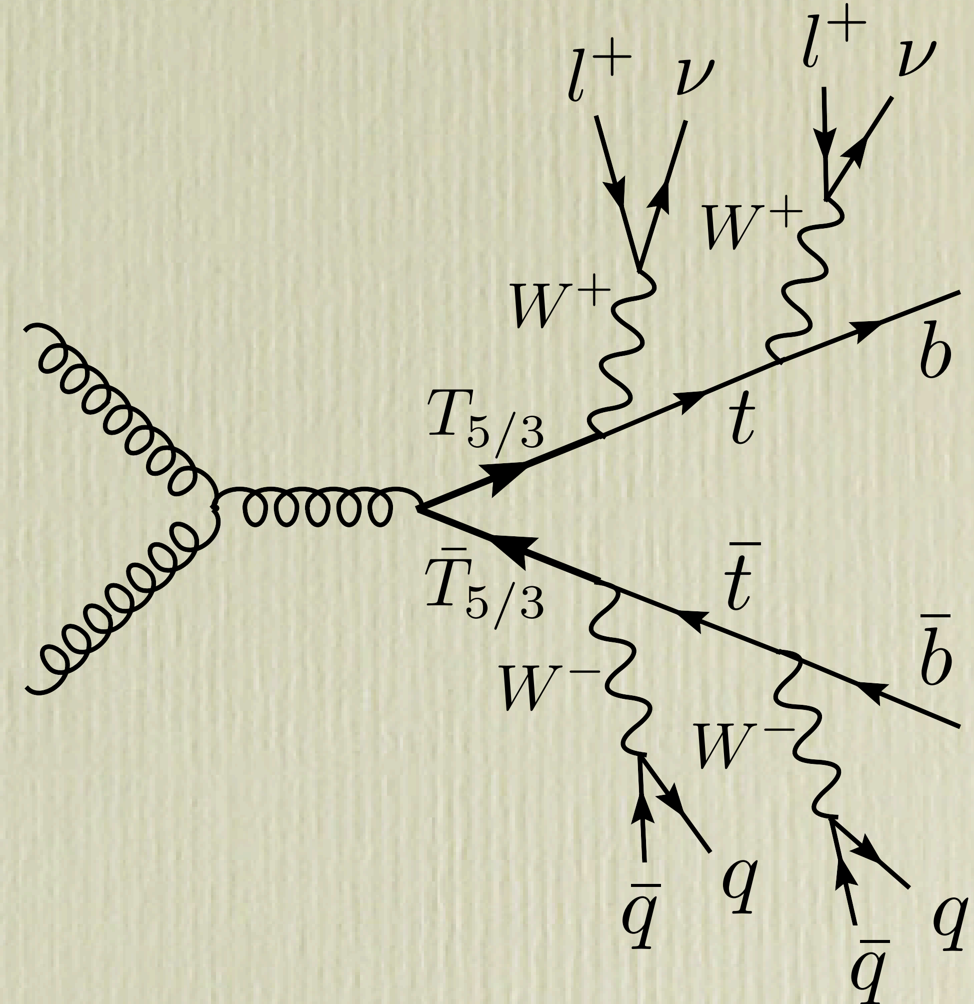
FCNC : absent for a 4th generation !



☞ Example: Look for $B\bar{B}$ and $T_{5/3}\bar{T}_{5/3}$ in same-sign di-lepton final states

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





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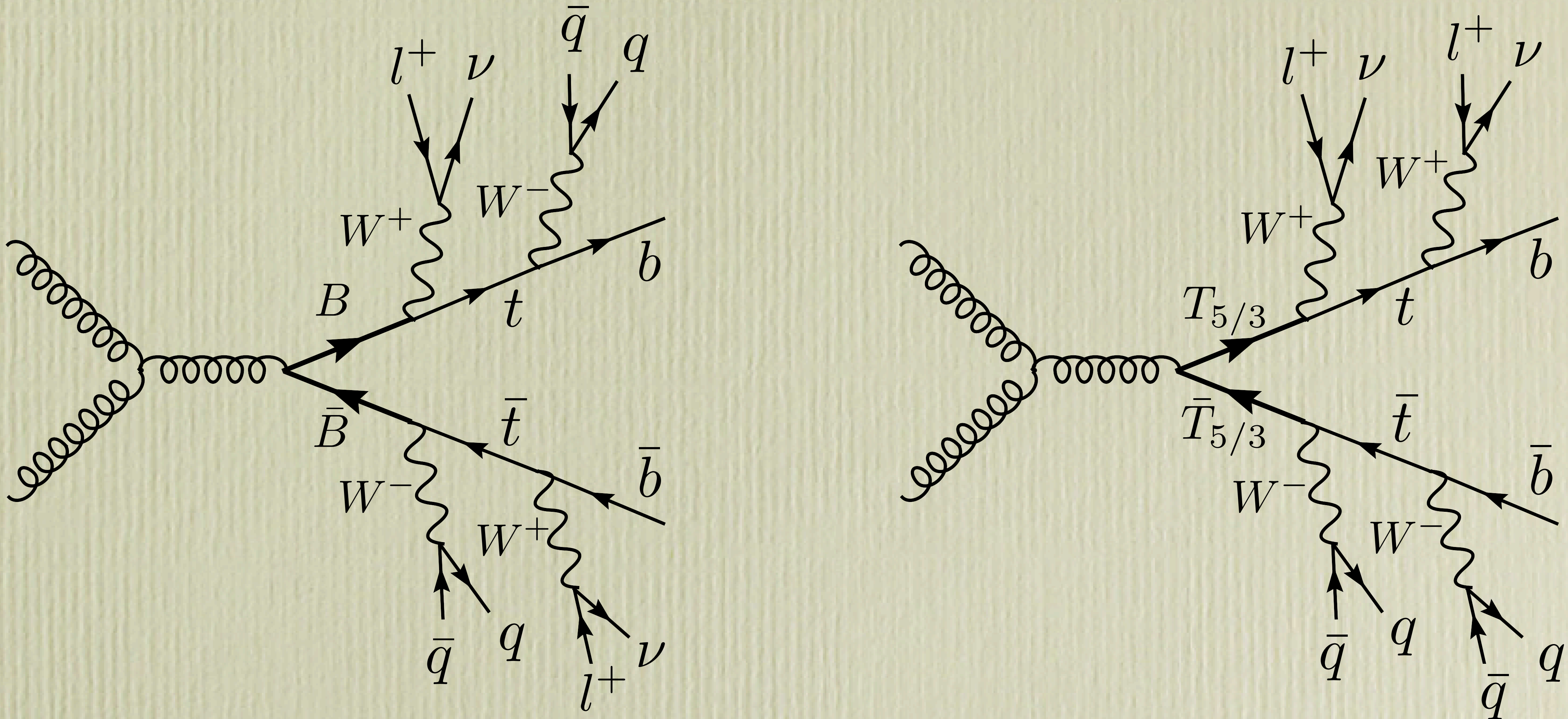

✓ $t\bar{t} + jets$ is not a background [except for charge mis-ID]

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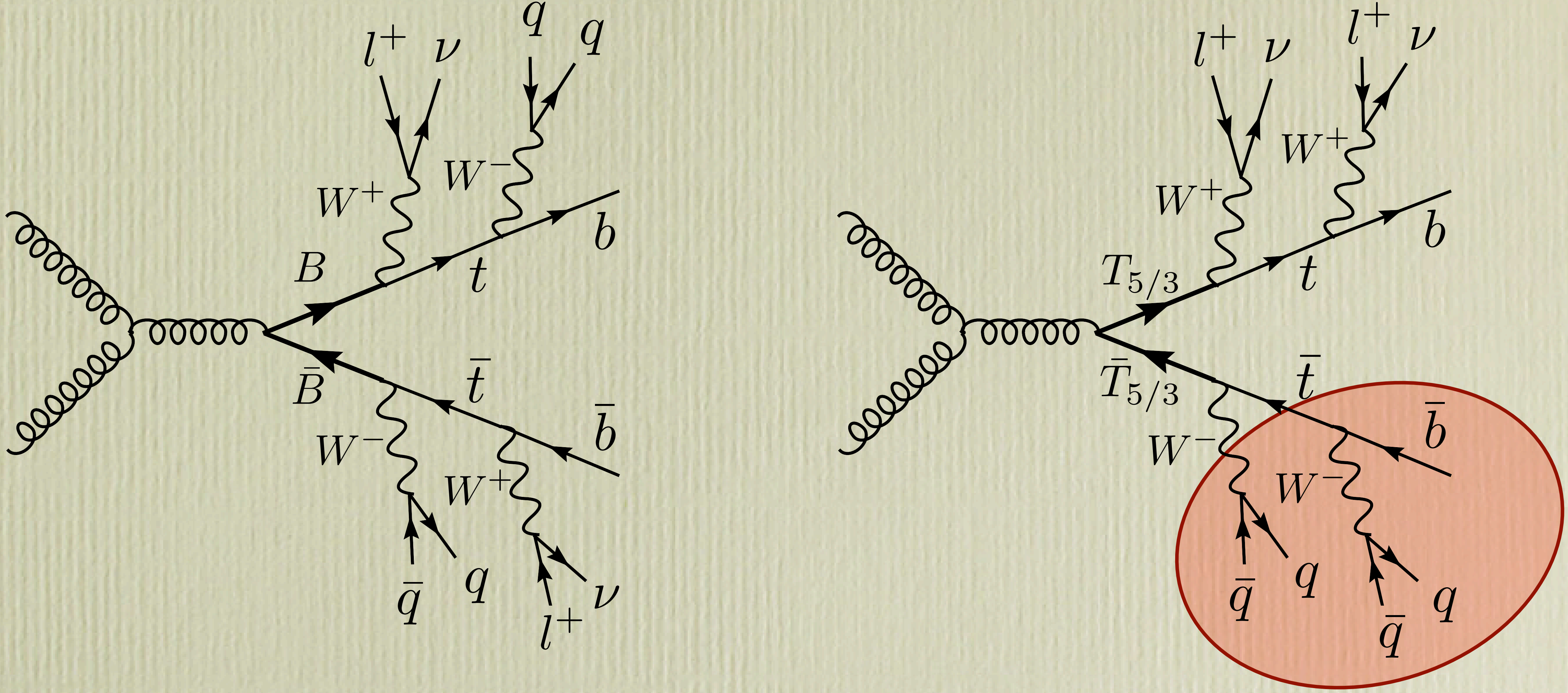

✓ $t\bar{t} + jets$ is not a background [except for charge mis-ID]

✓ 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 $\Delta R = 0.4\ ,\ E_T^{min} = 30\,\text{GeV}$
- Jet energy and momentum smeared by $100\%/\sqrt{E}$ to simulate the detector resolution

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

Strategy and cuts

★ We demand at least 5 hard jets ($p_T \geq 30$ GeV) :

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

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

	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

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Extra Cuts for M=1TeV:

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

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

	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

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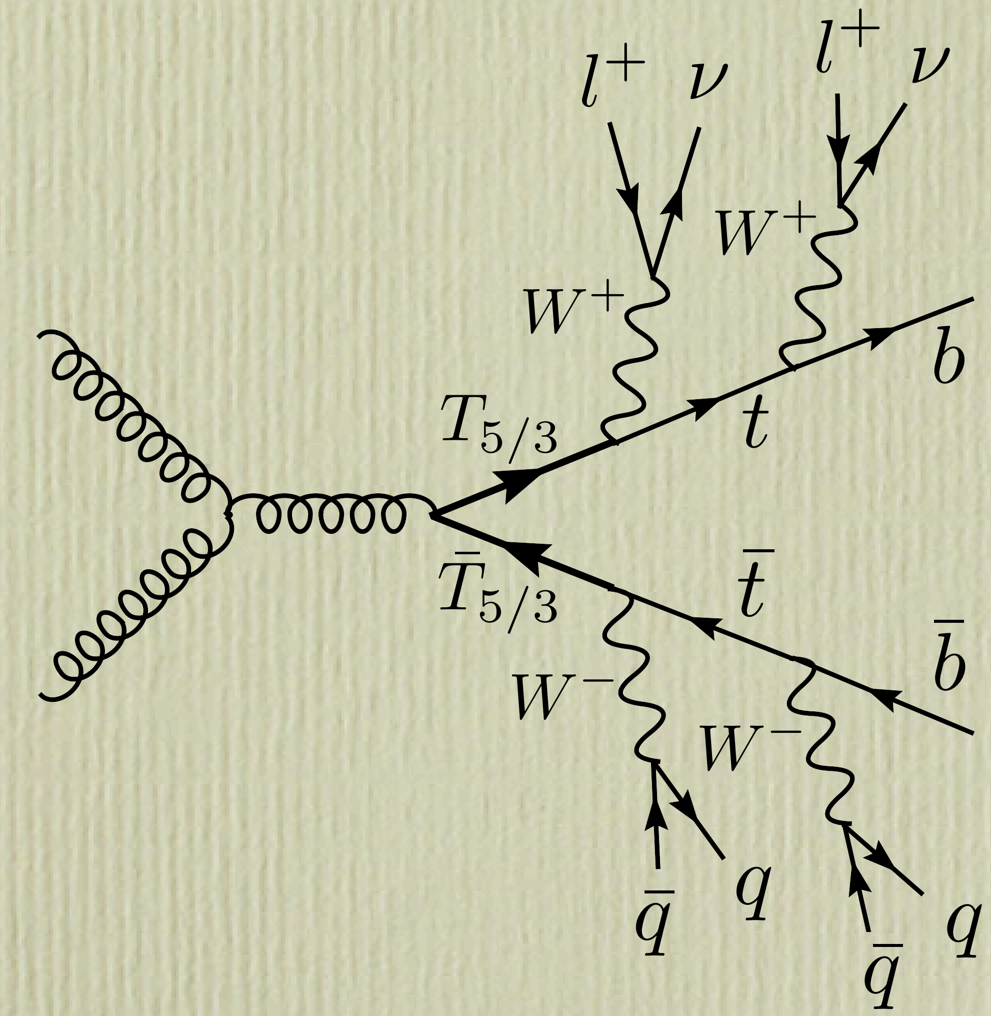
Discovery Potential:

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

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

Mass Reconstruction

M=500 GeV



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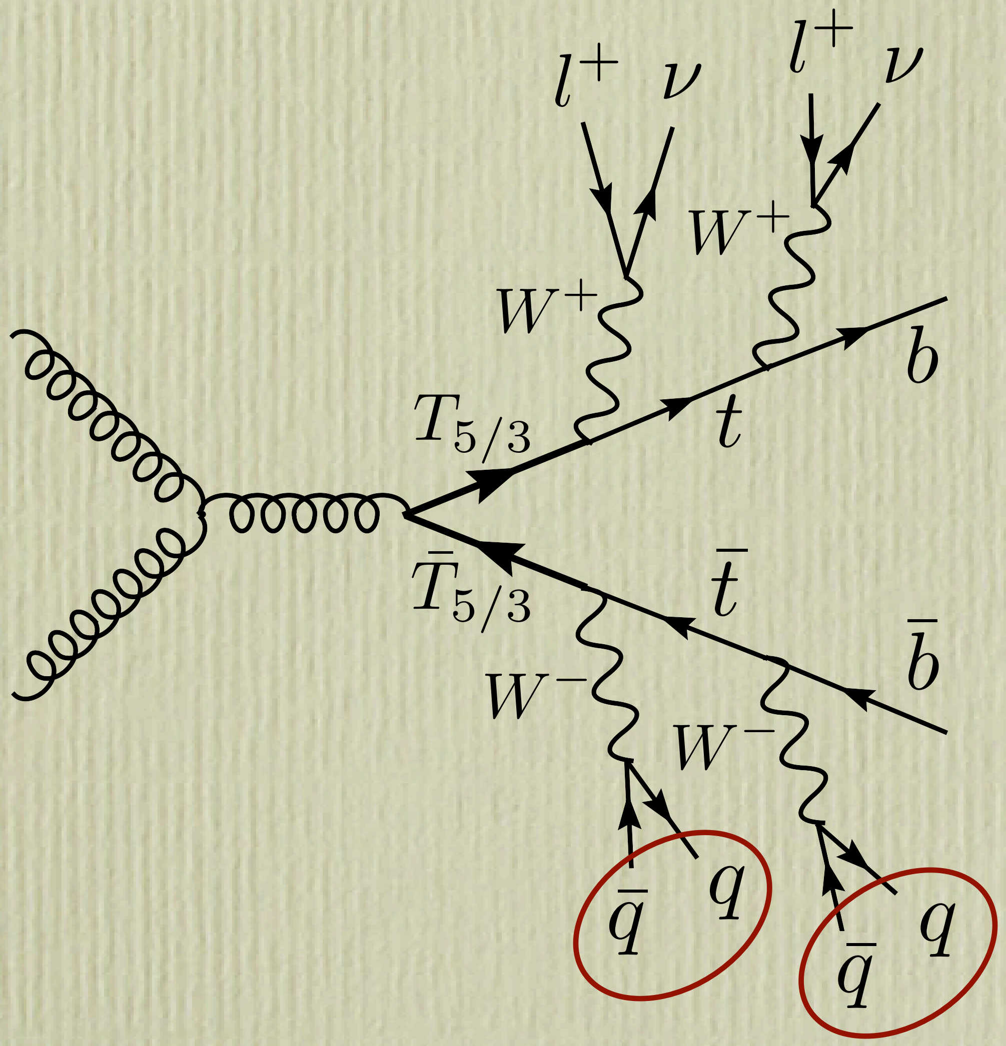

1. Reconstruct 2 W's

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

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

$$\Delta R_{jj}(\text{2nd pair}) \leq 2.0$$
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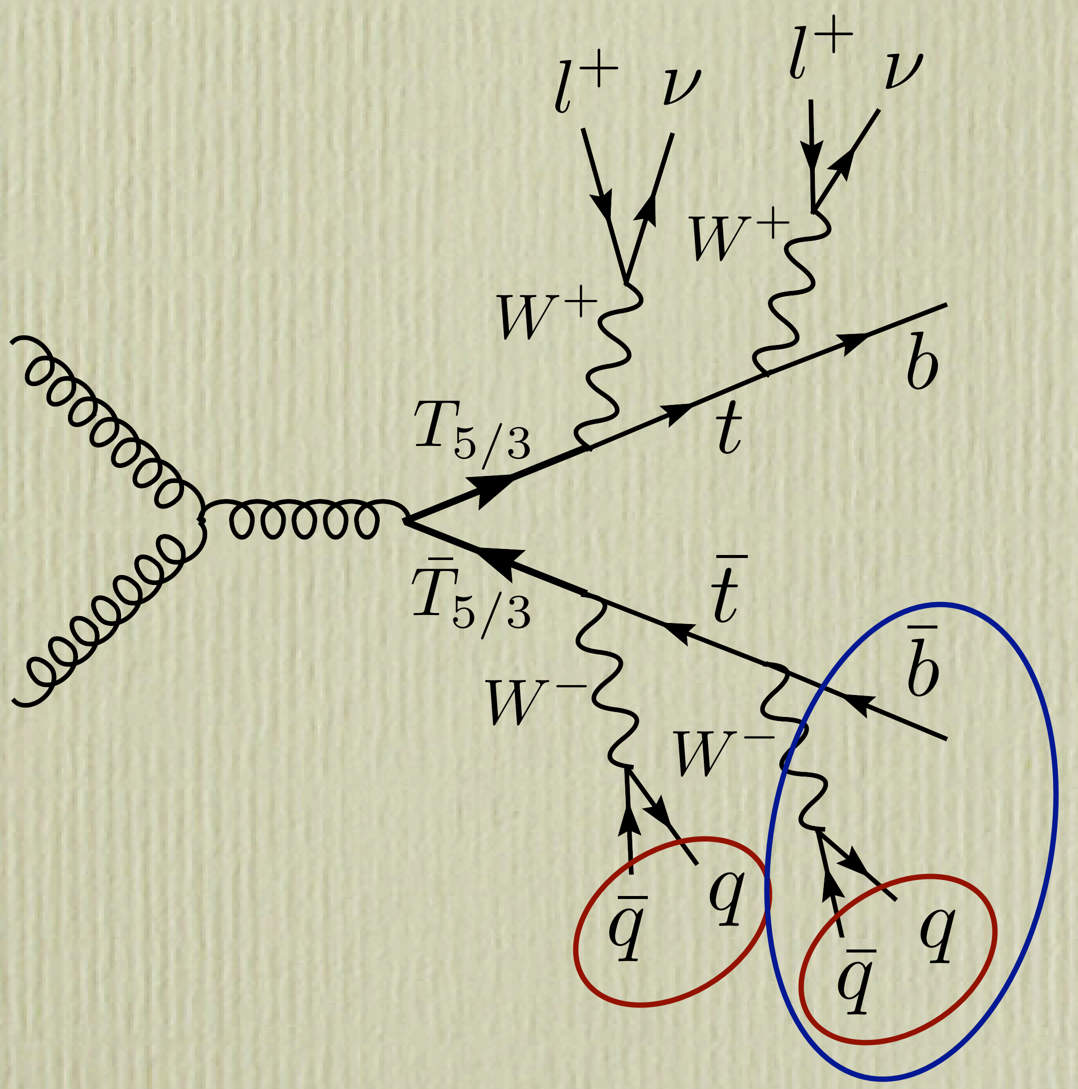

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2. Reconstruct 1 top (t=Wj)

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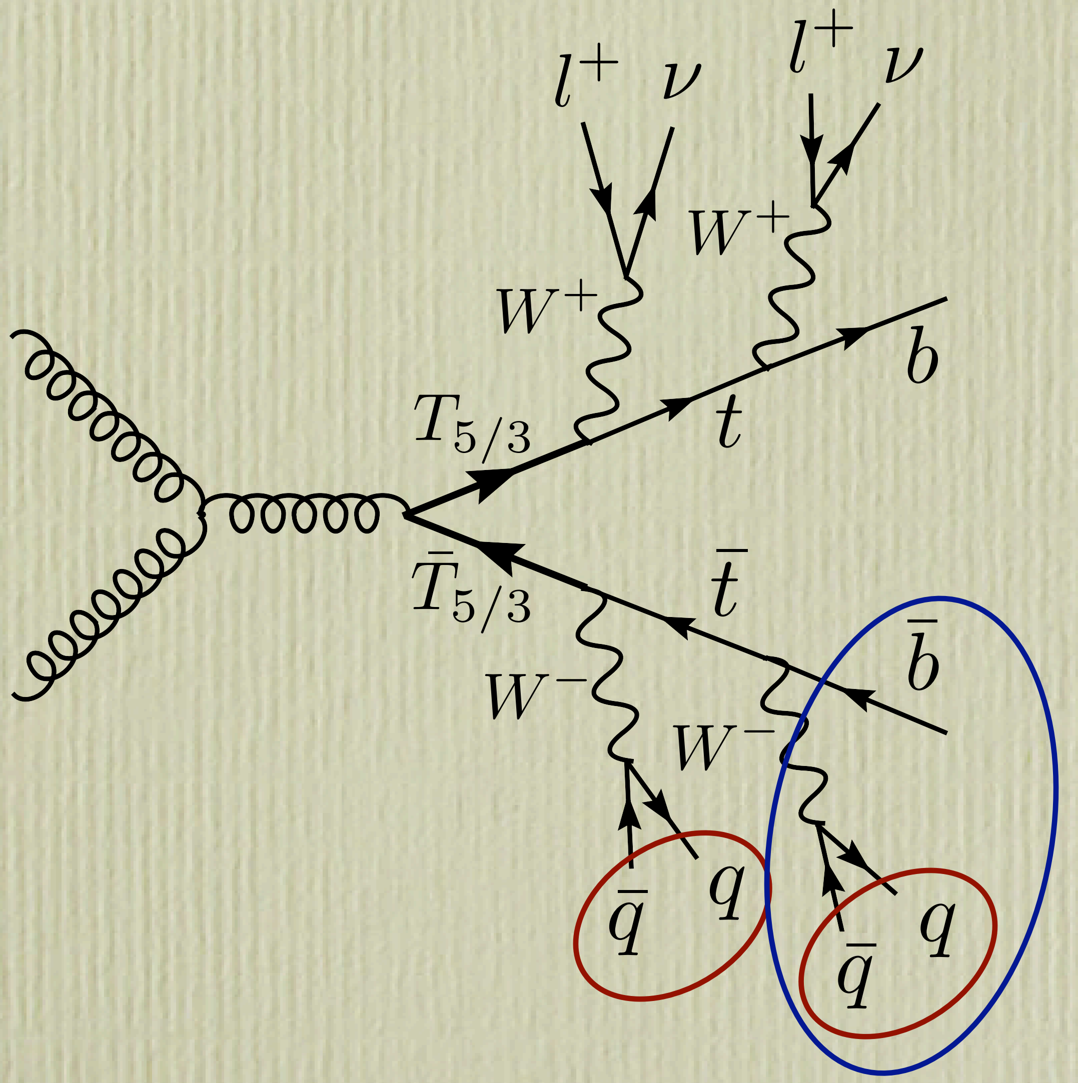

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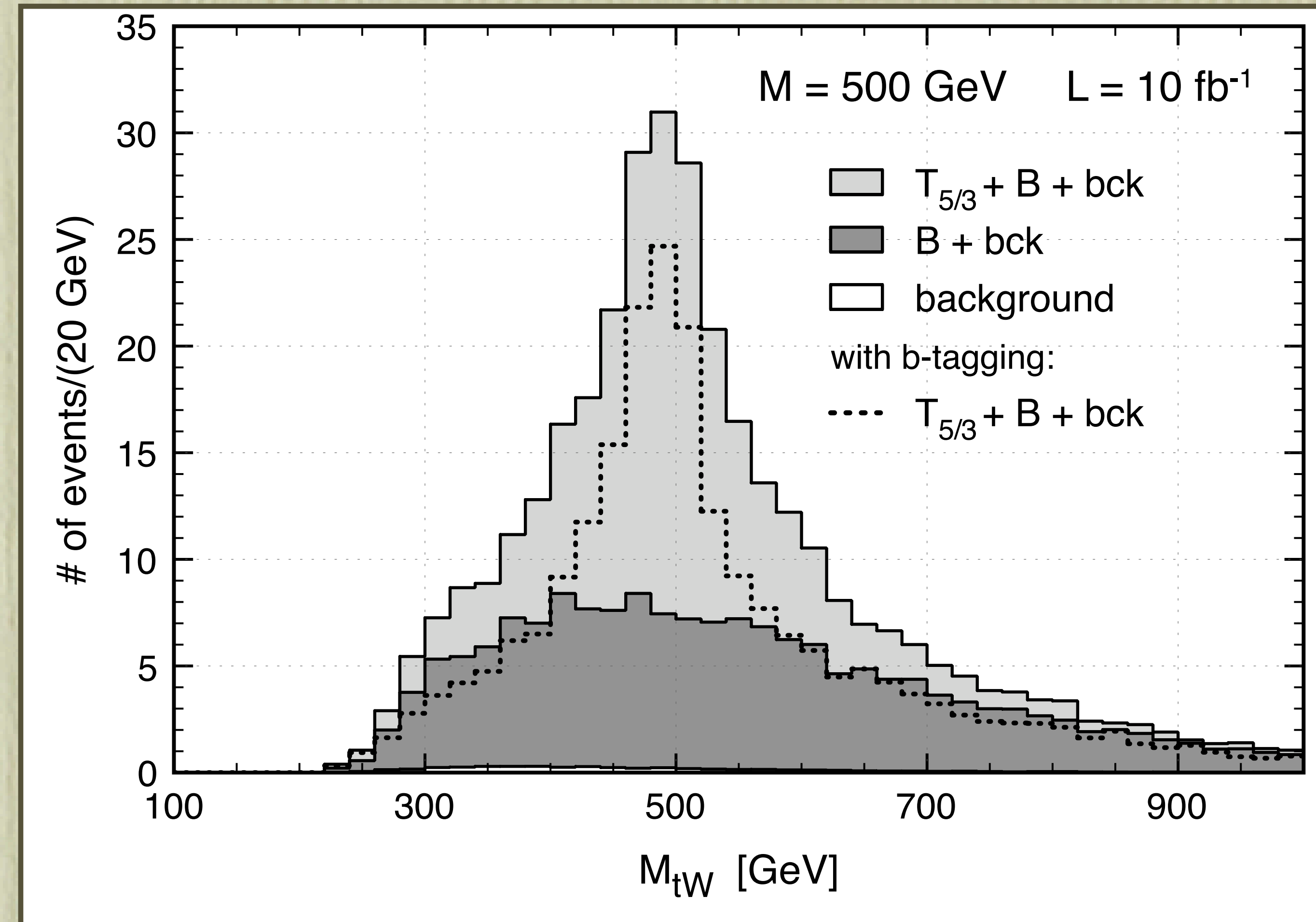
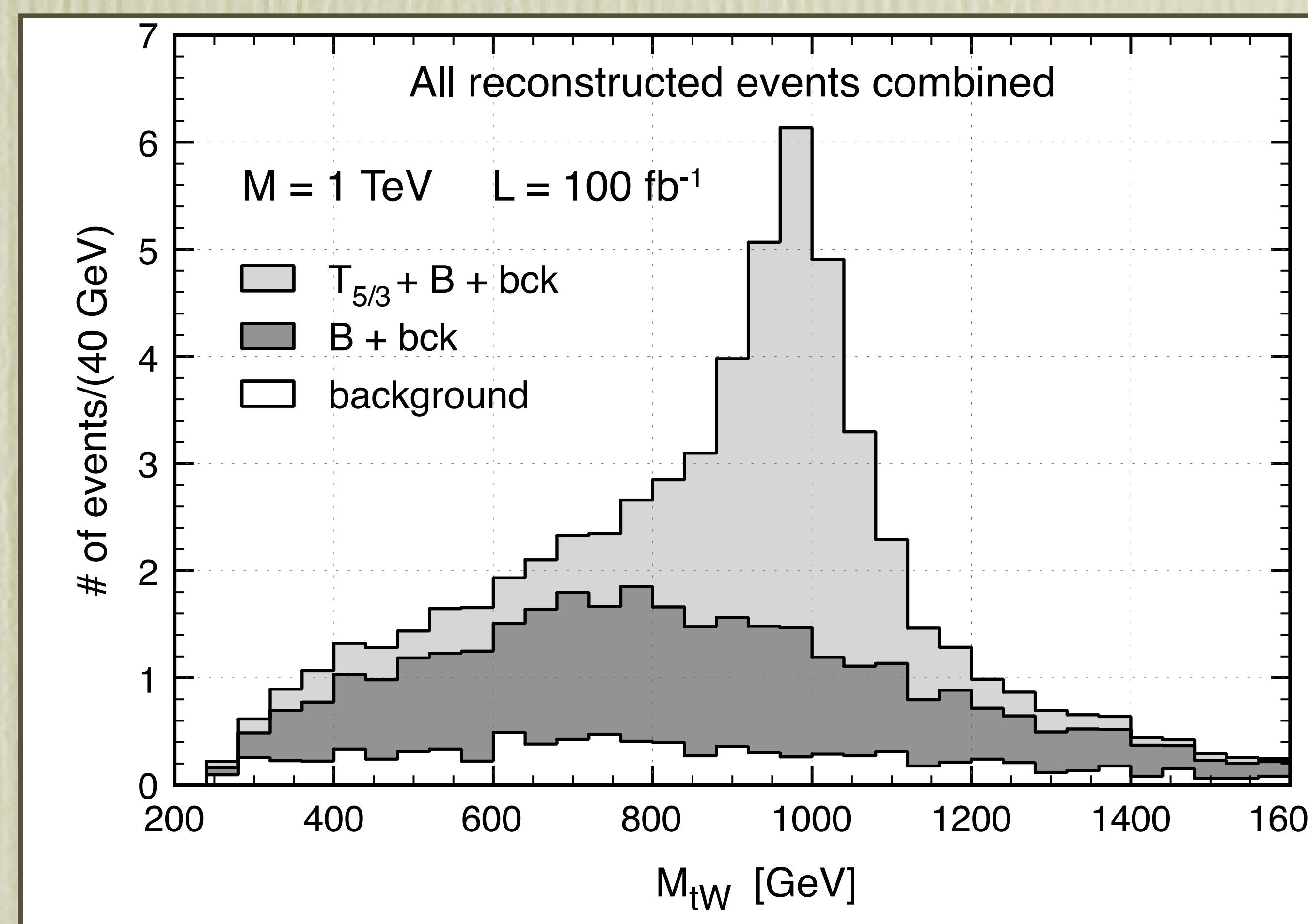
	signal ($M = 500$ GeV)	$t\bar{t}W$	$t\bar{t}WW$	WWW	WW
ϵ_{2W}	0.62	0.36	0.49	0.29	0.15
ϵ_{top}	0.65	0.56	0.64	0.35	0.35


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]


All reconstructed events combined
M = 1 TeV L = 100 fb-1
T5/3 + B + bck
B + bck
background
# of events/(40 GeV)
MtW [GeV]

Conclusions

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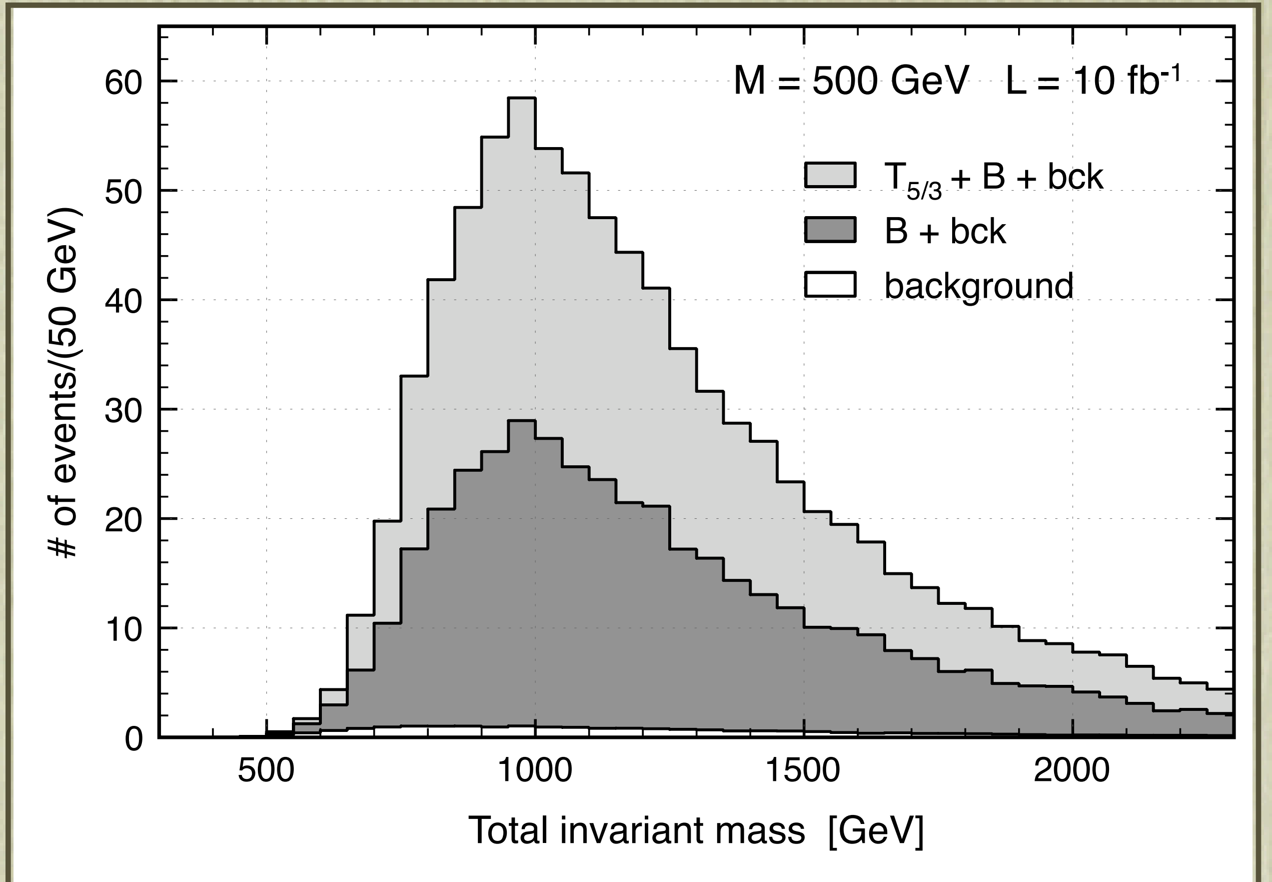
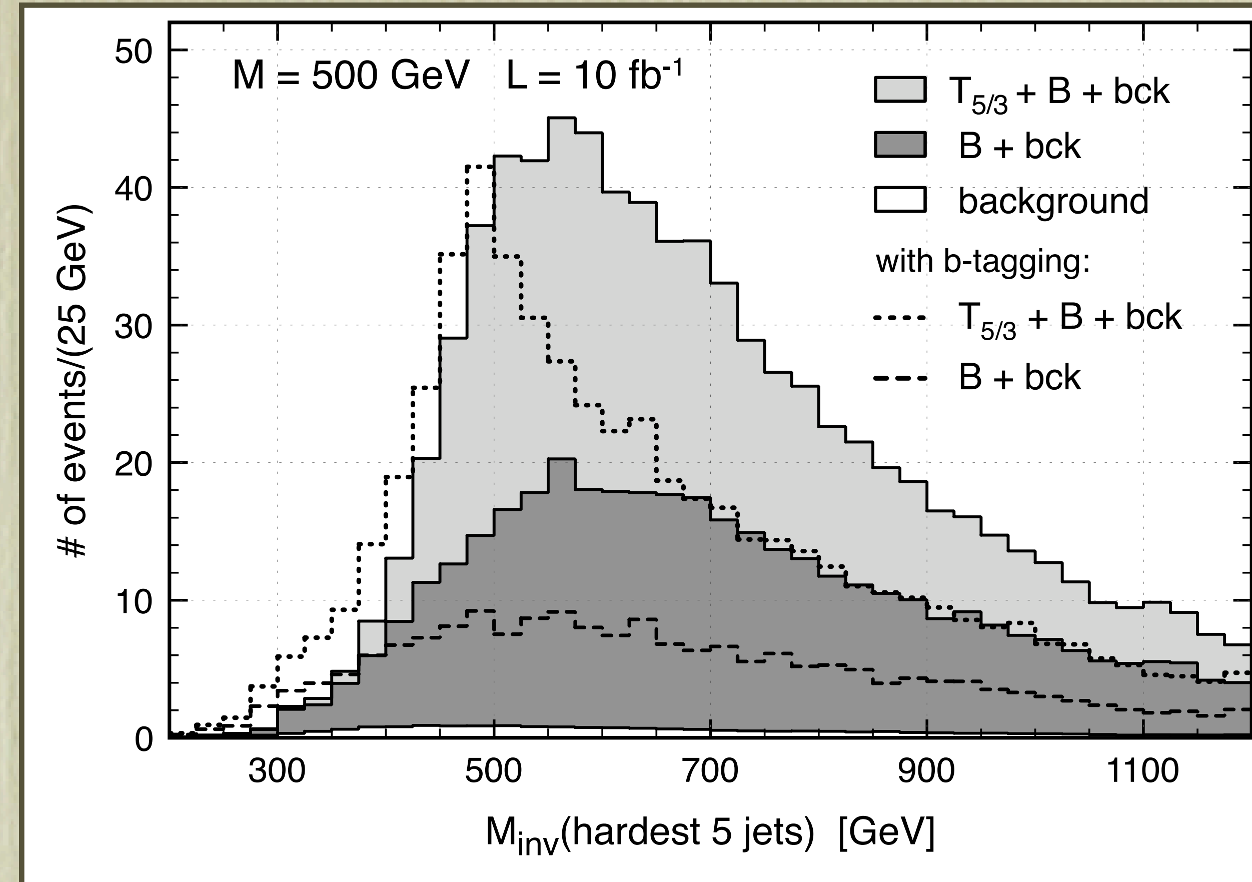
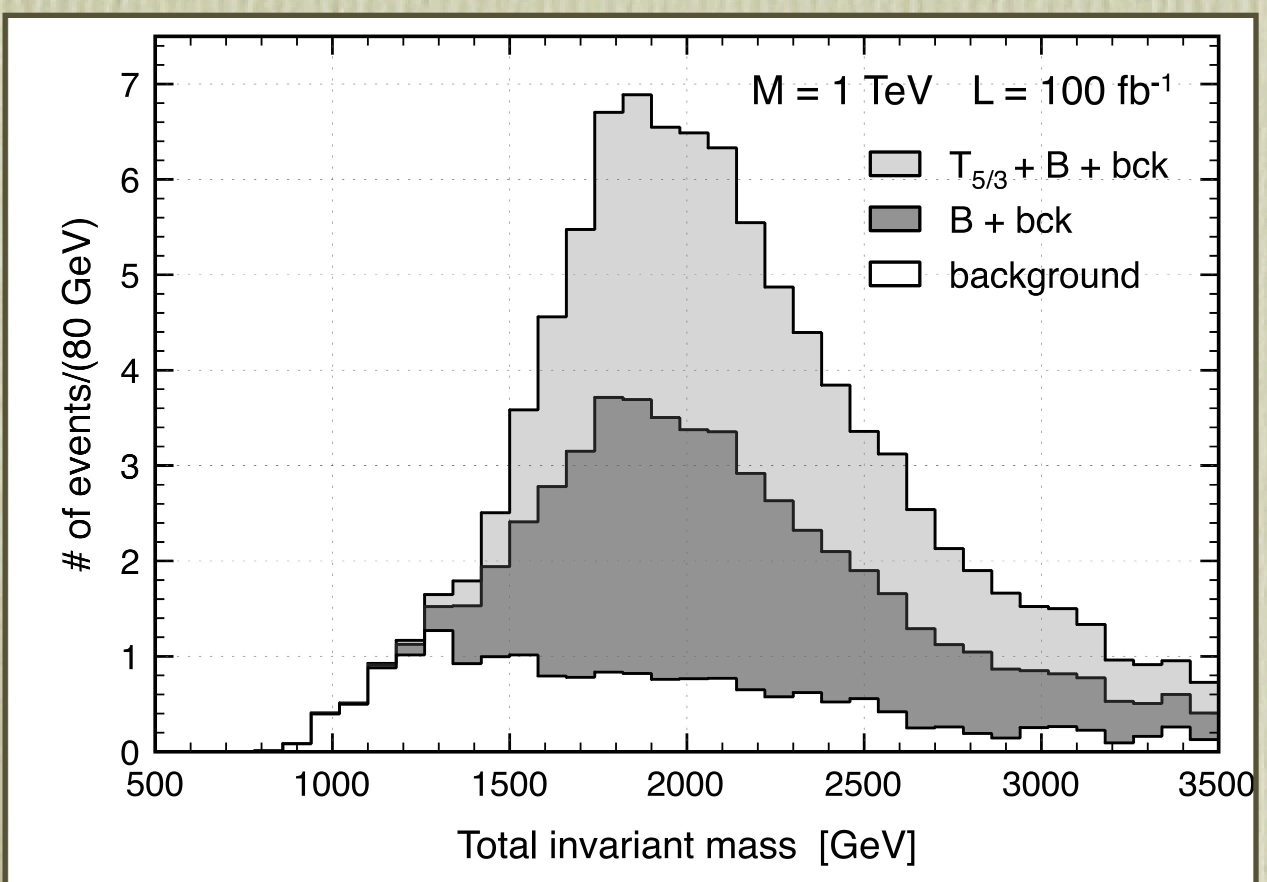
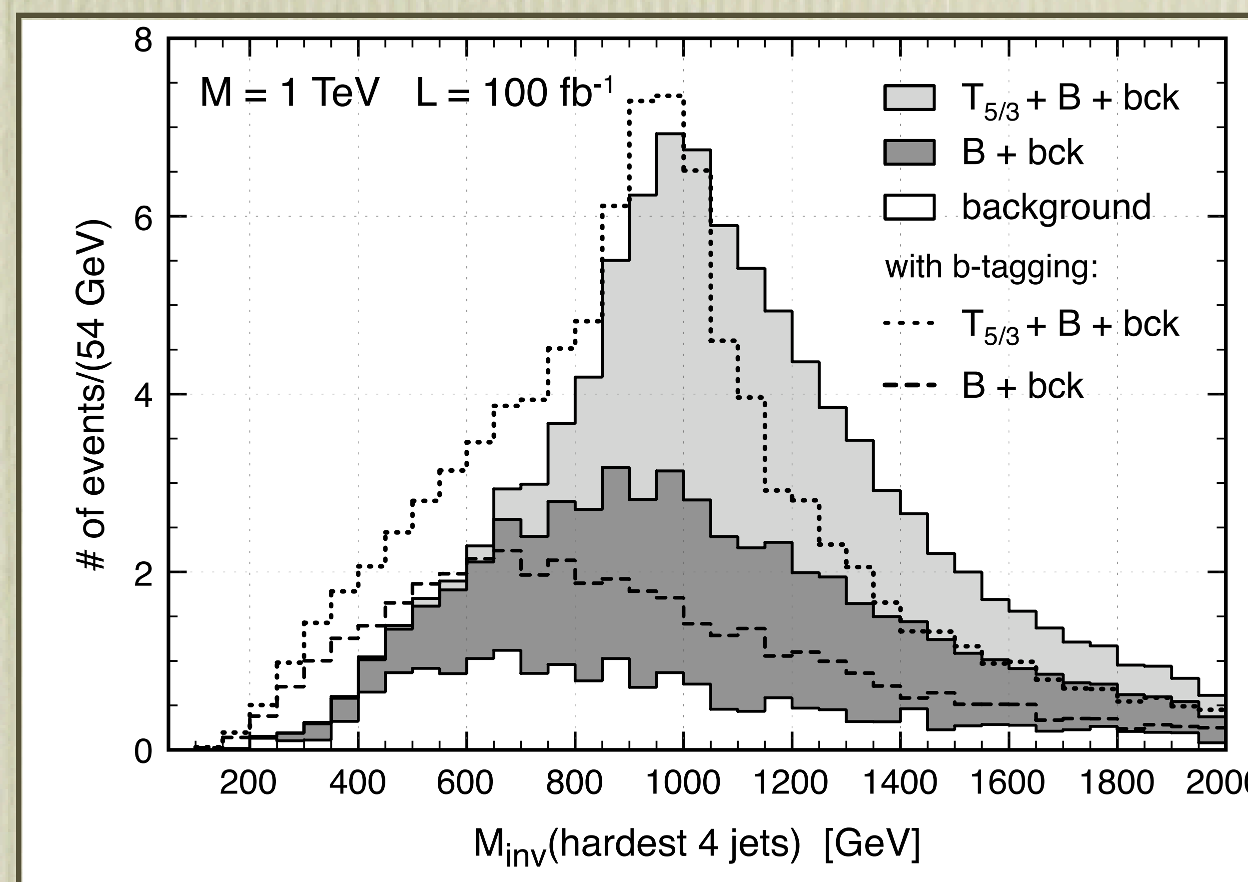
- Gauge-Higgs unification is another example of symmetry protection, beyond SuperSymmetry, to keep the Higgs light
- Prediction: Heavy tops and bottoms and possibly other exotic fermions
- Same-sign di-lepton channels promising for discovering B and $T_{5/3}$

Extra Slides


M = 500 GeV L = 10 fb-1
T5/3 + B + bck
B + bck
background
# of events/(50 GeV)
Total invariant mass [GeV]


M = 500 GeV L = 10 fb-1
T5/3 + B + bck
B + bck
background
with b-tagging:
T5/3 + B + bck
B + bck
# of events/(25 GeV)
Minv(hardest 5 jets) [GeV]


M = 1 TeV L = 100 fb-1
T5/3 + B + bck
B + bck
background
# of events/(80 GeV)
Total invariant mass [GeV]


M = 1 TeV L = 100 fb-1
T5/3 + B + bck
B + bck
background
with b-tagging:
T5/3 + B + bck
B + bck
# of events/(54 GeV)
Minv(hardest 4 jets) [GeV]