From Top to Heavy Quark

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Workshop on Very Heavy Quarks at the LHC

(Slides prepared by Jiang-Hao Yu at MSU)

Outline

- Top Quark is sensitive to New Physics
  Heavy Quark can decay into top quark
- Review Heavy Quark Theory and Constraints
- Pair Production of Heavy Quark
- Single Production of Heavy Quark
- Exotic Production: Anomalous B-prime via s-channel

Top Quark and New Physics

- 163,000 top quark pairs and 76,000 single top events produced during the 7 TeV, 1 fb^{-1} LHC run.
- Natural new physics models *always* have non-trivial couplings between tops and new physics: Higgsless, LH, RS, SUSY, TC, ...

In Little Higgs, composite Higgs and SUSY, top sector stabilizes the electroweak symmetry breaking

Motivation for Heavy Quark

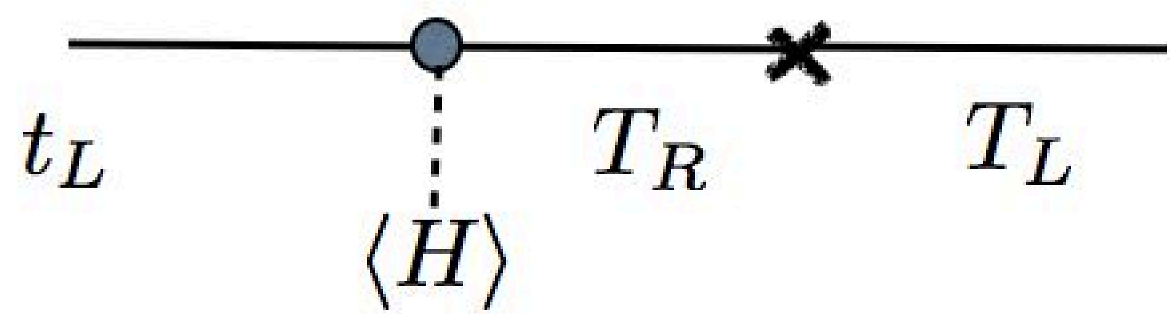
- New Heavy Quarks loop contribution stabilize EWSB
- New Heavy Quarks condensates to form BCS type EWSB
- New Heavy Quarks to explain B_s and other flavor puzzles
- New Heavy Quarks to explain CP violation and Baryon asymmetry (W.S. Hou)

Talk to SM through mass mixing

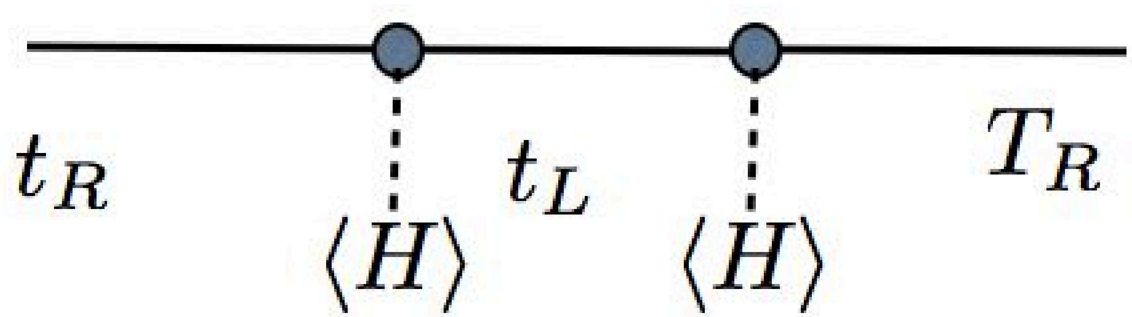
Heavy Quark Mixing (Singlet)

- Singlet/Triplet Vector-like quark mass mixing

$$\mathcal{L} = -y_t v \bar{t}_L t_R - \lambda v \bar{t}_L T_R - M \bar{T}_L T_R + h.c.$$



$$\sin\theta_L \sim \lambda \frac{v}{M}$$



$$\sin\theta_R \sim y_t \lambda \frac{v^2}{M^2}$$

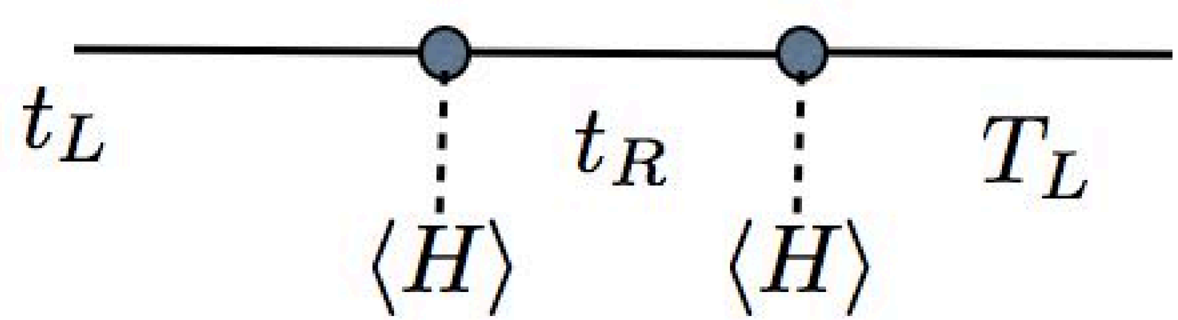
$$\sin\theta_R = \frac{y_t v}{M} \sin\theta_L$$

Mainly left-handed mixing

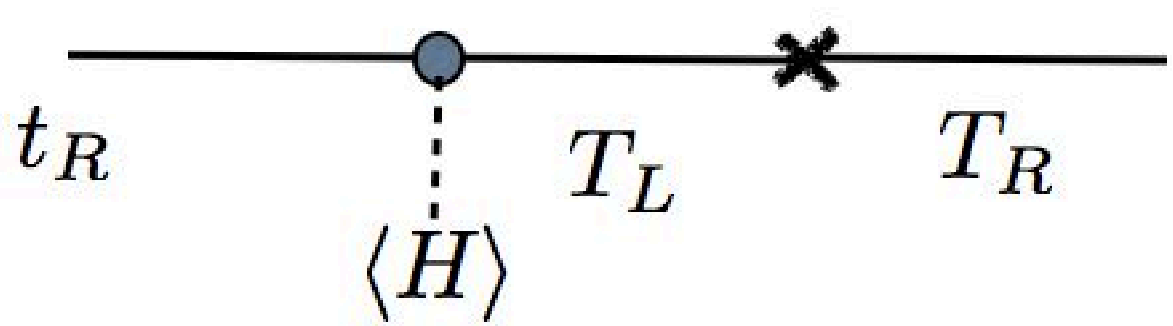
Heavy Quark Mixing (Doublet)

- Doublet/Bi-doublet Vector quark mass mixing

$$\mathcal{L} = -y_t v \bar{t}_L t_R - \lambda v \bar{T}_L t_R - M \bar{T}_L T_R + h.c.$$



$$\sin\theta_L \sim y_t \lambda \frac{v^2}{M^2}$$



$$\sin\theta_R \sim \lambda \frac{v}{M}$$

$$\sin\theta_L = \frac{y_t v}{M} \sin\theta_R$$

Mainly right-handed mixing

Heavy Quark Mixing (4th Generation)

- CKM Mixing with the top quark

$$-\mathcal{L}_Q = Y_U^{ij} \bar{Q}_L \tilde{\Phi} U_R + Y_D^{ij} \bar{Q}_L \Phi D_R + h.c.$$

$$U = (u, c, t, T)^T \quad D = (d, s, b, B)^T \quad Q = \begin{pmatrix} U \\ D \end{pmatrix}$$

Charge currents only involves the left-handed mixing rotation matrices

$$V_{CKM} = V_L^{u\dagger} V_L^d \qquad V_L^{u\dagger} Y_U Y_U^\dagger V_L^u = M_U^2/v$$

Neutral currents are not relevant to the mixing rotation matrices

Heavy Quark Mixing (4th Generation)

$$V_{CKM}^{3\times3} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9738 & 0.225 & 0.0039 \\ 0.22 & > 0.85 & 0.041 \\ < 0.14 & < 0.5 & > 0.78 \end{pmatrix}$$

Extend to fourth generation

$$V_{CKM}^{4\times4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ud_4} \\ V_{cd} & V_{cs} & V_{cb} & V_{cd_4} \\ V_{td} & V_{ts} & V_{tb} & V_{td_4} \\ V_{u_4 d} & V_{u_4 s} & V_{u_4 b} & V_{u_4 d_4} \end{pmatrix} = \begin{pmatrix} 0.9738 & 0.225 & 0.0039 & < 0.06 \\ 0.22 & 0.96 & 0.041 & < 0.22 \\ < 0.1 & < 0.2 & > 0.78 & < 0.65 \\ < 0.1 & < 0.22 & < 0.65 & > 0.78 \end{pmatrix}$$

Often, focus on third and fourth generation mixing

Large mixing among 4th and 1st or 2nd generation quarks can generate large new physics signals.

Review of Heavy Quarks

Classify based on EW gauge couplings:

- Chiral Fermion (Fourth Generation)
- Vector-like Singlet
- Vector-like Doublet
- Vector-like Triplet
- Vector-like Bi-doublet

Focus on gauge couplings and chiral structure in this talk

Review of Heavy Quark Type

Mass Mixing and Heavy Quark Couplings to Higgs

Chiral Doublet

$$-\mathcal{L}_Q = Y_U^{ij}\bar{Q}_L\tilde{\Phi}U_R + Y_D^{ij}\bar{Q}_L\Phi D_R + h.c.$$

- **SU(2) singlet**

  SM Yukawa — FCNC Yukawa — Explicit Dirac mass

  - Up-type $-\mathcal{L}_T = Y_t\,\overline{q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_T\,\overline{q_{0L}}\,\widetilde{\Phi}\,T_{0R} + M_T\,\overline{T_{0L}}T_{0R} + \text{H.c.}$
  - Down-type $-\mathcal{L}_B = Y_b\,\overline{q_{0L}}\,\Phi\,b_{0R} + Y_B\,\overline{q_{0L}}\,\Phi\,B_{0R} + M_B\,\overline{B_{0L}}B_{0R} + \text{H.c.}$

- **SU(2) doublet**

$$-\mathcal{L}_Q = Y_t\,\overline{q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_T\,\overline{Q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_B\,\overline{Q_{0L}}\,\Phi\,b_{0R} + M\,\overline{Q_{0L}}Q_{0R} + \text{H.c.}$$

$$-\mathcal{L}_{Q'} = Y_t\,\overline{q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_T\,\overline{Q'_{0L}}\,\Phi\,t_{0R} + M\,\overline{Q'_{0L}}Q'_{0R} + \text{H.c.}$$

$$Q_{0L} = \begin{pmatrix} T_{0L} \\ B_{0L} \end{pmatrix},\ Q_{0R} = \begin{pmatrix} T_{0R} \\ B_{0R} \end{pmatrix}\quad Q'_{0L} = \begin{pmatrix} Y \\ T_{0L} \end{pmatrix},\ Q'_{0R} = \begin{pmatrix} Y \\ T_{0R} \end{pmatrix}$$

- **SU(2) triplet**

  Exotic Q=5/3 fermion

$$-\mathcal{L}_\Sigma = Y_t\,\overline{q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_T\,\overline{q_{0L}}\,\tau^a\,\widetilde{\Phi}\,\Sigma_{0R} + M\,\overline{\Sigma_{0L}}\Sigma_{0R} + \text{H.c.}$$

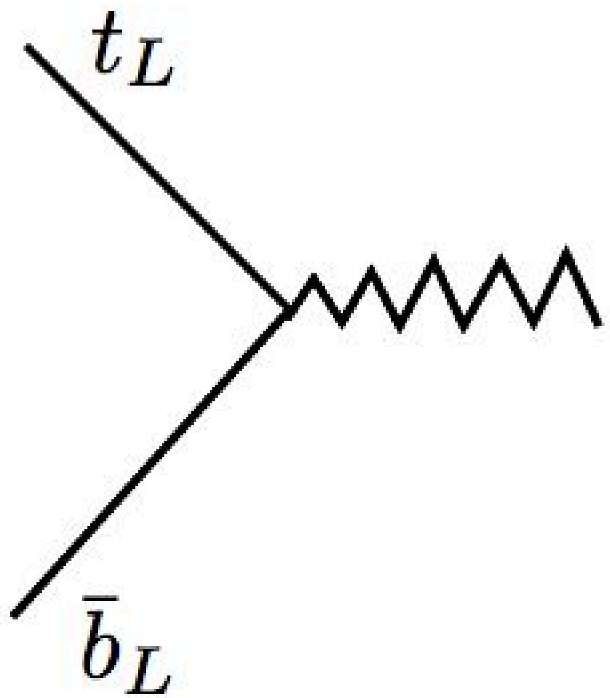
$$-\mathcal{L}_{\Sigma'} = Y_t\,\overline{q_{0L}}\,\widetilde{\Phi}\,t_{0R} + Y_T\,\overline{q_{0L}}\,\tau^a\,\Phi\,\Sigma'_{0R} + M\,\overline{\Sigma'_{0L}}\Sigma'_{0R} + \text{H.c.}$$

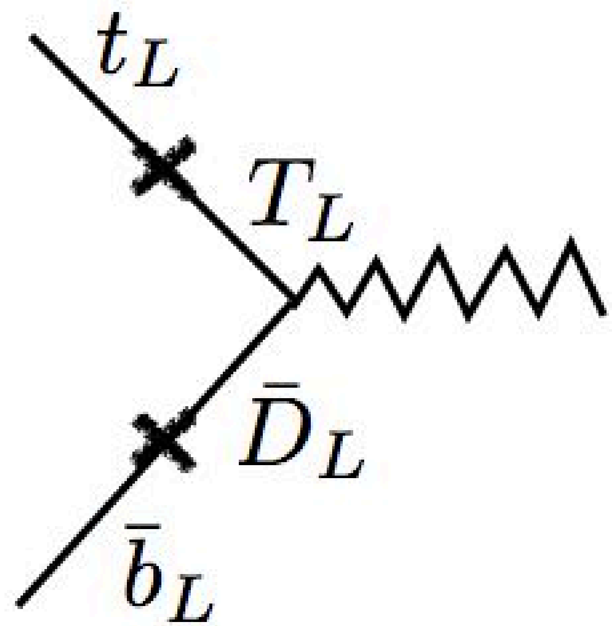
$$\Sigma_{0L} = \begin{pmatrix} X_{0L} \\ T_{0L} \\ B_{0L} \end{pmatrix},\ \Sigma_{0R} = \begin{pmatrix} X_{0R} \\ T_{0R} \\ B_{0R} \end{pmatrix}\quad \Sigma'_{0L} = \begin{pmatrix} T_{0L} \\ B_{0L} \\ X_{0L} \end{pmatrix},\ \Sigma'_{0R} = \begin{pmatrix} T_{0R} \\ B_{0R} \\ X_{0R} \end{pmatrix}$$

Exotic Q=-4/3 fermion

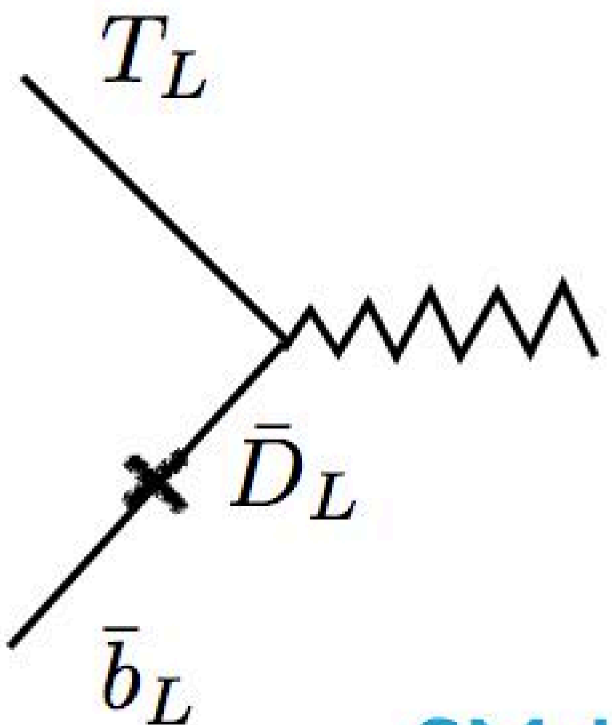
G. Cacciapaglia, A. Deandrea, D. Harada, and Y. Okada, 2010

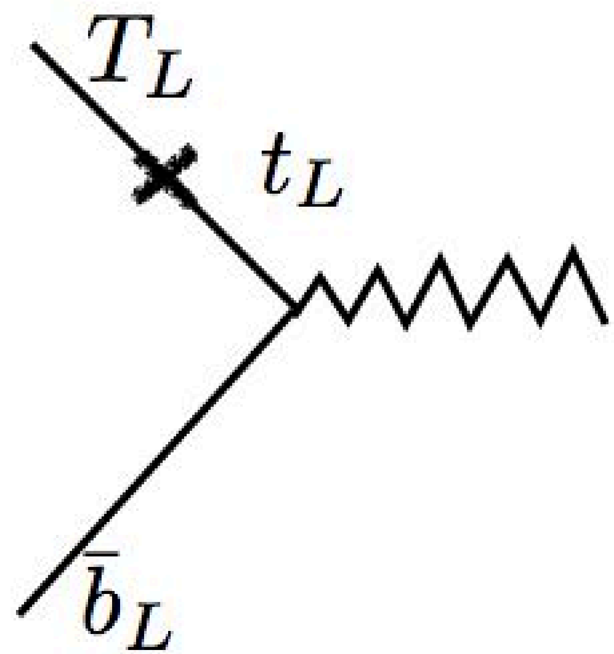
Gauge Couplings (4th Generation)





$$\frac{g}{\sqrt{2}} V_{33}^{CKM} \gamma^\mu P_L$$

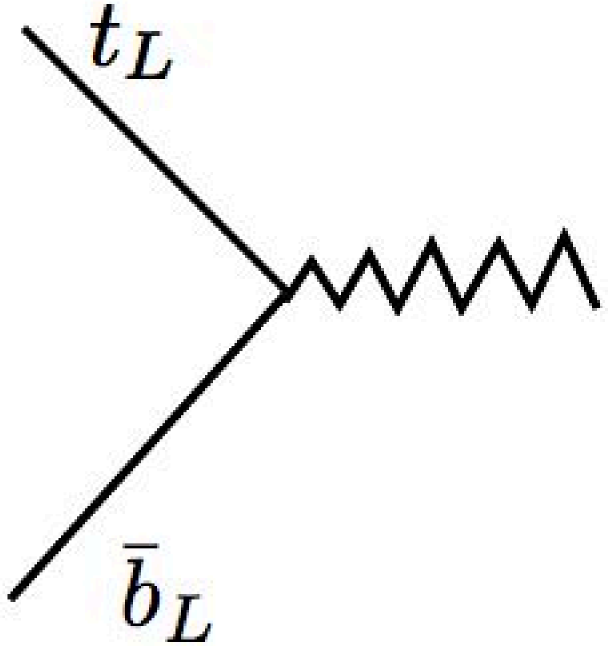




$$\frac{g}{\sqrt{2}} V_{34}^{CKM} \gamma^\mu P_L$$

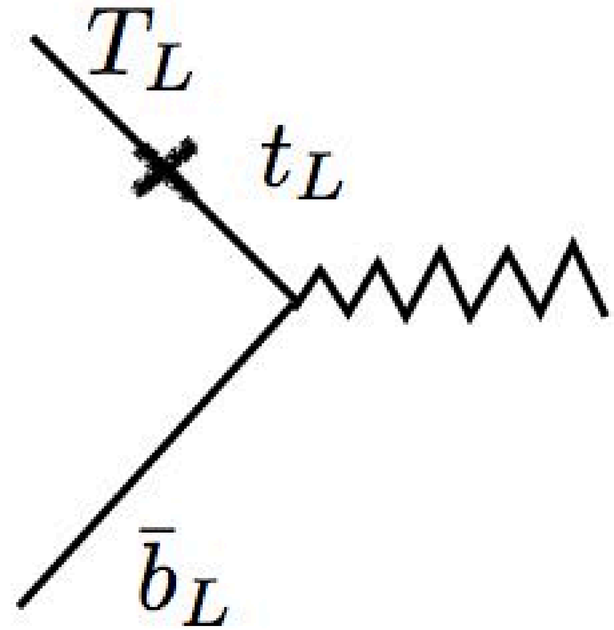
SM-like Gauge Couplings with CKM mixing

Gauge Couplings (Vector-like Singlet)



$$\frac{g}{\sqrt{2}} c_L \gamma_\mu P_L$$

$$s_L \gg s_R$$

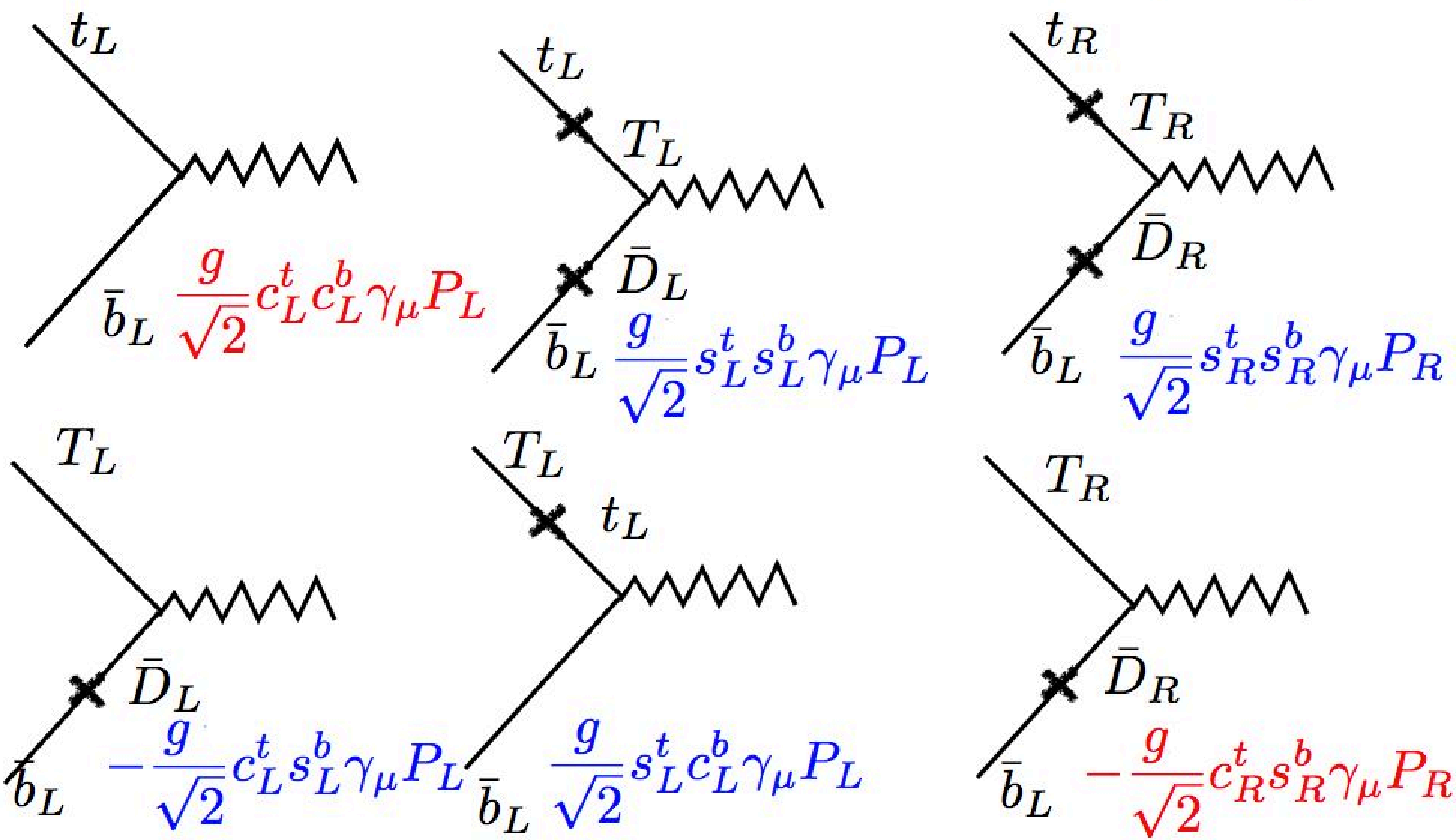


$$\frac{g}{\sqrt{2}} s_L \gamma_\mu P_L$$

$$\frac{g}{\sqrt{2}} W_\mu^+ \, \bar{b}_L \gamma_\mu \left(c_L t_L + s_L t'_L \right) + \text{H.c.}$$

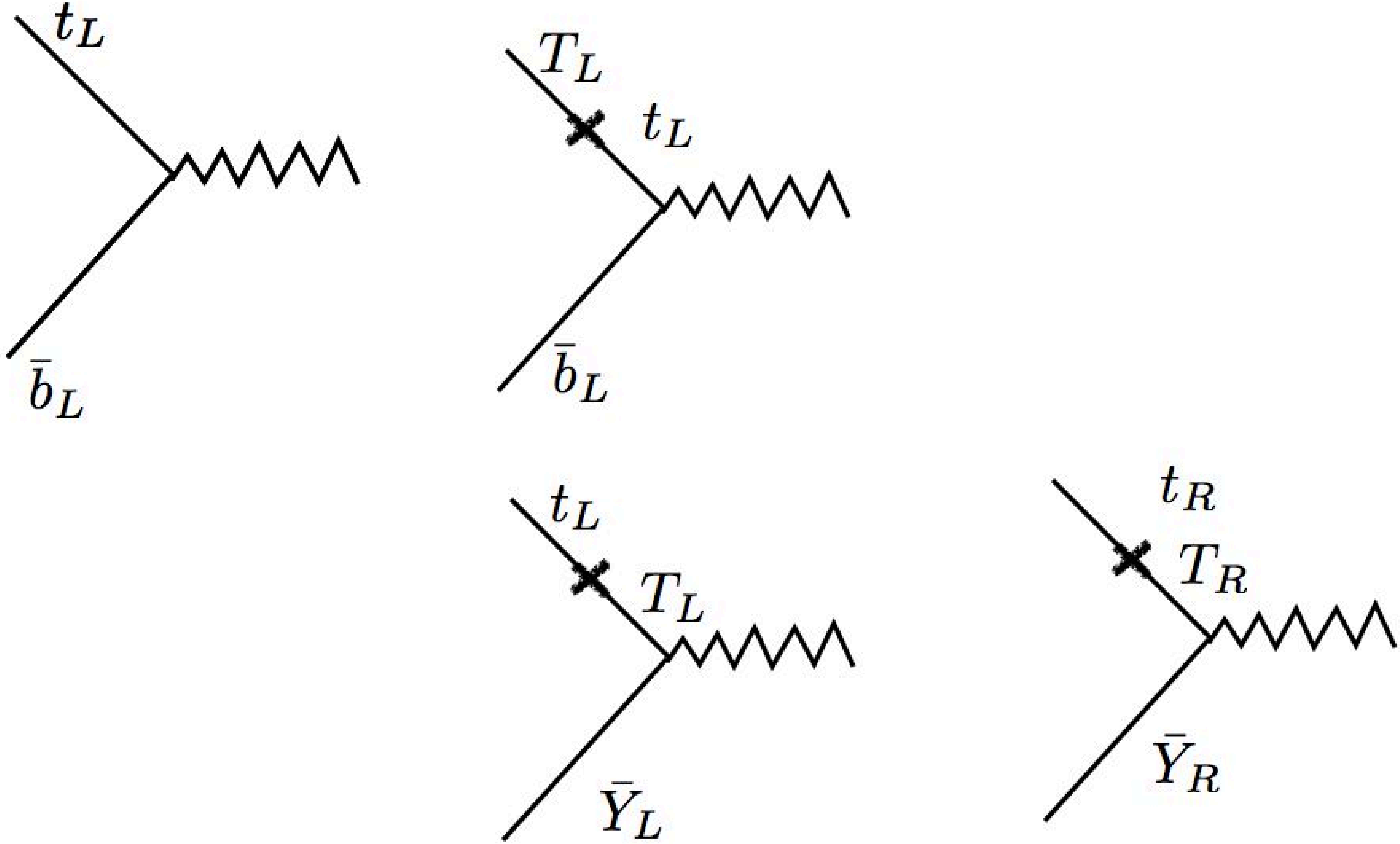
Gauge Couplings (Vector Doublet)

$s_R \gg s_L$



Gauge Couplings (Vector Doublet Q=5/3)

$s_R \gg s_L$



Indirect Constraints

- S, T parameters
- Zbb corrections
- Single top t-b-w coupling
- b to s gamma
- Other flavor constraints (B, Charm)
- Higgs Search limits (heavy quark loop)
- WW scattering and Unitarity

Indirect Constraints

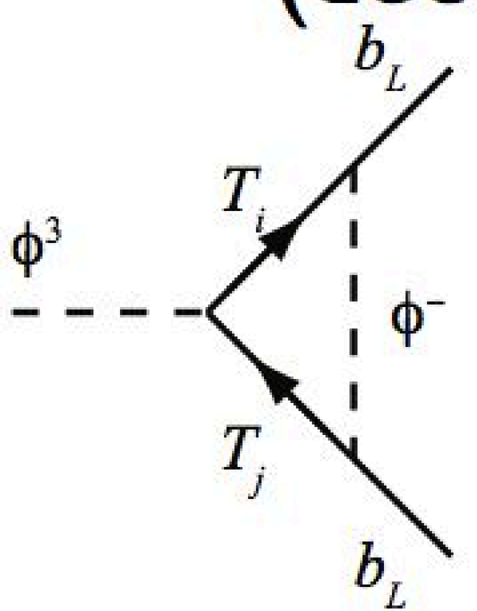
$$\Delta S = \frac{1}{3\pi}\sum_j N_{cj}[I_{3L}(j) - I_{3R}(j)]^2$$

For 4th Generation, only left-handed contribute

For vector-like quark, S is negligible.

For vector-like quark $T \sim \frac{3m_t^2}{16\pi^2}\frac{\lambda^2 v^2}{M^2}\log\frac{M^2}{m_t^2}$

T approaches to zero in heavy mass limit (decouple limit for vector-like quark)



Zbb can be calculated in gaugeless limit

Indirect Constraints

STU Parameter Example: Top See-Saw in Top-Flavor Model

$Q_{3L} = (t_L, b_L)^T$, $L_3 = (\nu_{\tau_L}, \tau_L)^T$, and $S = (\mathcal{T}, \mathcal{B})^T$.

Type-I	$SU(3)_c$	$SU(2)_t$	$SU(2)_f$	$U(1)_y$
Q_{3L}	**3**	**2**	**1**	1/3
(t_R, b_R)	**3**	**1**	**1**	(4, −2)/3
S_L	**3**	**1**	**2**	1/3
S_R	**3**	**2**	**1**	1/3

Type-II	$SU(3)_c$	$SU(2)_w$	$U(1)_t$	$U(1)_f$
Q_{3L}	**3**	**2**	1/3	0
(t_R, b_R)	**3**	**1**	0	(4, −2)/3
S_L	**3**	**2**	0	1/3
S_R	**3**	**2**	1/3	0

$$-(\overline{t_L}, \overline{\mathcal{T}_L}) \begin{pmatrix} 0 & \kappa \\ m_{st} & M_S \end{pmatrix} \begin{pmatrix} t_R \\ \mathcal{T}_R \end{pmatrix}$$
$$-(\overline{b_L}, \overline{\mathcal{B}_L}) \begin{pmatrix} 0 & \kappa \\ m_{sb} & M_S \end{pmatrix} \begin{pmatrix} b_R \\ \mathcal{B}_R \end{pmatrix} + \text{h.c.}$$

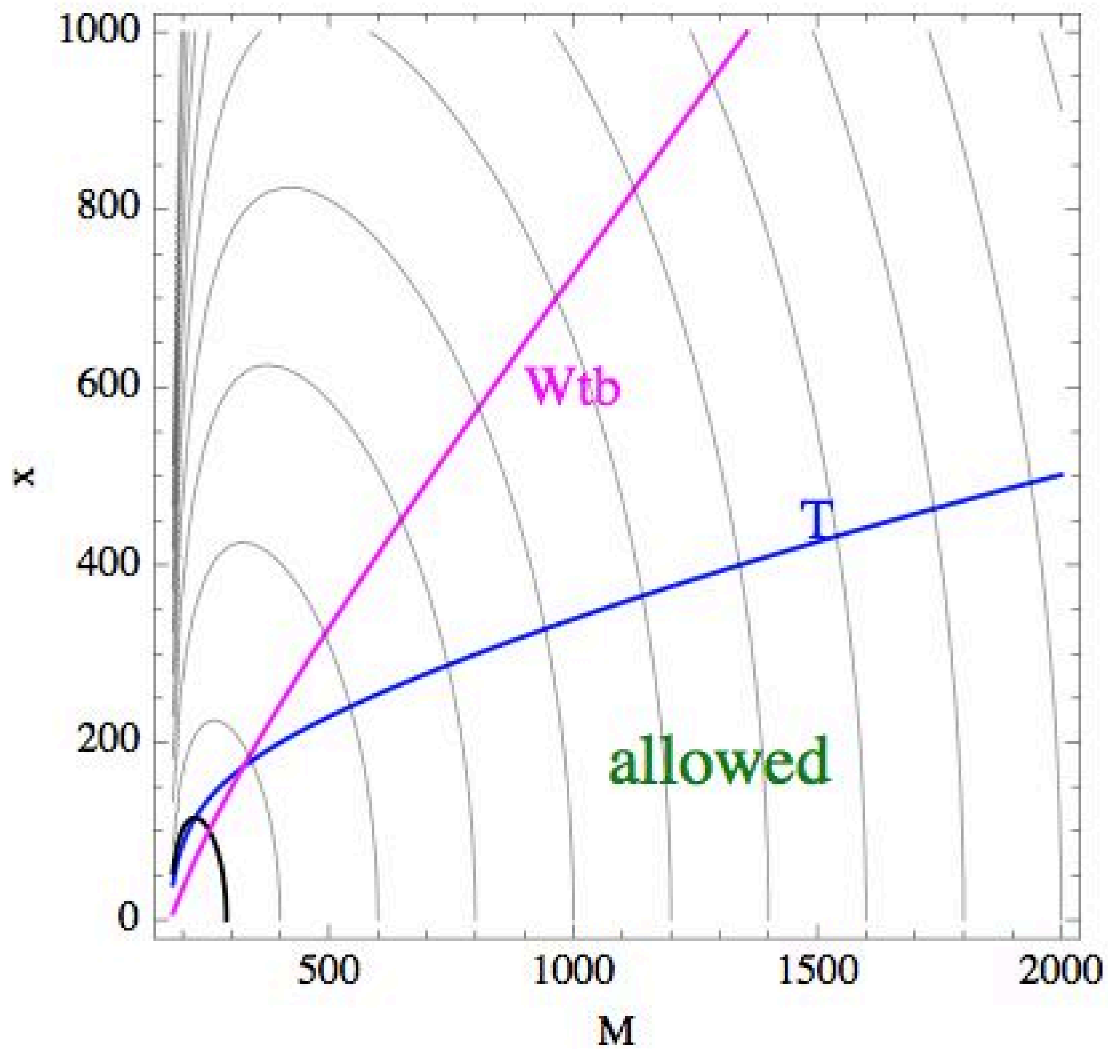
$\longrightarrow$

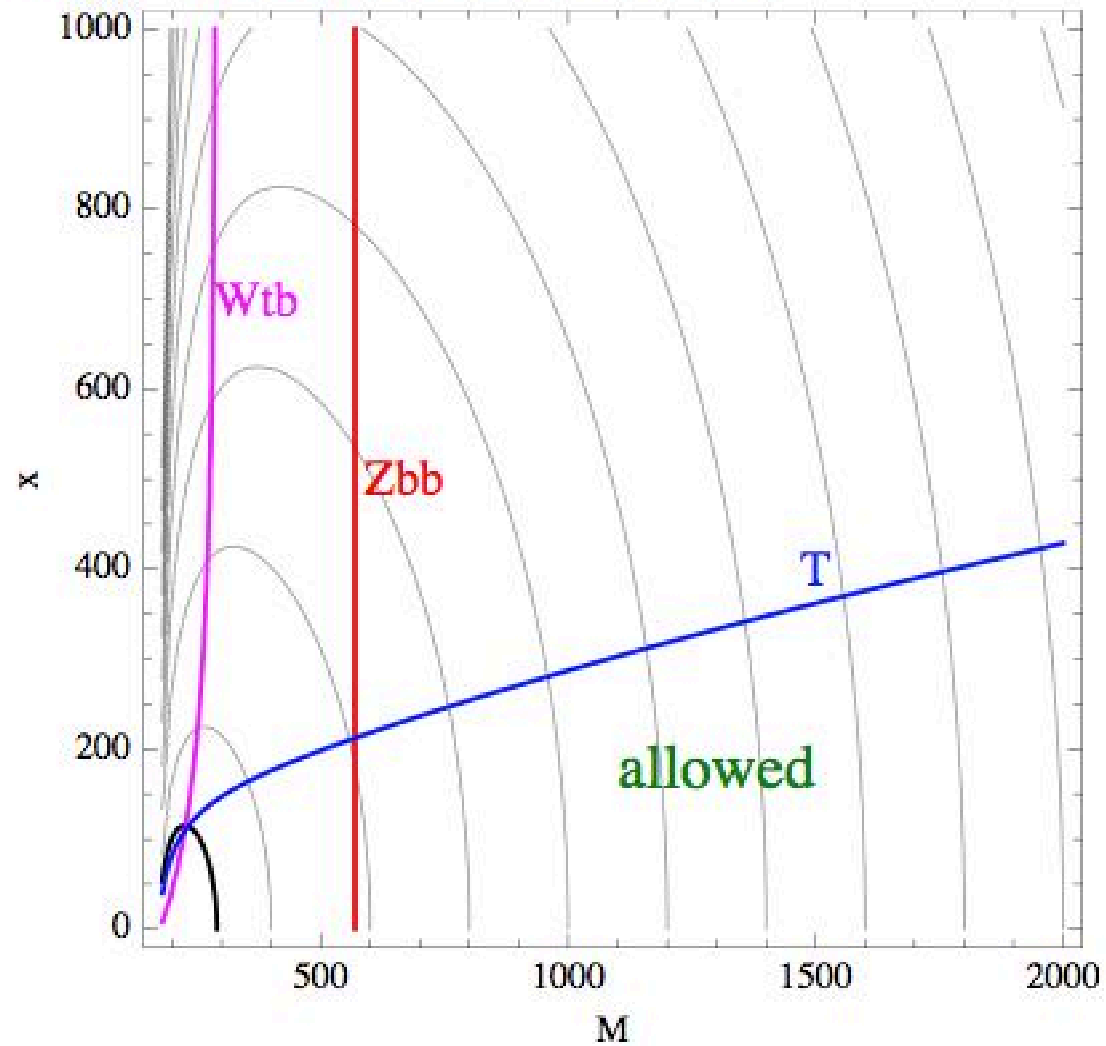
$$S = \frac{4N_c}{9\pi}\left[\ln\frac{M_{\mathcal{T}}}{m_t} - \frac{7}{8} + \frac{1}{16h_t} - \frac{1}{560h_t^2}\right]\frac{z_t^2}{1+r},$$
$$T = \frac{N_c h_t}{16\pi s_w^2 c_w^2}\left[8\ln\frac{M_{\mathcal{B}}}{m_t} + \frac{4}{3r} - 6\right]\frac{z_t^2}{1+r},$$
$$U = \frac{N_c}{6\pi}\left[1 + \frac{1}{10h_t} + \frac{1}{70h_t^2}\right]\frac{z_t^2}{1+r},$$

H.J. He, T. Tait, and C.-P. Yuan, 1998

Indirect Constraints

Constraints from T, Zbb and Wtb



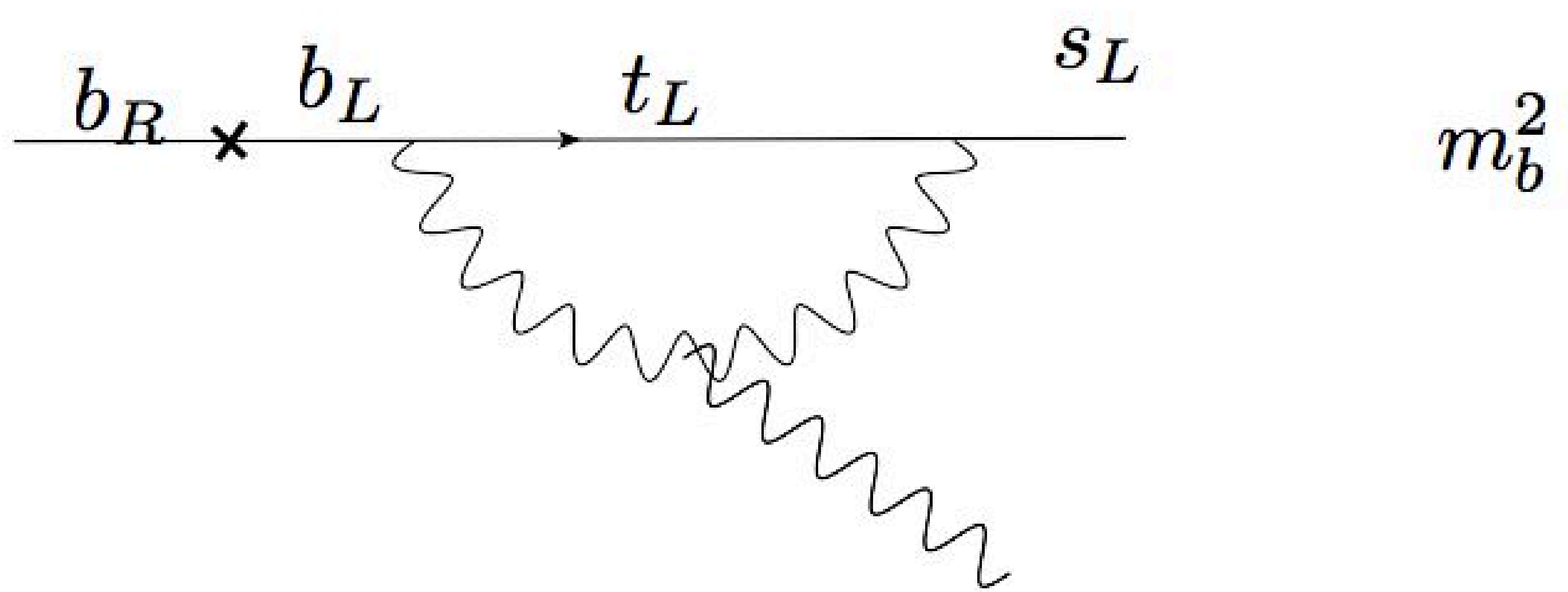


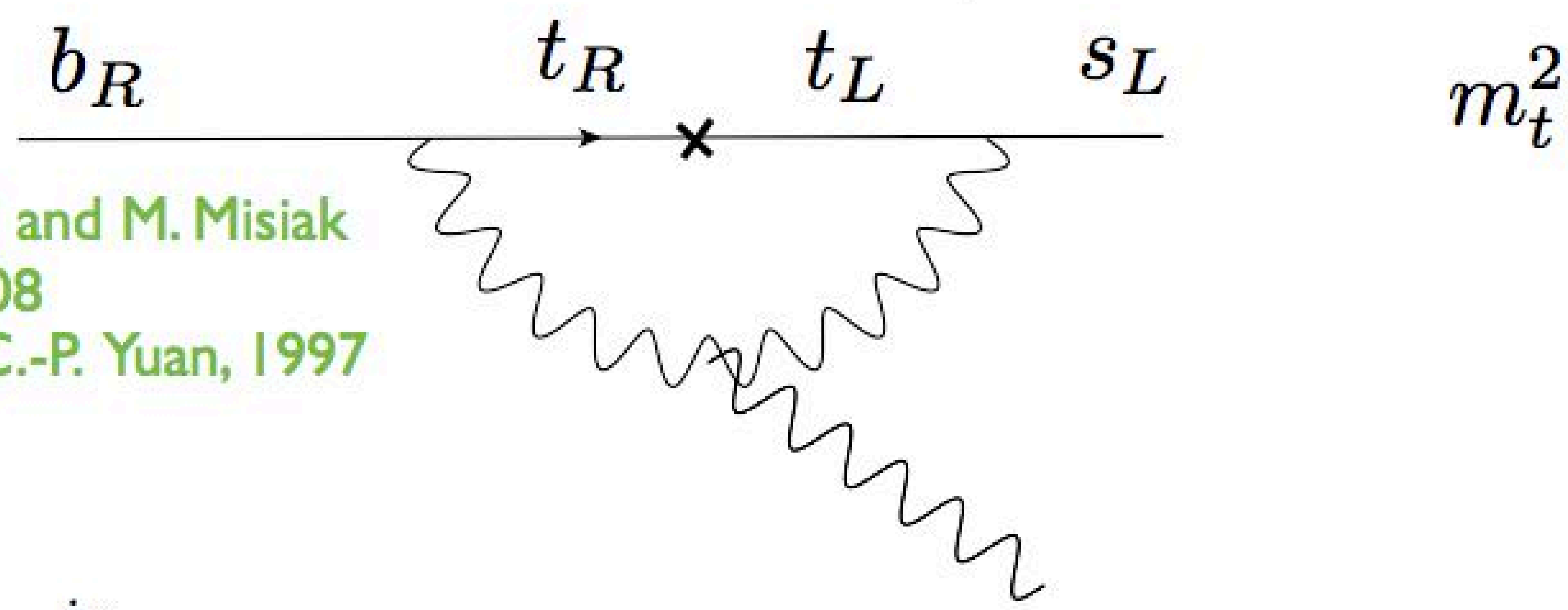
Singlet Case **SM Doublet Case**

$x = \lambda v$

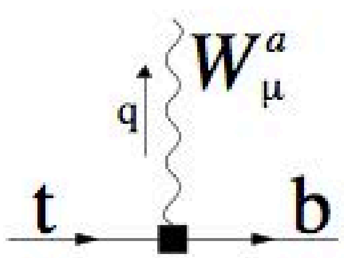
G. Cacciapaglia, A. Deandrea, D. Harada, and Y. Okada, 2010

Indirect Constraints





B. Grzadkowski and M. Misiak 2008
E. Malkawi and C.-P. Yuan, 1997

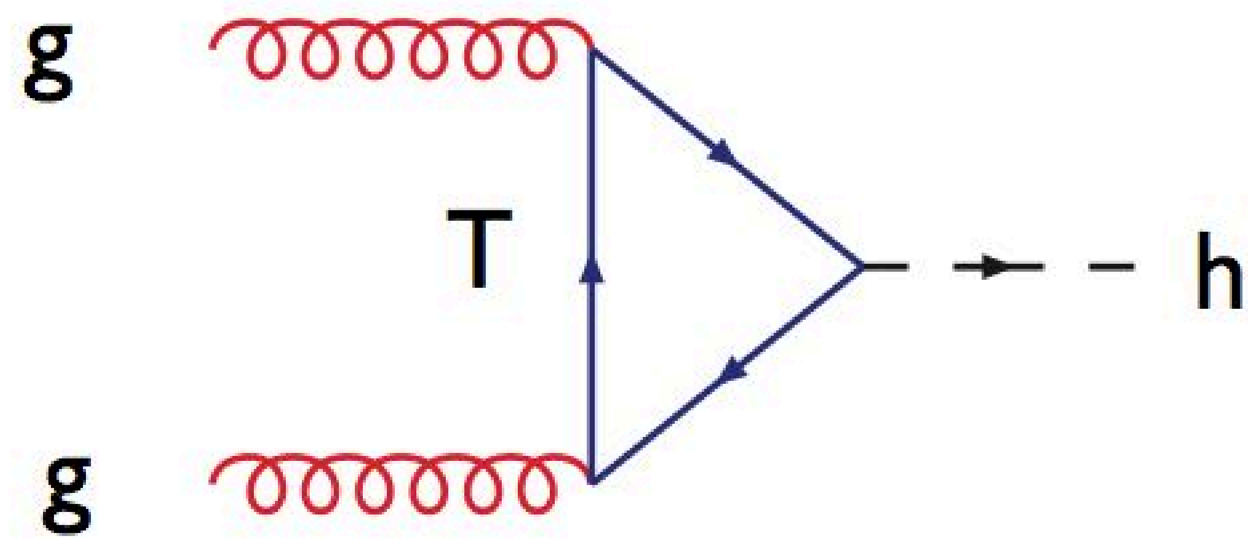


$$= -\frac{ig_w}{\sqrt{2}}\left[\gamma_\mu(v_L P_L + v_R P_R) + \frac{i\sigma_{\mu\nu}q^\nu}{M_W}(g_L P_L + g_R P_R)\right]$$

bound	δv_L	v_R	g_L	g_R
upper	0.03	0.0025	0.0004	0.57
lower	−0.13	−0.0007	−0.0013	−0.15

Indirect Constraints

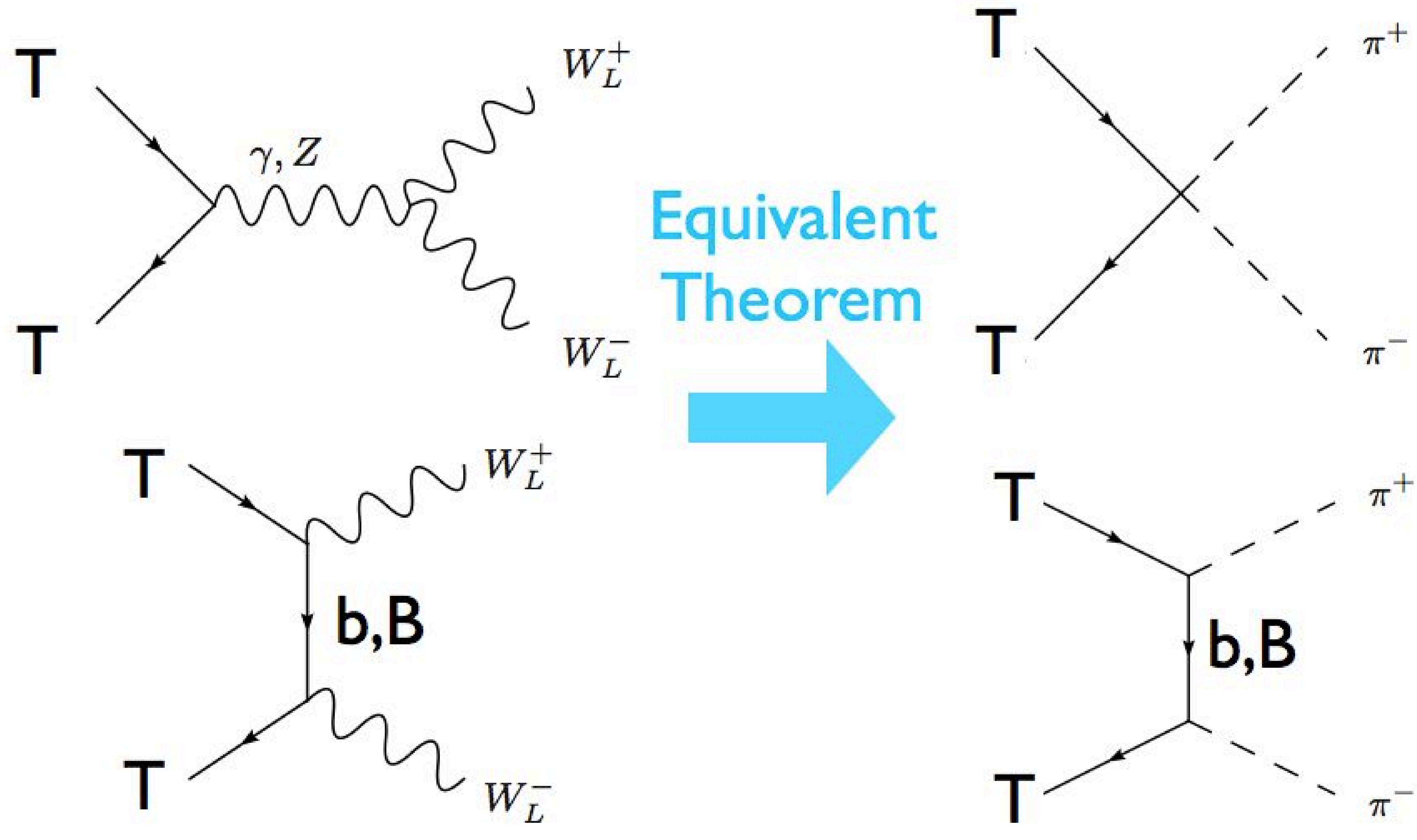
Constrain on number of heavy flavors



In Heavy Quark mass limit, approach to effective ggh couplings

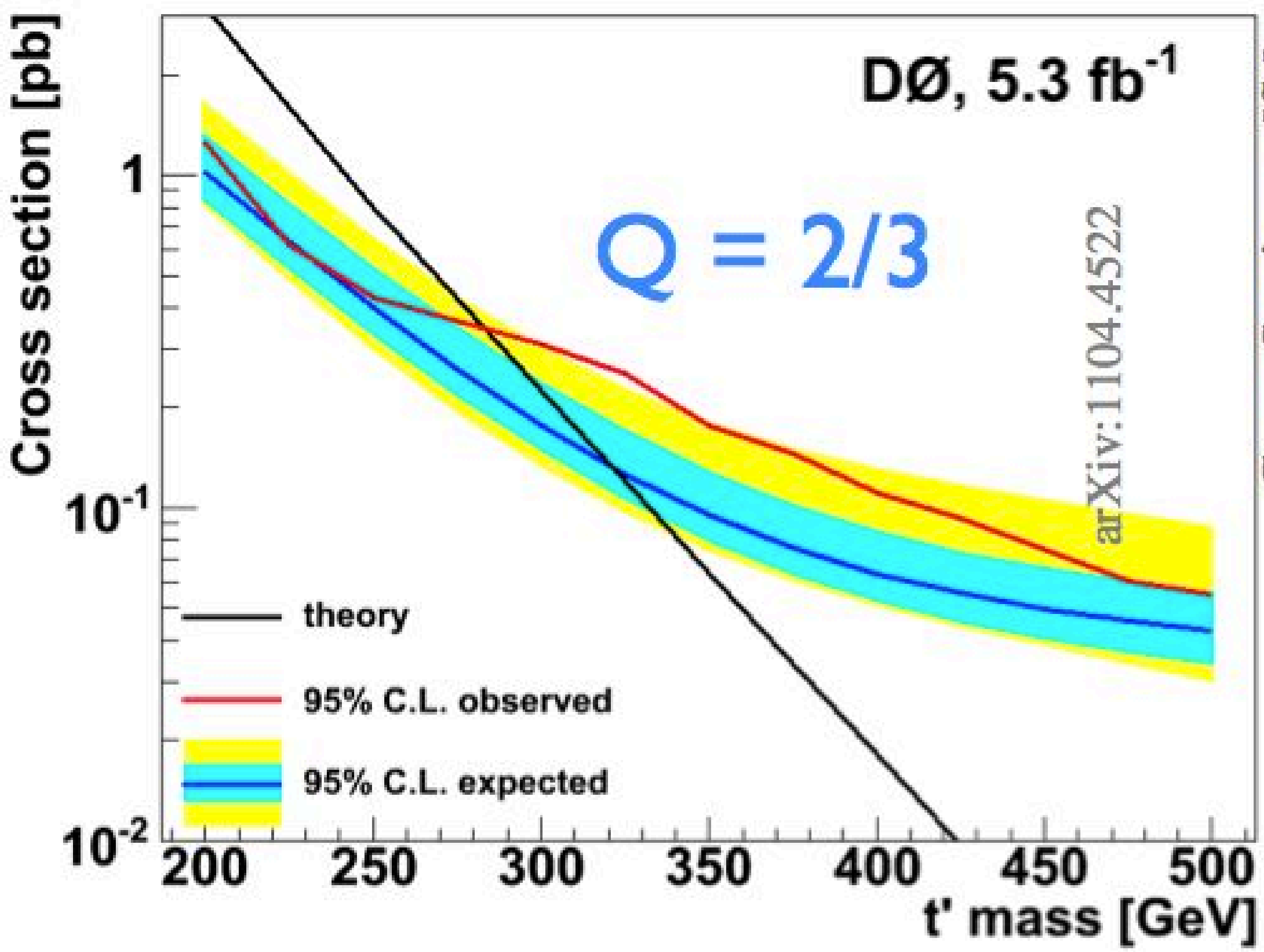
Indirect Constraints

Unitarity Constraint: WW TT scattering

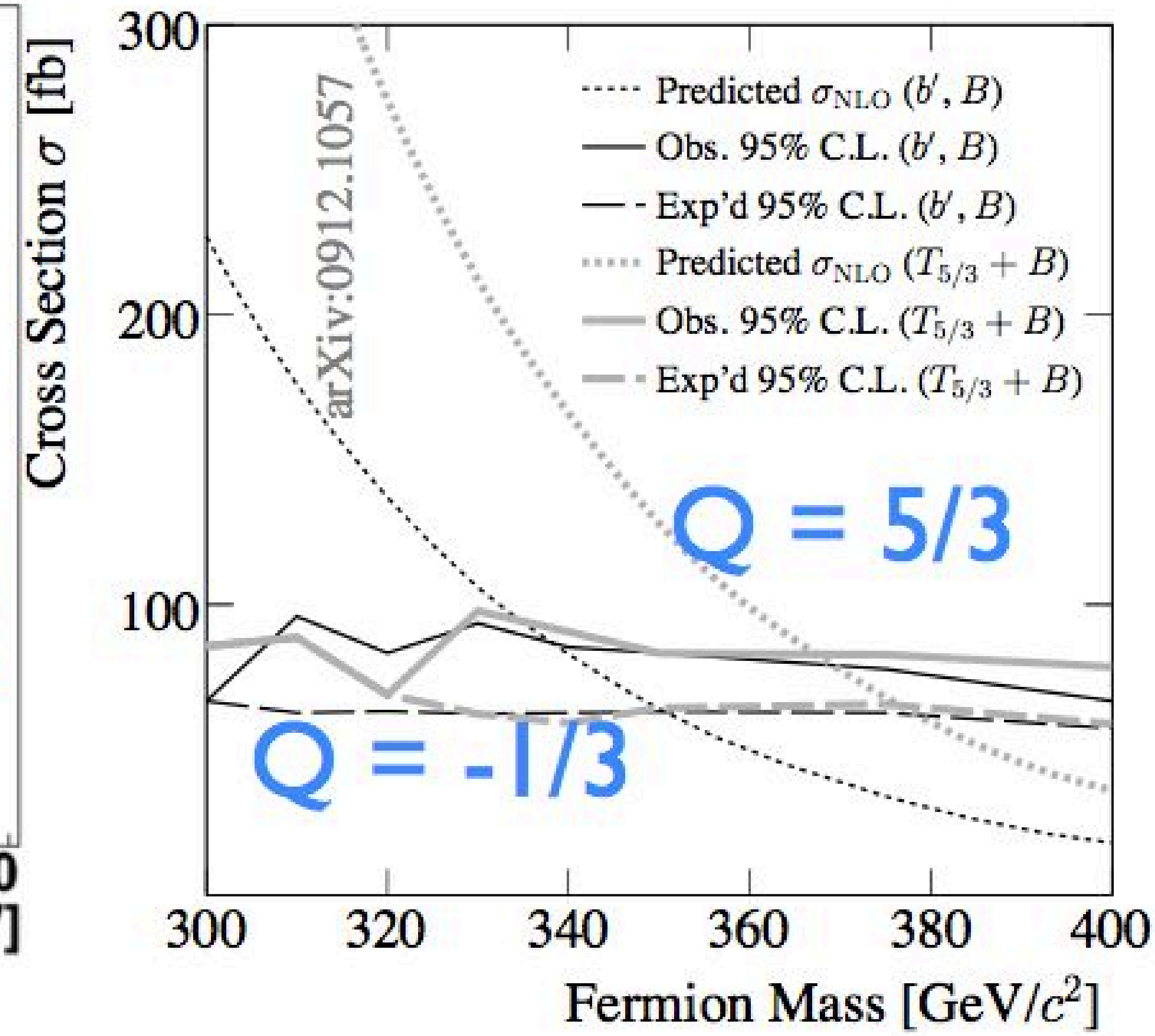


Direct Search at Tevatron

$t'\bar{t}' \to WbW\bar{b} \to \ell\bar{\nu}bq\bar{q}\bar{b}$

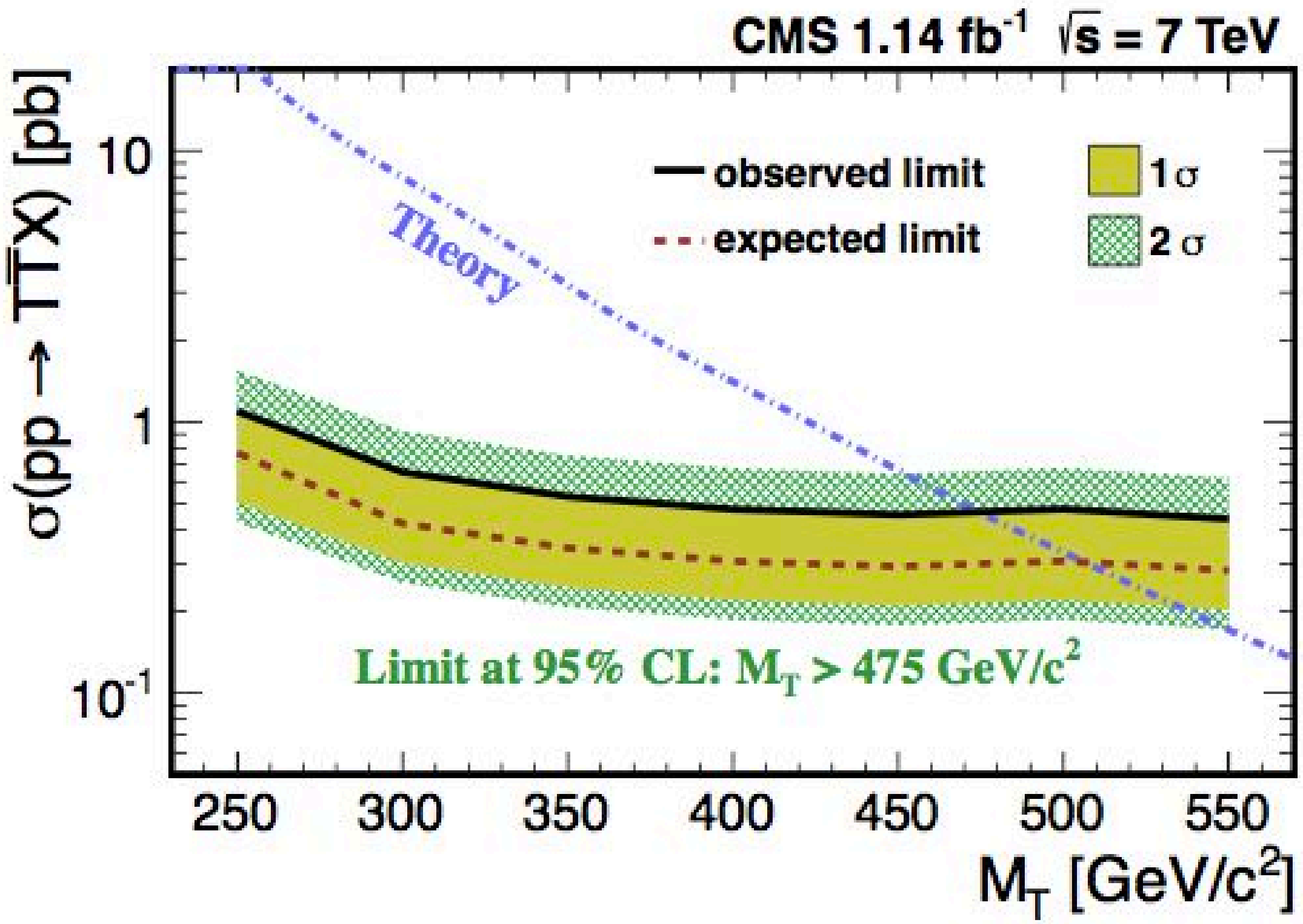


$Q\bar{Q} \to (tW^{\mp})(\bar{t}W^{\pm})$ in Same-Charge Dilepton Events

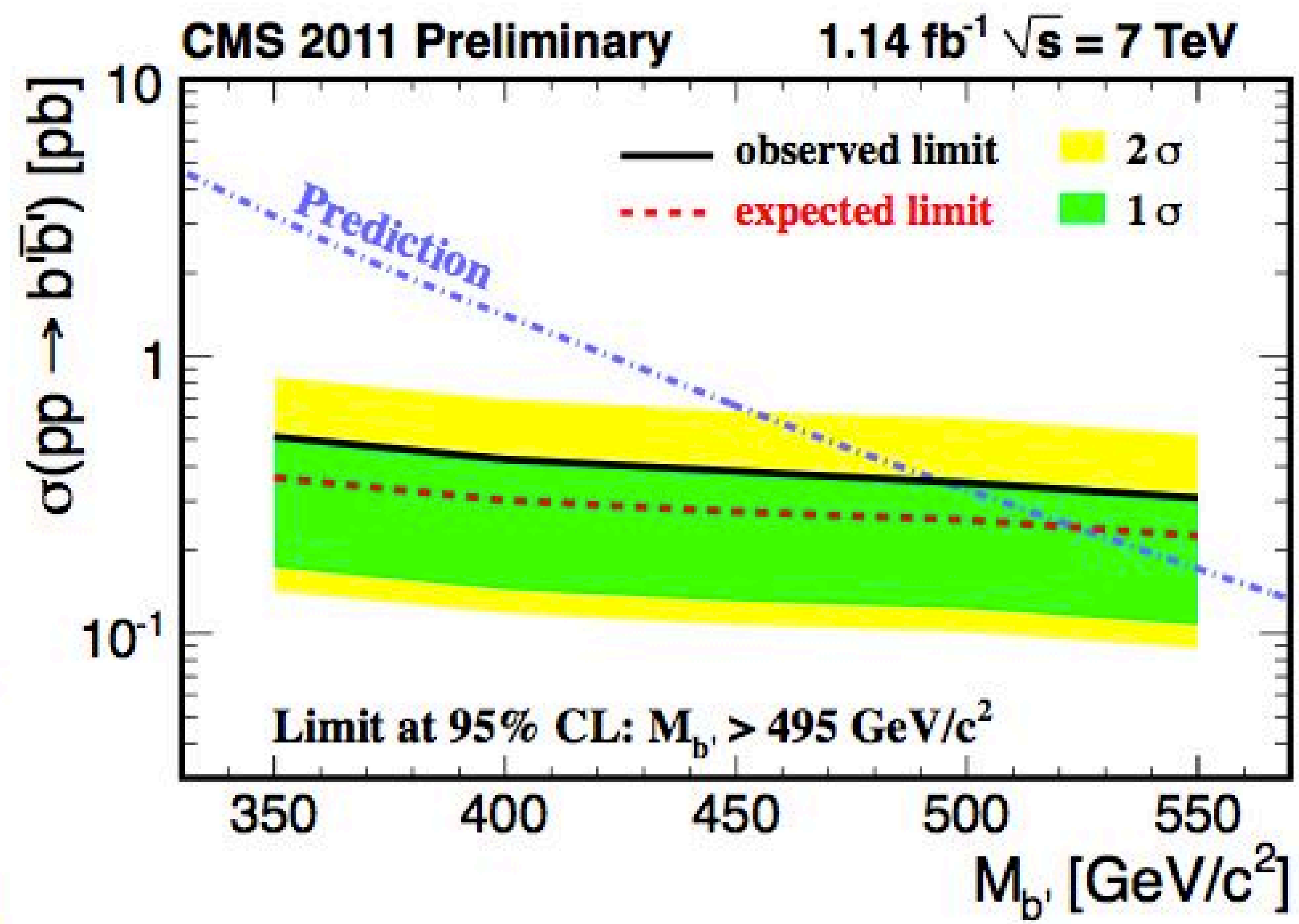


Search Limits at LHC

$$t'\bar{t}' \to WbW\bar{b} \to \ell\nu bq\bar{q}\bar{b}$$

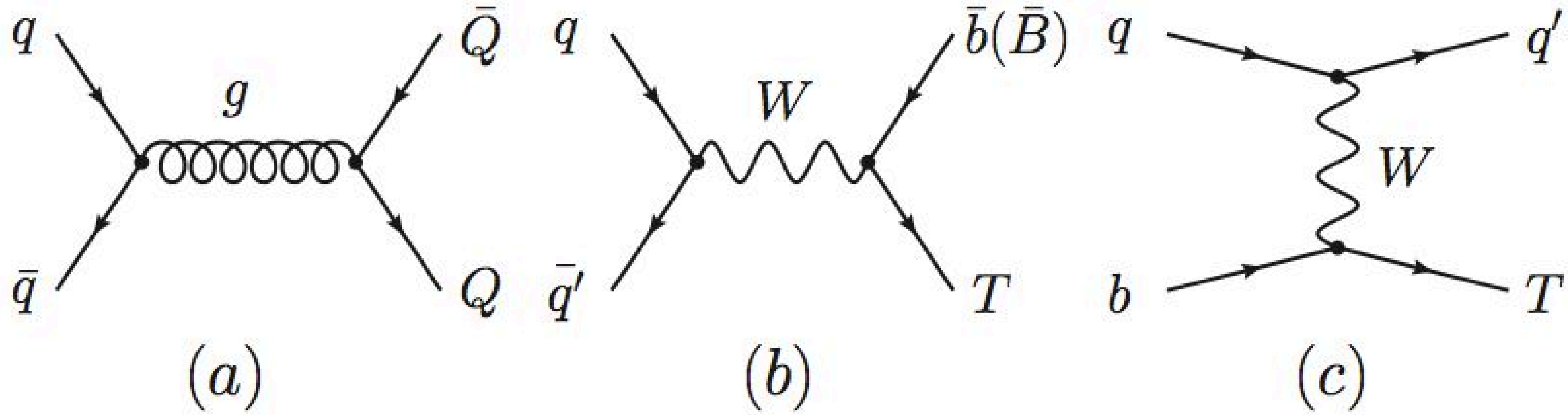


$$b'\bar{b}' \to tW^-\bar{t}W^+$$



same sign dilepton + trilepton combined results

Heavy Quark Production



Pair Production: QCD process

Single Production (s-channel): EW process

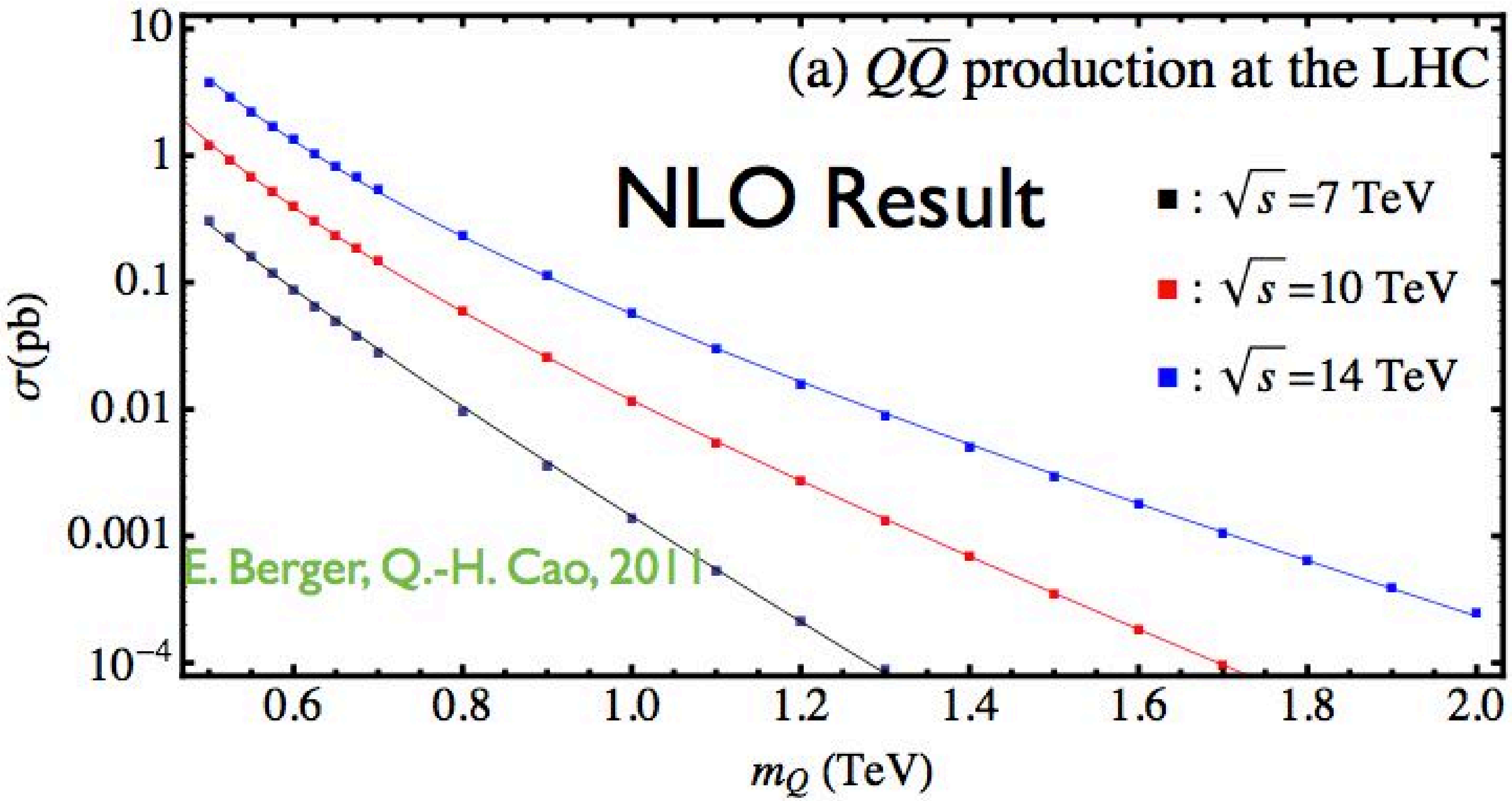
Single Production (T-channel): EW process, with longitudinal W enhancement at high energy

Pair Production

QCD process   Discover resonance

Main discovery channel for small Q mass

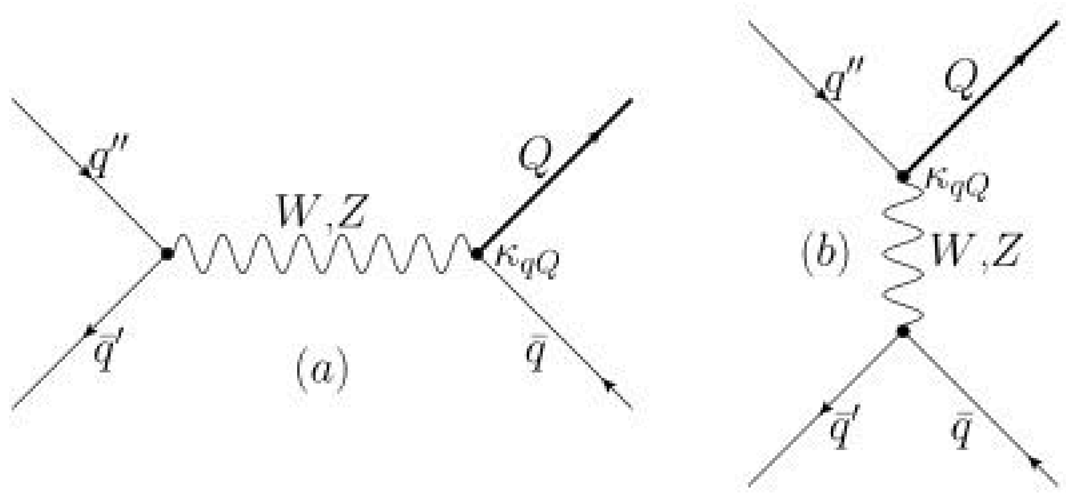
Sensitive to decay branching ratios, not determination of couplings

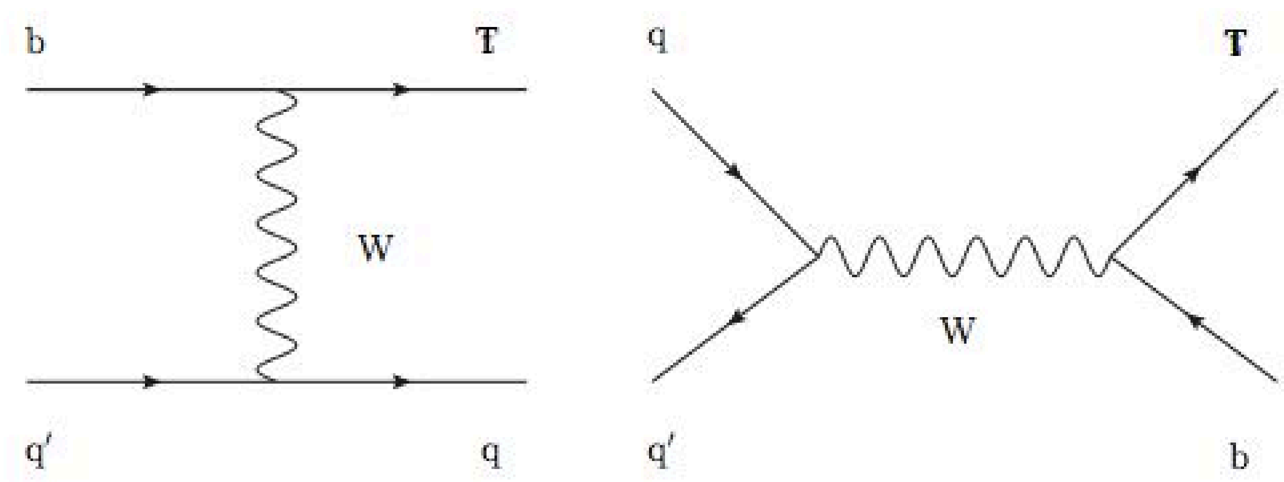


Single Production

- Two Types of Single Production

Determine the gauge coupling strength of heavy quark





Q couples to light quark

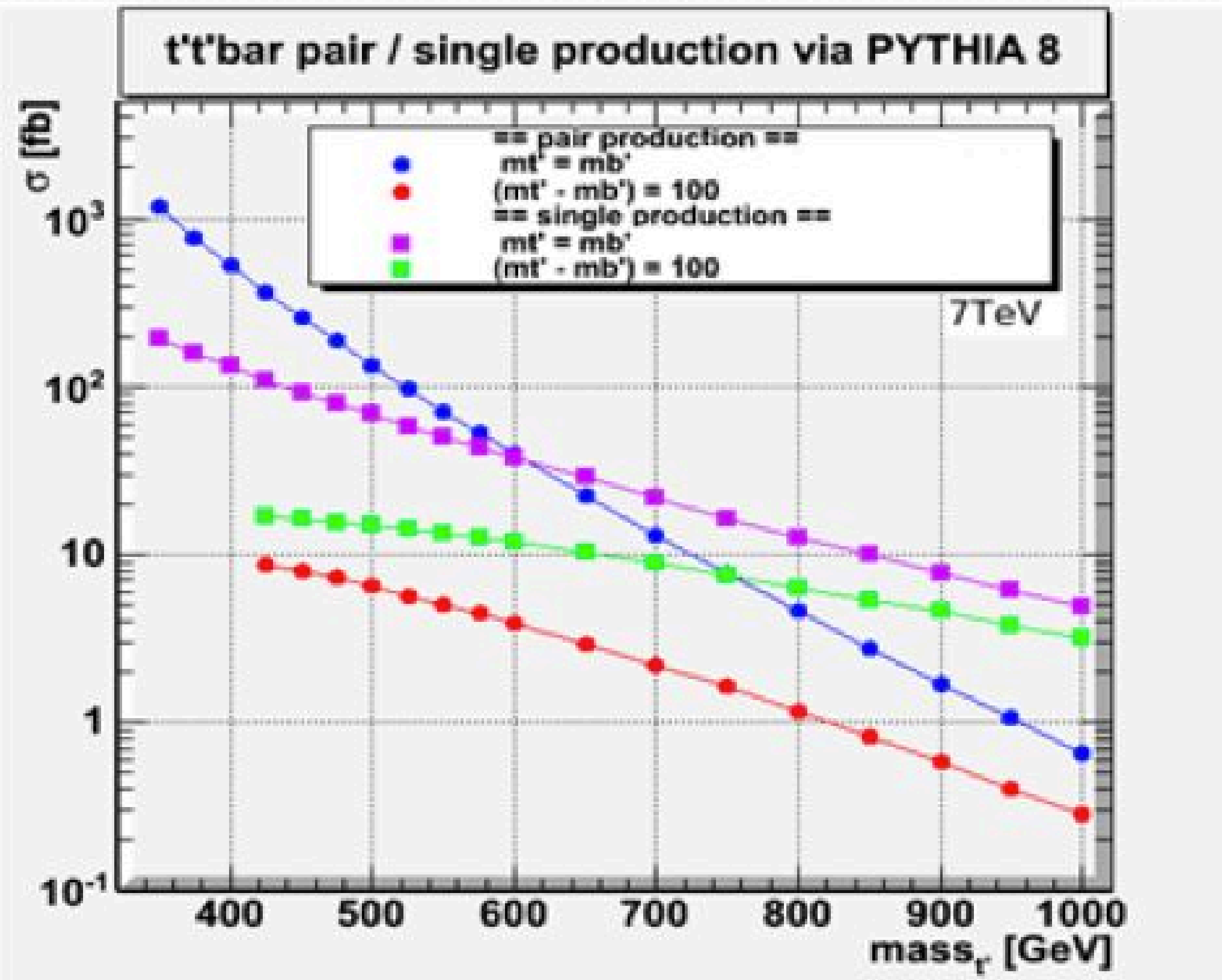
Main discovery channel for light Q mass

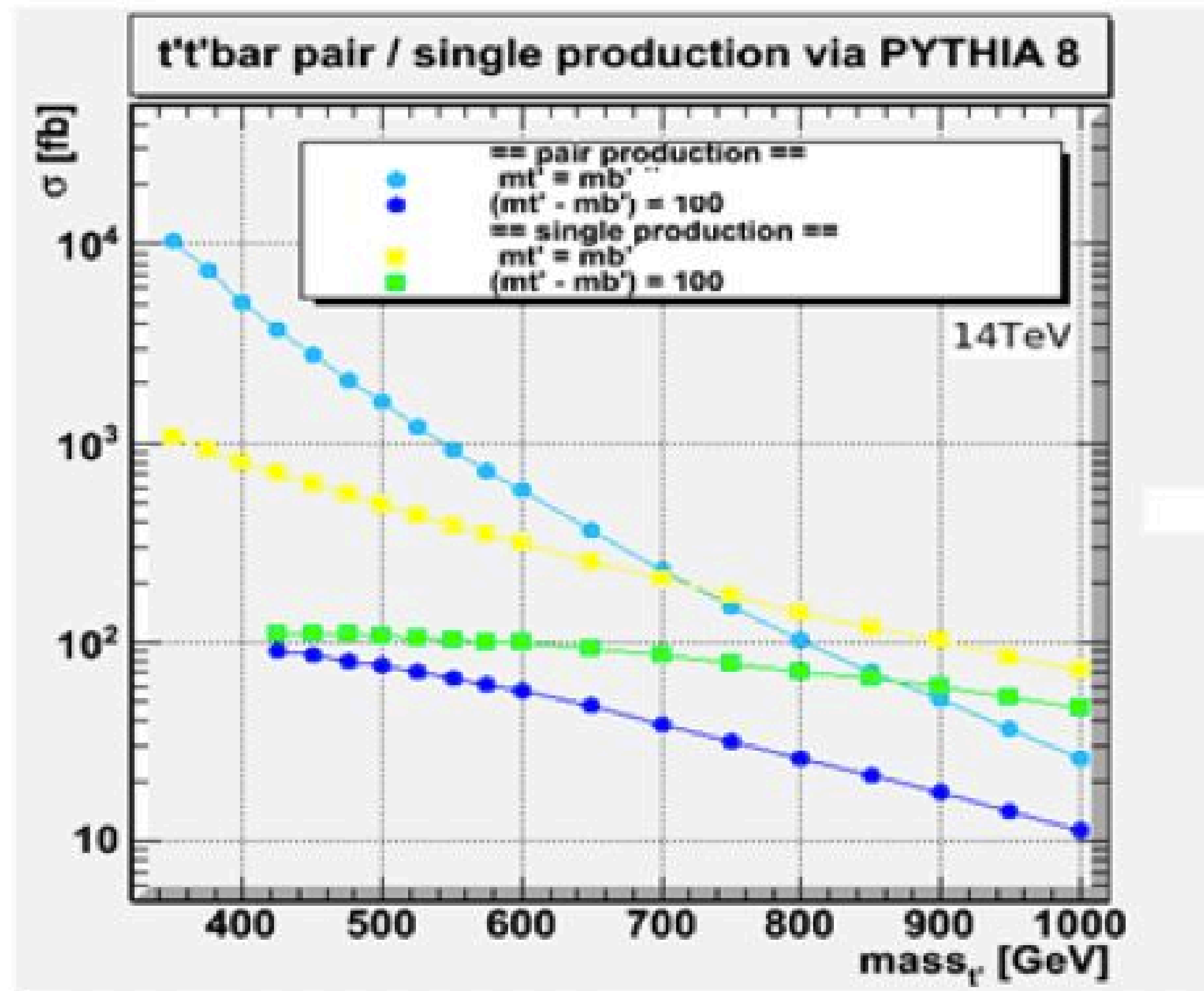
Q couples to 3rd Generation

Main discovery channel for heavy Q mass

4th Generation T-prime

Cross sections for pair and single productions



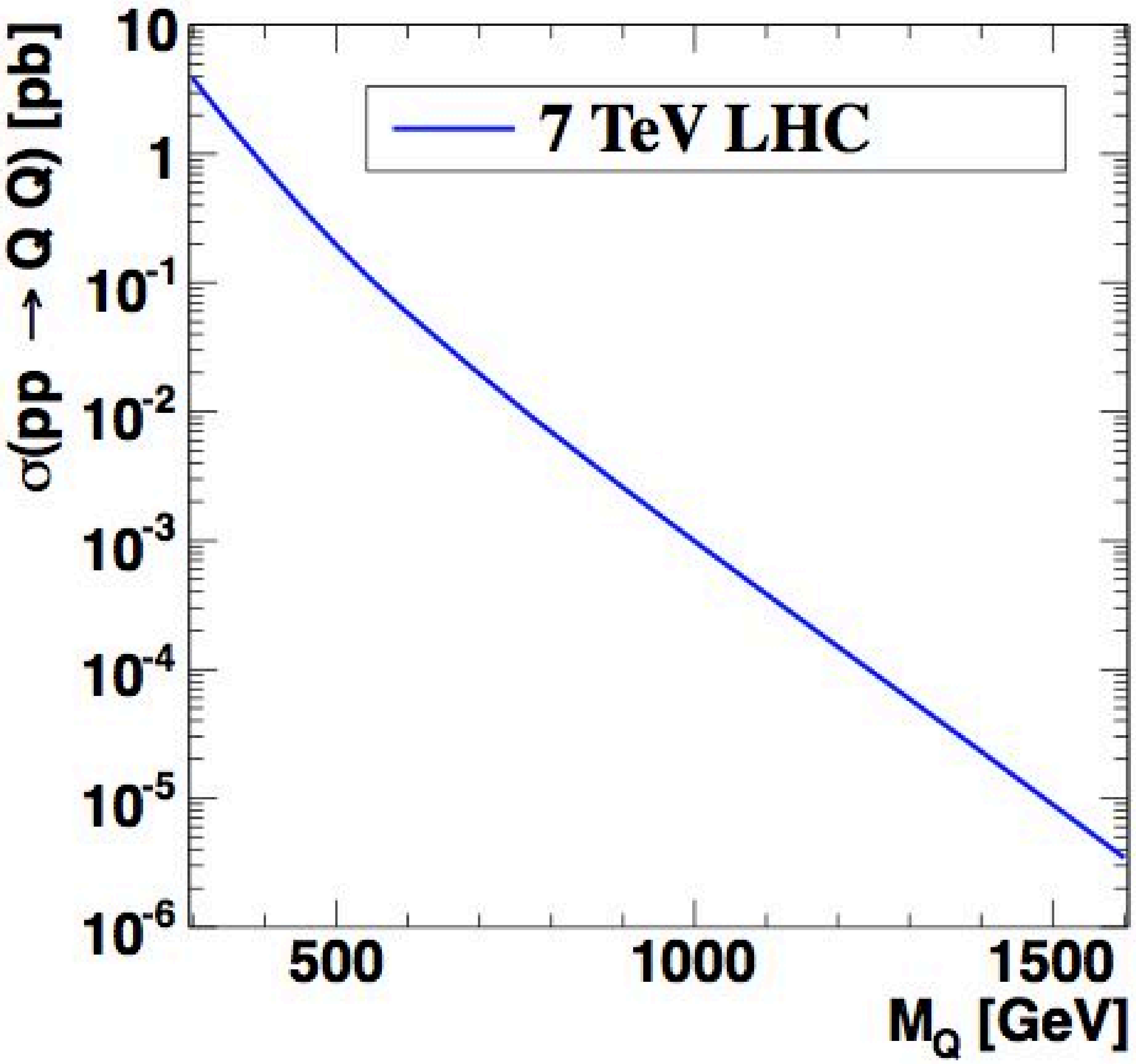


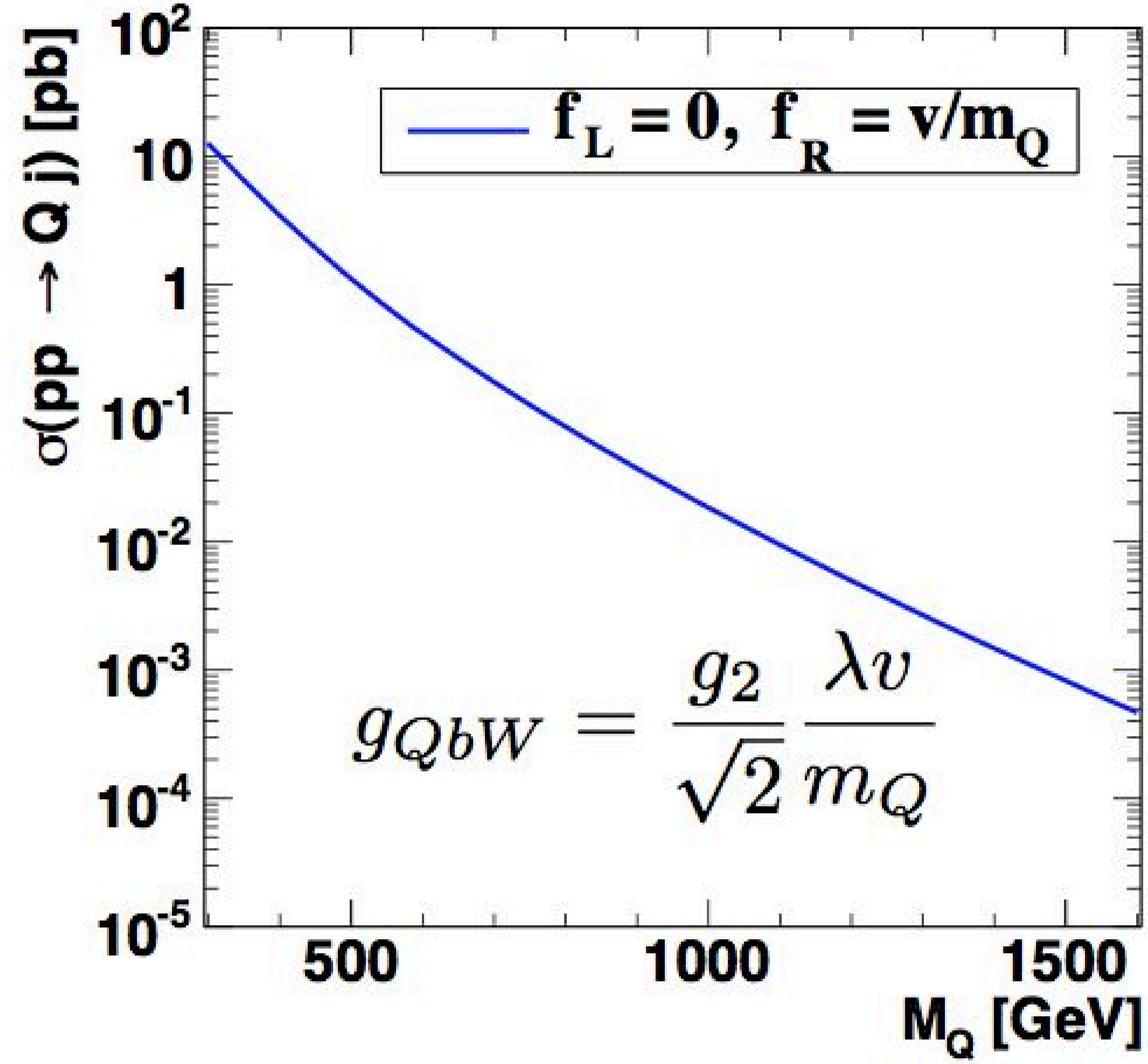
t' mass > b' mass

Vt'b = 0.1 in Pythia 8 (default parameter) O. Ducu, 2011

Vector-like T-prime

Q couples to 3rd Generation



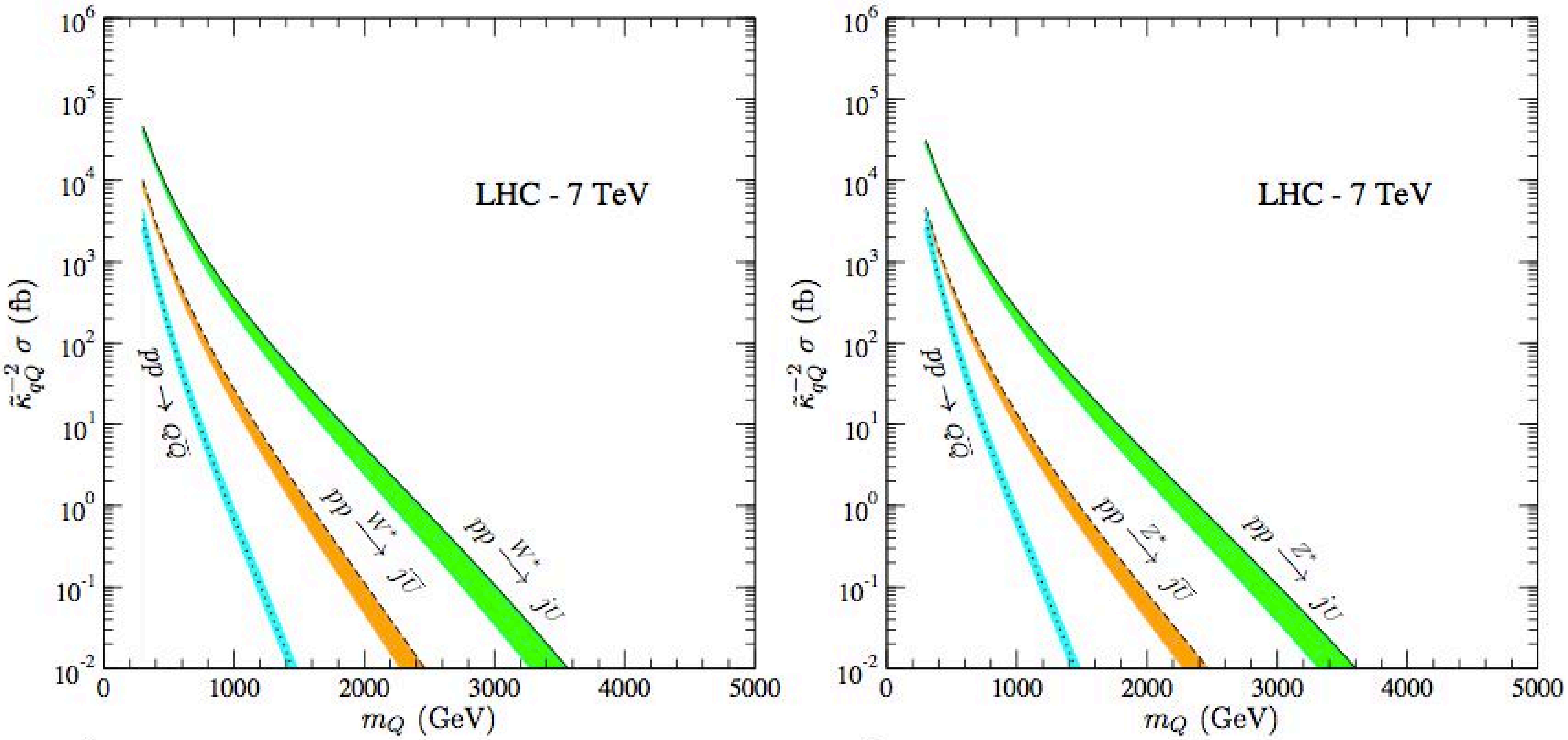


Single production is larger if $\lambda \simeq 1$

Vector-like T-prime

Q couples to light quark

$\lambda \simeq 1$



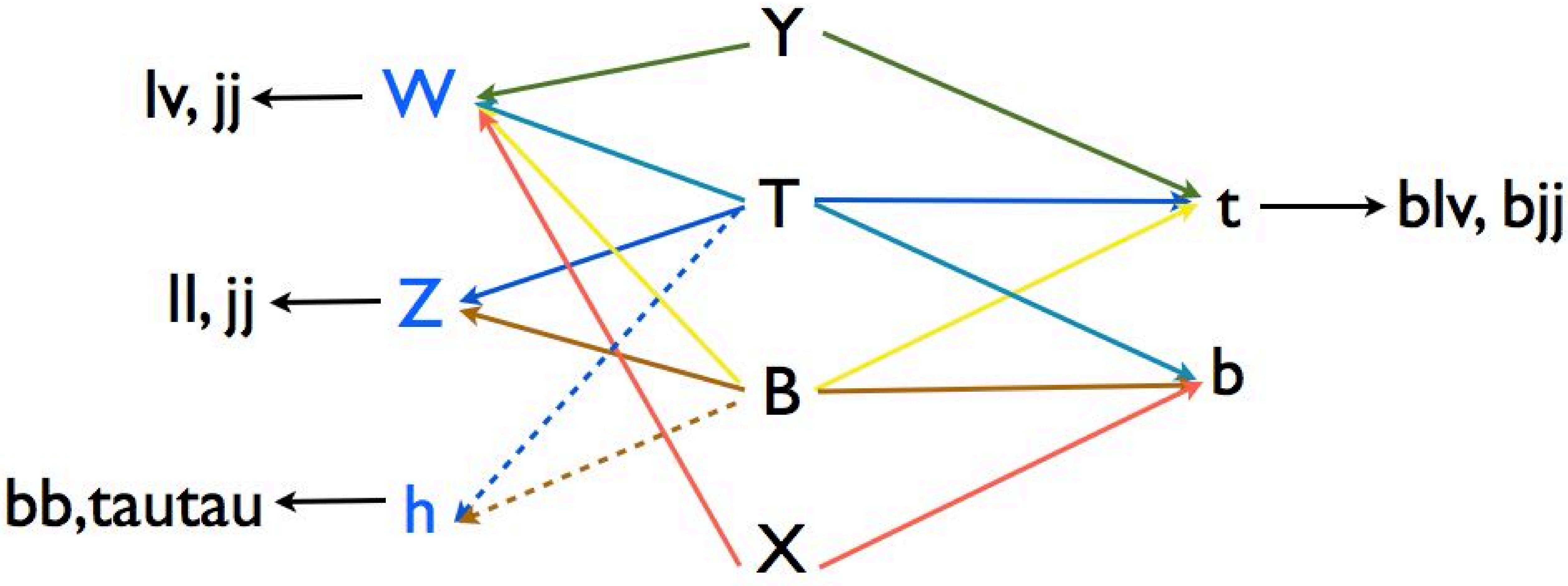
A. Atre, et.al. 2011

Main discovery channel: Single Production

Decay Channels

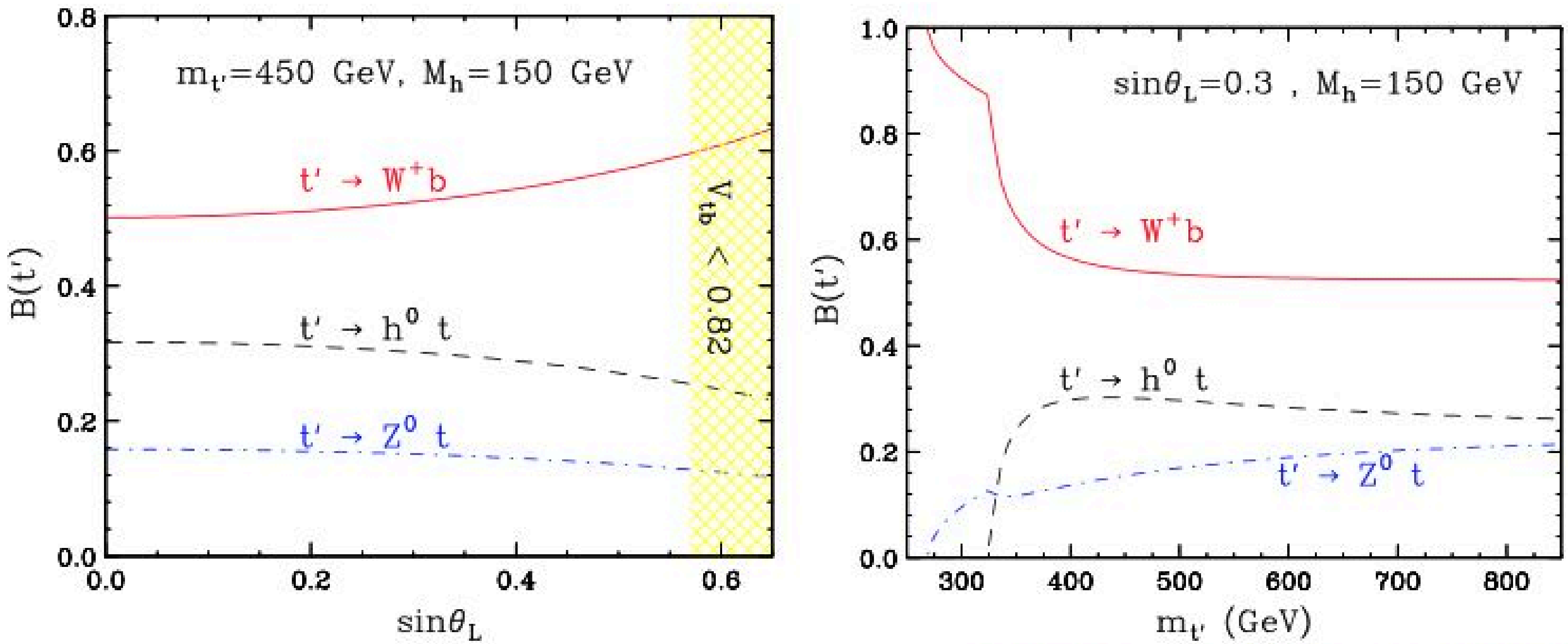
$T \rightarrow t\,z,\ b\,w,\ t\,h;\quad B \rightarrow t\,w,\ b\,z,\ b\,h$

$Y \rightarrow t\,w;\ X \rightarrow t\,w$



Branching Ratio

Take vector-like singlet as an example



B. Dobrescu, K. Kong, and R. Mahbubani, 2009

Equivalent Theorem in heavy quark mass limit:

$$\Gamma(T \to bW^+) = 2\Gamma(T \to tZ) = 2\Gamma(T \to th) \simeq \frac{1}{32\pi} M_Q |\frac{\lambda v}{M}|^2$$

Pair Production

- Discovery Channel:

$$p\,p \to g \to Q\,\bar{Q}$$

Large Production Rate

- Signal for discovery:

HT distributions, ...

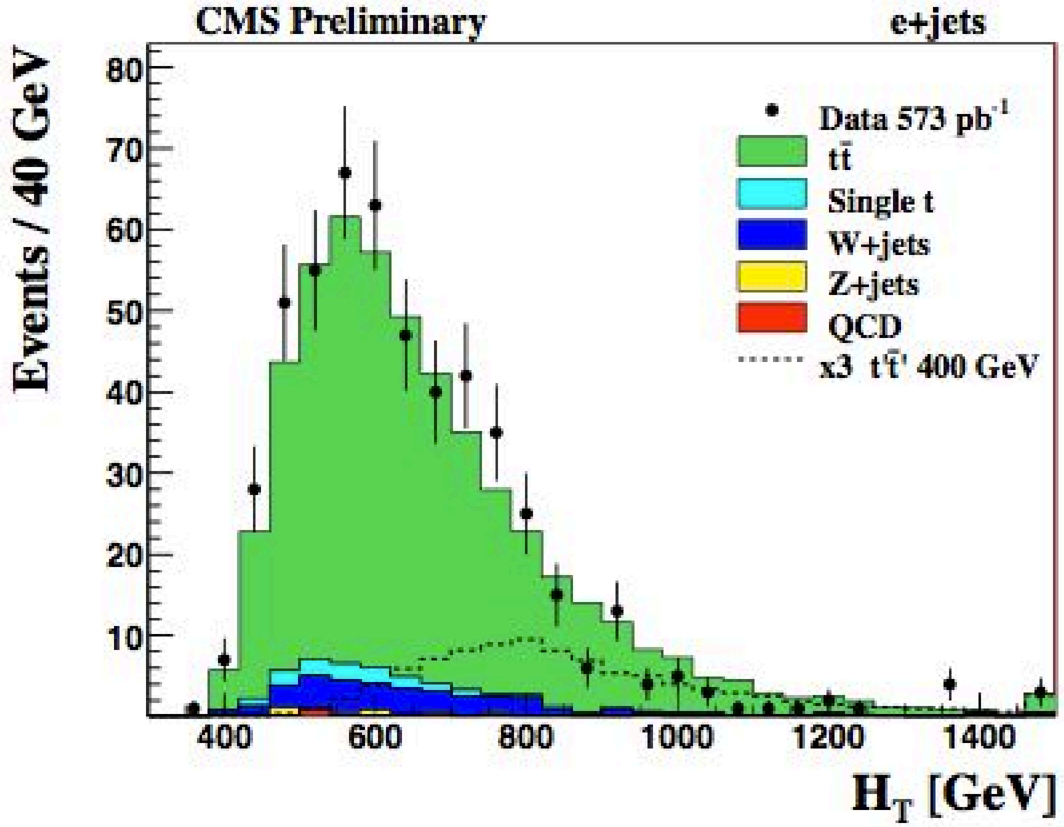
- Resonance Peak and Mass Determination:

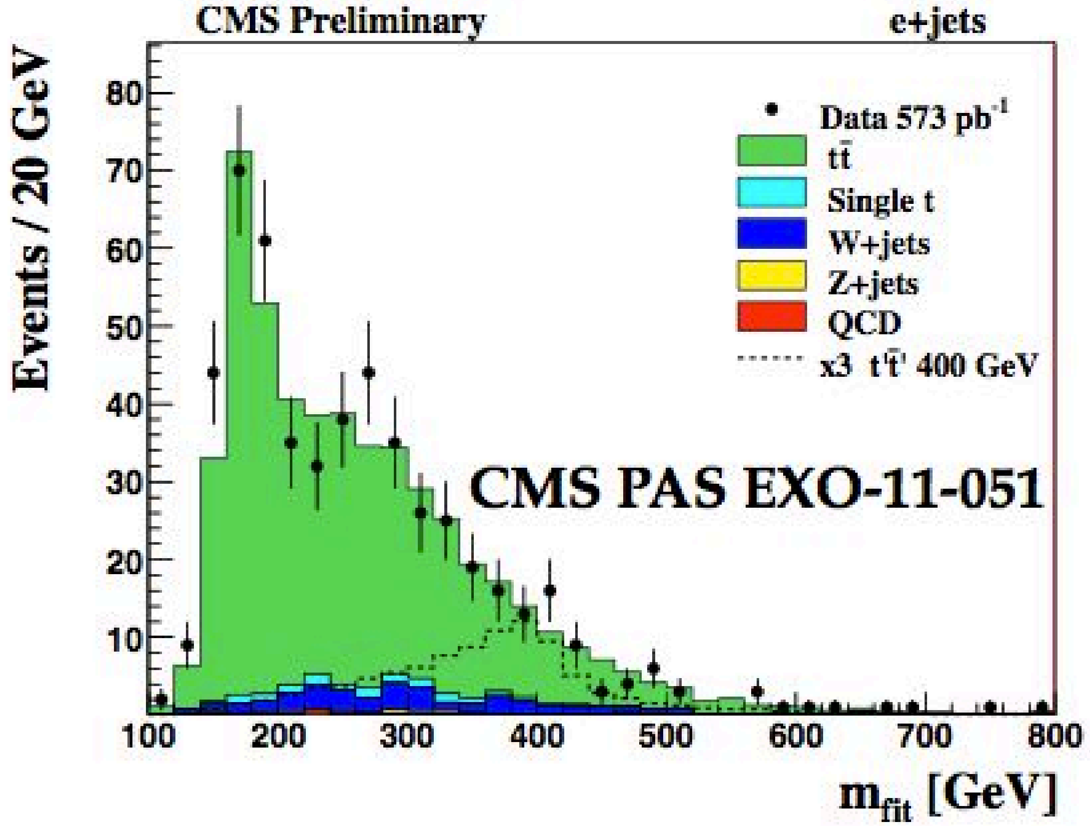
Reconstructed Heavy Quark Mass distributions

- Charge and Spin Determination

T-prime Pair Production

$$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow \ell\bar{\nu}bq\bar{q}\bar{b}$$





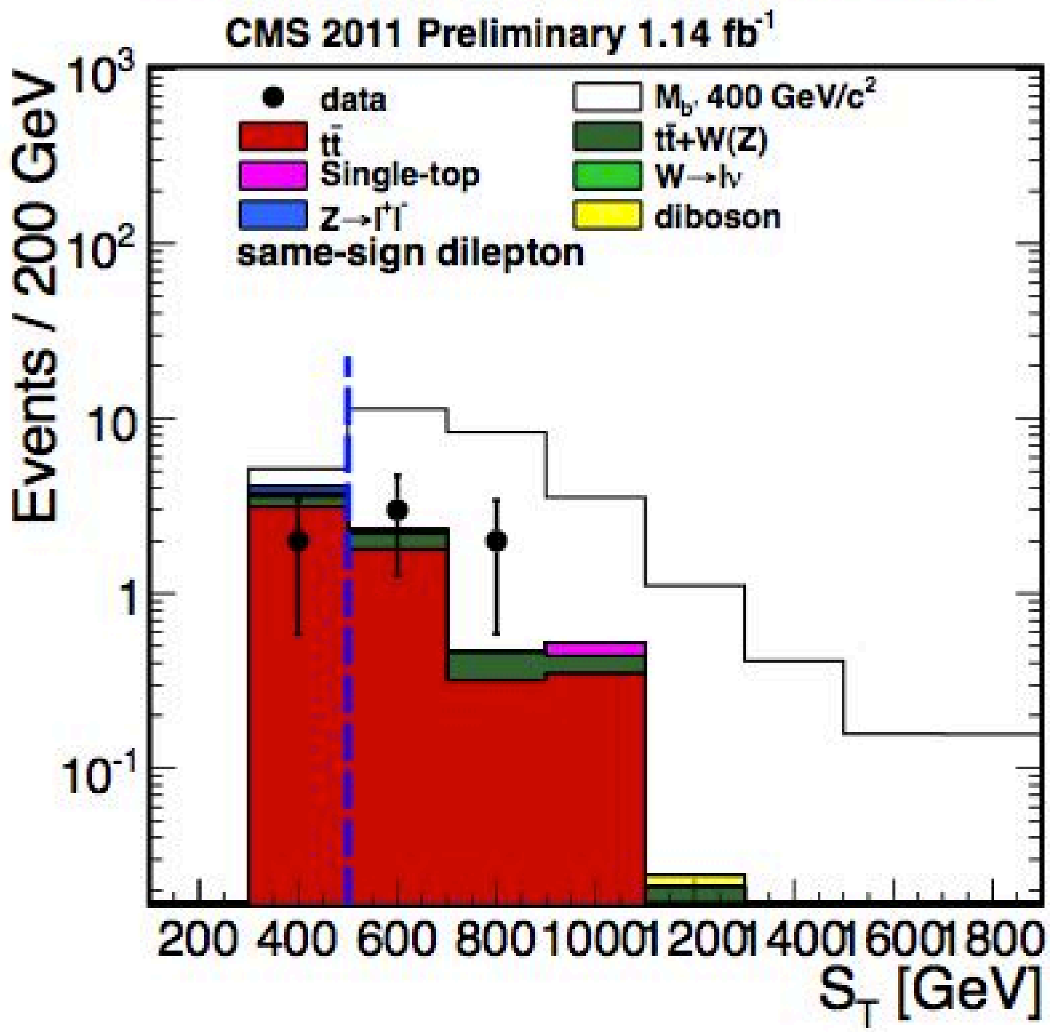
Discovery: HT distributions

Resonance and mass: Mass distributions

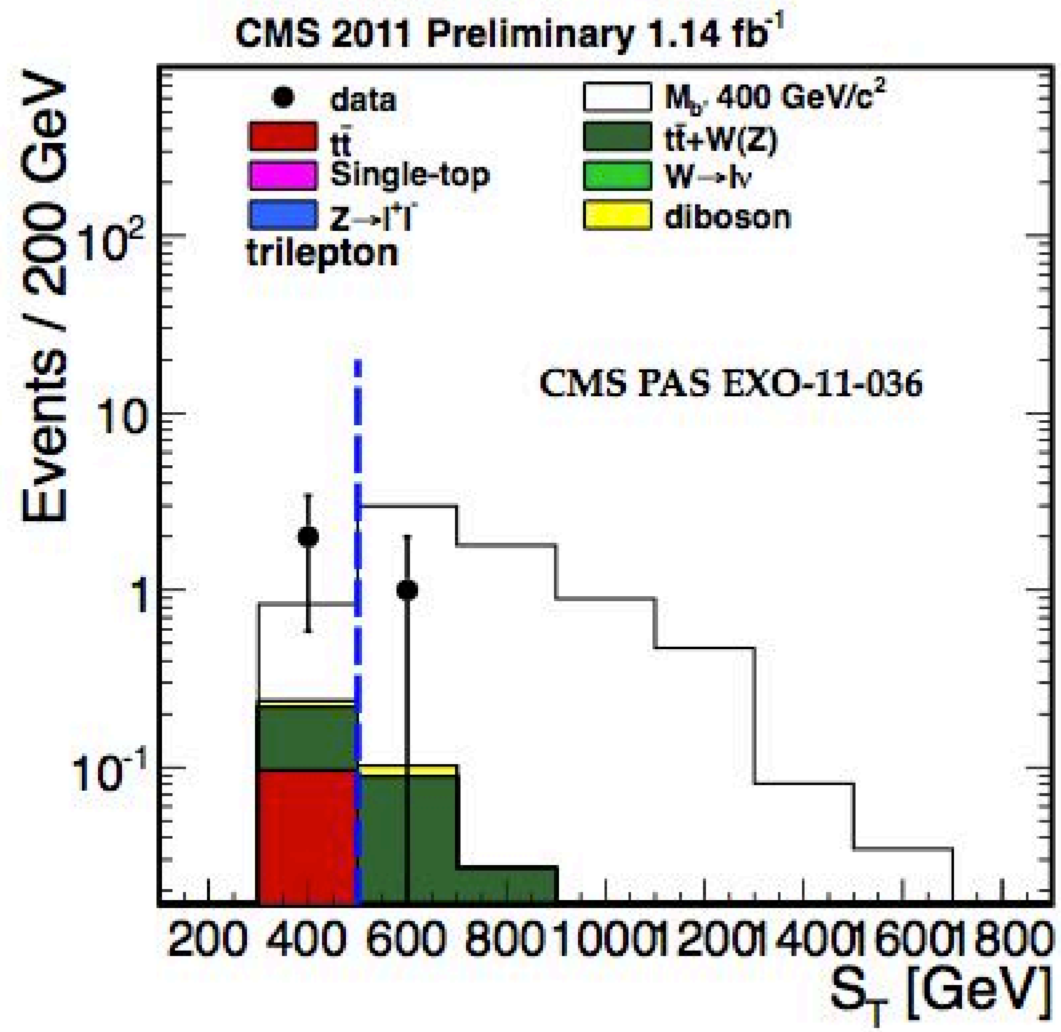
B-prime Pair Production

$$b'\bar{b}' \rightarrow tW^{-}\bar{t}W^{+}$$

Same sign dilepton



Trilepton



Signal: HT distributions

Single Production

- Large Production Rate
- Now focus on a detailed study to distinguish different types of heavy quarks:

  Probe T-b-W, T-t-Z, or T-q-W, T-q-Z couplings

  Determine the chiral structure of heavy quark

- Single Production at 7 TeV LHC:

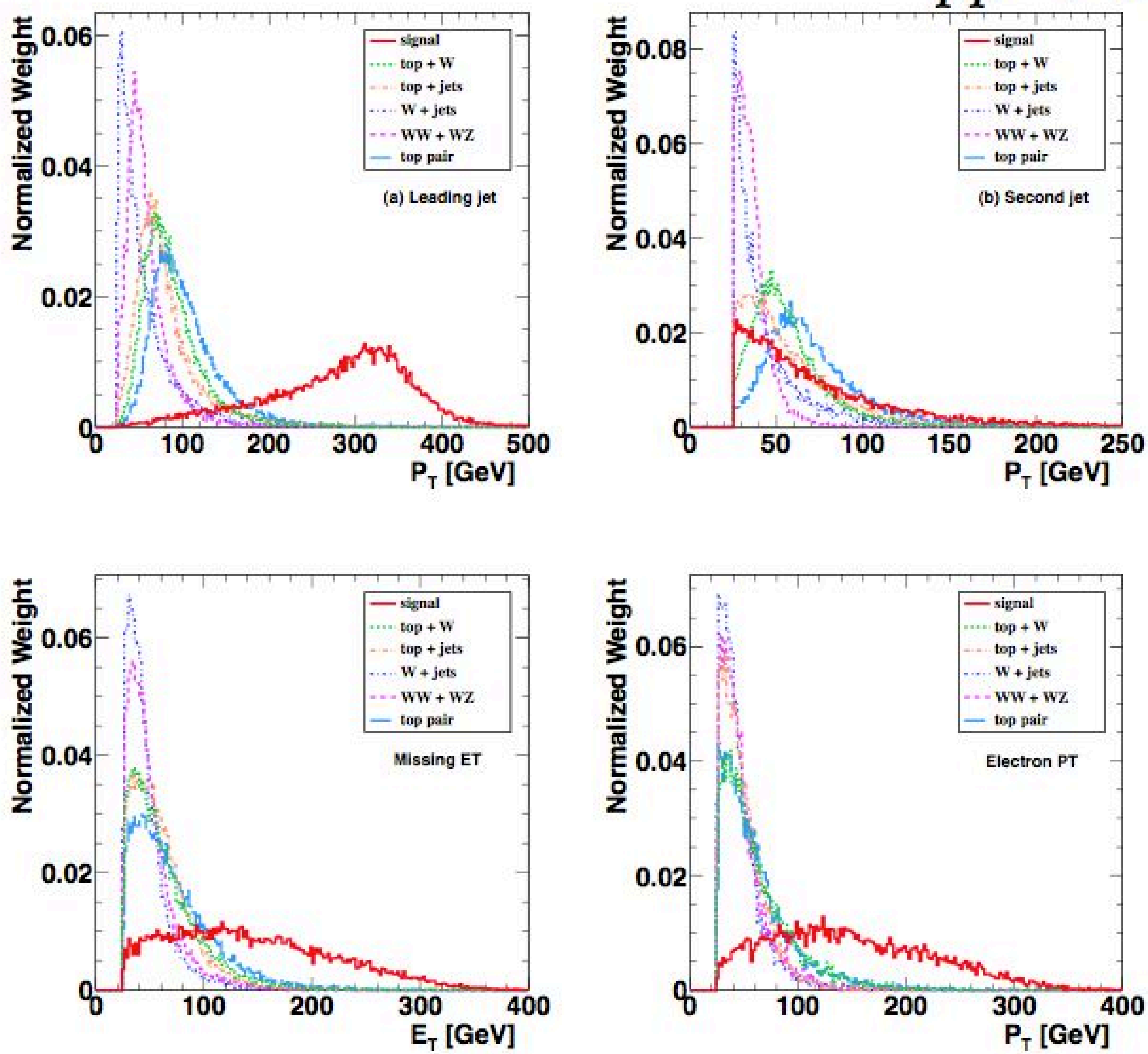
$$pp \to Tj \to Wjj \qquad pp \to Tj \to bWj \to bl\nu j$$

$$pp \to Tj \to Zjj \qquad pp \to Bj \to bZj \to bllj$$

D. Walker, C.-P. Yuan and J.-H. Yu, in preparation

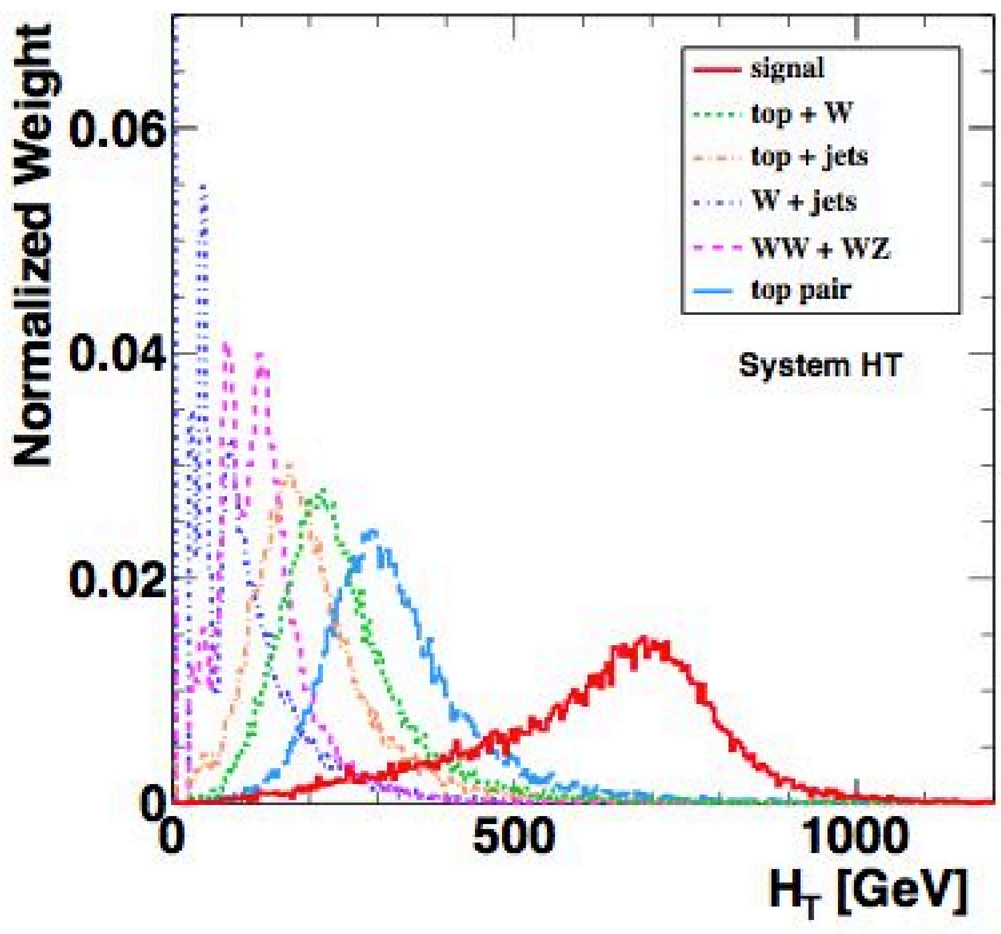
Distributions

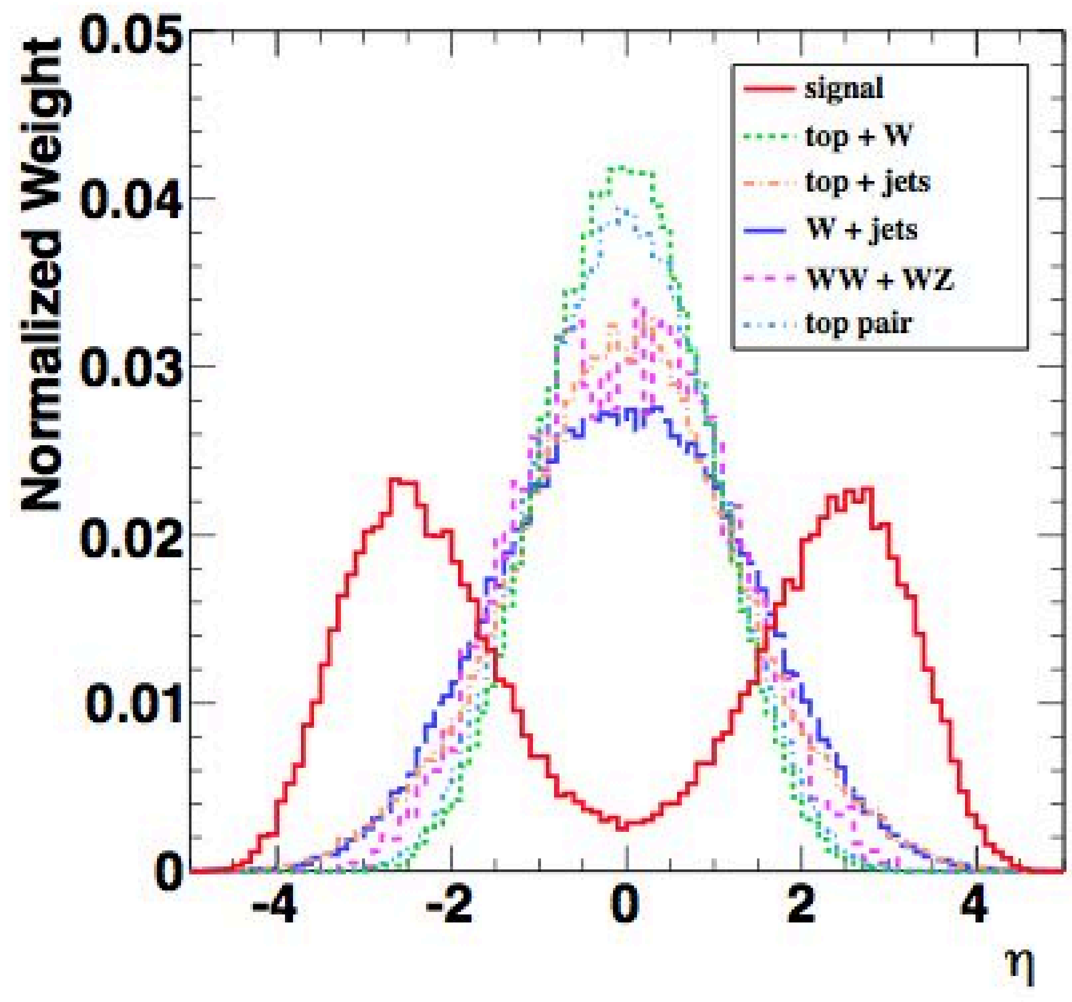
$$pp \to Tj \to bl\nu j$$



HT and Rapidity

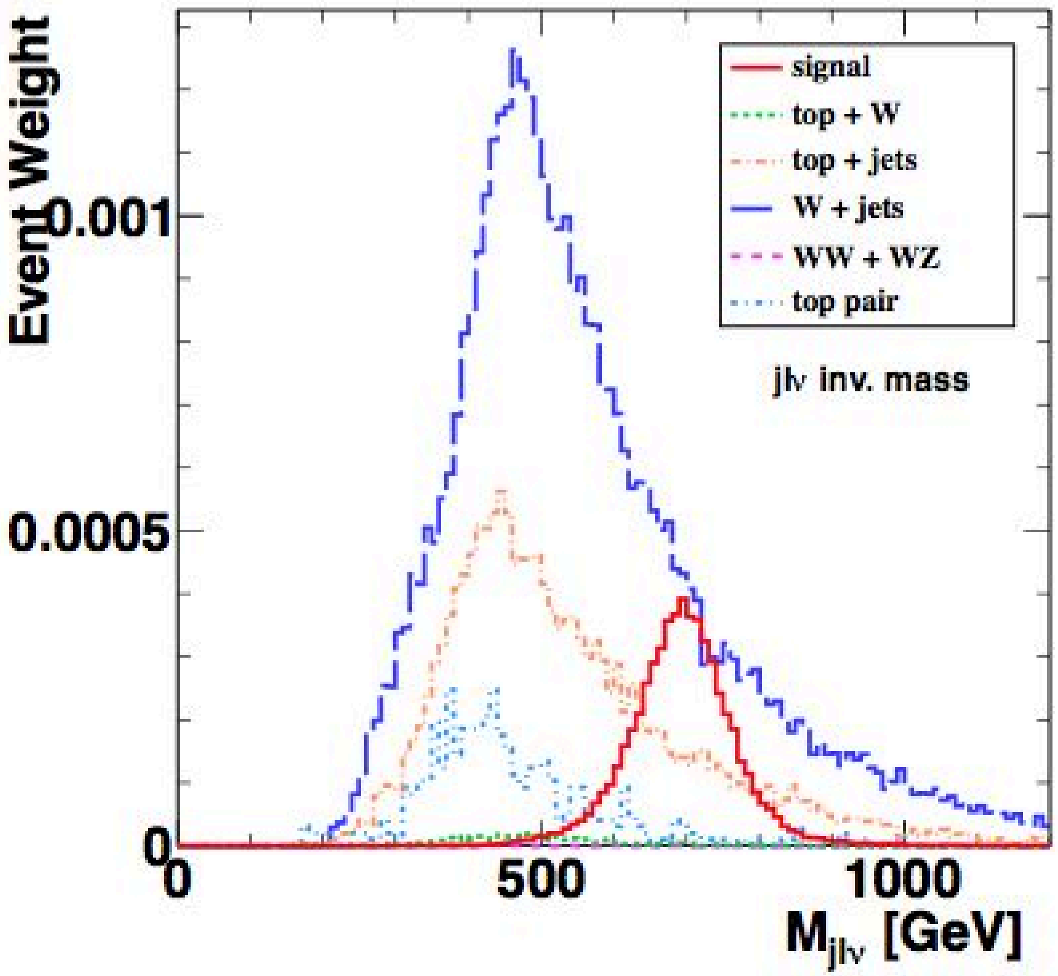
$$pp \to Tj \to bl\nu j$$

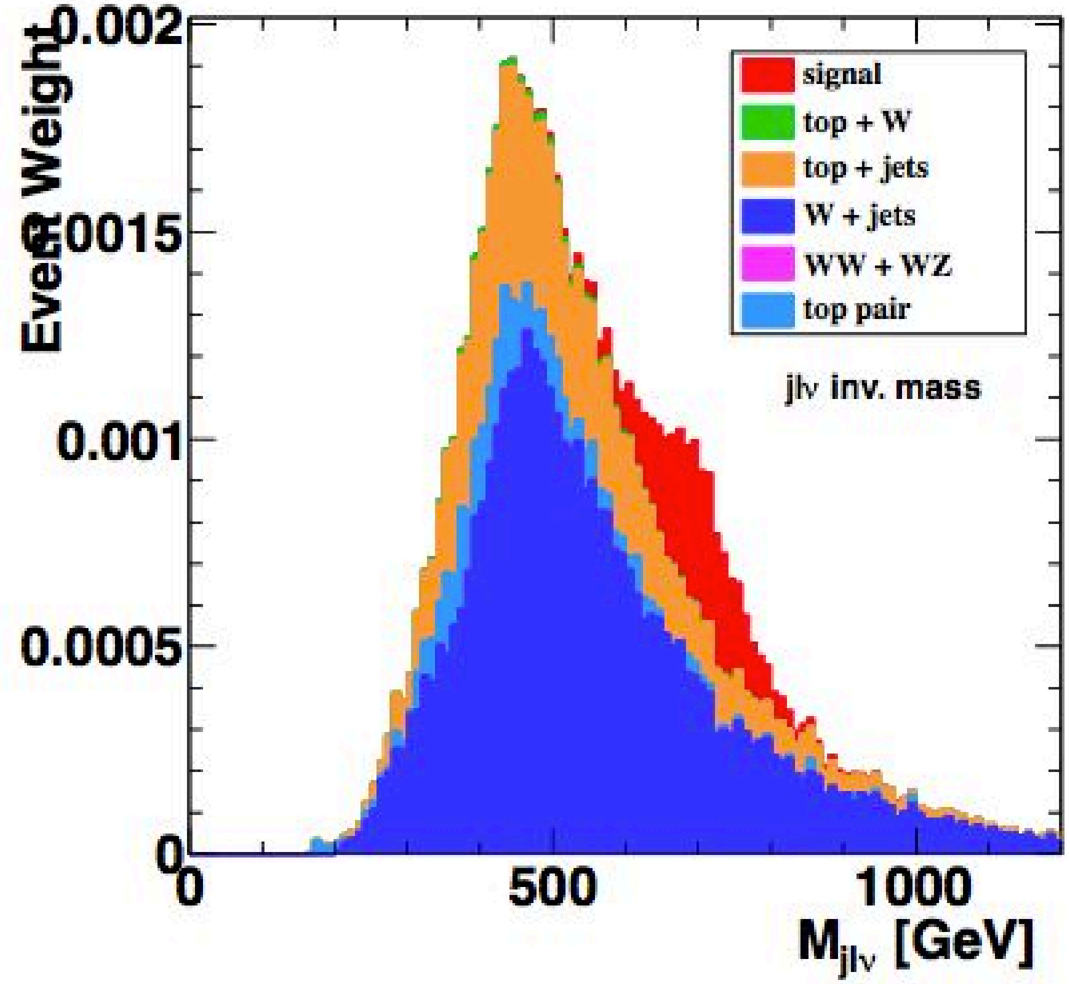




Forward light jet

Reconstructed Mass



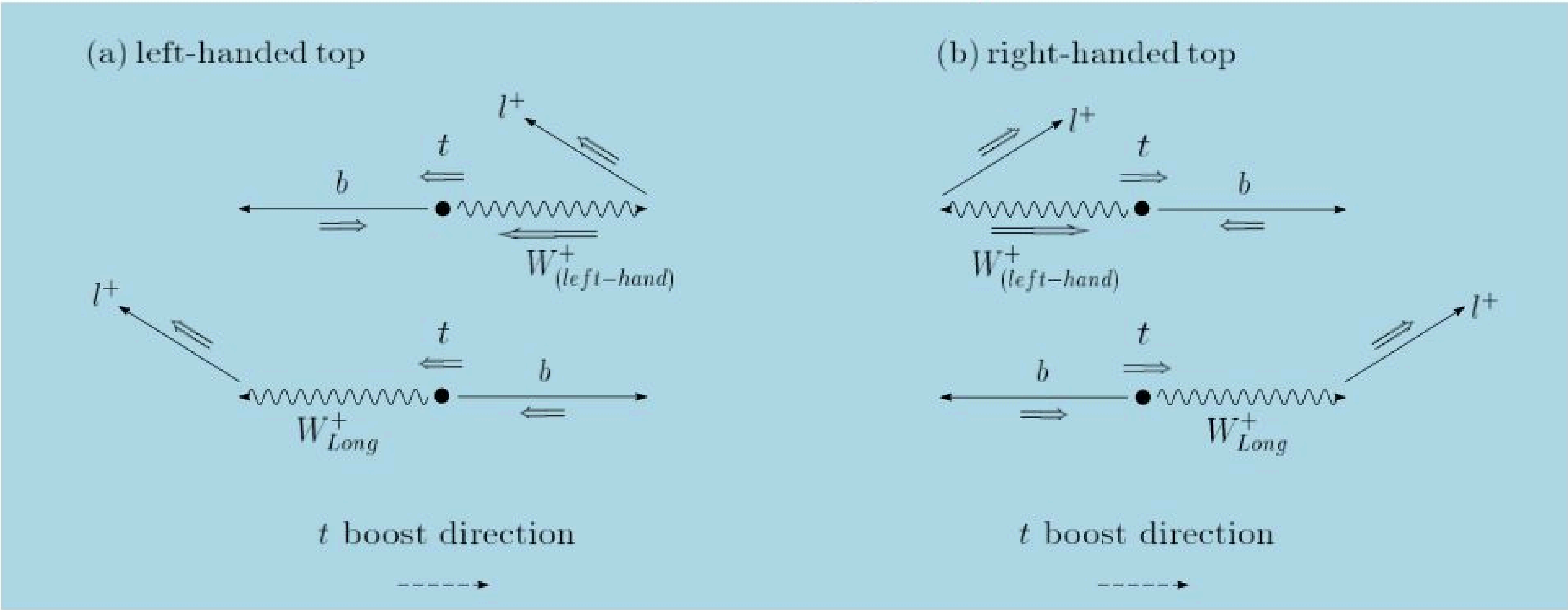


Heavy Quark Polarization

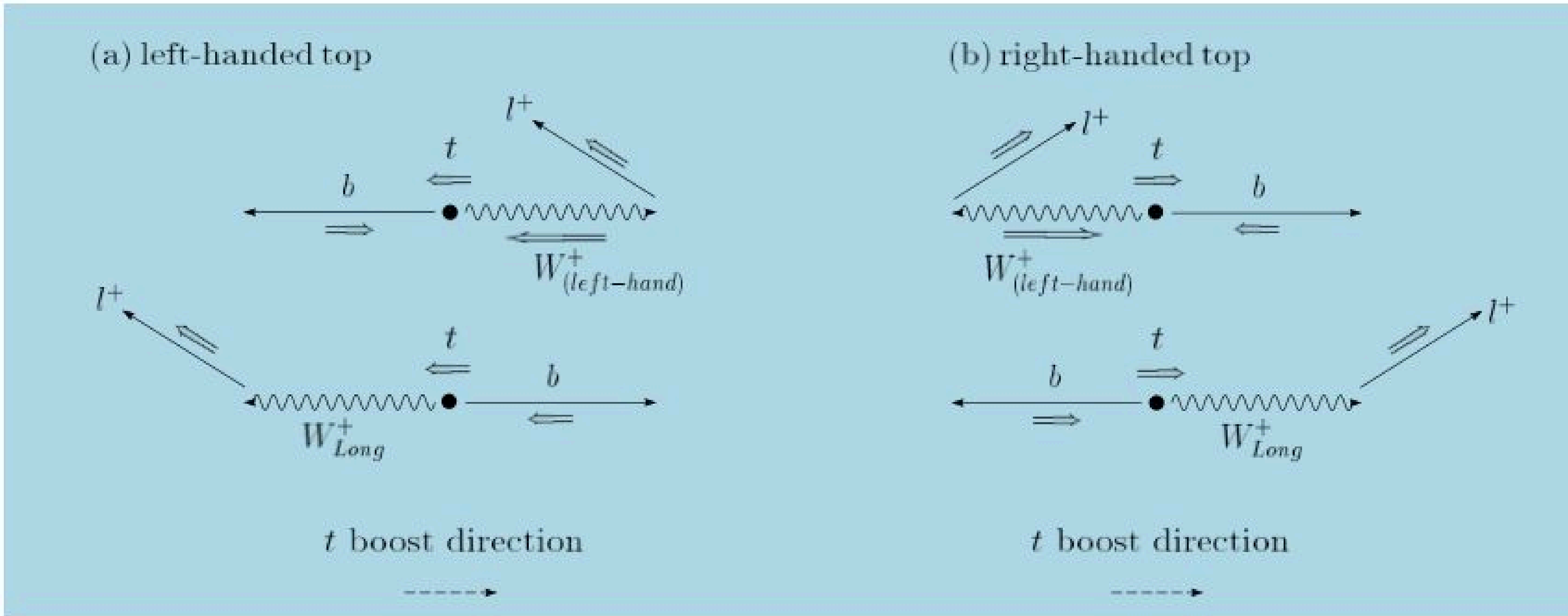
left-handed heavy quark (vector singlet case),

right-handed heavy quark (vector double case)

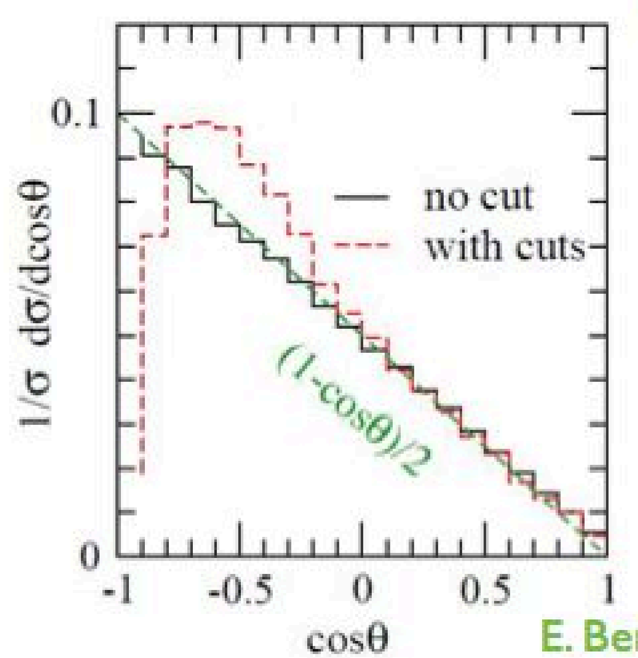
Similar to top polarization, use charged lepton distribution in the heavy top rest frame

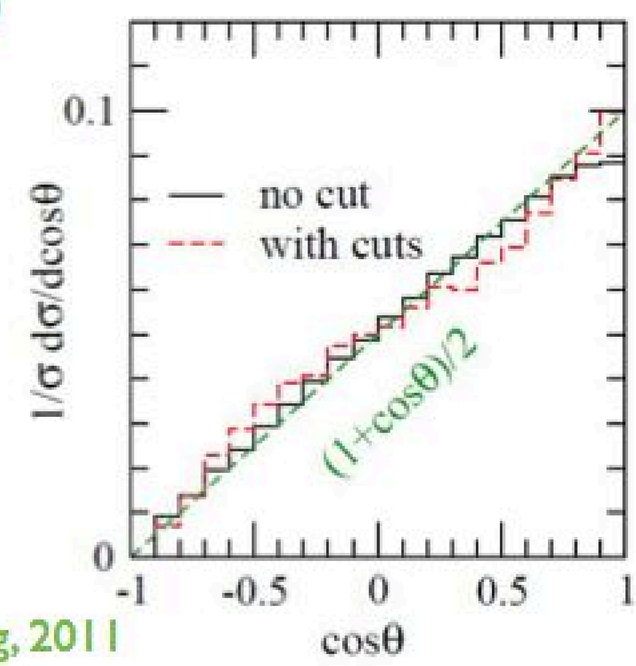


Top Quark Polarization



D. Carlson, C.-P. Yuan 1995

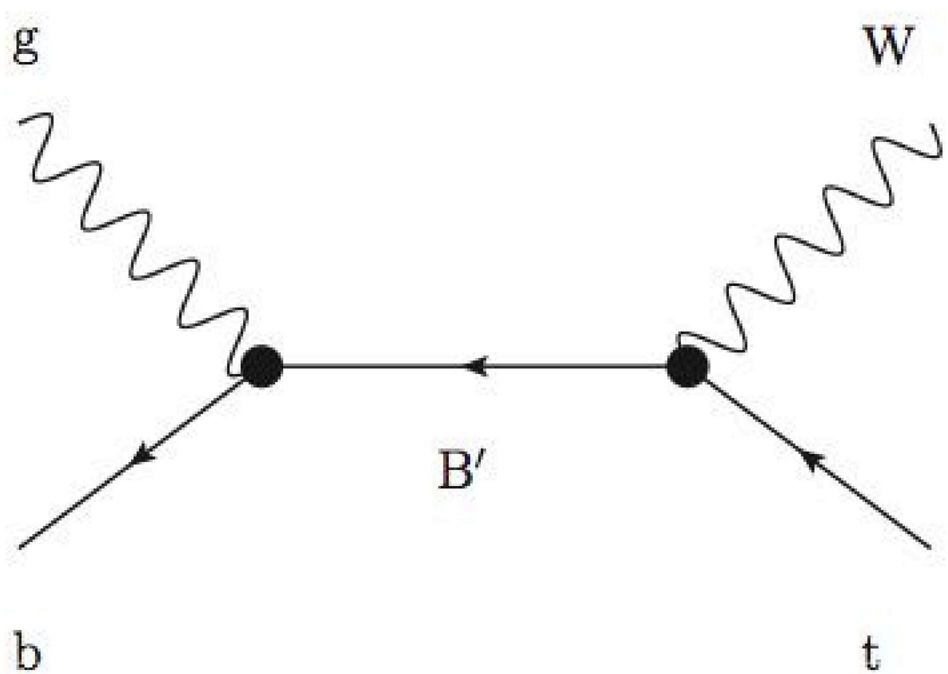


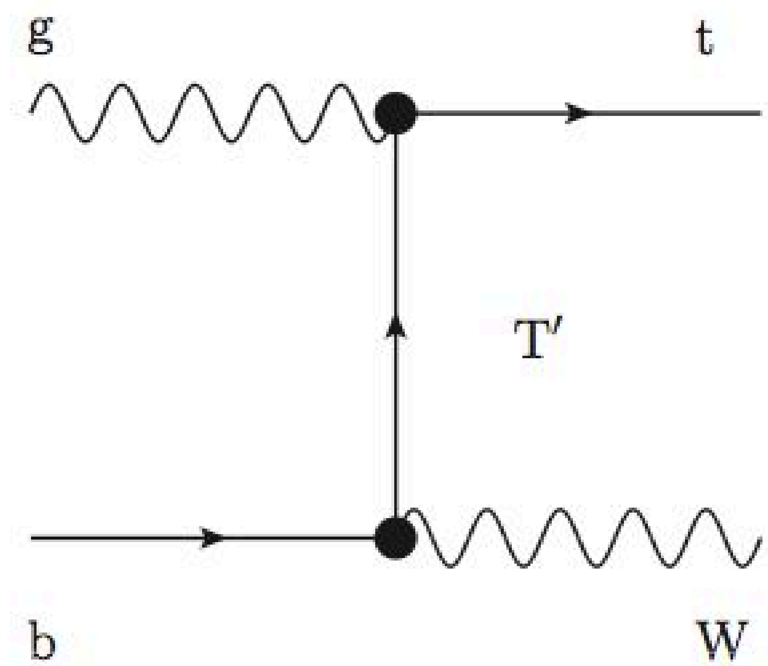


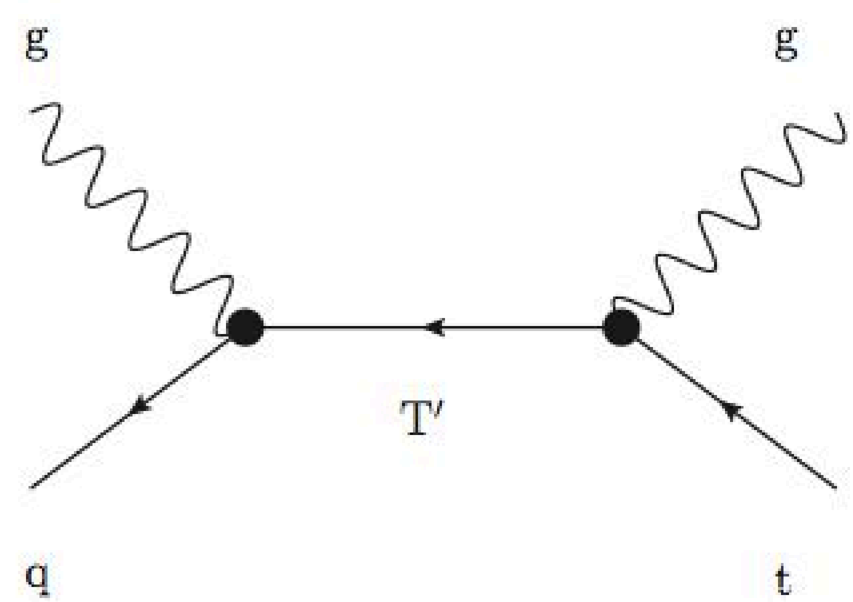
E. Berger, Q.-H. Cao, C.-R. Chen, H. Zhang, 2011

Anomalous Single Production

Feynman diagrams for tW final states:



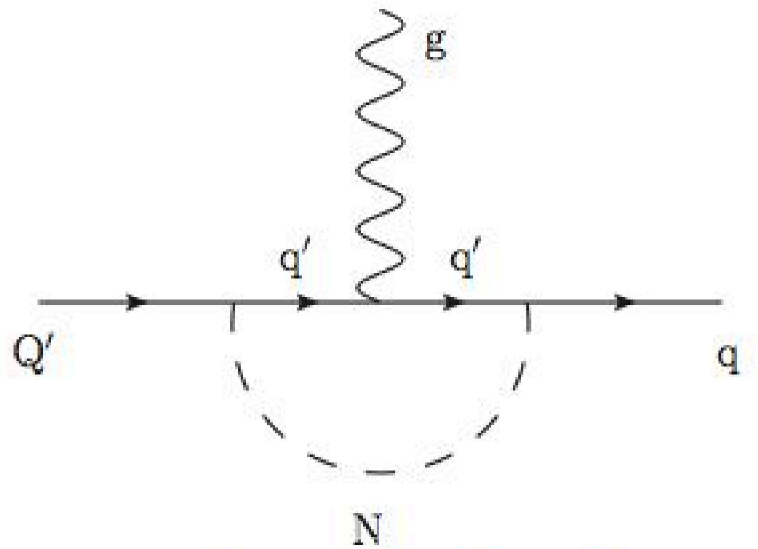




D. Walker, C.-P. Yuan and J.-H. Yu, in preparation

Anomalous Couplings

- Anomalous couplings in initial states:



$$\mathcal{O}_1 = \frac{g_s\,\lambda^2}{16\,\pi^2}\,\frac{1}{\Lambda}\,\overline{Q}'\,\sigma^{\mu\nu}\,\frac{\lambda^a}{2}\,G_{\mu\nu}\,q_L$$

$$\frac{\lambda^2}{16\pi^2} \sim 1$$

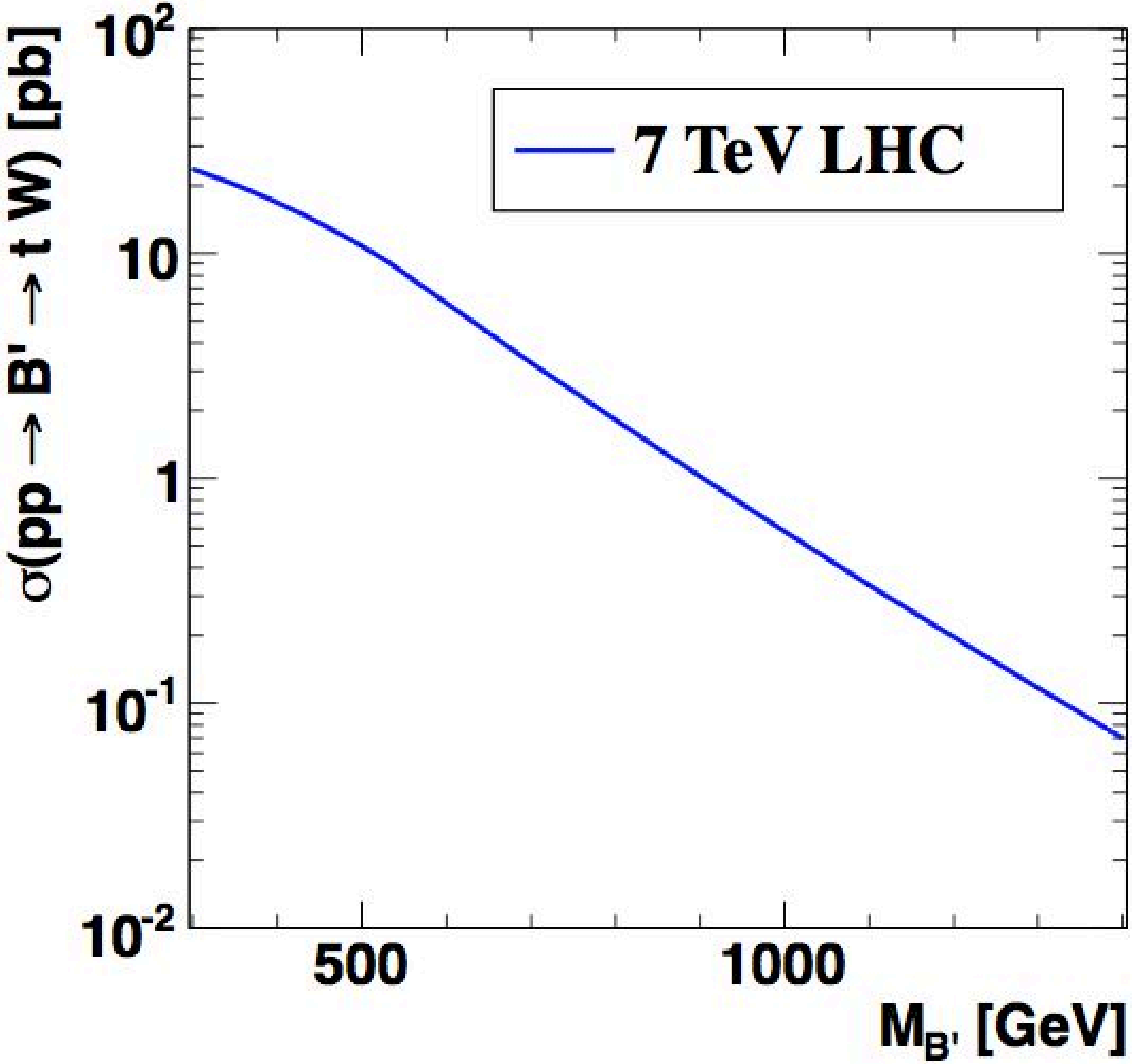
Assume: Strong/colored physics generates effective operators.

- Bounds on Heavy quarks:

Direct stringent bounds on the mass of heavy quarks from ATLAS and CMS

Production Cross Section

$$pp \to B' \to tW$$



$$\frac{g_s \lambda^2}{16\pi^2} \frac{1}{\Lambda} \simeq \frac{1}{m_Q}$$

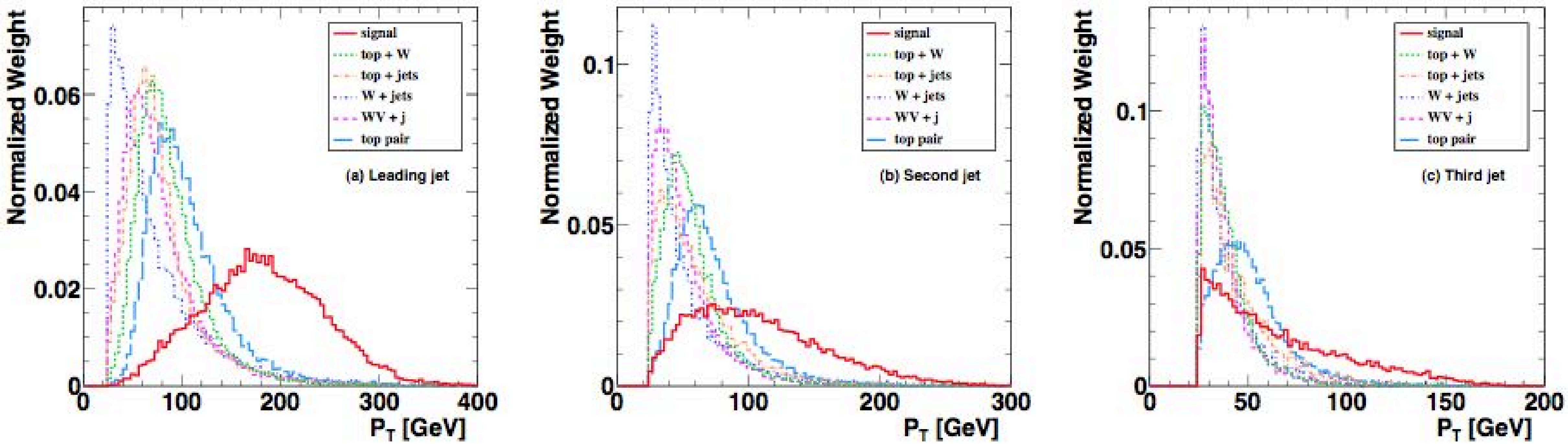
$$\Lambda \simeq M_Q$$

$$g_{b'tW} = \frac{g_2}{\sqrt{2}} \frac{\lambda v}{m_Q}$$

Cuts and Distributions

$$pp \to B \to tW^- \to bjjl^-\nu \;,$$

$$pp \to \bar{B} \to \bar{t}W^+ \to \bar{b}jjl^+\nu \;,$$



Basic cuts

$$p_T^j \geq 25\,\text{GeV}, \qquad |\eta_j| \leq 5.0$$

$$p_T^\ell \geq 25\,\text{GeV}, \qquad |\eta_\ell| \leq 2.0,$$

$$\Delta R_{jj,j\ell,\ell\ell} > 0.4, \quad \not{E}_T > 25\ \text{GeV}.$$

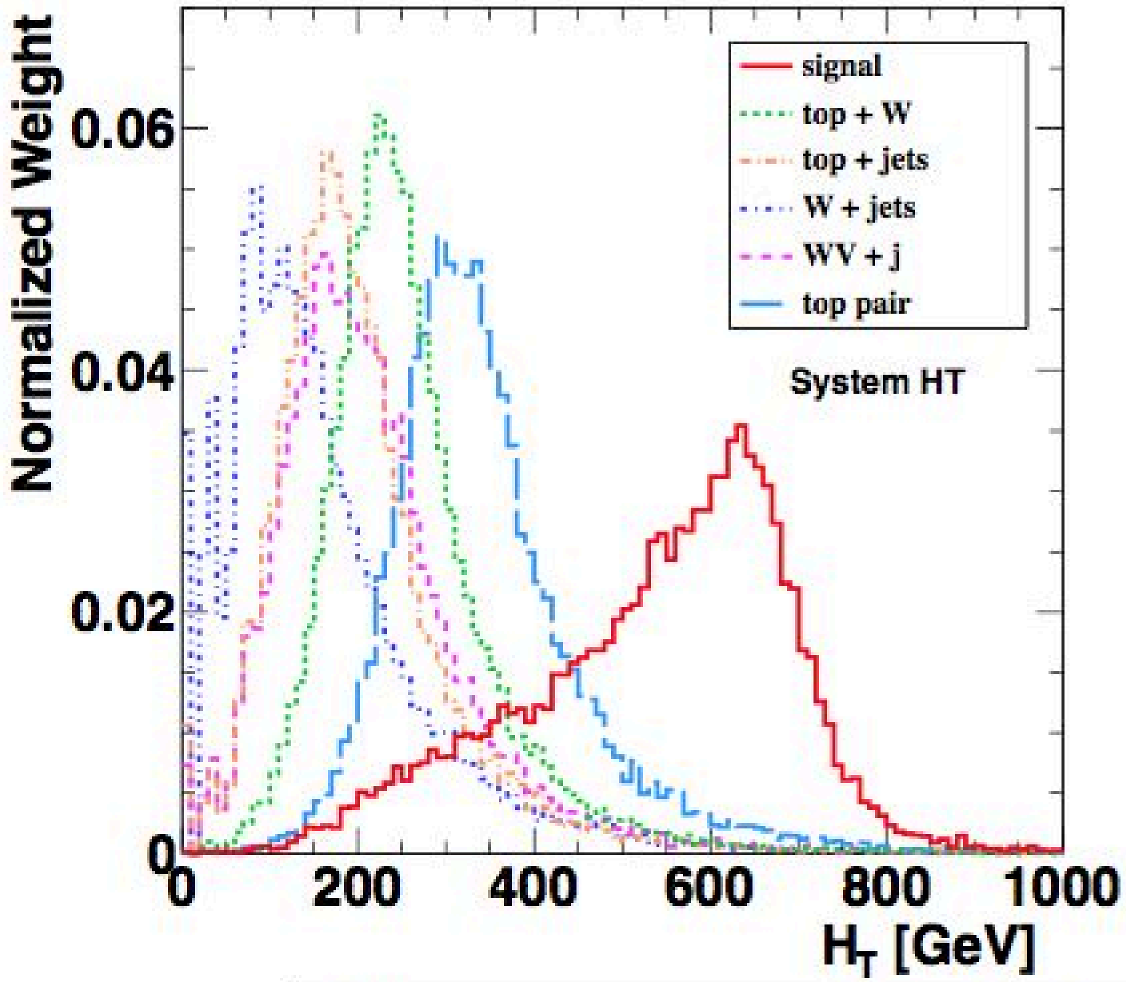
Hard cuts

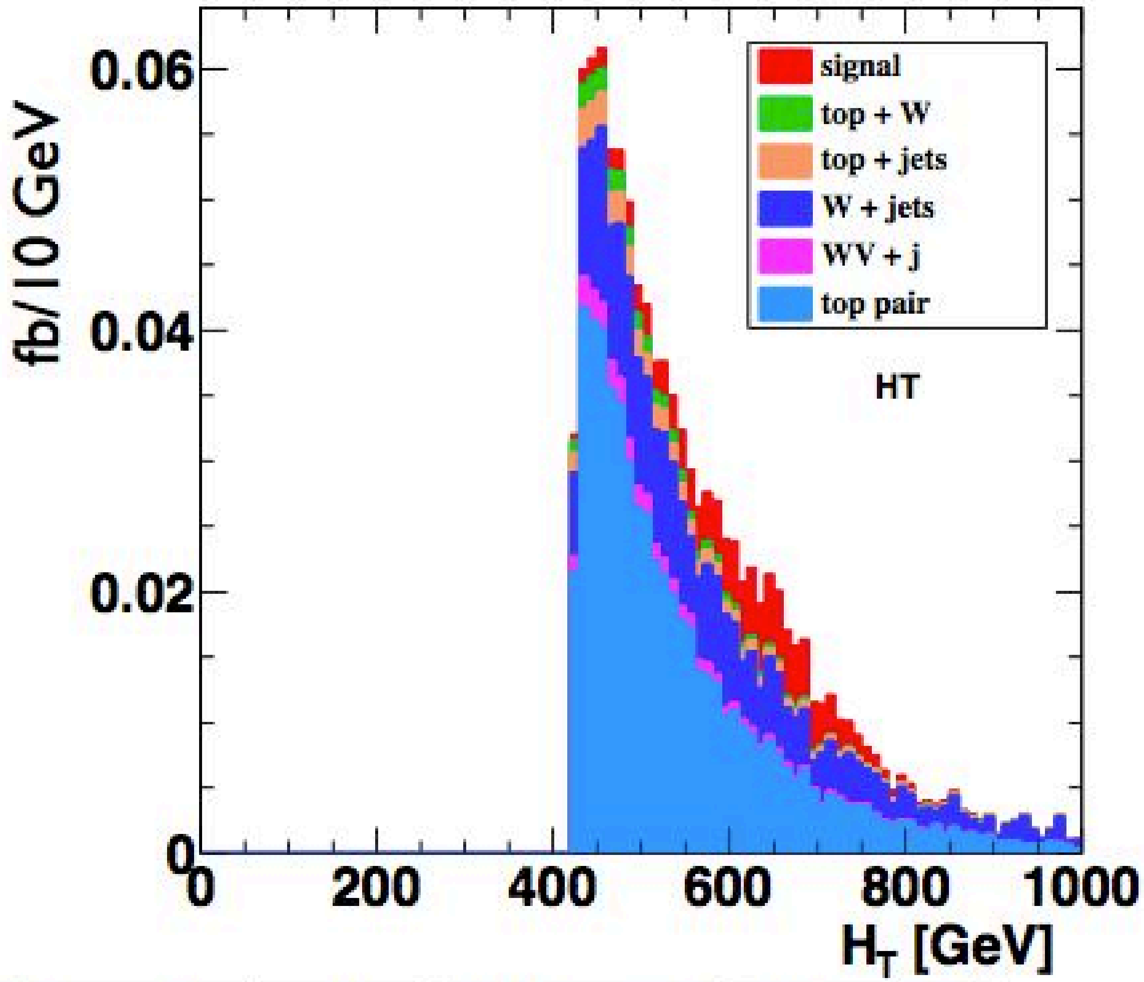
$$p_T^{1st} \geq 80\text{GeV},$$

$$p_T^{2nd} \geq 50\text{GeV},$$

$$p_T^{3rd} \geq 40\text{GeV}.$$

HT

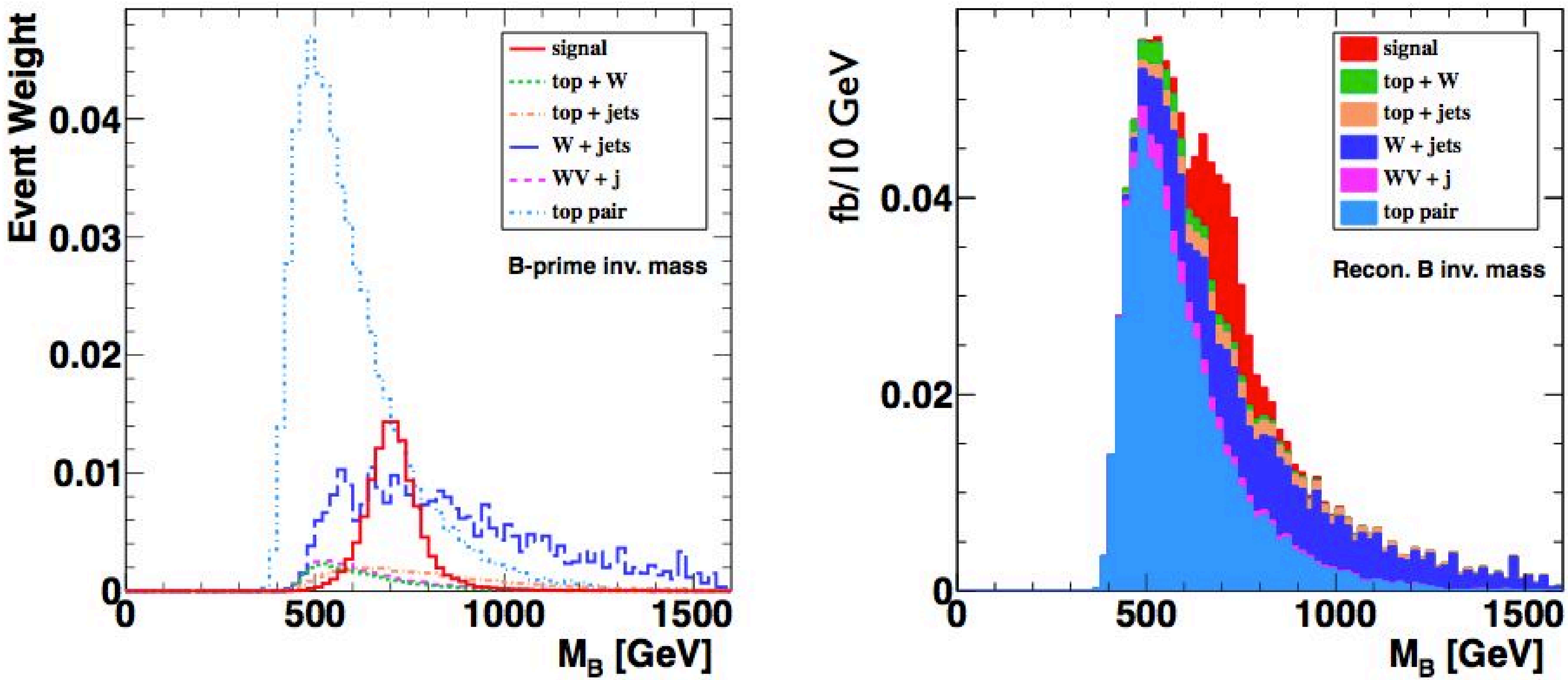




σ(fb)	Signal	$t+W$	$t+$jets	$t\bar{t}$	$WV+$jets	$W+$jets
No cuts	681	2861	18877	22200	10007	2457400
basic cuts	326	833	4049	5575	1721	88343
+smearing	318	787	3873	5231	1613	82814
+hard cuts	210	151	257	2888	288	23713
+HT cuts	196	52.3	90.6	1247	125	12901
+Tagging 1 b-jet	118	33.4	46	580	32.5	284
+Mass window cuts	98.4	12.7	17.9	147	10.0	81.3

Reconstructed Mass

$$pp \to B' \to tW \to bl\nu jj$$



$$M_{B'} = 700 \text{ GeV}$$

$$\Gamma_{B'} = 34 \text{ GeV}$$

Summary

- Top Quark is sensitive to New Physics

  Heavy Quark can decay into top quark

- Review Heavy Quark Theory and Constraints
- Discovery New Resonance: Pair Production
- Determine Coupling: Single Production

Measure polarization of top, from decay of top quark

- Exotic Production: Anomalous B-prime via s-channel

Thank You