Mono Vector-Quark Production at the LHC

Haiying Cai

Department of Physics, Peking University

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Introduction

Vector-like quark exists in many models of new physics beyond the Standard Model: Little Higgs model, Composite Higgs model and strong dynamic models, etc. The chiral top quarks need one pair of vector like partners to stablize the EW scale or for EW symmetry breaking.

collider phenomenology of heavy quarks has been studied:

- pair production of heavy quarks via gluon fusions

$$gg \to X_{5/3}\bar{X}_{5/3}, B\bar{B}$$

  analysis is conducted in same-sign dilepton final states

  R.Contino and G.Servant, 2008

- associate production with one light quark mediated by W, Z

$$qq' \to jT, jB, jX_{5/3}, jY_{-4/3}$$

  Atre, Azuelos, Carena *et al.* **2011**

- mono production of heavy quark as an s-channel resonance.

$$qg \to T, B, X_{5/3}, Y_{-4/3}$$

I only consider the mono production of heavy top quark T. This process can be induced by FCNC anomalous g-q-T couplings.

Outline of this talk:

- Review varieties of vector-quark models
- Electroweak constraints on model parameters
- Collider simulation I: $pp \to T \to tg$
- Collider simulation II: $pp \to T \to bW^+$
- Conclusion

Vector Like Quark Models

$\mathcal{Q}^{(m)}$	$\mathcal{U}_1$	$\mathcal{D}_1$	$\mathcal{D}_2$	$\mathcal{D}_X$	$\mathcal{D}_Y$	$\mathcal{T}_X$	$\mathcal{T}_Y$
	U	D	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
$SU(2)_L$	0	0	2	2	2	3	3
Y	2/3	-1/3	1/6	7/6	-5/6	2/3	-1/3

- $\mathcal{D}_2$: standard doublet vector-quarks with one up type quark and one down type quark.
- $\mathcal{D}_X$: non-standard doublet vector-quarks with one up type quark and one exotic $5/3$ charged heavy quark X.
- $\mathcal{D}_Y$: non-standard doublet vector-quarks with one up type quark and one exotic $-4/3$ charged heavy quark Y.

  Aguila, Victoria and Santiago, 2000

Quark Mixing via Yukawa Terms

$$
\begin{aligned}
\mathcal{L}_{Y,\mathrm{SM}} &= -y_u \bar{q}_L H^c u_R - y_d \bar{q}_L H d_R \\
\mathcal{L}_{Y,\mathrm{new}} &= -\lambda_u \bar{q}_L H^c \mathcal{U}_R - \lambda_u \bar{\mathcal{D}}_{2L} H^c u_R - \lambda_d \bar{\mathcal{D}}_{2L} H d_R \\
&\quad -\lambda_u \bar{\mathcal{D}}_{XL} H u_R - \lambda_u \bar{q}_L \tau^a H^c \mathcal{T}^a_{XR} - \lambda_u \bar{q}_L \tau^a H \mathcal{T}^a_{YR} \\
\mathcal{L}_{\ \mathrm{mass}} &= -M \bar{\mathcal{U}}_L \mathcal{U}_R - M \bar{\mathcal{D}}_{2L} \mathcal{D}_{2R} - M \bar{\mathcal{D}}_{XL} \mathcal{D}_{XR} \\
&\quad -M \bar{\mathcal{T}}_{XL} \mathcal{T}_{XR} - M \bar{\mathcal{T}}_{YL} \mathcal{T}_{YR}
\end{aligned}
$$

- vector-quarks mix with chiral quarks via Yukawa interactions.
- mixing patterns are determined by their $SU(2)_L \times U(1)_Y$ gauge assignments.
- singlets and triplets mix in the same pattern and doublets mix in another pattern.
  Cacciapaglia, Deandrea, Harada and Okada, 2010

Mixing with Third Generation

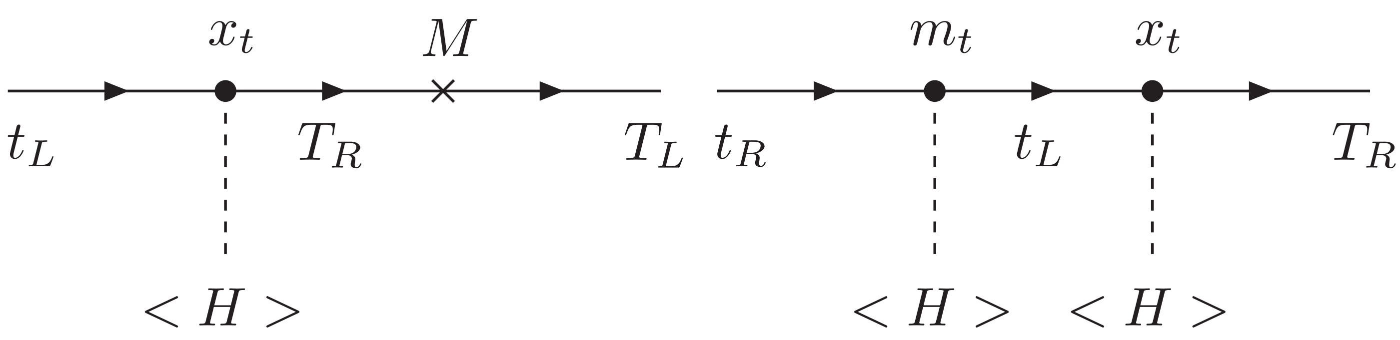
For simplicity, we consider the scenario that the vector-quarks mix only with the third-generation quark in the SM.

$$
\begin{aligned}
t'_{L,R} &= \cos\theta^u_{L,R} t_{L,R} + \sin\theta^u_{L,R} T_{L,R}, \\
T'_{L,R} &= -\sin\theta^u_{L,R} t_{L,R} + \cos\theta^u_{L,R} T_{L,R},
\end{aligned}
$$

$$
\begin{aligned}
b'_{L,R} &= \cos\theta^d_{L,R} b_{L,R} + \sin\theta^d_{L,R} B_{L,R}, \\
B'_{L,R} &= -\sin\theta^d_{L,R} b_{L,R} + \cos\theta^d_{L,R} B_{L,R},
\end{aligned}
$$

Defining $x_t = \lambda_u v/\sqrt{2}$ and $x_b = \lambda_d v/\sqrt{2}$, those mixing angles depend on x_t, x_b and gauge invariant mass M.

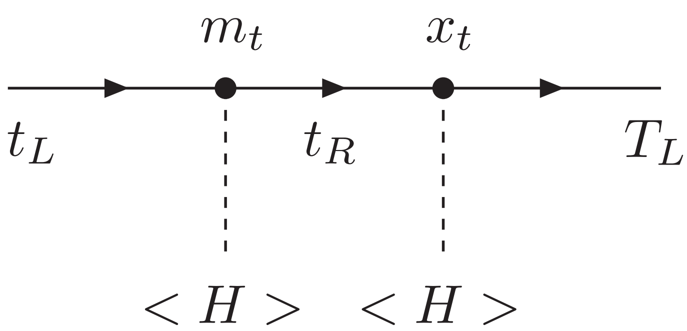
Mixing Pattern: singlet/triplet

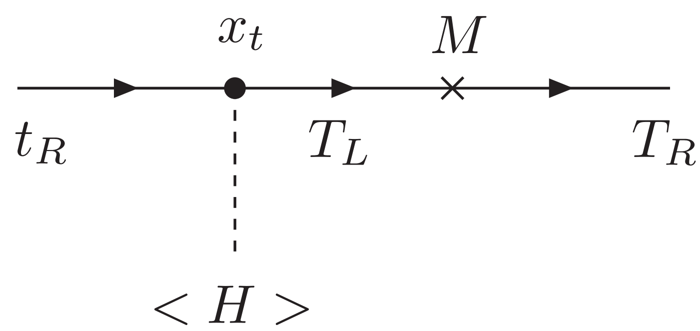


$$\sin\theta_L^u \approx \frac{x_t}{M}$$

$$\sin\theta_R^u \approx \frac{m_t}{M}\frac{x_t}{M}$$

Mixing Pattern: doublets





$$\sin\theta_L^u \approx \frac{m_t}{M}\frac{x_t}{M}$$

$$\sin\theta_R^u \approx \frac{x_t}{M}$$

Compared with singlet/triplet senario, the LH and RH mixing angles are simply exchanged in doublet senarioes.

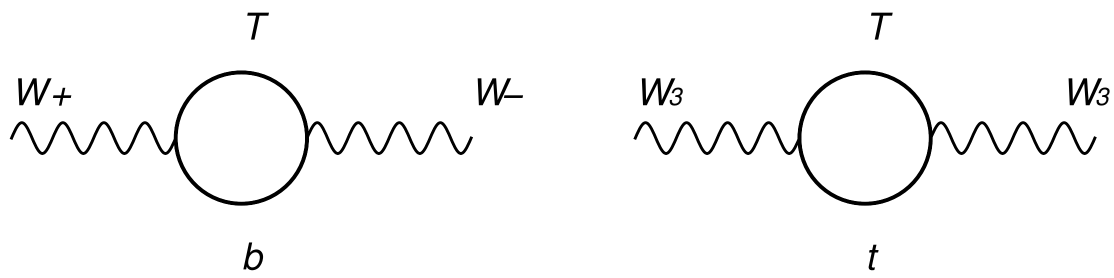
Electroweak Constraints

Quark mixing would inevitably modify the W-t-b and Z-b-b couplings in the SM, which in turn severely constrain the model parameters.

- Mass splitting among the fermions will contribute to T parameter through the vacuum polarization of the gauge bosons:

$$T = \frac{4\pi}{s^2 c^2 M_Z^2}(\Pi_{11}(0) - \Pi_{33}(0))$$

Charged and neutral currents are modified according to weak isospin of vector-quarks. (Note heavy top's isospin is not always 1/2)



SM contribution is substructed and divergence is cancelled.

Electroweak precision measurements:

$$T = 0.05 \pm 0.11 \ ,$$

mainly put constraints on singlet and doublet models.

M.Peskin and T.Takeuchi, 1990

L. Lavoura and J. Silva, 1993

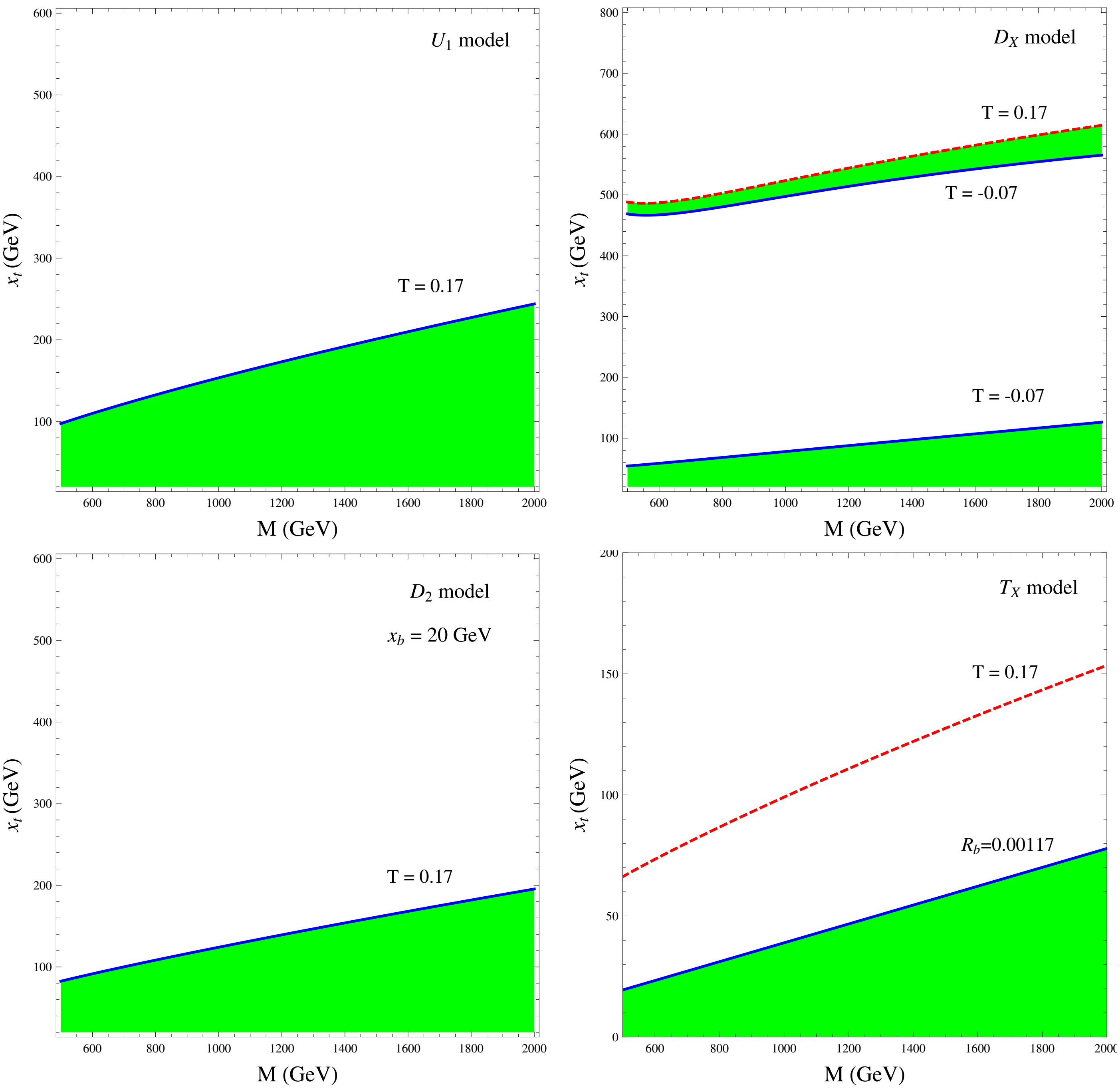
- Mixing between the vector bottom quarks and the chiral bottom quarks induces δg_L^{NP} and δg_R^{NP}, related to the deviation of R_b:

$$\delta R_b \quad = \quad 2R_b(1-R_b)\left(\frac{g_L}{g_L^2+g_R^2}\delta g_L^{NP} + \frac{g_R}{g_L^2+g_R^2}\delta g_R^{NP}\right)$$

Electroweak precision measurements:

$$\delta R_b = 0.00051 \pm 0.00066 \ ,$$

mainly put constraints on triplet vector-quark models.


U_1 model
T = 0.17
x_t (GeV)
M (GeV)
D_X model
T = 0.17
T = -0.07
T = -0.07
x_t (GeV)
M (GeV)
D_2 model
x_b = 20 GeV
T = 0.17
x_t (GeV)
M (GeV)
T_X model
T = 0.17
R_b=0.00117
x_t (GeV)
M (GeV)

Chromo-magnetic-dipole Couplings

In the approach of Effective Field Theory, all the possible dimension-6 effective operators describing the strong magnetic g-q-$\mathcal{Q}$ interaction are:

$$
\begin{aligned}
\mathcal{L}_{gq\mathcal{Q}} \;=\;& \frac{\kappa_{u,R}}{\Lambda^2}\,\bar{q}_L\sigma^{\mu\nu}\lambda^A\mathcal{S}_{u,R}\tilde{\phi}G^A_{\mu\nu} + \frac{\kappa_{d,R}}{\Lambda^2}\,\bar{q}_L\sigma^{\mu\nu}\lambda^A\mathcal{S}_{d,R}\phi G^A_{\mu\nu} \\
+\;& \frac{\kappa_{u,L}}{\Lambda^2}\,\overline{\mathcal{D}}_{2L}\sigma^{\mu\nu}\lambda^A u_R\tilde{\phi}G^A_{\mu\nu} + \frac{\kappa_{d,L}}{\Lambda^2}\,\overline{\mathcal{D}}_{2L}\sigma^{\mu\nu}\lambda^A d_R\phi G^A_{\mu\nu} \\
+\;& \frac{\kappa_{X,L}}{\Lambda^2}\,\overline{\mathcal{D}}_{XL}\sigma^{\mu\nu}\lambda^A u_R\phi G^A_{\mu\nu} + \frac{\kappa_{Y,L}}{\Lambda^2}\,\overline{\mathcal{D}}_{YL}\sigma^{\mu\nu}\lambda^A d_R\tilde{\phi}G^A_{\mu\nu} \\
+\;& \frac{\kappa_{X,R}}{\Lambda^2}\,\overline{\mathcal{T}}_{XR}\sigma^{\mu\nu}\lambda^A\left(\phi\tau^I q_L\right)G^A_{\mu\nu} + \frac{\kappa_{Y,R}}{\Lambda^2}\,\overline{\mathcal{T}}_{YR}\sigma^{\mu\nu}\lambda^A(\tilde{\phi}\tau^I q_L)G^A_{\mu\nu}
\end{aligned}
$$

The cross section of mono production of heavy quark depends on the effective g-q-T couplings.

Possible decaying channels: $T \to tg$, $T \to bW^+$, $T \to tZ$ and $T \to th$. In the collider simulation sections we are going to analyze the first two.

Collider Simulation I

Mono heavy top production and decaying into t plus one jet:

$$ug \to T \to tg, \quad t \to b\ell^+\nu,$$

Signature suffers from a few SM backgrounds as follows:

- Single top productions

  $q\bar{q}' \to W^* \to t\bar{b}$

  $bq \to tq'$, $b\bar{q}' \to t\bar{q}$

  $qq', gq \to tjj \; (gb \to tW^-(jj))$

- $W+$ two jets productions

  Wbj, $Wb\bar{b}$, Wjj , $WZ(b\bar{b})$

- $t\bar{t}$ production

Signature is analyzed in the simplified scenario $x_t = 0$.

Event Selection I

- Basic event-selection cuts (b-tagging is required) :

$$p_T^b > 20 \text{ GeV}, \ \ |\eta_b| < 2.5,$$
$$p_T^\ell > 20 \text{ GeV}, \ \ |\eta_l| < 2.5,$$
$$\Delta R_{jj} > 0.4, \ \Delta R_{jl} > 0.4 \ .$$

- Veto cuts are demanded:

$$p_T(j, \ell^\pm) < 10 \text{ GeV or } |\eta(j, \ell^\pm)| > 3.5 \ .$$

Either falling into a large rapidity region or carrying a too small transverse momentum to be detected

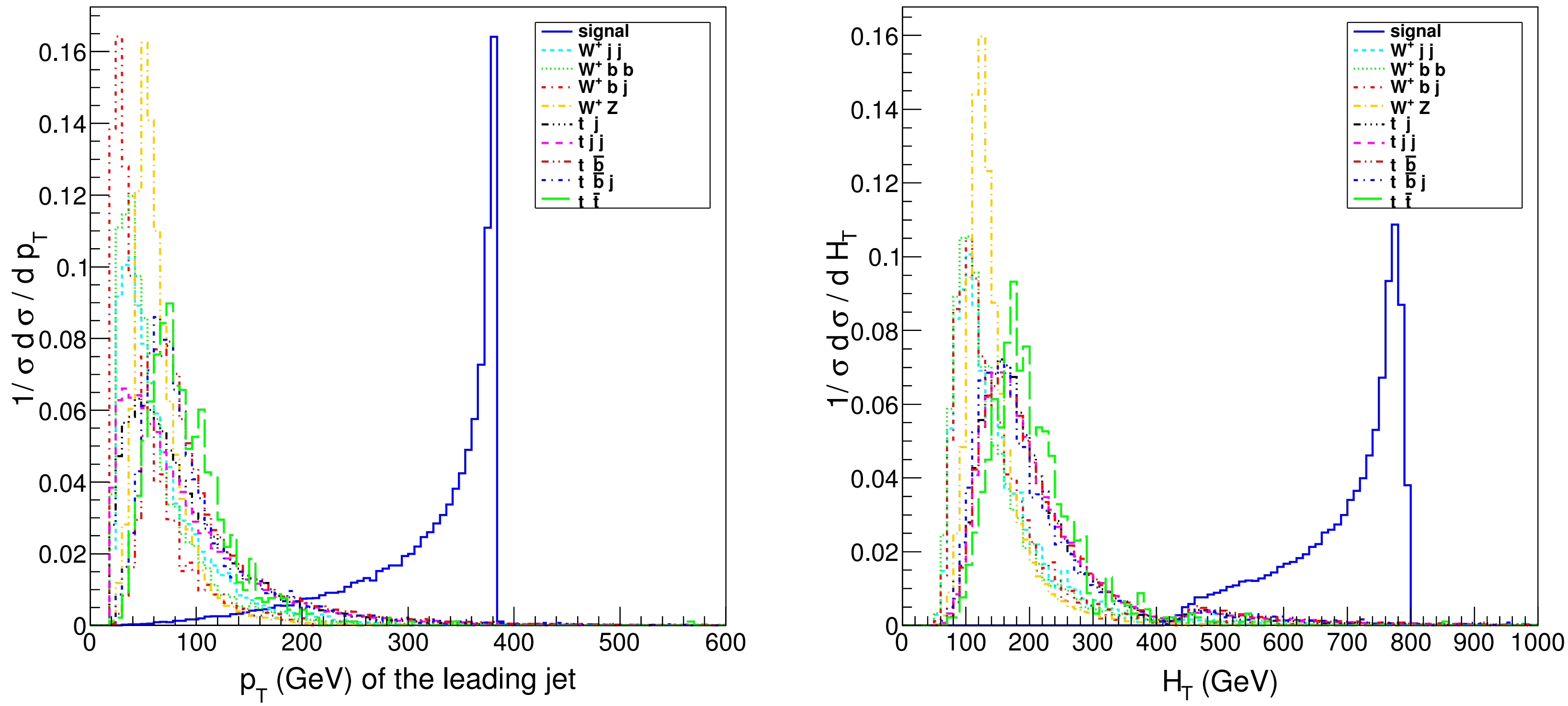


Figure 1: P_T distribution in the left panel and H_T distribution in the right panel after basic and veto selection cuts. Each plot is normalized.

- Hard P_T and H_T cuts:

$$p_T(j_{1st}) > 200 \text{ GeV}, \quad H_T > 400 \text{ GeV}.$$

- Longitudinal momentum of neutrino is reconstructed according to:

$$\begin{aligned} p_\nu(x) &= -\not{E}_T(x),\ p_\nu(y) = -\not{E}_T(y), \\ m_W^2 &= (p_\ell + p_\nu)^2. \end{aligned}$$

- Two mass window cuts are imposed to optimize the signal events:

$$\begin{aligned} \Delta M_W &= |m_{\ell\nu} - m_W| < 10 \text{ GeV} \\ \Delta M_t &= |m_{\ell\nu b} - m_t| < 10 \text{ GeV} \end{aligned}$$

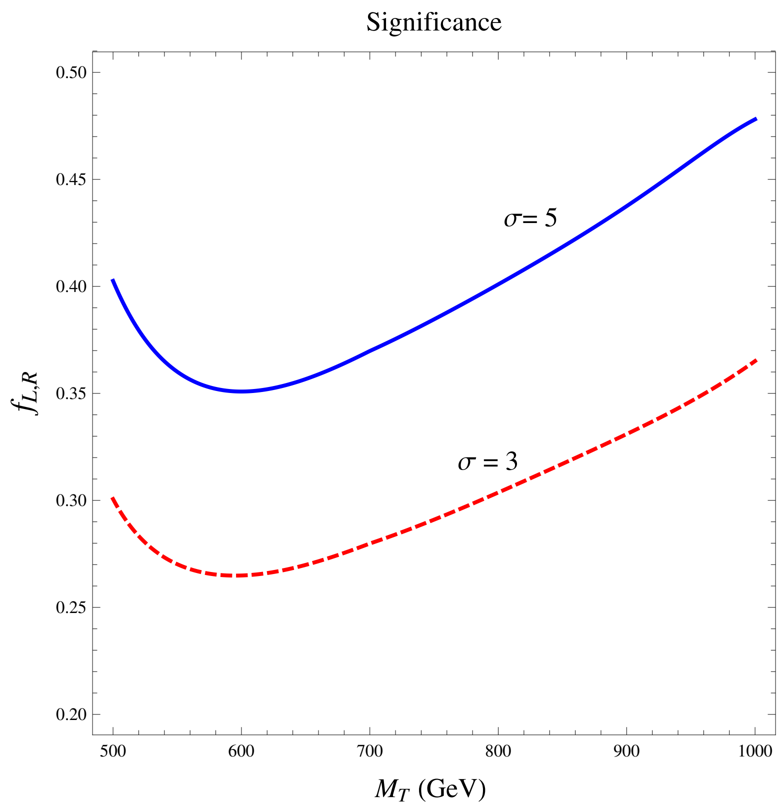


Figure 2: Contour of discovery potential at the 14 TeV LHC with an integrated luminosity of 1 fb^{-1}. Red line represents the 3 σ exclusion limit; Blue line represents the 5 σ discovery limit.

Top Quark Polarization

The behavior of the angle between the lepton in the rest frame of the top quark and the top quark moving direction in the center of mass frame can be factorized out.

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{t\ell}} = \frac{1}{2}(1 + a\cos\theta_{t\ell}),$$

with $a = 1$ for doublet T-quark and $a = -1$ for singlet/triplet T-quark.

singlet/triplet T-quark $\Rightarrow$ left-handed polarized top quark

doublet T-quark $\Rightarrow$ right-handed polarized top quark

Jezabek and Kuhn, 1989
Mahlon and Parke, 1996

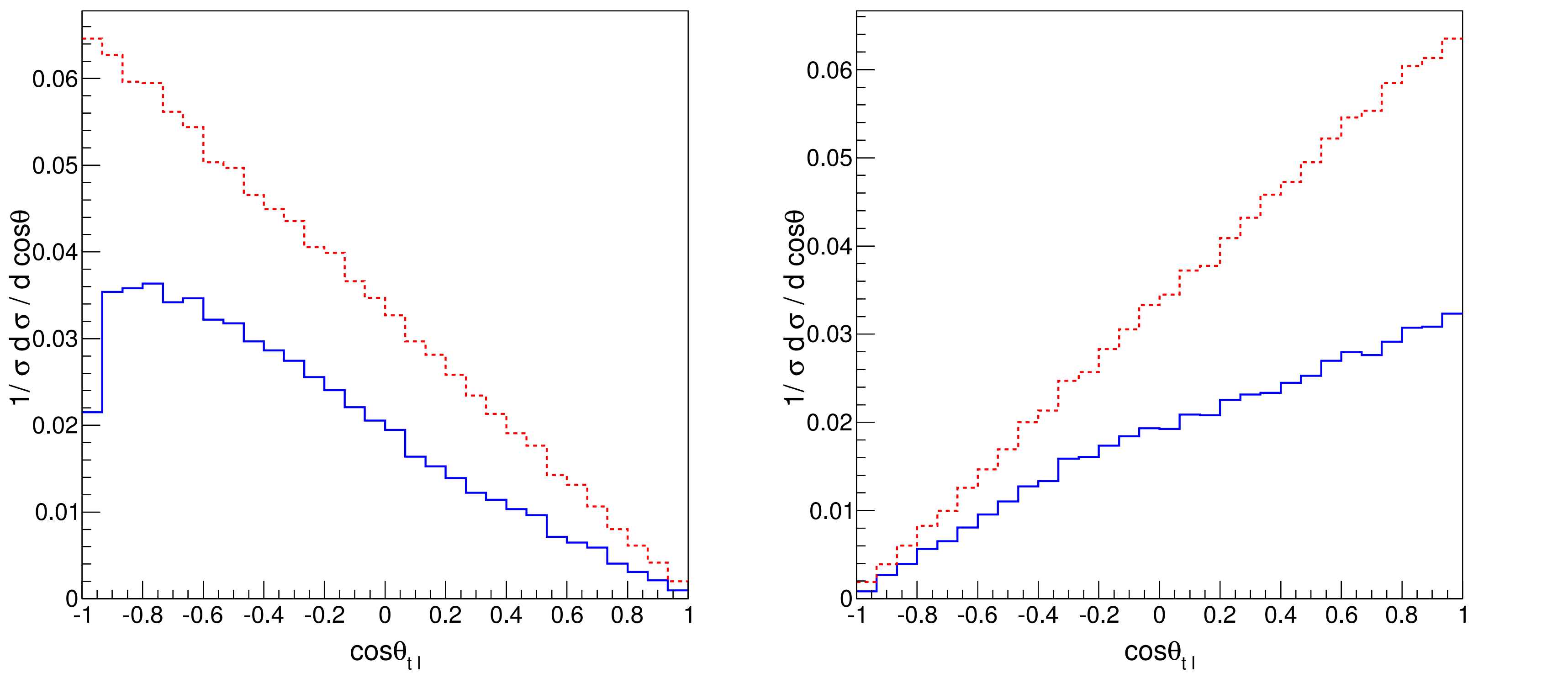


Figure 3: $\cos\theta_{t\ell}$ distribution with no cut and after mass-window cuts: (a) singlet/triplet T-quark, (b) doublet T-quark.

Collider Simulation II

The following process has the collider signature of $b\ell^+ \not{E}_T$:

$$gq \to T, \; T \to bW^+ \to b\ell^+\nu$$

Main SM backgrounds (very less) are:
(1) W^+j
(2) W^+bj, $qb \to q't(bW^+)$
(3) $q\bar{q}' \to t(bW^+)\bar{b}$

Basic cuts are:

$$\begin{aligned} &p_T^b > 50 \text{ GeV}, \qquad |\eta_b| < 2.0, \\ &p_T^l > 20 \text{ GeV}, \qquad |\eta_l| < 2.4, \\ &\Delta R_{bl} > 0.7. \end{aligned}$$

Hard cuts are:

$$p_T(b) > 200 \text{ GeV}, \quad \Delta R(\ell^+, \nu) < 1.5.$$

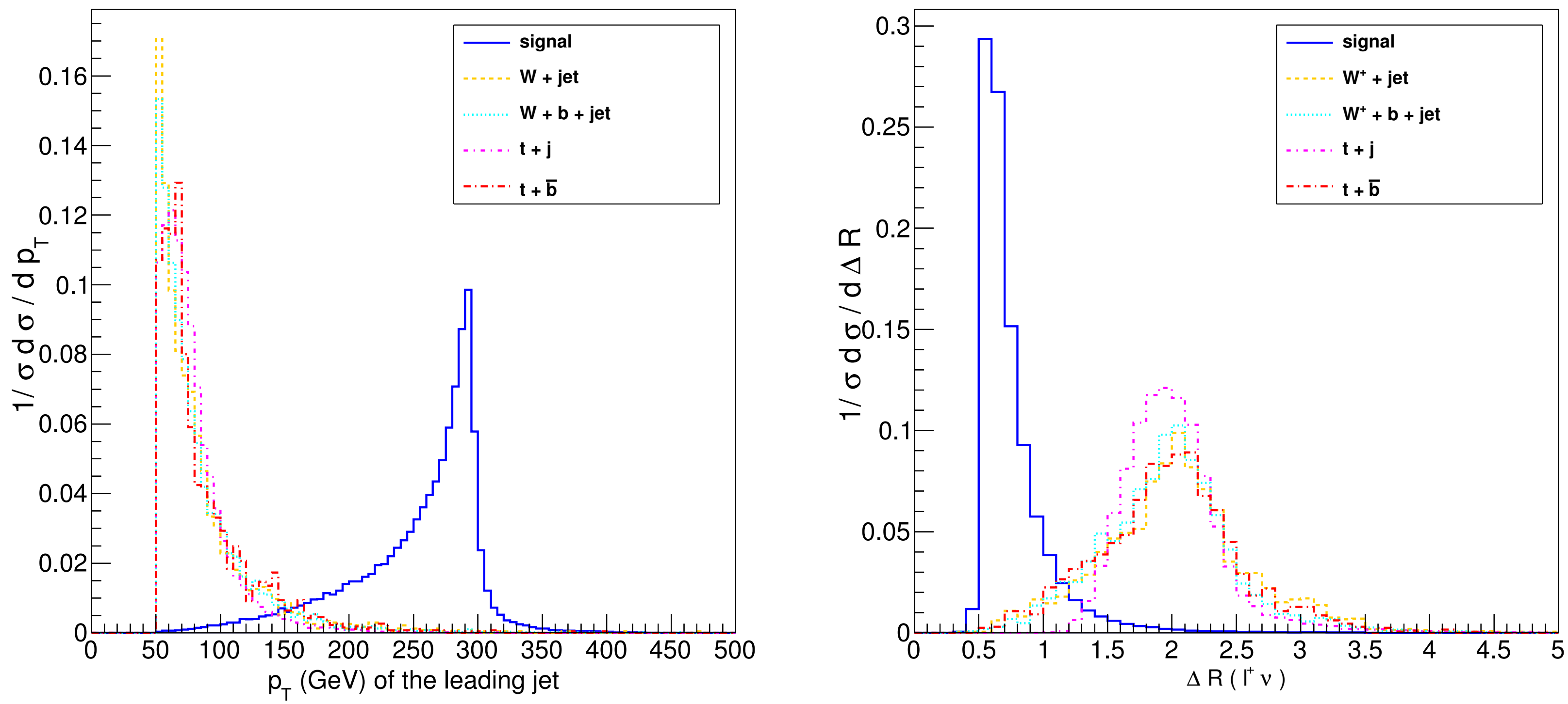


Figure 4: P_T distribution in the left panel and $\Delta R(\ell^+, \nu)$ distribution in the right panel after the basic and veto selection cuts. Each plot is normalized.

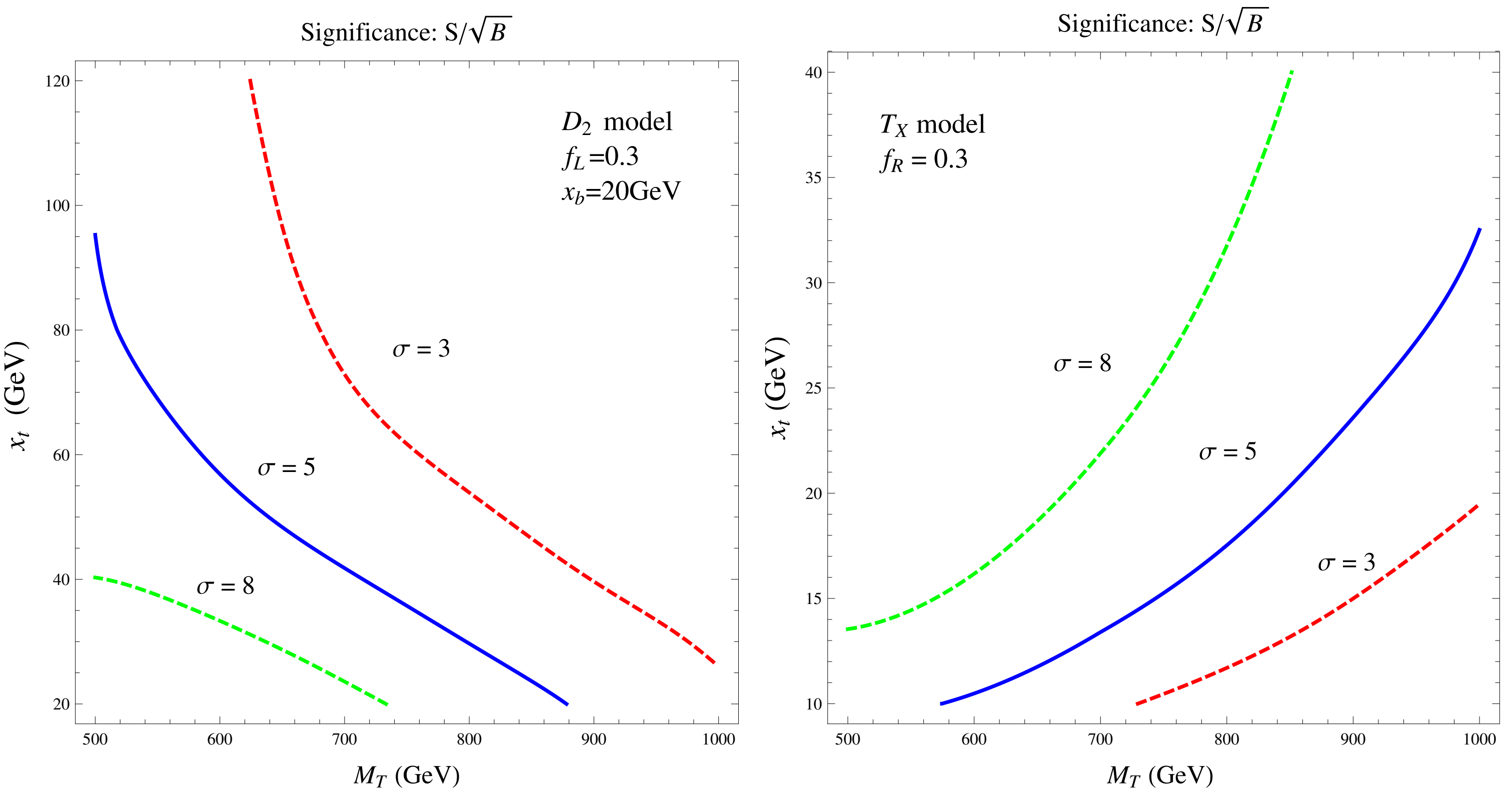


Figure 5: Significance contour at the 14 TeV LHC with an integrated luminosity of 1 fb^{-1}. In the doublet scenario x_t decreases with M; In the triplet scenario x_t increases with M.

Leptonic angular distribution

The differential cross section with respect to $\cos\theta_\ell$ for the $ug \to T \to b\ell^+\nu$ in the c.m. frame in the limit of $m_W \ll \sqrt{s}$ are found to be:

$$\frac{1}{\hat{\sigma}}\frac{d\hat{\sigma}(u_R g \to b\ell^+\nu)}{d\cos\theta_\ell} = \frac{{g_W^L}^2}{{g_W^L}^2 + {g_W^R}^2}(1-\cos\theta_\ell) + \frac{{g_W^R}^2}{{g_W^L}^2 + {g_W^R}^2}(1+\cos\theta_\ell) - \frac{{g_W^R}^2}{{g_W^L}^2 + {g_W^R}^2}\cdot\mathcal{O}(m_W^2/s)\cdot\cos\theta_\ell$$

$$\frac{1}{\hat{\sigma}}\frac{d\hat{\sigma}(u_L g \to b\ell^+\nu)}{d\cos\theta_\ell} = \frac{{g_W^L}^2}{{g_W^L}^2 + {g_W^R}^2}(1+\cos\theta_\ell) + \frac{{g_W^R}^2}{{g_W^L}^2 + {g_W^R}^2}(1-\cos\theta_\ell) + \frac{{g_W^R}^2}{{g_W^L}^2 + {g_W^R}^2}\cdot\mathcal{O}(m_W^2/s)\cdot\cos\theta_\ell$$

Note that the $\mathcal{O}(m_W^2/s)$ correction is only for the term proportional to the right-handed T-b-W coupling.

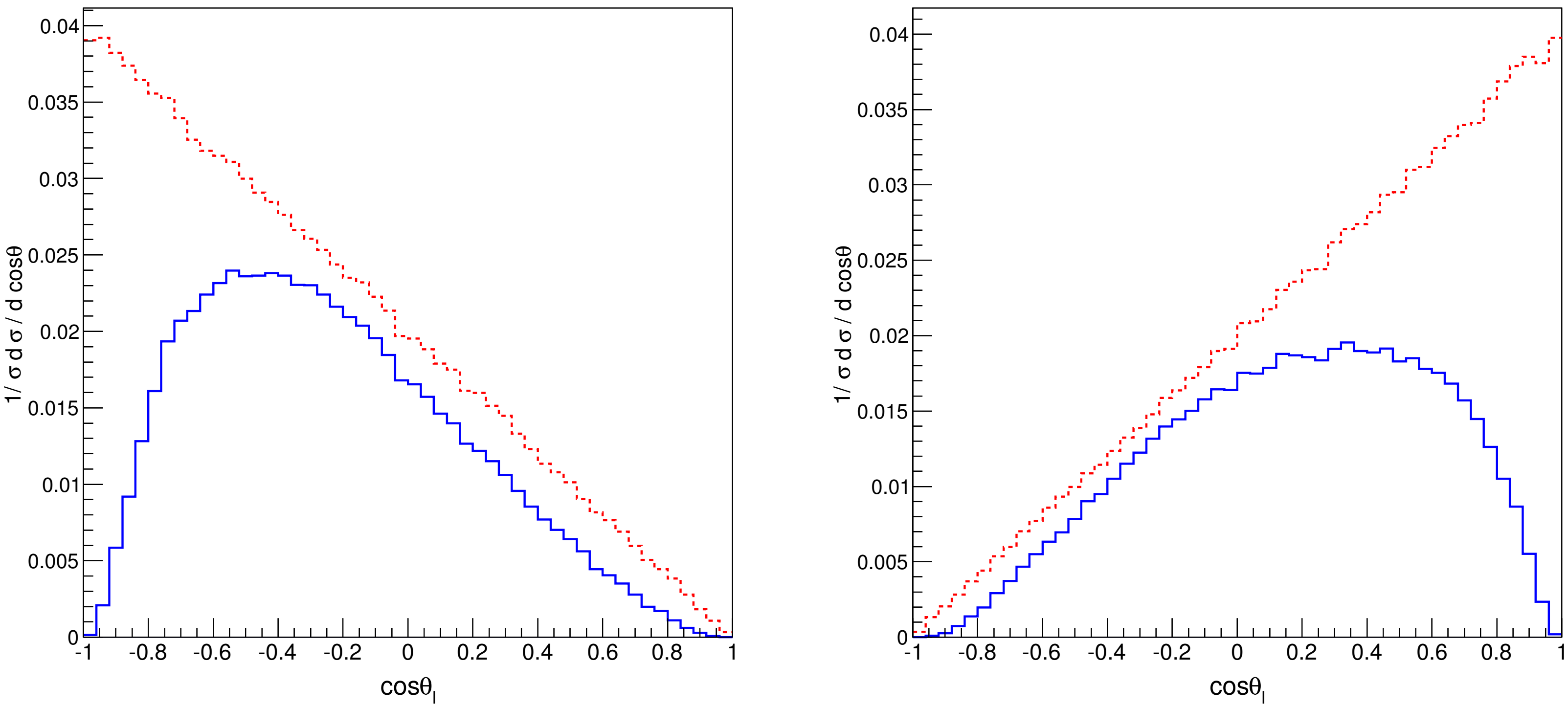


Figure 6: The $\cos\theta_\ell$ distribution between the lepton and gluon moving directions with no cut and after the mass-window cut in the models with dominate g_W^L coupling: (a) the singlet T-quark, (b) the doublet T-quark (when there is no heavy bottom quark or its effect can be ignored).

Conclusion

- Electroweak precision measurements impose strong bounds on the model parameters of vector-quark models.

- The leptonic angular distribution is a favored analyzing power for identifying the chiral property of couplings, therefore distinguish varieties of vector-quark models.

- It is promising to explore the existence of vector-quarks in mono production channel, depending on specific assumptions.

  model independent approach $\Rightarrow$ pair production

Thank You