Heavy Quarks Above the “Top” at Hadron Colliders

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Fermilab

Based on

PRD 79 (2009) 054018 : AA, Marcela Carena, Tao Han, Jose Santiago

arXiv:09xx.xxxx : AA, Georges Azuelos, Marcela Carena, Tao Han, Erkcan Ozcan, Jose Santiago, Gokhan Unel

Simple example:

SM fields plus two vector like quark SU(2)L doublets with Y = 1/6 and 7/6

$$Q^{(0)}_{L,R} = \begin{pmatrix} q^{(0)u}_{L,R} \\ q^{(0)d}_{L,R} \end{pmatrix}_{1/6}, \quad X^{(0)}_{L,R} = \begin{pmatrix} \chi^{(0)u}_{L,R} \\ \chi^{(0)d}_{L,R} \end{pmatrix}_{7/6}$$

Electric charges equal $2/3$ for q^u and χ^d, $1/3$ for q^d and $5/3$ for χ^u

with degenerate masses (same higher multiplet) and coupling to u_R,
Yukawa mixing only with u_R in the basis of diagonal up-type Yukawas

$$\mathcal{L} = \mathcal{L}_{\rm K} - \Big[\lambda^i_u \bar{q}^{(0)i}_L \tilde{\varphi} u^{(0)i}_R + \lambda^j_d V_{ij} \bar{q}^{(0)i}_L \varphi d^{(0)j}_R + \lambda_Q(\bar{Q}^{(0)}_L \tilde{\varphi} + \bar{X}^{(0)}_L \varphi) u^{(0)}_R + m_Q(\bar{Q}^{(0)}_L Q^{(0)}_R + \bar{X}^{(0)}_L X^{(0)}_R) + \text{h.c.}\Big]$$

Due to precision measurements on light quark couplings, new vector like quarks are typically allowed to mix sizeably only mainly with the top

However, in models of Warped Extra dimensions vector-like quarks can couple sizably to SM fermions without upsetting usual SM fermions couplings or generating unacceptably large FCNC.

$$\mathcal{L}^Z = -\frac{g}{2c_W}\left[\bar{\psi}^u_{iL} X^L_{ij} \gamma^\mu \psi^u_{jL} - \bar{\psi}^d_{aL} X^L_{ab} \gamma^\mu \psi^d_{bL} + (L \to R) + \ldots - 2s^2_W J^\mu_{\rm EM}\right] Z_\mu,$$

$$\mathcal{L}^W = -\frac{g}{\sqrt{2}}\left[\bar{\psi}^u_{iL} W^L_{ia} \gamma^\mu \psi^d_{aL} + \bar{\chi}^u_L \widetilde{W}^L_{\tilde{\chi}^u j} \gamma^\mu \psi^u_{jL} + (L \to R) + \ldots\right] W^+_\mu + \text{h.c.},$$

$$\mathcal{L}^H = -\left[\bar{\psi}^u_{iL} Y^u_{ij} \psi^u_{jR} + \bar{\psi}^d_{iL} Y^d_{ij} \psi^d_{jR} + \ldots + \text{h.c.}\right] \frac{H}{\sqrt{2}},$$

$$J^\mu_{\rm EM} \equiv \sum_\psi \bar{\psi} \gamma^\mu Q \psi$$

Effects on SM quark couplings due to new quarks

$$X^R_{uu} = 0, \quad W^R_{ud_i} = 0, \quad Y^u_{uu} = c_R(\lambda_u c_L + \sqrt{2}\lambda_Q s_L) \approx \lambda_u \left(1 - 3\lambda^2_Q \frac{v^2}{m^2_Q}\right),$$

$$X^L_{uu} = c^2_L \approx 1 - 2\lambda^2_Q \lambda^2_u \left(\frac{v}{m_Q}\right)^4, \quad W^L_{ud_i} = c_L \approx V_{ud_i}\left[1 - \lambda^2_Q \lambda^2_u \left(\frac{v}{m_Q}\right)^4\right]$$

Very Small Changes to SM couplings

Heavy Quark - SM quark couplings

$$X^L_{uq^-} = \sqrt{2}W^L_{uq^d} = \sqrt{2}\widetilde{W}^L_{\chi^u u} = s_L \approx -\sqrt{2}\lambda_u\lambda_Q\left(\frac{v}{m_Q}\right)^2$$

$$X^L_{uq+} = -s_L c_L \approx \sqrt{2}\lambda_u\lambda_Q\left(\frac{v}{m_Q}\right)^2$$

$$X^R_{uq^-} = \sqrt{2}W^R_{uq^d} = \sqrt{2}\widetilde{W}^R_{\chi^u u} = s_R \approx -\sqrt{2}\lambda_Q\frac{v}{m_Q}$$

$$Y^u_{q+u} = c_R(-\lambda_u s_L + \sqrt{2}\lambda_Q c_L) \approx \sqrt{2}\lambda_Q$$

$$W^L_{q^+d_i} = -V_{ud_i}s_L \approx \sqrt{2}V_{ud_i}\lambda_u\lambda_Q\left(\frac{v}{m_Q}\right)^2,$$

$$Y^u_{uq^+} = -s_R(\lambda_u c_L + \sqrt{2}\lambda_Q s_L) \approx \sqrt{2}\lambda_u\lambda_Q\frac{v}{m_Q},$$

$$X^R_{uq^+} = W^L_{q^-d_i} = W^R_{q^-d_i} = W^R_{q^+d_i} = Y^u_{uq^-} = Y^u_{q^-u} = 0.$$

Heavy Quarks in New Physics

- In the era of hadron colliders!
- Chiral quarks - couplings to light quarks very constrained
- Vector like fermions - many BSM scenarios
- Eg: SM + two vector like doublets

$$(\chi^u{}_{L,R}, \chi^d{}_{L,R})_{7/6} \; (q^u{}_{L,R}, q^d{}_{L,R})_{1/6}$$

- Appear in RS models, e.g *Carena, Ponton, Santiago, Wagner*

  Agashe, Contino, da Rold, Pomarol

  Medina, Shah, Wagner

  Cacciapaglia, Csaki, Marandella, Terning

We study generic heavy quarks!

Model Independent Study of Heavy Quarks

Two new quarks *D (*charge -1/3) and *U* (charge 2/3)

Generic heavy quarks with arbitrary CC and NC couplings

$$\frac{g}{\sqrt{2}} W_\mu^+ (\kappa_{uD}\, \overline{u}_R \gamma^\mu D_R + \kappa_{dU}\, \overline{d}_R \gamma^\mu U_R) + \frac{g}{2c_W} Z_\mu (\kappa_{uU}\, \overline{u}_R \gamma^\mu U_R + \kappa_{dD}\, \overline{d}_R \gamma^\mu D_R) + \mathrm{h.c.}$$

$$\kappa_{qQ} = (\mathrm{v}/m_Q)\, \tilde{\kappa}_{qQ}, \quad \mathrm{v} \equiv 174 \text{ GeV}$$

$\tilde{\kappa}_{qQ}$ is dimensionless parameter that encodes model dependence

Study both CC and NC processes for Tevatron and LHC

From our Warped ED Gauge-Higgs Unification models we have

$$\tilde{\kappa}_{uU} \simeq -\sqrt{2}\lambda_Q \simeq \mathcal{O}(1) \;\text{ and }\; \tilde{\kappa}_{\mathrm{uD}} \simeq -\lambda_{\mathrm{Q}} \simeq \mathcal{O}(1)$$

Similarly, a Warped ED model with 2 vector-like doublet with hypercharges 1/6 and -5/6, mixing only with d_R will generate $\tilde{\kappa}_{dU}$ and $\tilde{\kappa}_{\mathrm{dD}}$

Model Independent Study of Heavy Quarks

- Extra quarks with exotic charges (*5/3* or -*4/3*) that couple with *u* and *d* via CC - include via enhanced rate
- Heavy quark Higgs couplings not explicitly written down
  - No appreciable rate for production process of interest
  - For the decay of heavy quarks, reabsorb Higgs decay modes in definition of BRs which are unsepcified.
- Results do not depend on choice of chiral couplings appreciably as angular correlations are not studied.
  - RH couplings appear in the case of vector-like doublets
  - LH couplings appear in the case of vector-like singlets
  - Both types of New quarks can be present in Warped ED models

Signal Process: Production

QCD pair production vs Electroweak single production

Include K-factors:

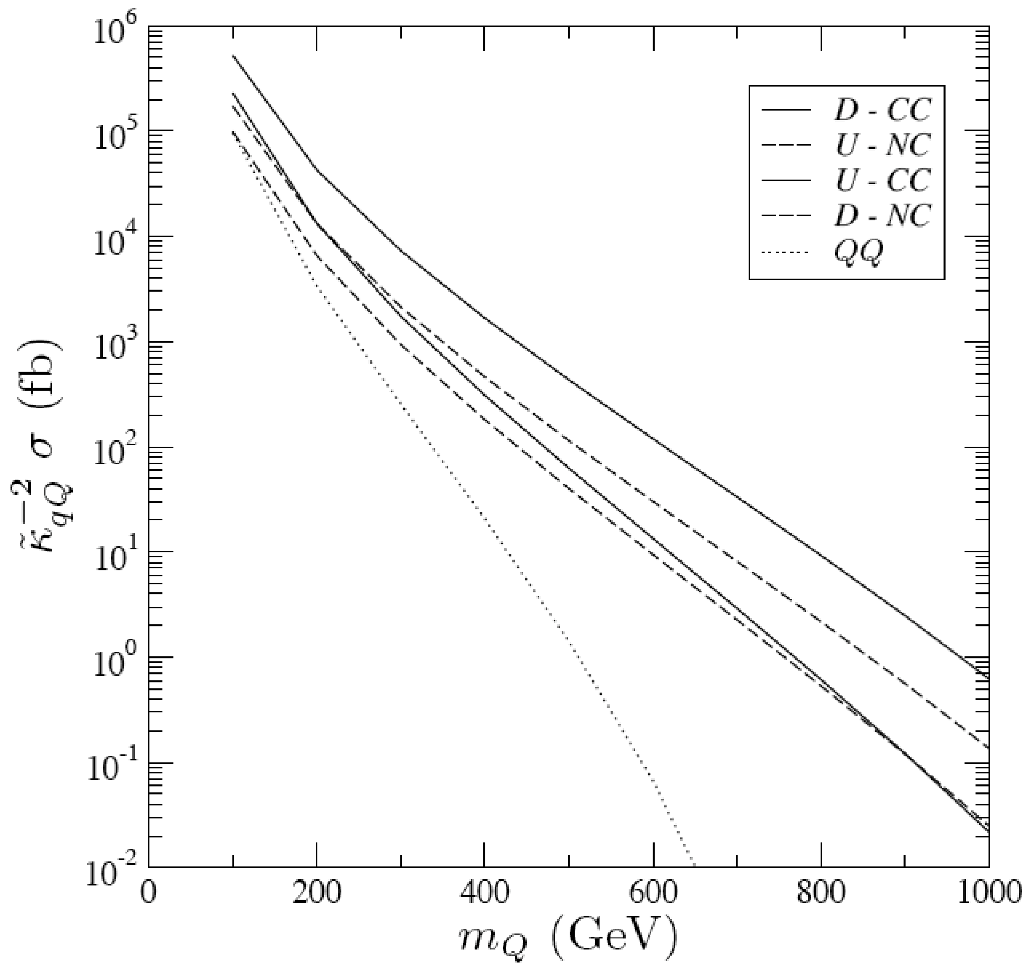
$K_{QQ} = 1.5$

$K_Q = 0.96$

Current Tevatron bound at 95% CL for

U(D) decaying via CC(NC)

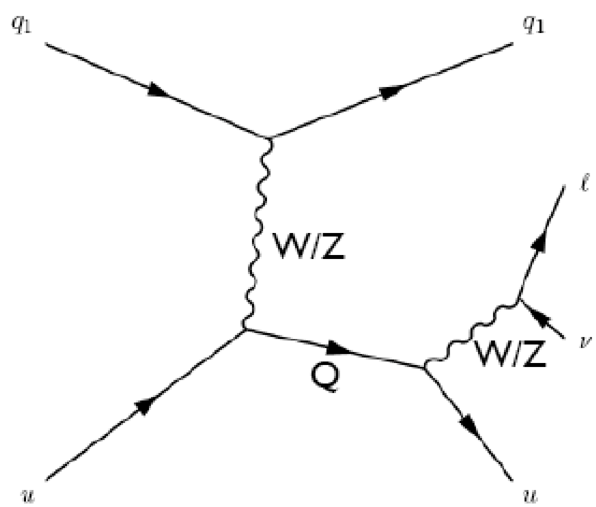
$m_{U(D)} > 284\ (270)$ GeV

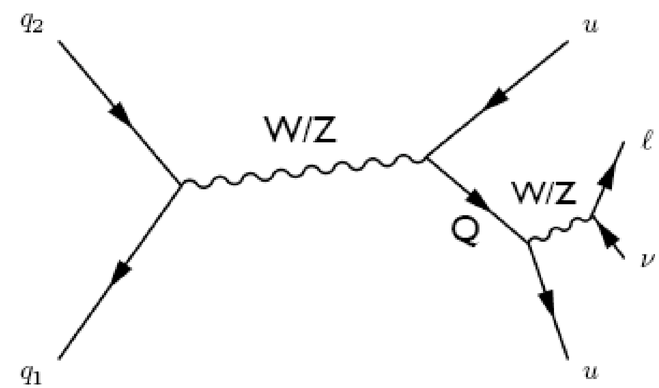


Heavy Quark Signals:

via Charged Current or Neutral Current Interactions

$$D \to W^- u,\ Zd,\ hd, \quad U \to W^+ d,\ Zu,\ hu.$$





$pp(p\bar{p}) \to qQ \to quW \to qul\nu$ $\Rightarrow \text{Signal}: \ 2j + l + \not{E}_T$

$pp(p\bar{p}) \to qQ \to quZ \to qul^+l^-$ $\Rightarrow \text{Signal}: \ 2j + l^+l^-$

$pp(p\bar{p}) \to qQ \to quZ \to qu\nu\bar{\nu}$ $\Rightarrow \text{Signal}: \ 2j + \not{E}_T$

Both D and $\bar{\text{D}}$ or U and $\bar{\text{U}}$ considered

Single Quark Production

Decay modes are $D \to W^- u,\ Zd,\ hd, \quad U \to W^+ d,\ Zu,\ hu.$

Ignore Higgs channel for simplicity (separate analysis)

Model independent parameterization

$$\sigma(pp \to q_1 q_2 f\bar{f}) \equiv S_Q^{CC(NC)}\ \sigma_{prodn}^{CC(NC)}\ Br(V \to f\bar{f})$$

under narrow width approximation

$\sigma_{prodn}^{CC(NC)}$ only depends on the mass of the heavy quark

$S_Q^{CC(NC)}$ encode model-dependent mixing terms

Model dependent mixing terms are

defined as

$$\begin{aligned} S_D^{CC} &\equiv (\tilde{\kappa}_{uD}^2 + \alpha_D^{CC}\ \tilde{\kappa}_{dD}^2)\ Br(D \to qW), \\ S_U^{CC} &\equiv (\tilde{\kappa}_{dU}^2 + \alpha_U^{CC}\ \tilde{\kappa}_{uU}^2)\ Br(U \to qW), \\ S_D^{NC} &\equiv (\tilde{\kappa}_{dD}^2 + \alpha_D^{NC}\ \tilde{\kappa}_{uD}^2)\ Br(D \to qZ), \\ S_U^{NC} &\equiv (\tilde{\kappa}_{uU}^2 + \alpha_U^{NC}\ \tilde{\kappa}_{dU}^2)\ Br(U \to qZ), \end{aligned}$$

where

$$\alpha_Q^{CC} \equiv \sigma_{prodn}^{NC}/\sigma_{prodn}^{CC} \text{ and } \alpha_Q^{NC} \equiv \sigma_{prodn}^{CC}/\sigma_{prodn}^{NC}$$

For degenerate bidoublets only one gauge boson decay mode available for each new quark

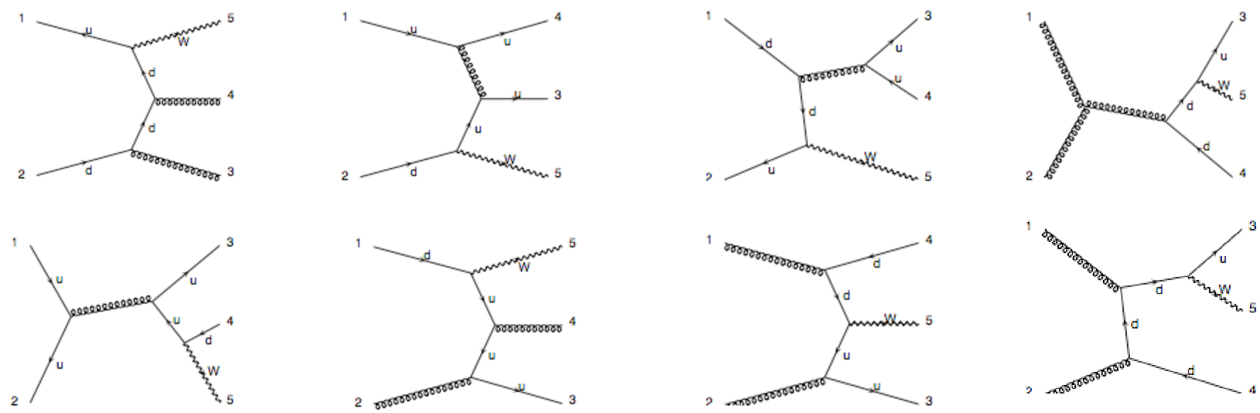
$Br[Q \to qW(Z)]$ is 100%

$S_D^{CC} = \tilde{\kappa}_{uD}^2$ and $S_U^{NC} = \tilde{\kappa}_{uU}^2$

Background Processes

Main Background:

QCD processes $p\bar{p} \rightarrow 2j + W^{\pm} \rightarrow 2j + \ell^{\pm} + \nu$



Other Background:

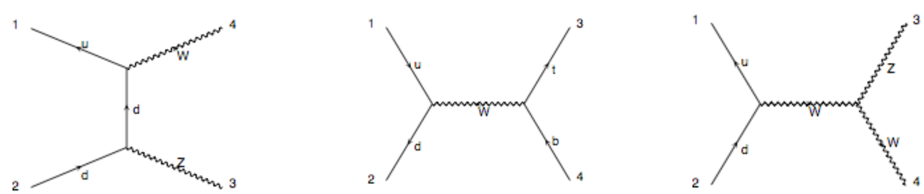
EW processes

$p\bar{p} \rightarrow Z + W^{\pm} \rightarrow 2j + \ell^{\pm} + \nu$

$p\bar{p} \rightarrow W^{\mp} + W^{\pm} \rightarrow 2j + \ell^{\pm} + \nu$

Single top $p\bar{p} \rightarrow t + b \rightarrow W^{\pm}bb \rightarrow 2j + \ell^{\pm} + \nu$

Top pair $p\bar{p} \rightarrow t + \bar{t} \rightarrow W^{+}W^{-}b\bar{b} \rightarrow 2j + \ell^{+} + \ell^{-} + \nu + \bar{\nu}$



Cuts

Basic Cuts:

$$p_T(jet) > 15\ GeV \qquad |\eta_{jet}| < 3 \qquad \Delta R_{jj} > 0.7$$

$$p_T(lep) > 15\ GeV \qquad |\eta_{lep}| < 2 \qquad \Delta R_{j\ell} > 0.5$$

$$p_T(miss) > 15\ GeV \qquad \Delta R_{\ell\ell} > 0.3$$

Additional lepton/$\not\!\!E_T$ veto to reduce $t\bar{t}$ background

CC: veto 2nd lepton:

$p_T(\ell) > 15$ GeV, $|\eta_\ell| < 2$ and $\Delta R(j\ell) > 0.5$

NC: veto events with any lepton or w/ $\not\!\!E_T > 15$ GeV

Smearing:

$$\Delta E_\ell / E_\ell = 0.135/\sqrt{E_\ell/\mathrm{GeV}} \oplus 0.02$$

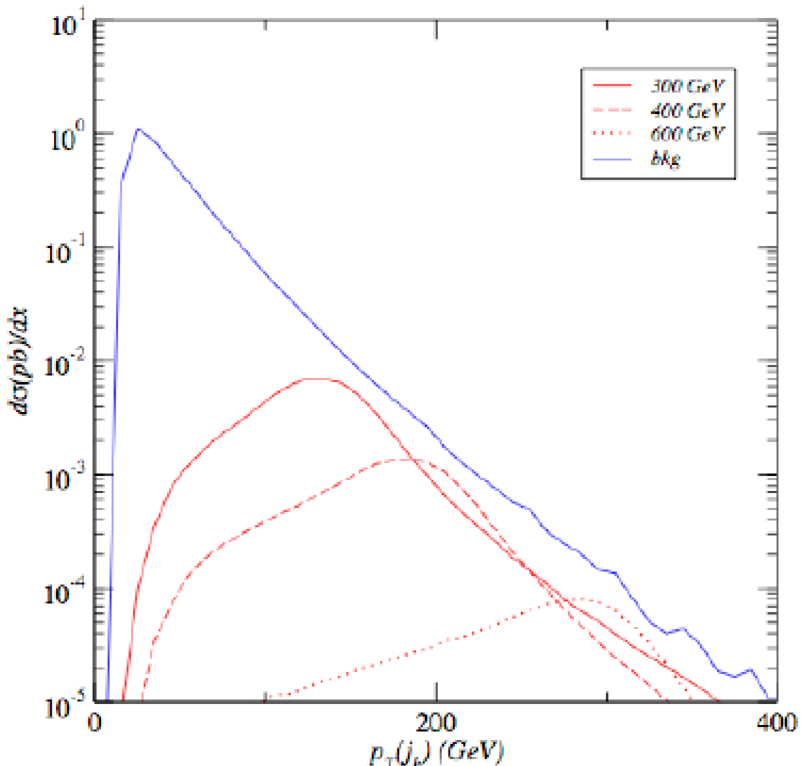
$$\Delta E_j / E_j = 0.75/\sqrt{E_j/\mathrm{GeV}} \oplus 0.03$$

Signal vs Background Distributions

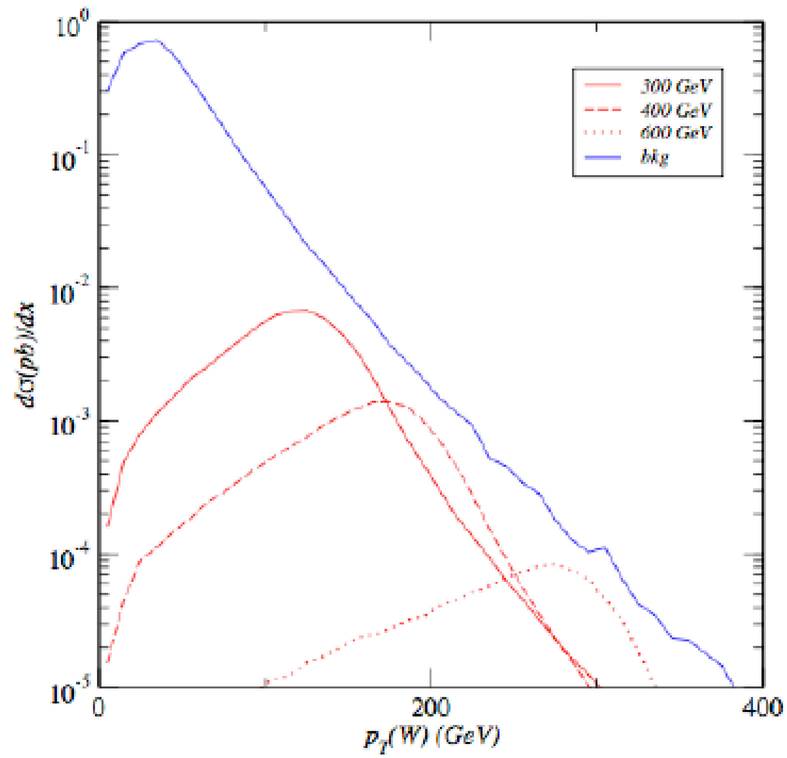
Improved Cuts:1

jet from heavy quark decay is very energetic

Similarly, W/Z from heavy quark decays are energetic



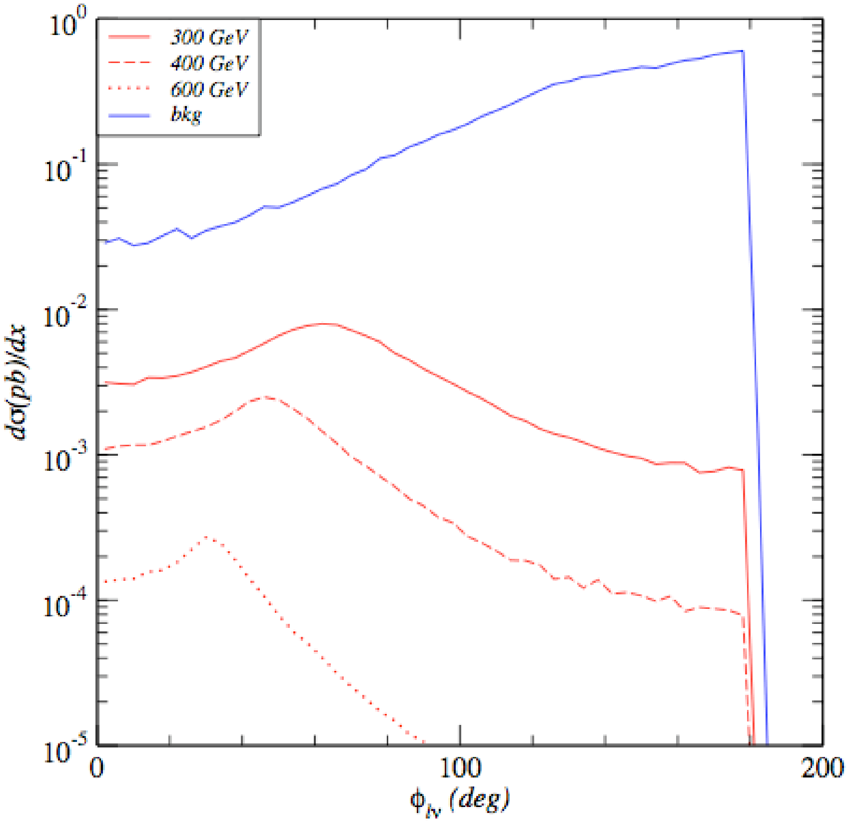
$$p_T(j_h) > \frac{1}{4} m_Q$$

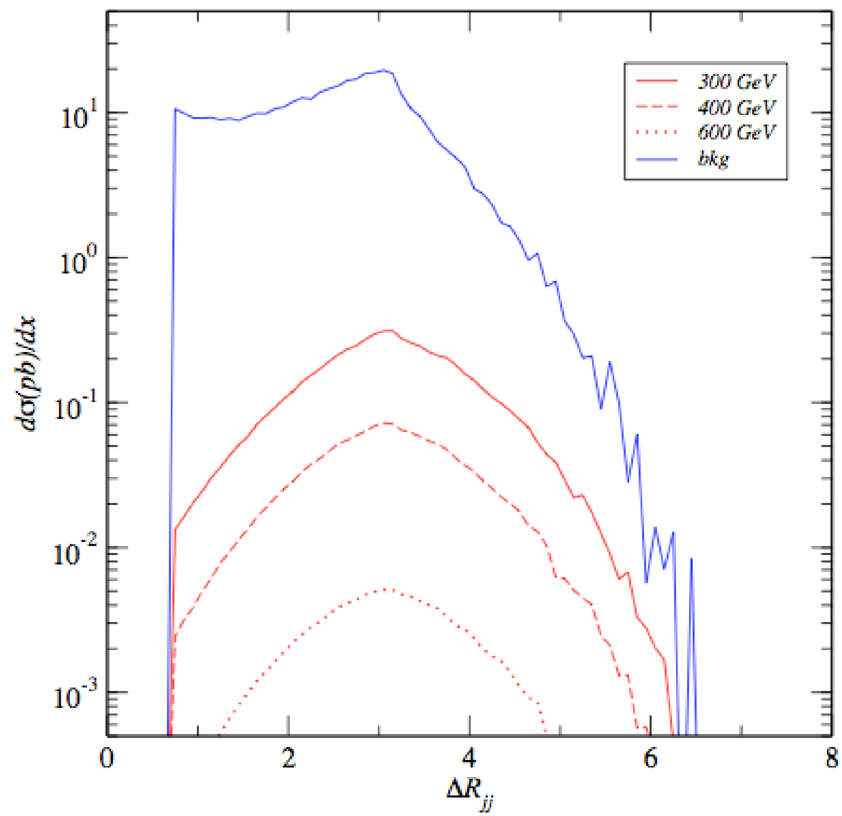


$$p_T(W/Z) > \frac{1}{5} m_Q$$

Signal vs Background Distributions

Improved Cuts:2





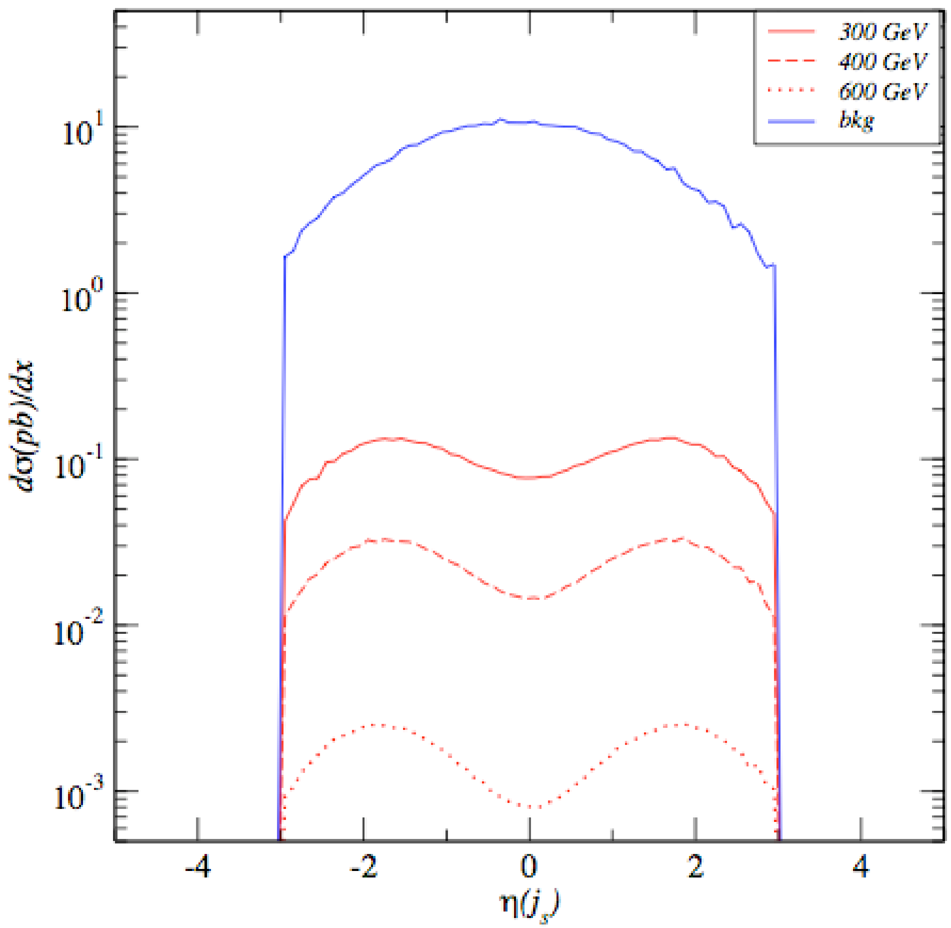
Optimized cuts on phi

$$\Delta R_{jj} > 1.5$$

$$\Delta R_{j\ell} > 0.8$$

Signal vs Background Distributions

Improved Cuts: 3



$$0.5 < |\eta(j_s)| < 3.0$$

Charge Identification

$$D : \eta(j_s) < 0 \;\&\; \ell^-$$

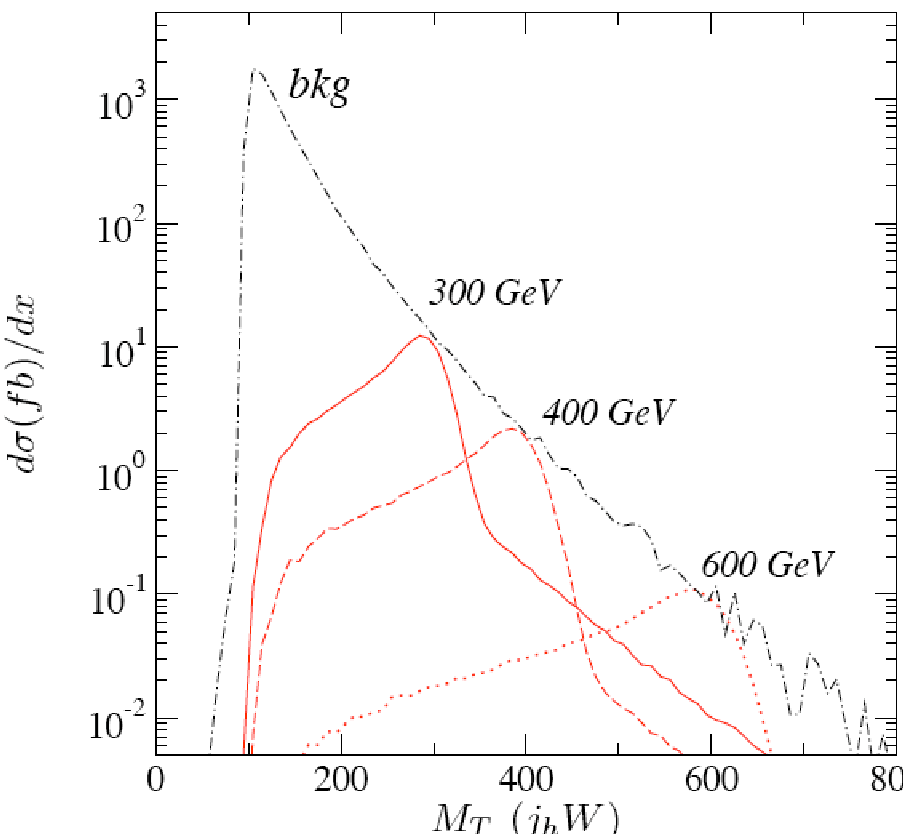
$$\overline{D} : \eta(j_s) > 0 \;\&\; \ell^+$$

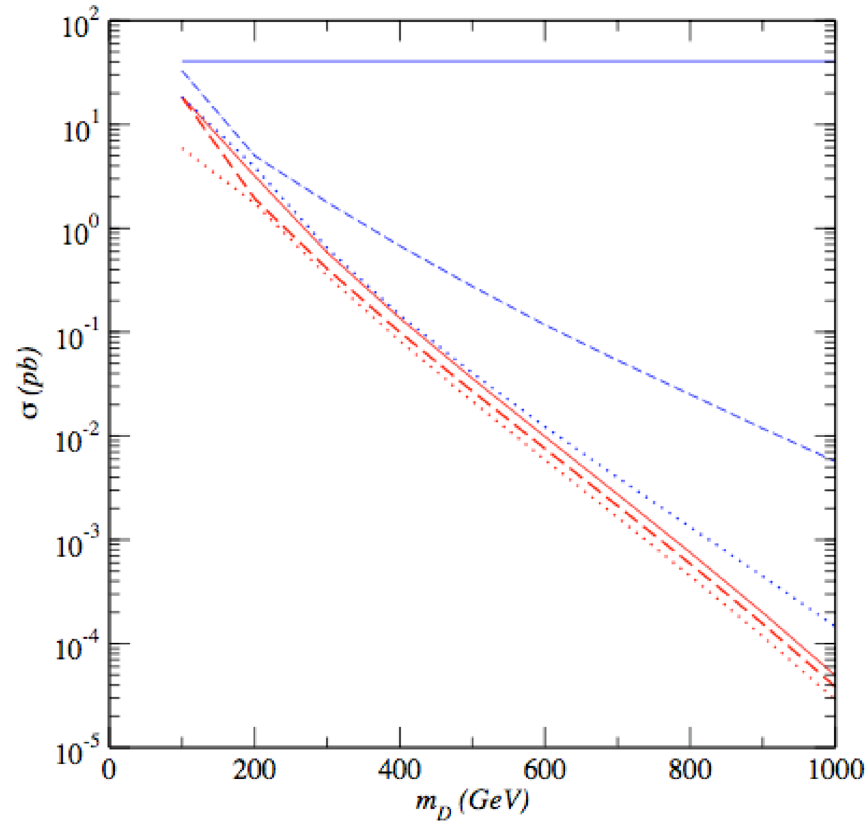
$$U : \eta(j_s) < 0 \;\&\; \ell^+$$

$$\overline{U} : \eta(j_s) > 0 \;\&\; \ell^-$$

Signal vs Background Distributions

Improved Cuts: 4 $$M_T^2 = \left(\sqrt{p_{TW,Z}^2 + M_{W,Z}^2} + p_{Tj_h}\right)^2 - (\vec{p}_{TW,Z} + \vec{p}_{Tj_h})^2 .$$

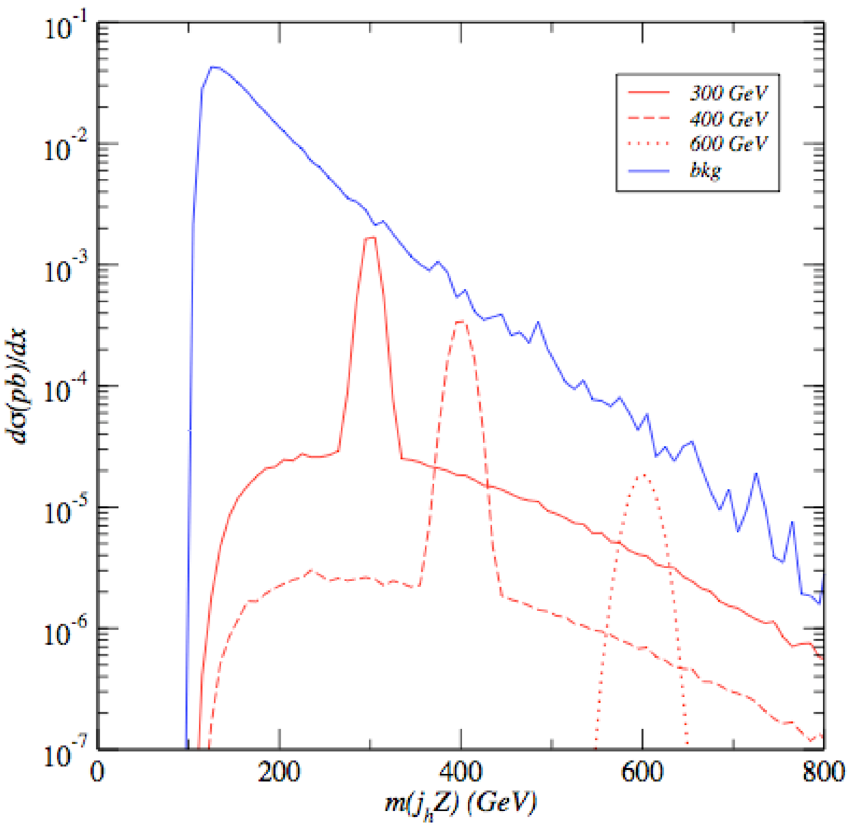


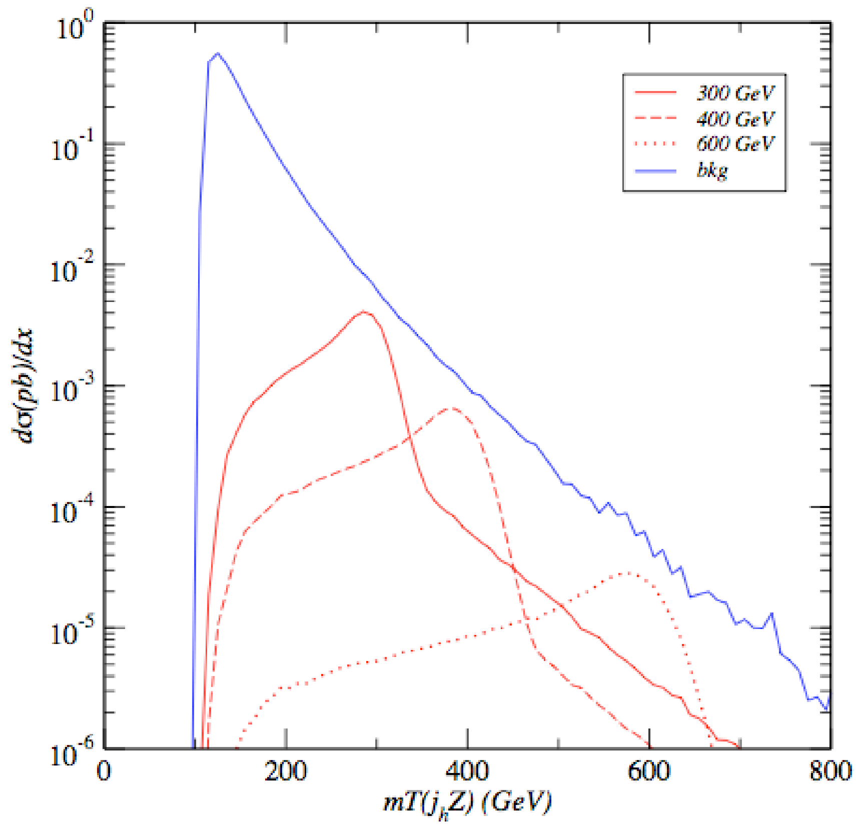


$$m_Q - \frac{1}{4}m_Q \ < \ M_T(j_h W/Z) < m_Q + 50 \text{ GeV}.$$

NC Channels

$p_T(j_h) > \frac{m_Q}{4}$ $p_T(Z) > \frac{m_Q}{5}$ $0.5 < |\eta(j_s)| < 3.0$ $\Delta R_{jj} > 1.5$ $\Delta R_{j\ell} > 0.8$ $\Delta R_{\ell\ell} > 0.3$





$$M_T^2 = \left(\sqrt{p_{TW,Z}^2 + M_{W,Z}^2} + p_{Tj_h}\right)^2 - (\vec{p}_{TW,Z} + \vec{p}_{Tj_h})^2$$

$$m_Q - \frac{1}{4} m_Q \; < \; M_T(j_h W/Z) < m_Q + 50 \text{ GeV}$$

$$m_Q - 30 \text{ GeV} \; < \; M(j_h Z) < m_Q + 30 \text{ GeV}$$

Current Constraints

- Searches for extra quarks
  - Limits on b\` are around 270 GeV from *1.06* fb^{-1}
  - Limits are from $b` \rightarrow b\,Z$ decay mode
  - No $b` \rightarrow Wj$ mode analysis available

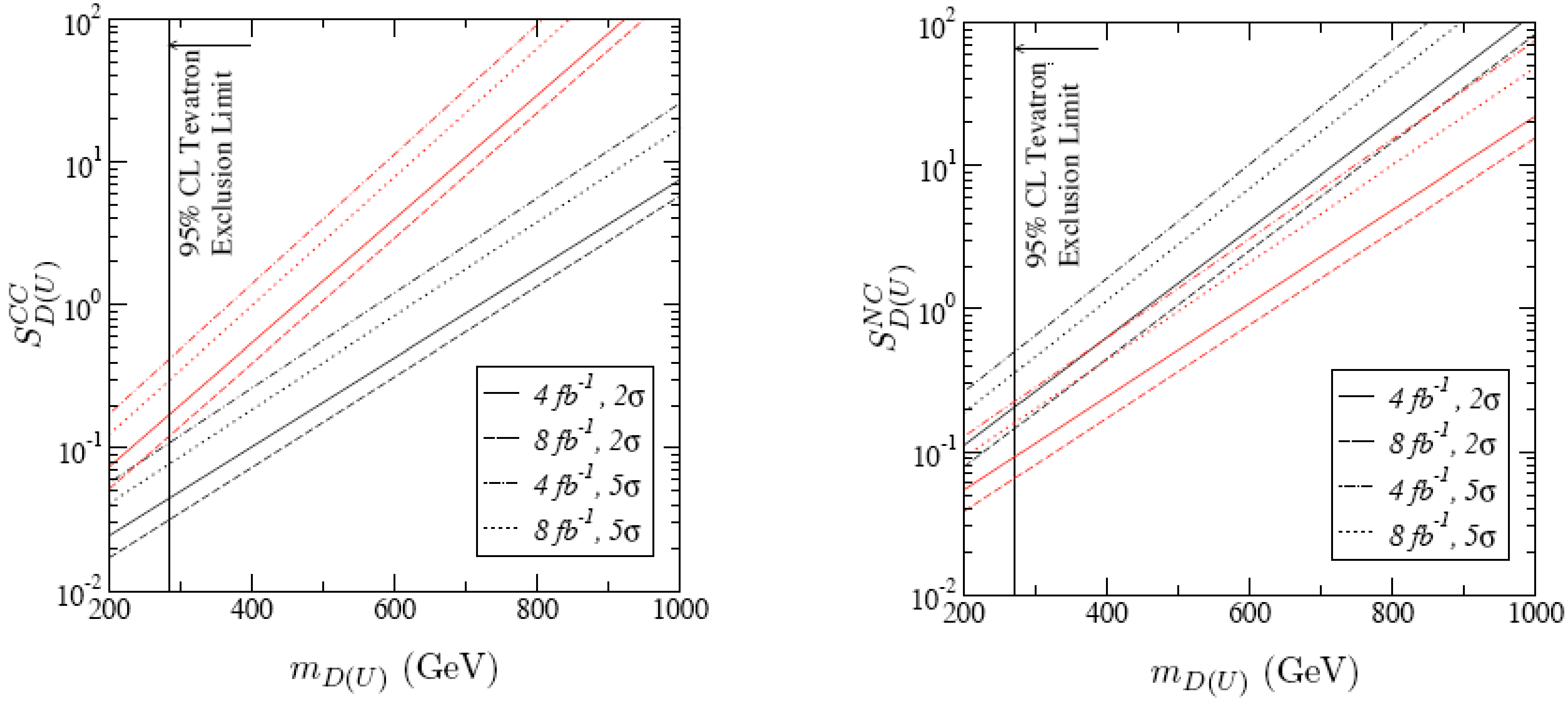
Aaltonen et al, PRD76, 072006 (2007)

- Limits on a $t`$ $(\rightarrow Wb)$ are 284 GeV with 2.3 fb^{-1}

CDF-note-9234

- Both are in pair production channel and both limits are at 95% CL

Sensitivity at Tevatron



$\int \mathcal{L}dt$	4 fb^{-1}		8 fb^{-1}	
Sensitivity	2σ	5σ	2σ	5σ
m_D for $S_D^{CC} = 1$ (2)	720 (820)	580 (670)	760 (860)	630 (710)
m_U for $S_U^{CC} = 1$ (2)	470 (530)	370 (440)	490 (560)	400 (470)
m_D for $S_D^{NC} = 1$ (2)	450 (530)	350 (420)	490 (570)	380 (470)
m_U for $S_U^{NC} = 1$ (2)	590 (680)	460 (540)	640 (730)	510 (590)