Heavy Quarks Above the “Top” at the Tevatron

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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

Introduction

- In the era of hadron colliders - Tevatron and LHC
- Due to precision measurements of light quark couplings, new vector-like quarks are typically allowed to mix sizably mainly with the top

Simple example:

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

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

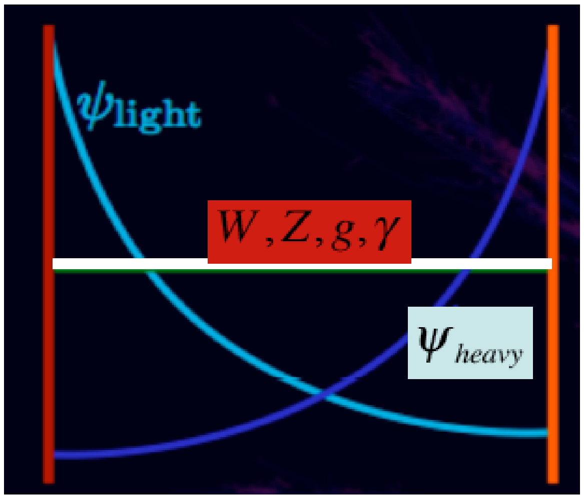
Electric charges equal $2/3$ for q^u and χ^d, $1/3$ for q^d and $5/3$ for χ^u

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

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

- SM quark couplings and SM-heavy quark couplings
- Can also have two vector-like doublets with hypercharges 1/6 and -5/6 mixing only with d_R

Introduction



UV brane

IR brane
Higgs + KK mode:

Metric: $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$

$v \sim \tilde{k} \equiv k\, e^{-kL} \approx M_{Pl}\, e^{-kL} \sim \text{TeV}$

Contino, Nomura, Pomarol 03
Agashe, Contino, Da Rold, Pomarol 05, 06
Agashe, Delgado, Sumdrum, May
Carena, Ponton, Santiago, Wagner 06, 07
Carena, Medina, Shah, Wagner …….

- Geometry of extra dimension generates hierachy exponentially
- Gauge and matter fields propagate in the bulk
- SM hierarchical fermion masses from localization - masses depend on overlap with Higgs/IR brane
- KK modes localized towards IR brane - weak bosons, gluons, fermions

⇒Large corrections to SM gauge boson masses and couplings due to Higgs induced mixing

⇒ Gauge group extended to

$SU(2)_L \times SU(2)_R \times U(1)_X \times P_{RL}$

avoid precision EW constraints

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

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

$$\kappa_{qQ}=(v/m_Q)\tilde{\kappa}_{qQ}$$

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

Study both CC and NC processes

In warped extra dimension models consistent with precision EW observables, we have light KK fermions without upsetting SM measurements of light quarks

For eg: $m_U = m_D = 480$ GeV; $k_{uD} = 0.57$ and $k_{uU} = 0.81$

Carena, Ponton, Santiago, Wagner
Agashe, Contino, Da Rold, Pomarol
Carena, Medina, Shah, Wagner,

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 unspecified.
- 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

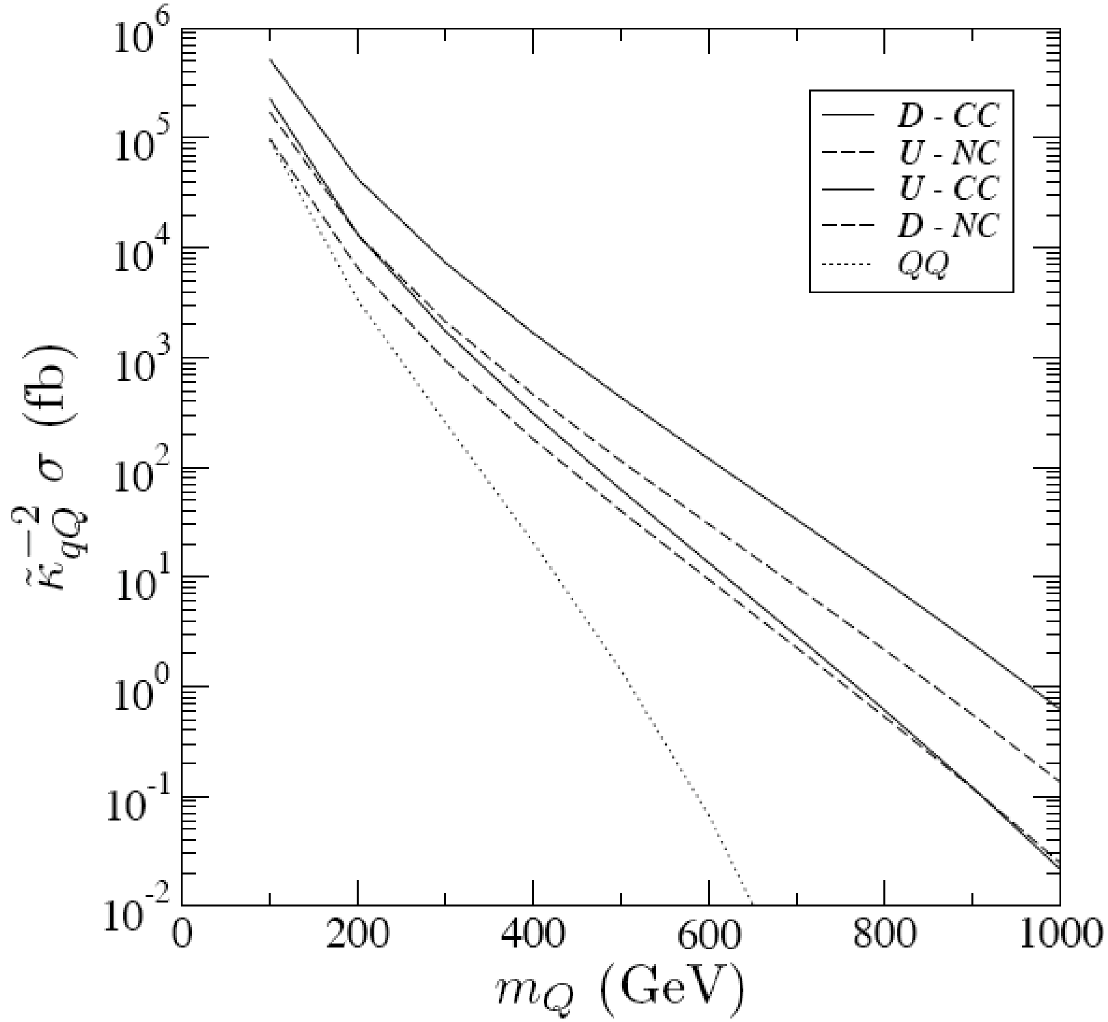
Include K-factors:

- $K_{QQ} = 1.5$
- $K_Q = 0.96$

Current Tevatron bound at 95% CL for

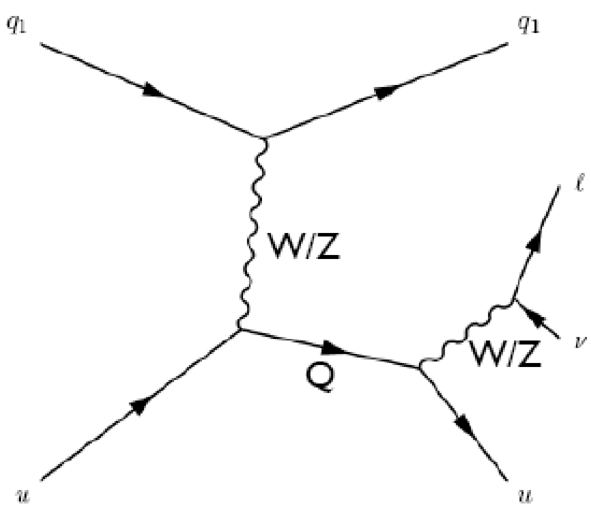
U decaying via CC
$m_U > 284$ GeV

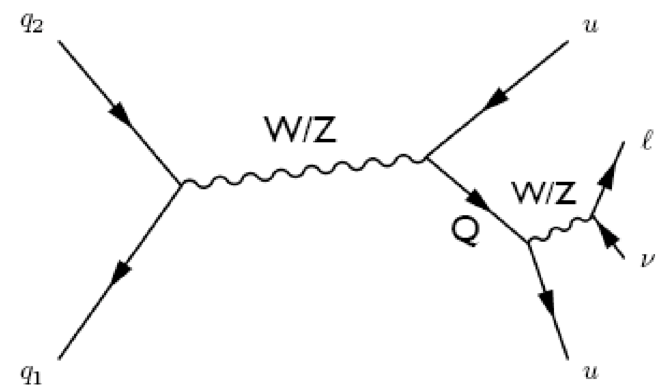
D decaying via NC
$m_D > 270$ GeV



Heavy Quark Signals:
via Charged Current or Neutral Current Interactions

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





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

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

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

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

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

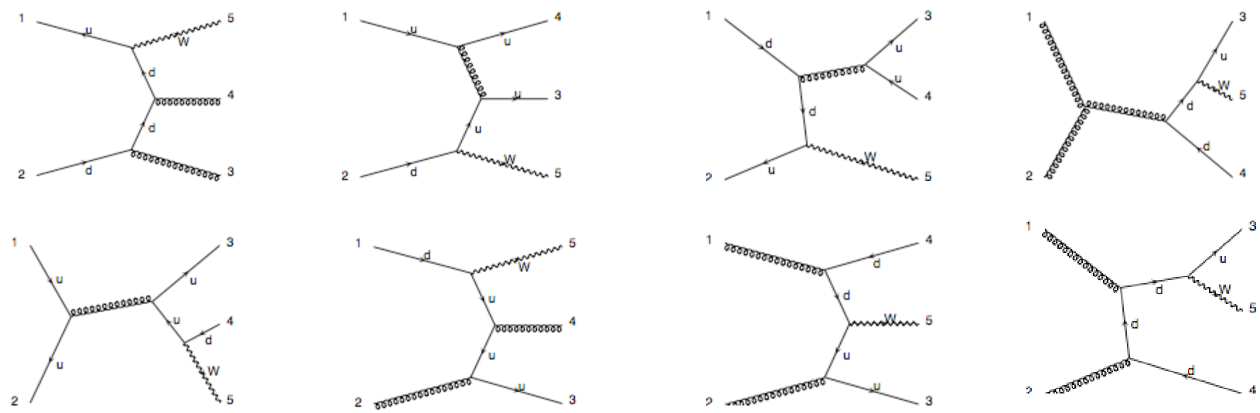
$\alpha_Q^{CC} \equiv \sigma_{prodn}^{NC}/\sigma_{prodn}^{CC}$ and $\alpha_Q^{NC} \equiv \sigma_{prodn}^{CC}/\sigma_{prodn}^{NC}$

where

Background Processes

Main Background:

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



Other Background:

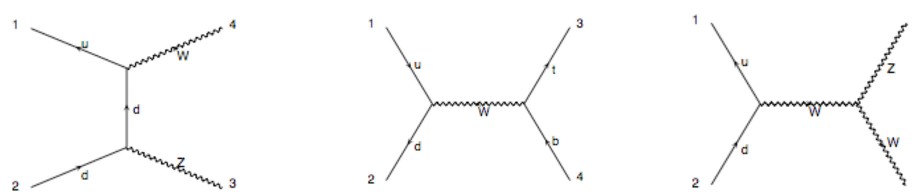
EW processes

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

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

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

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



Cuts

Basic Cuts:

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

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

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

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:

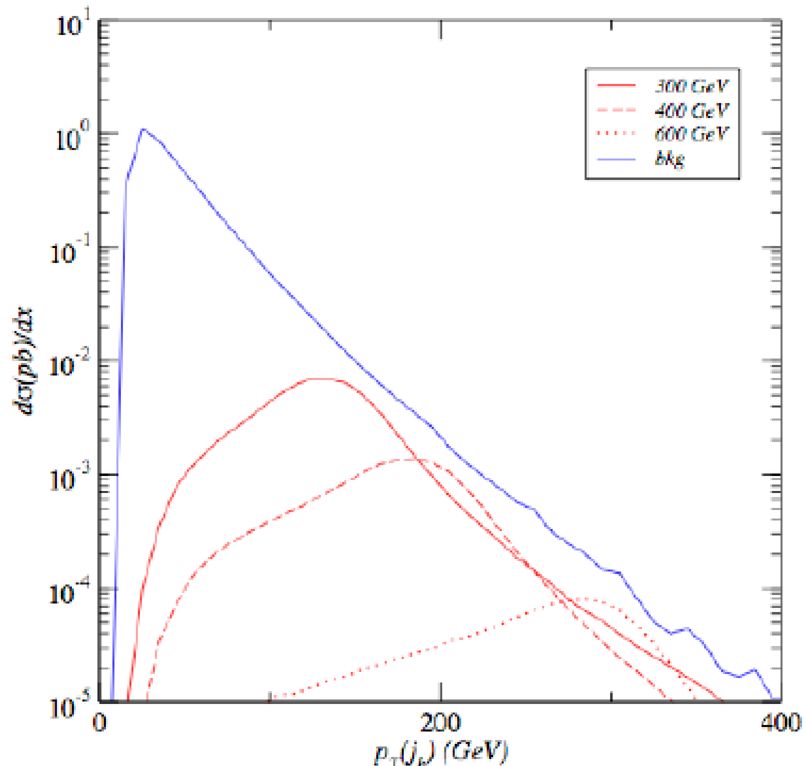
$$\Delta E_\ell / E_\ell = 0.135/\sqrt{E_\ell/\mathrm{GeV}} \oplus 0.02$$

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

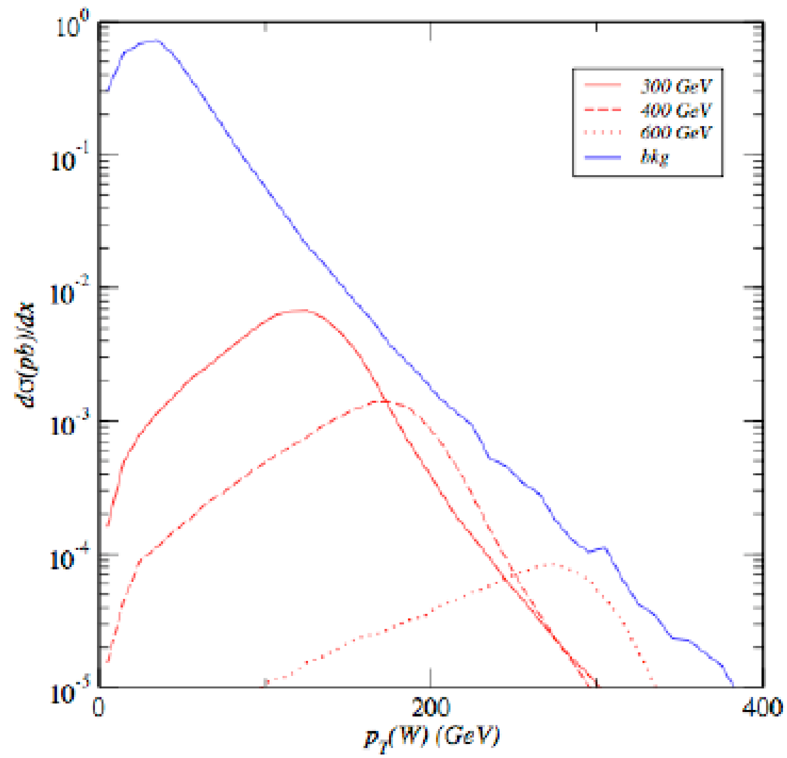
Signal vs Background Distributions

Improved Cuts:1 Jet from heavy quark decay energetic

Similarly, W/Z from heavy quark decay energetic as well



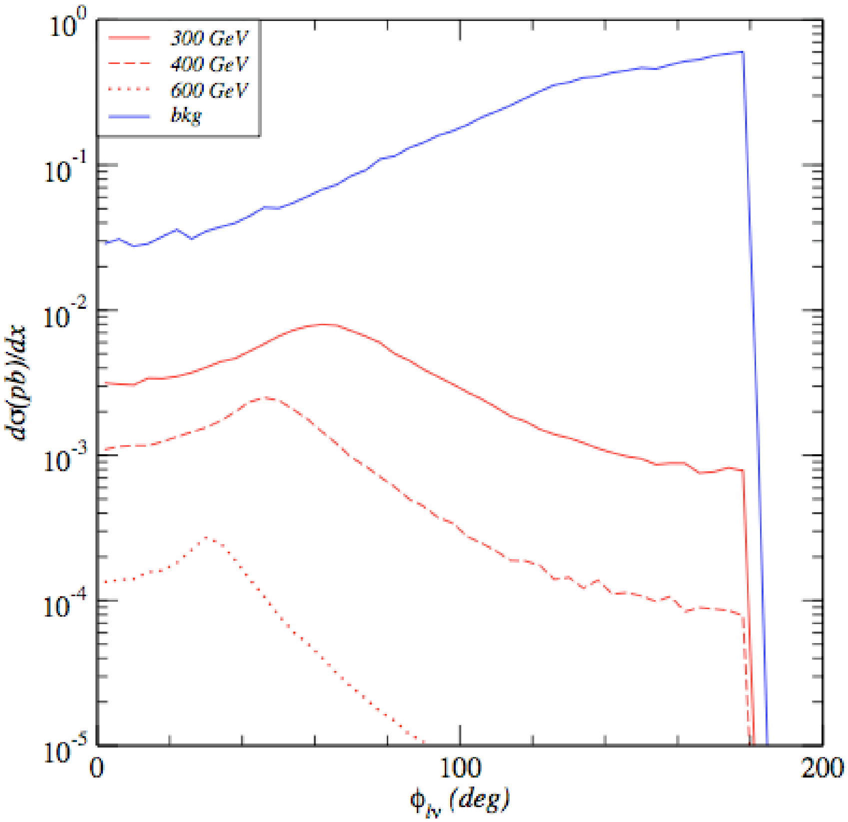
$$p_T(j_h) > \frac{1}{4} m_Q$$

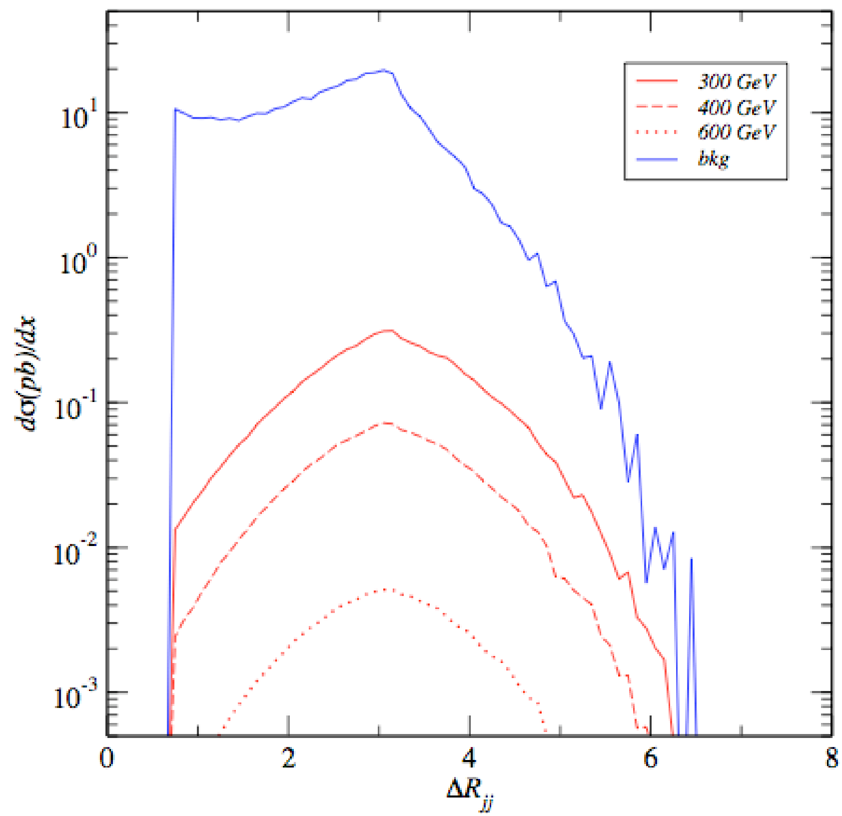


$$p_T(W/Z) > \frac{1}{5} m_Q$$

Signal vs Background Distributions

Improved Cuts:2





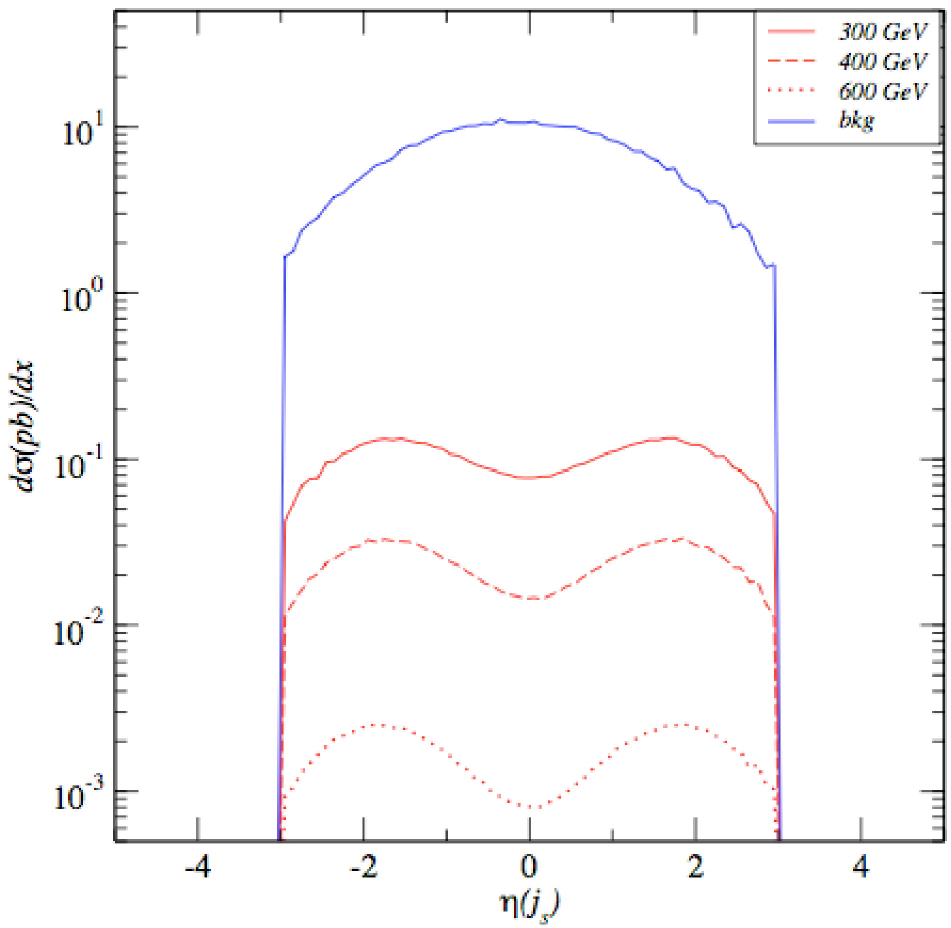
Optimized cuts on phi

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

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

Signal vs Background Distributions

Improved Cuts: 3



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

Charge Identification

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

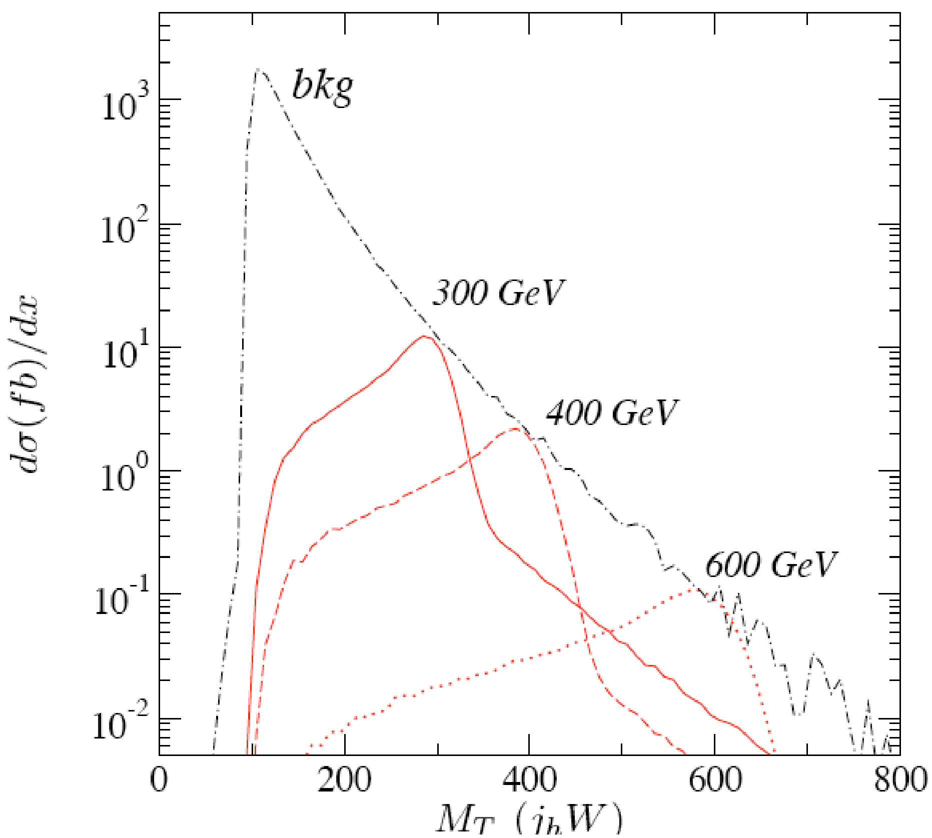
$$\overline{D} : \eta(j_s) > 0 \ \& \ \ell^+$$

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

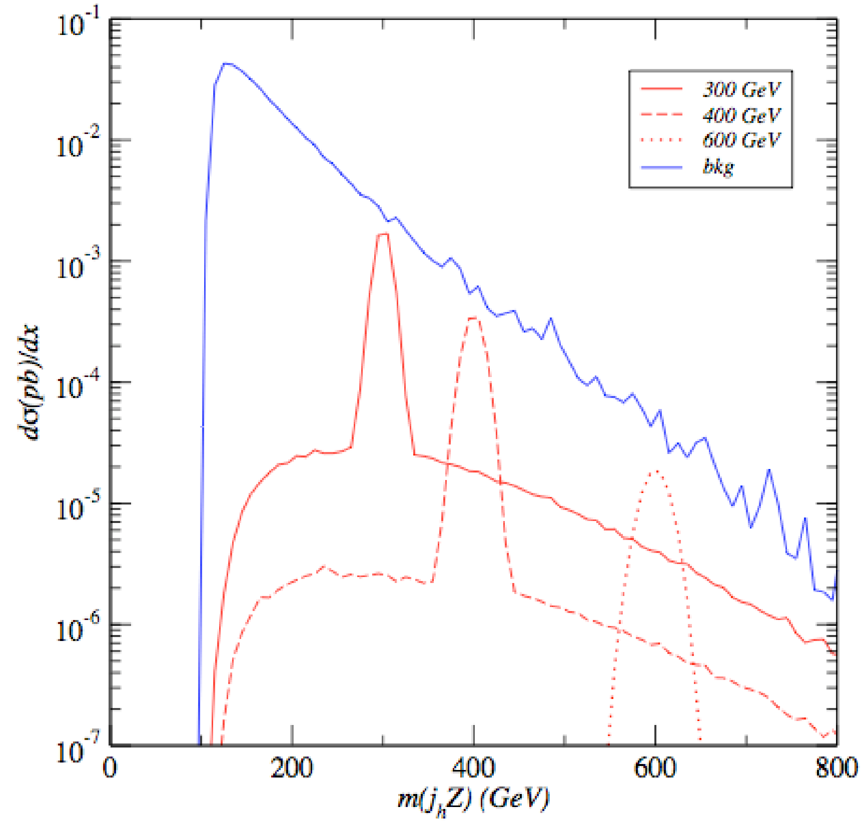
$$\overline{U} : \eta(j_s) > 0 \ \& \ \ell^-$$

Signal vs Background Distributions

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



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



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

Total cross-sections (in fb) for the signal with $m_Q = 400$ GeV and the leading SM backgrounds

CC current, with $S_Q^{CC}=1$

channels	Basic cuts (10)	High p_T (11)	m_Q (12)
$D \to W^\pm q$	270	190	160
$U \to W^\pm q$	49	35	29
$W^\pm + 2j$	79000	1200	280
$W^\pm W^\mp(\to 2j)$	1500	15	1.4
$W^\pm Z(\to 2j)$	230	4.7	0.52
single top: $W^\pm b\ j$	330	10	2.9
$t\bar{t}$: fully leptonic	170 (79)	2.0	0.40
$t\bar{t}$: semi-leptonic	600	0.19	-

$D + \overline{D}$ and $U + \overline{U}$ and the leptons $\ell = e, \mu$

For $t\bar{t}$
a veto on events with two isolated leptons.

	$D \to W^\pm q$	$W^\pm + 2j$	$\left(\frac{S}{\sqrt{B}}\right)_{fast\ sim}$	$\left(\frac{S}{\sqrt{B}}\right)_{partonic}$
Basic cuts (10)	200	28000	1.2	0.96
High p_T (11)	120	390	6.1	5.5
m_Q (12)	84	90	8.9	9.6

NC current, with $S_Q^{NC}=1$

channels	Basic cuts (10)	High p_T (11)	m_Q (12)
$D \to Z(\to \ell\ell)q$	8.8	6.0	5.7
$U \to Z(\to \ell\ell)q$	22	15	15
$Z(\to \ell\ell) + 2j$	7000	120	14
$Z(\to \ell\ell)W^\pm(\to 2j)$	60	0.65	0.08
$Z(\to \ell\ell)Z(\to 2j)$	55	1.1	0.11
$t\bar{t}$: fully leptonic	160 (1.7)	-	-

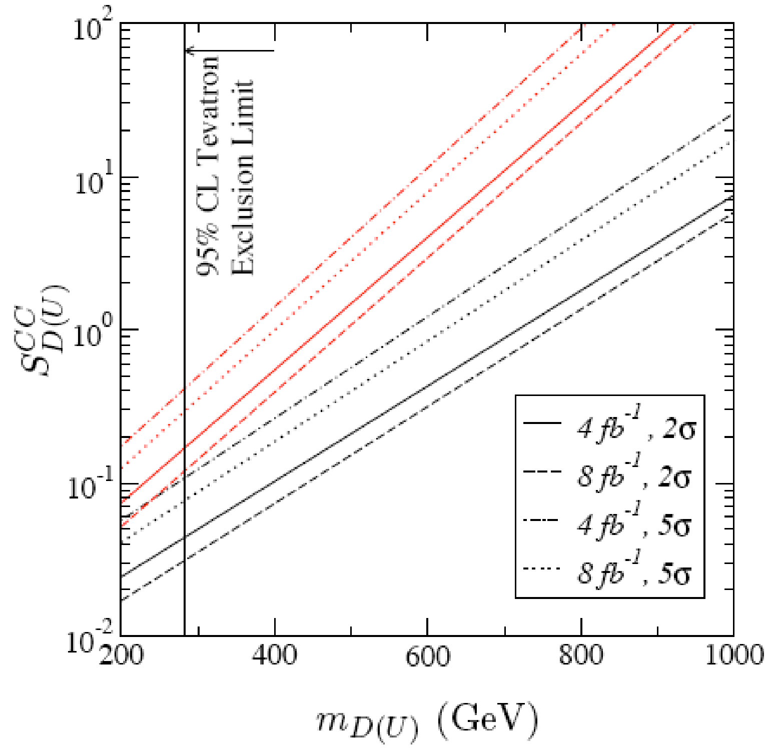
$\ell = e, \mu$ For $t\bar{t}$ a veto on events with $\not{E}_T$

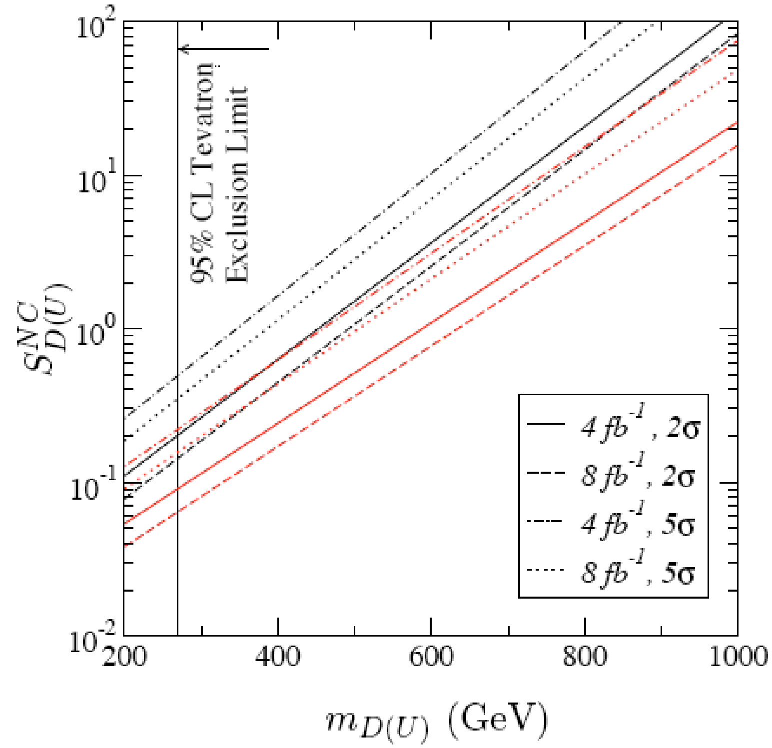
channels	Basic cuts (10)	High p_T (11)	m_Q (12)
$D \to Z(\to \nu\nu)q$	31	22	18
$U \to Z(\to \nu\nu)q$	79	56	46
$Z(\to \nu\nu) + 2j$	28000	630	160
$Z(\to \nu\nu)W^\pm(\to 2j)$	240	3.4	0.30
$Z(\to \nu\nu)Z(\to 2j)$	220	6.1	0.76
$t\bar{t}$: fully leptonic	260 (12)	1.5	0.89
$t\bar{t}$: semi-leptonic	880 (290)	2.3	1.1

$\nu = \nu_e, \nu_\mu, \nu_\tau$.

For $t\bar{t}$ a veto on events with isolated leptons.

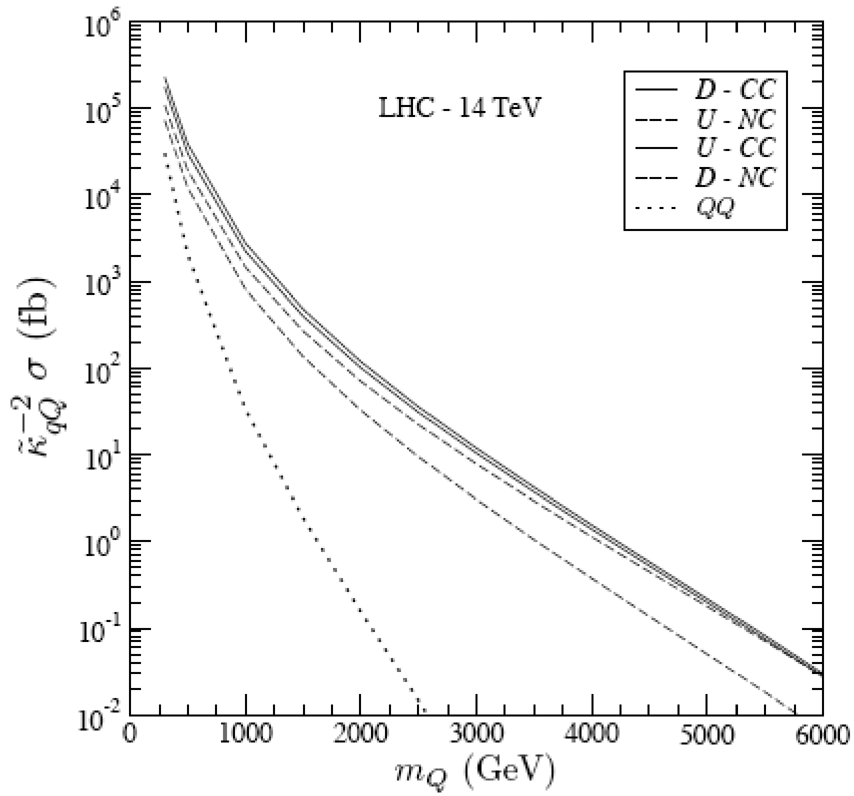
Sensitivity at Tevatron

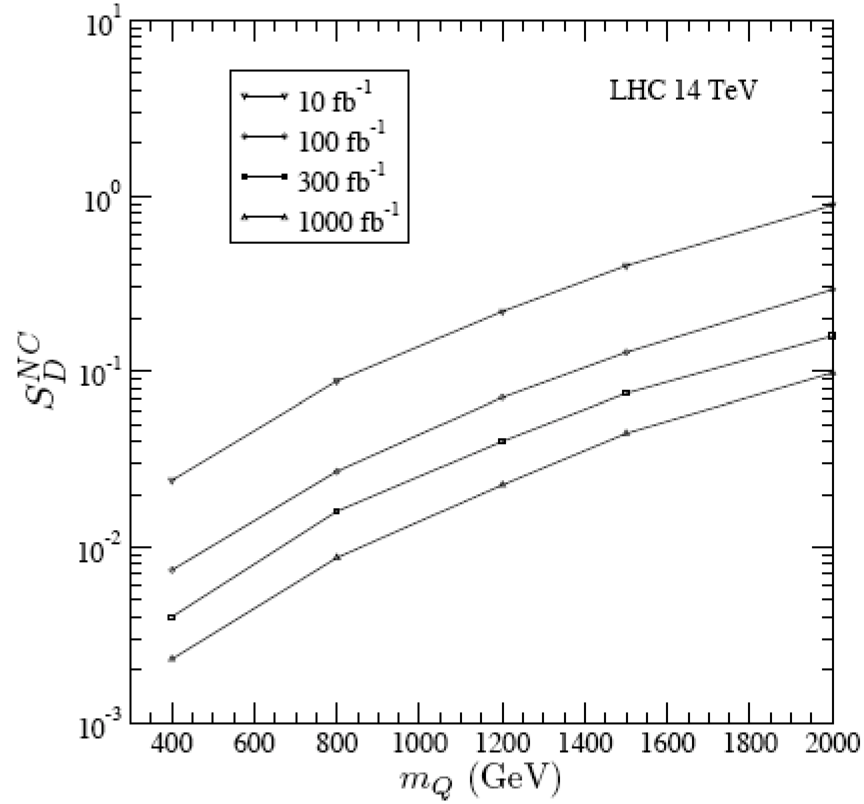




$\int \mathcal{L}dt$	4 fb^{-1}		8 fb^{-1}	
Sensitivity	2σ	5σ	2σ	5σ
m_D for $S_D^{CC} = 1$ (2)	720 (820)	580 (670)	760 (860)	630 (710)
m_U for $S_U^{CC} = 1$ (2)	470 (530)	370 (440)	490 (560)	400 (470)
m_D for $S_D^{NC} = 1$ (2)	450 (530)	350 (420)	490 (570)	380 (470)
m_U for $S_U^{NC} = 1$ (2)	590 (680)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

LHC peek





LHC reach via pair production:

D ~ 640 (720) GeV at 5sigma with 5 (10) fb^{-1} data at 14 TeV

Via single production in specific model and parameter choice

T' ~ 500 GeV at 5sigma with 3 (7) fb^{-1} data at 14 TeV

Conclusions

- New Physics at TeV scale required to address SM open questions - SUSY, warped ED, little higgs, etc
- Some new particles are expected with Tevatron/LHC reach
- Considered single production of heavy quarks with arbitrary coupling - has enhanced sensitivity compared to QCD pair production
- Can probe heavy quark mass up to 850 GeV at the Tevatron
- Enhanced sensitivity at LHC plus exotic charge quarks; model discrimination
- Heavy quarks can be found in many new physics scenarios

  Example: Light KK quarks in Randall-Sundrum models

Tevatron is still competitive with the LHC