Heavy Quarks Above the “Top” at Hadron Colliders

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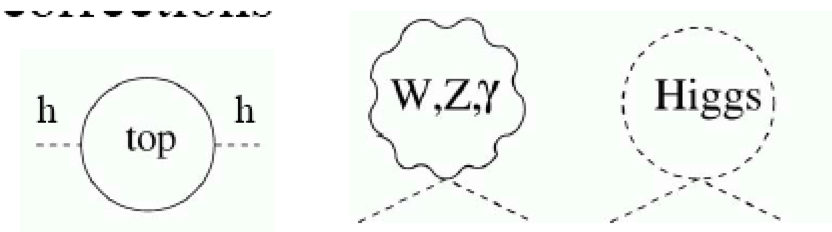
Outline

- Introduction
- Tevatron
- LHC
- Future analysis
- Conclusion

Introduction

- Standard Model of particle interactions is very successful
- Agrees remarkably well with experiments
- Not the whole story - dark matter, neutrino mass….
- Hierarchy problem



$$\delta M_h^2 = \frac{G_F}{4\sqrt{2}\pi^2}\Lambda^2\left(6M_W^2 + 3M_Z^2 + M_h^2 - 12M_t^2\right)$$

$$= -\left(\frac{\Lambda}{0.7\,\text{TeV}}\,200\,\text{GeV}\right)^2$$

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

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

$$M_\chi = M_q \text{ and } m = m_{\chi u} = m_{qu} >> m_u$$

$$\chi \text{ and } q \text{ mix only with } u_R$$

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

We study generic heavy quarks!

What we study

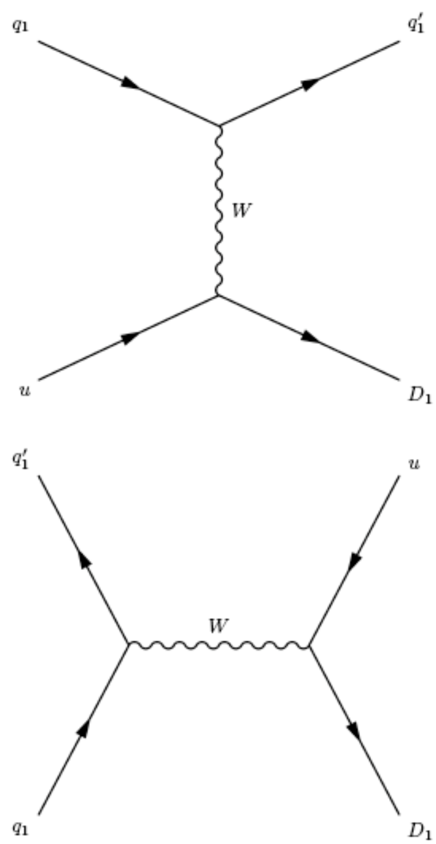
- Generic heavy quarks with arbitrary couplings

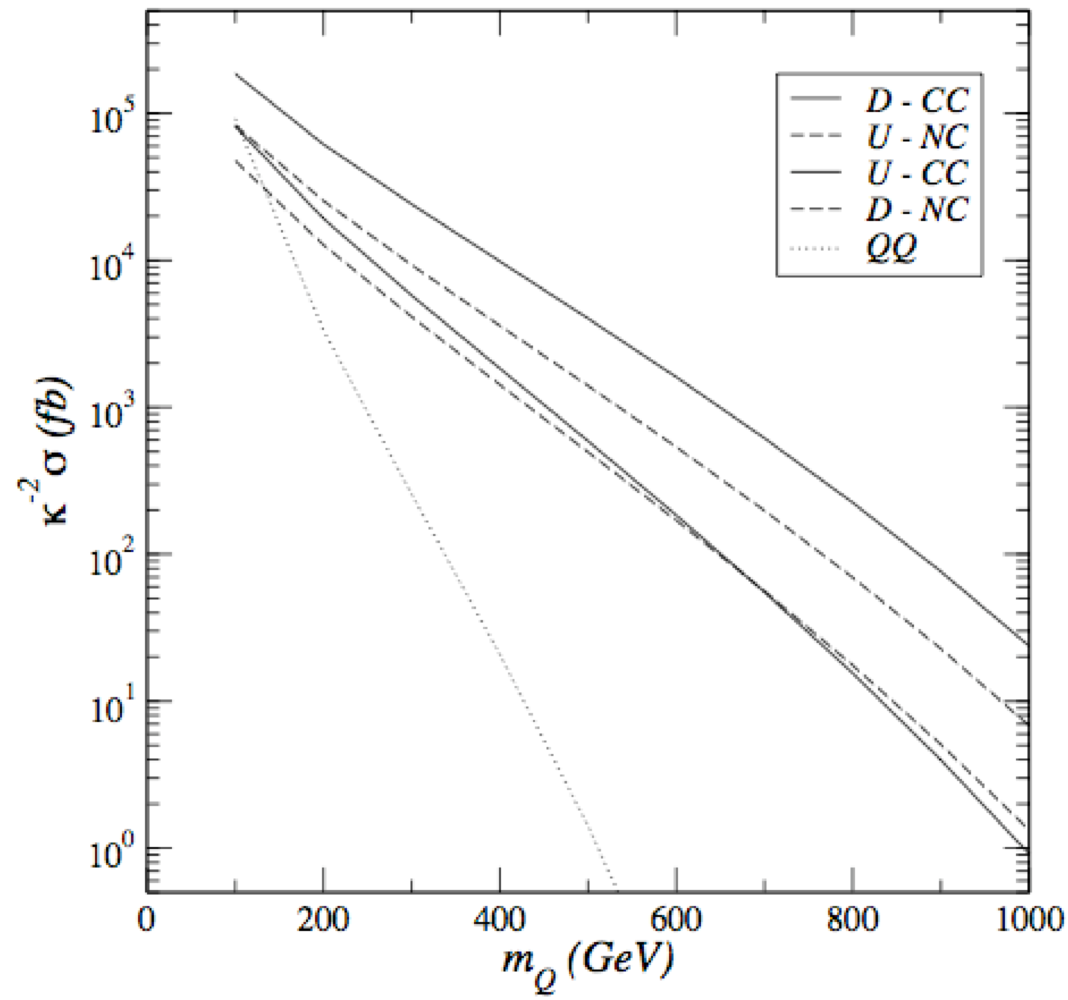
$$\frac{g}{\sqrt{2}} W_\mu^+ (\kappa_{uD} \bar{u}_R \gamma^\mu D_R + \kappa_{Ud} \bar{U}_R \gamma^\mu d_R) + \frac{g}{2c_W} Z_\mu (\kappa_{uU} \bar{u}_R \gamma^\mu U_R + \kappa_{dD} \bar{d}_R \gamma^\mu D_R) + \text{h.c.}$$

- D_i : charge -1/3 heavy quarks that mix with SM quark *of* i^{th} generation
- U_i : charge 2/3 heavy quarks that mix with SM quark of i^{th} generation
- Study both CC and NC processes for Tevatron and LHC

Signal Process: Production

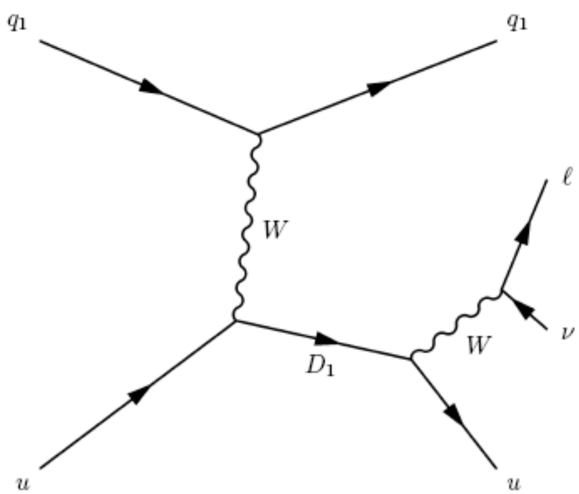
QCD pair production vs Electroweak single production

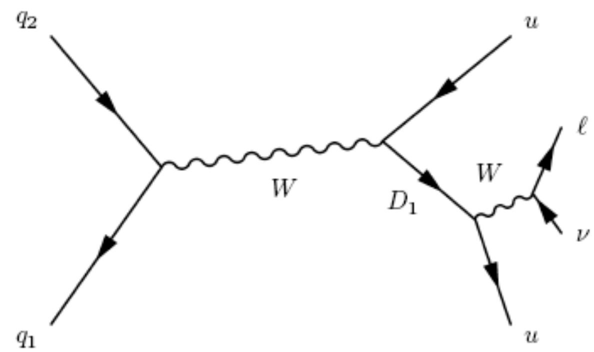




Signal Process: Decay

$$pp/p\bar{p} \rightarrow qD_1 \rightarrow quW \rightarrow qu\ell\nu$$



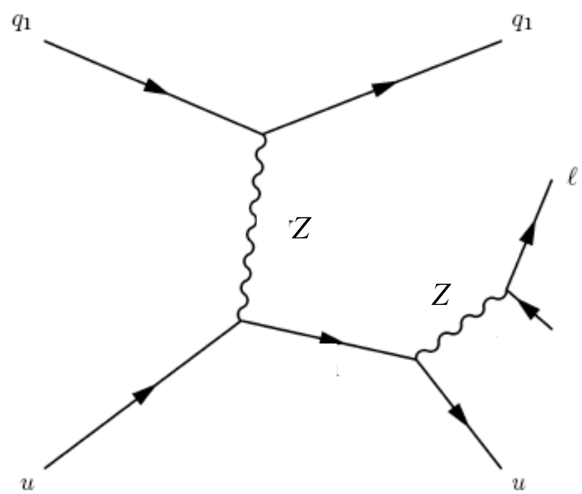


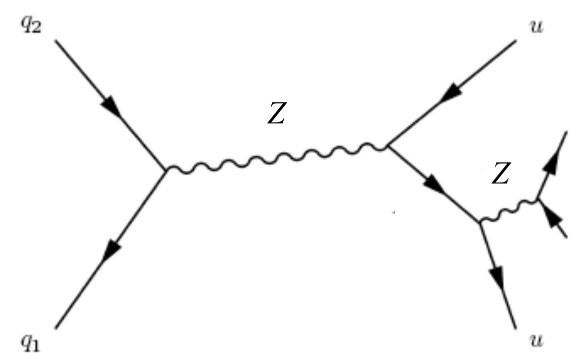
- Both D_1 and $\overline{D_1}$ considered, similarly U_1 and $\overline{U_1}$
- Full spin correlation maintained
- Tevatron, E_{cm} = 1.96 TeV

Signal: $2j + \ell + \not{E}_T$

Signal Process: Decay

$$pp\,/\,p\bar{p} \rightarrow qU_1 \rightarrow quZ \rightarrow qu\ell^+\ell^- \quad or \quad qu\nu\nu$$





- Both U_1 and $\overline{U}_1$ considered
- Both D_1 and D_1 considered
- Tevatron, E_{cm} = 1.96 TeV

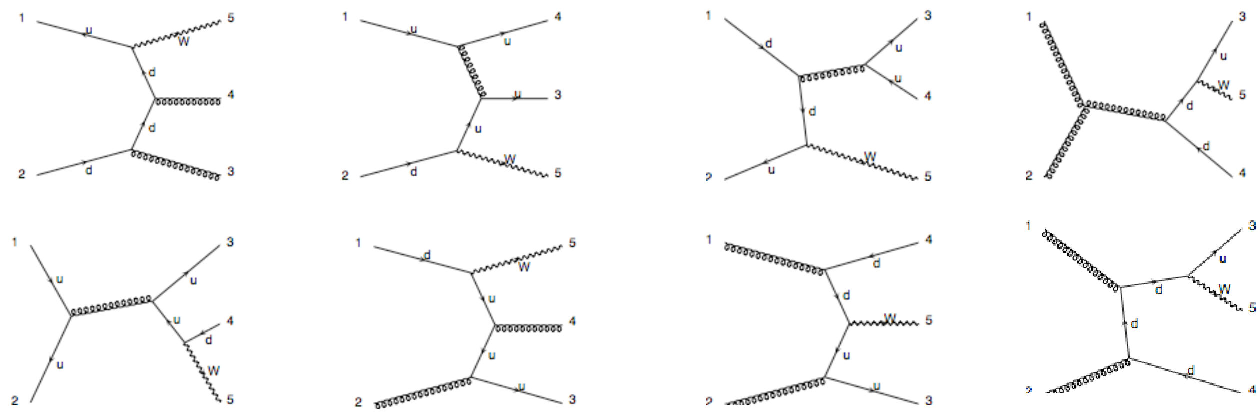
Signal: $2j + \ell^+\ell^-$

Signal: $2j + \not{E}_T$

Background Processes

Main Background:

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

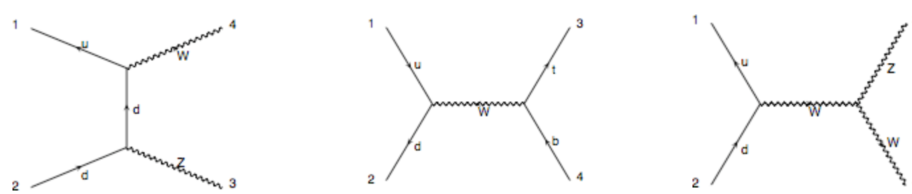


Other Background:

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:

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

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

$p_T(miss) > 15\ GeV$

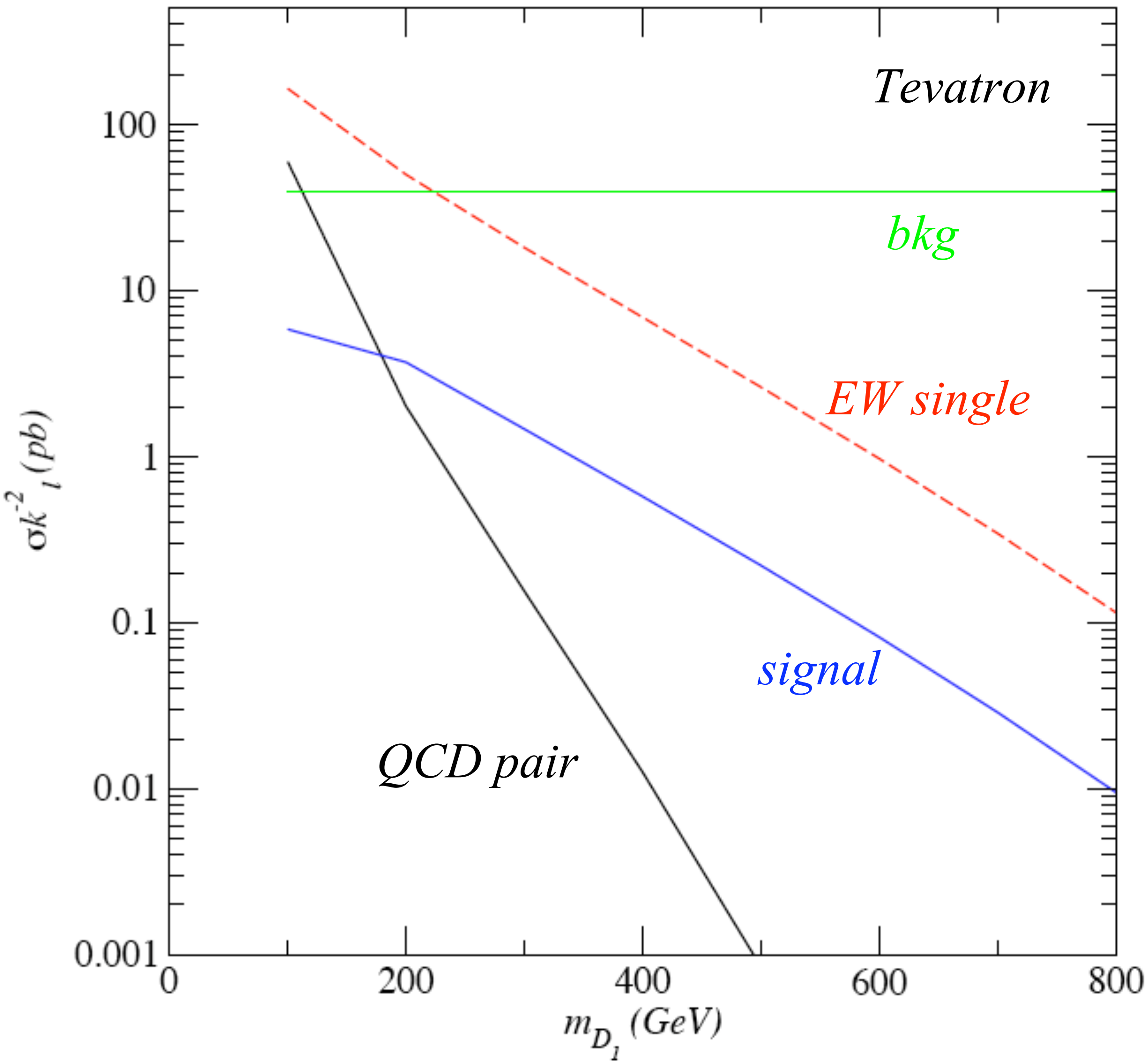
Smearing:

Energy resolution parameterized by: $\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \oplus b$

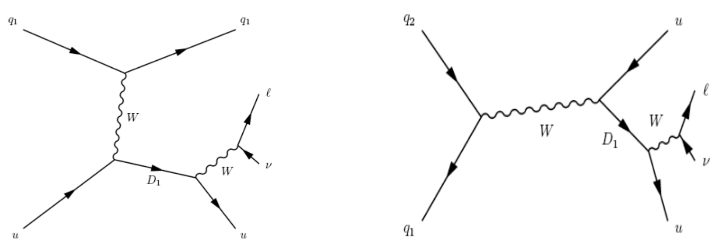
ECAL: $a = 13.5\%$ $b = 1.5\%$

HCAL: $a = 75\%$ $b = 3\%$

Signal vs Background



Signal vs Background Distributions

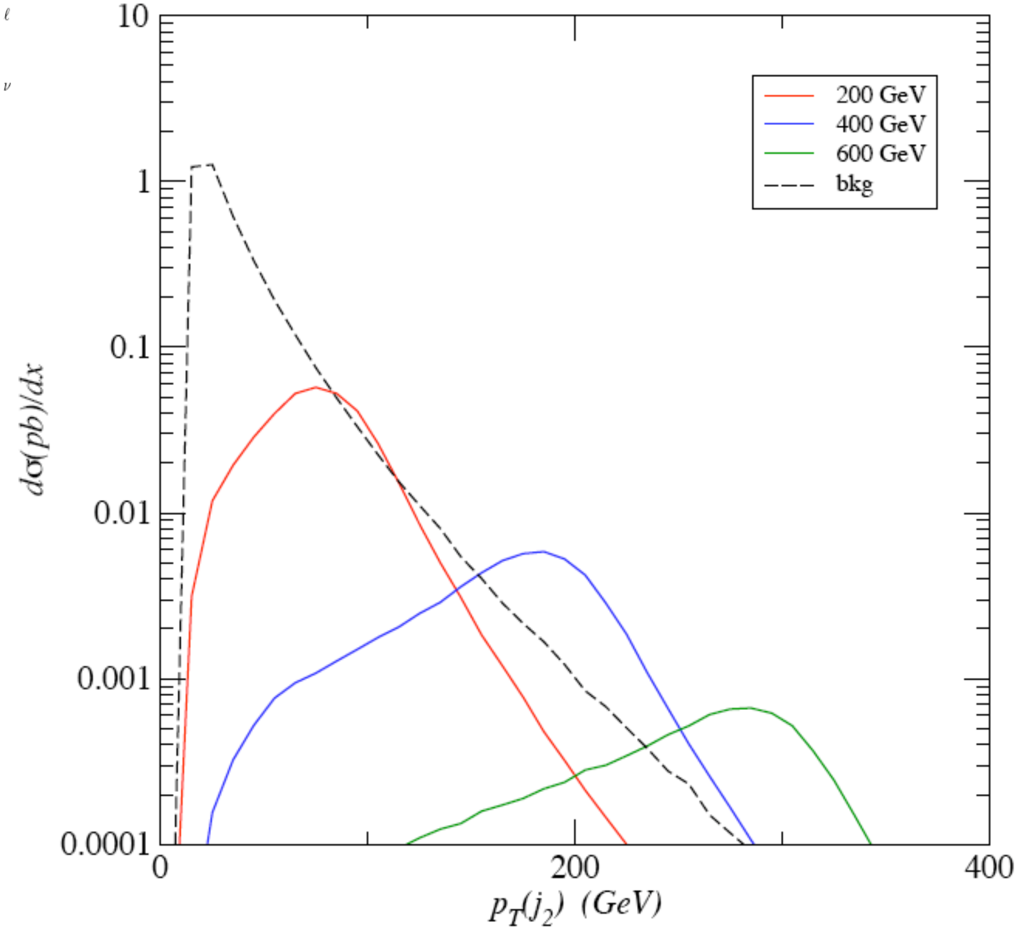


Improved Cuts:1

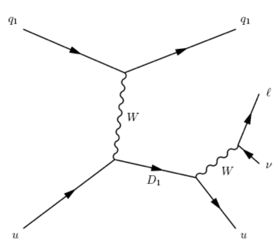
$$p_T(j_2) > \frac{m_{D_1}}{4}$$

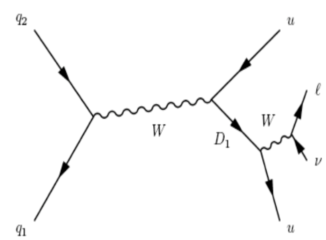
Signal efficiency:
~ 83 to 90%

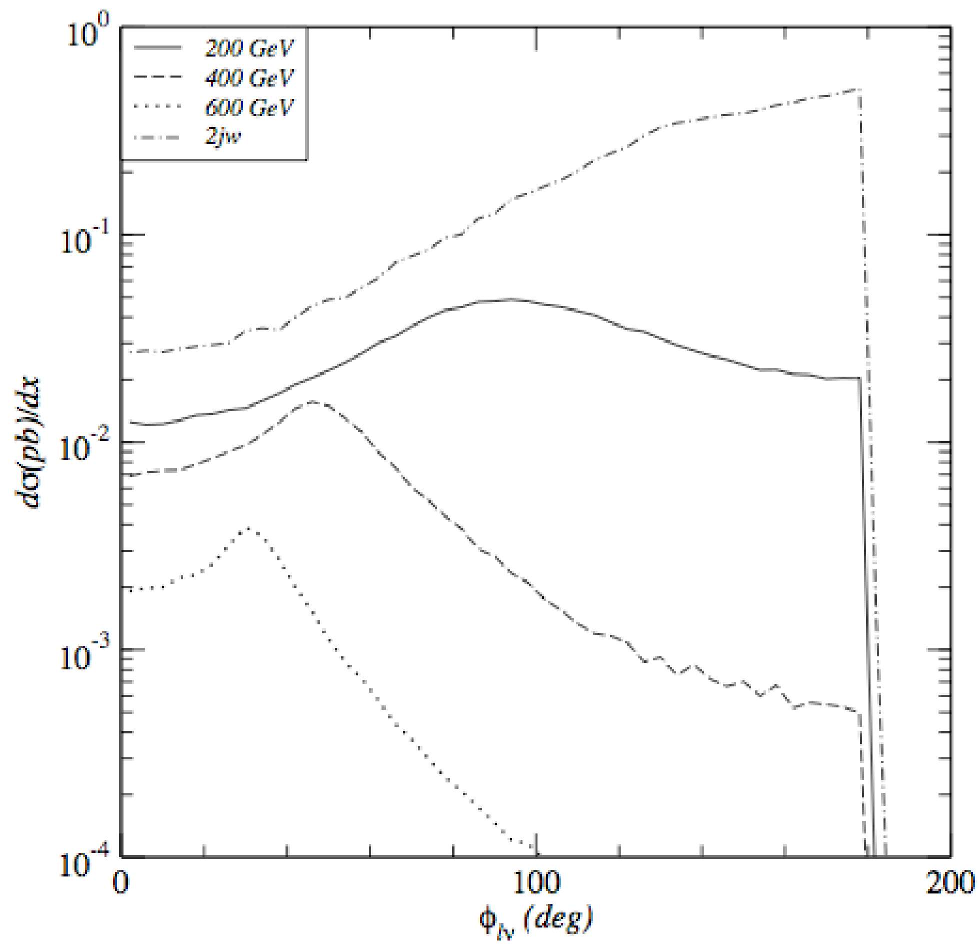
Background efficiency:
~ 0.1 to 14%



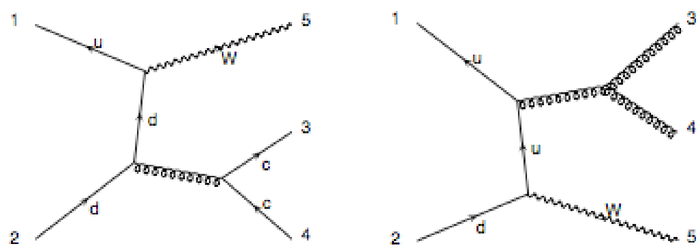
Signal vs Background Distributions







Signal vs Background Distributions

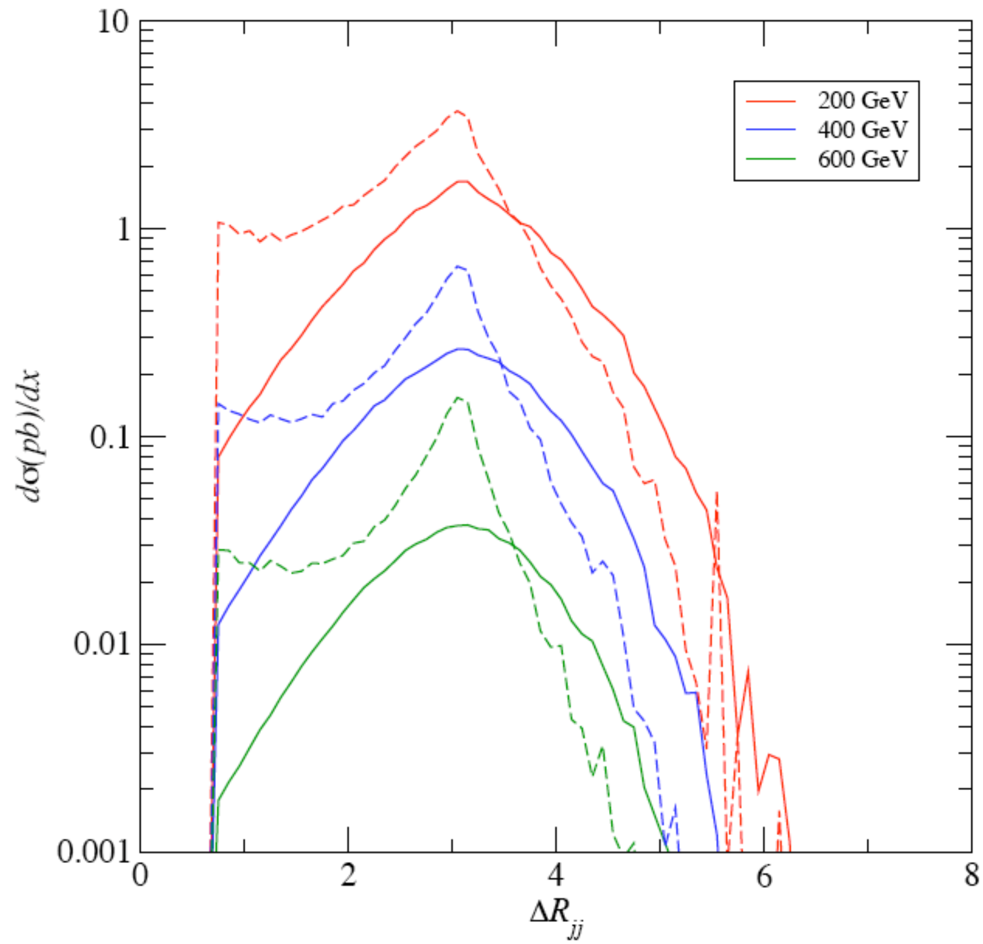


Improved Cuts: 2

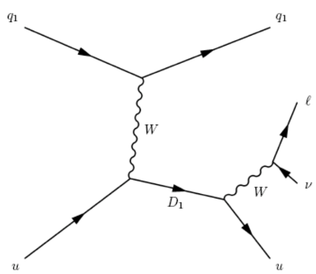
$$\Delta R_{jj} > 1.5$$

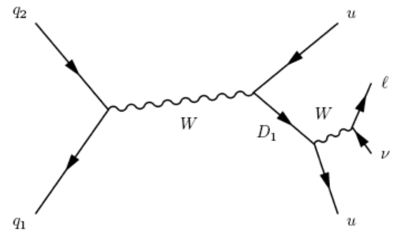
$$\Delta R_{j\ell} > 0.8$$

Signal efficiency:
~ 93 to 95%
Background efficiency:
~ 68 to 80%



Signal vs Background Distributions



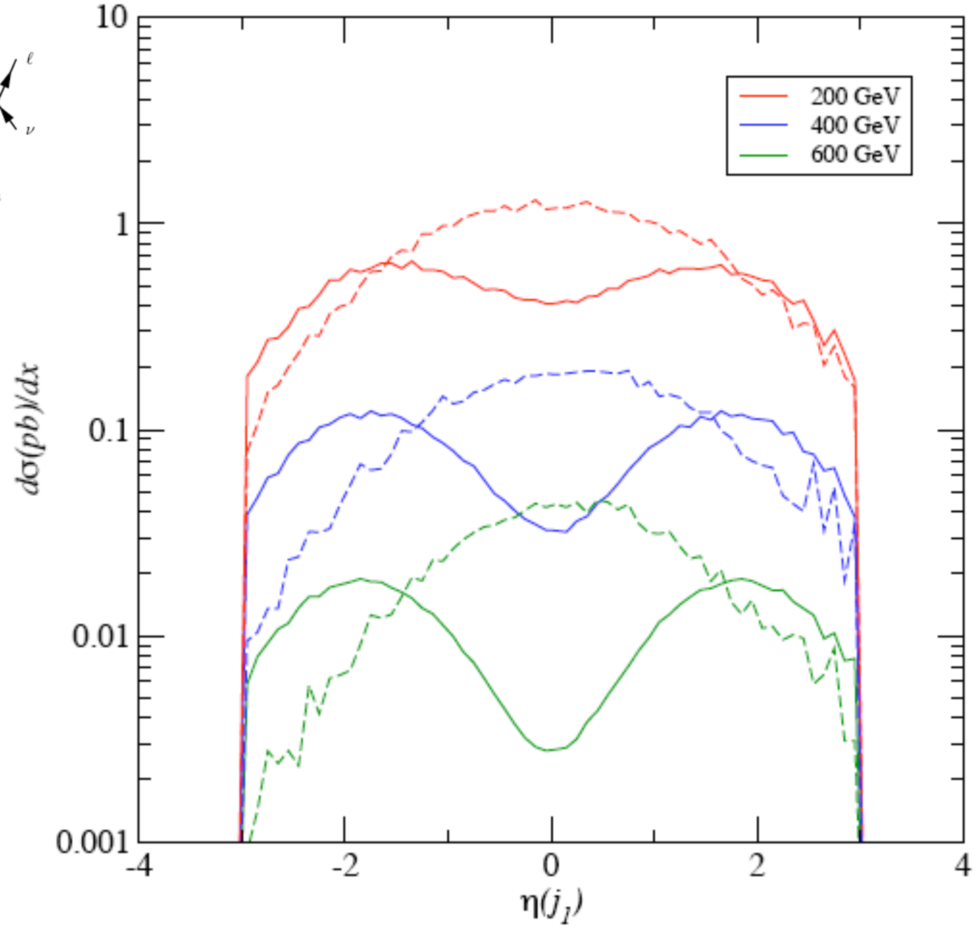


Improved Cuts: 3

$0.5 < |\eta(j_1)| < 3.0$

Signal efficiency:
~ 85 to 96%

Background efficiency:
~ 64 to 72%



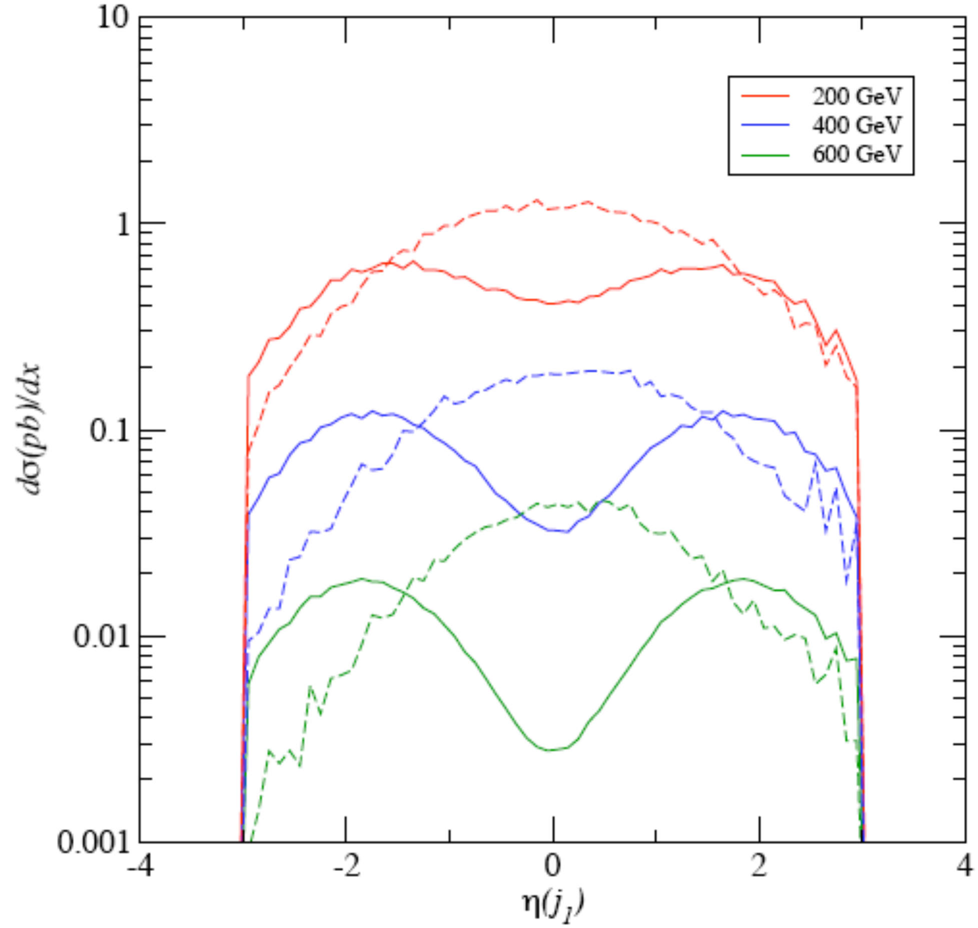
Charge Identification

D: backward jet & l-

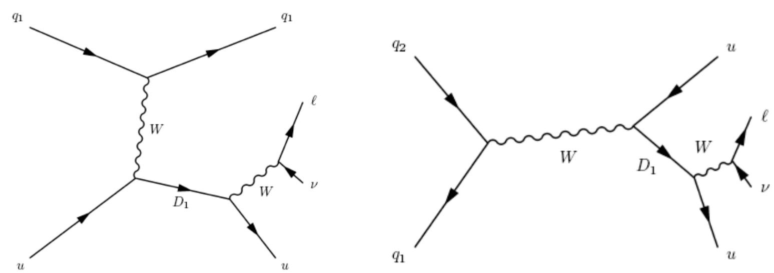
Dbar: forward jet & l+

U: forward jet & l+

Ubar: backward jet & l-



Signal vs Background Distributions

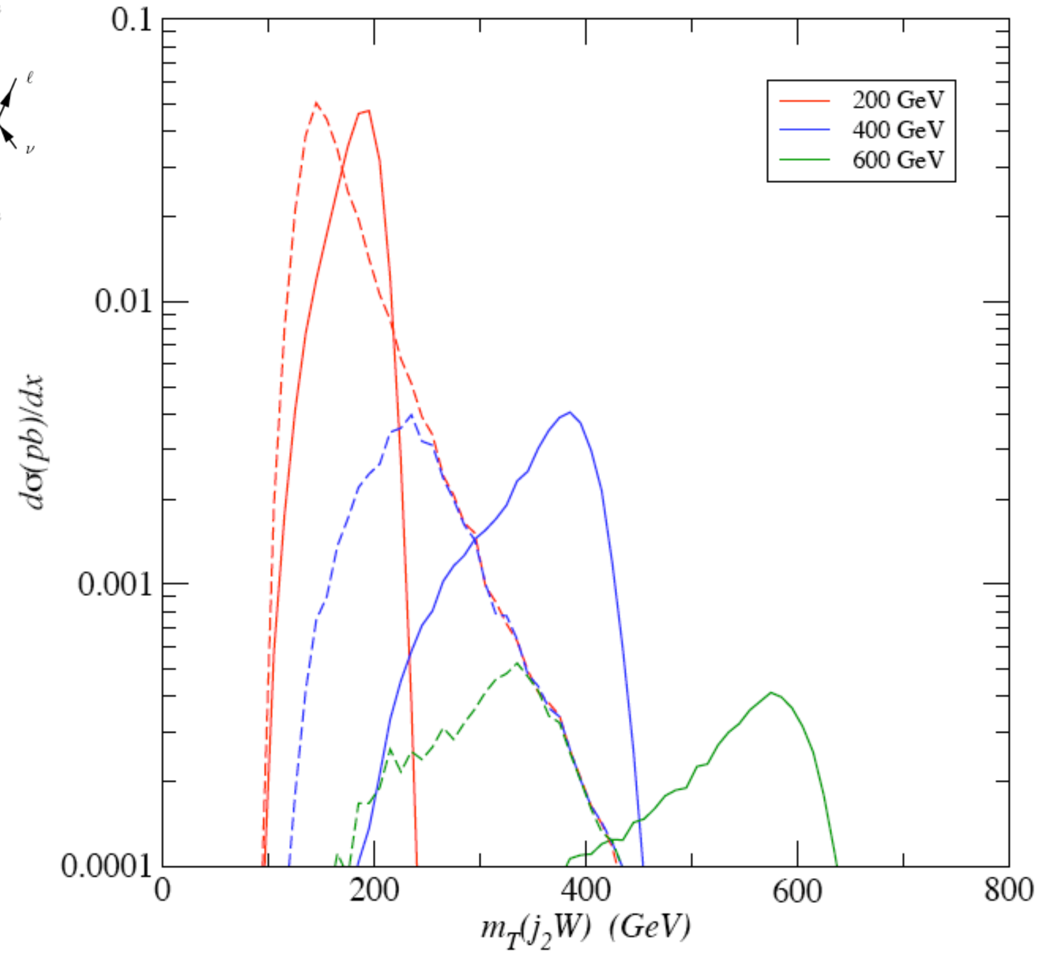


Improved Cuts: 4

$$m_{D_1} - \frac{1}{4} m_{D_1} < m_T(j_2 W)$$

$$m_{D_1} + 50GeV > m_T(j_2 W)$$

Signal efficiency:
~ 78 to 97%
Background efficiency:
~ 3 to 56%

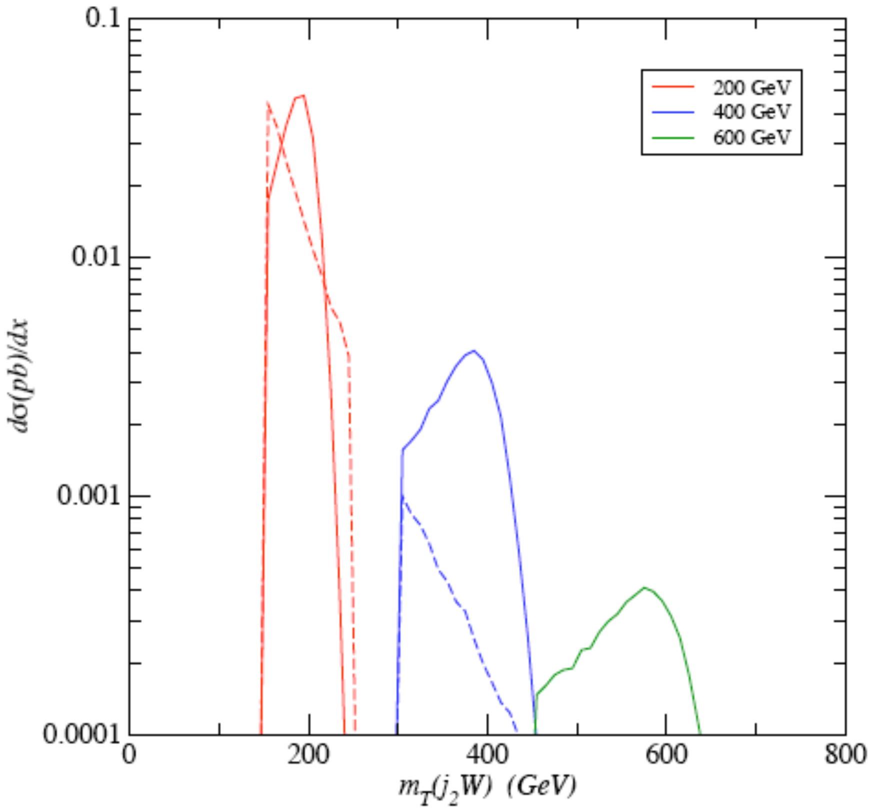


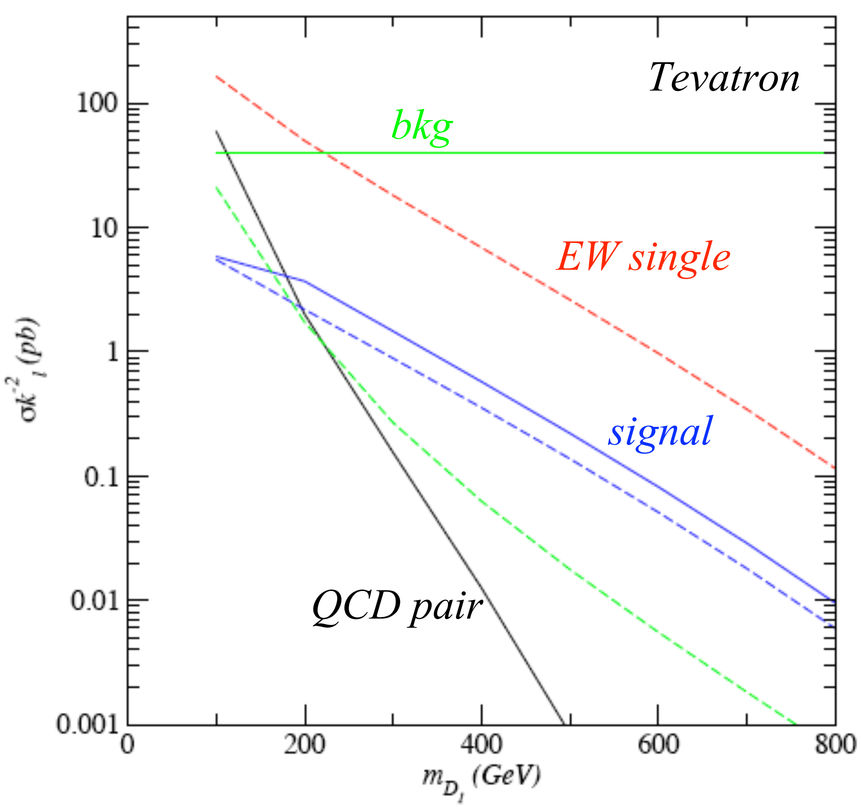
$$m_T^2(j_2 W) = [p_T^{j_2} + \sqrt{m_W^2 + (\vec{p}_T^{\,W})^2}]^2 - (\vec{p}_T^{\,j_2} + \vec{p}_T^{\,W})^2$$

Improved Cuts

$$p_T(j_2) > \frac{m_{D_1}}{4} \qquad \Delta R_{jj} > 1.5 \qquad m_{D_1} - \frac{1}{4} m_{D_1} < m_T(j_2 W)$$

$$0.5 < |\eta(j_1)| < 3.0 \qquad \Delta R_{j\ell} > 0.8 \qquad m_{D_1} + 50GeV > m_T(j_2 W)$$

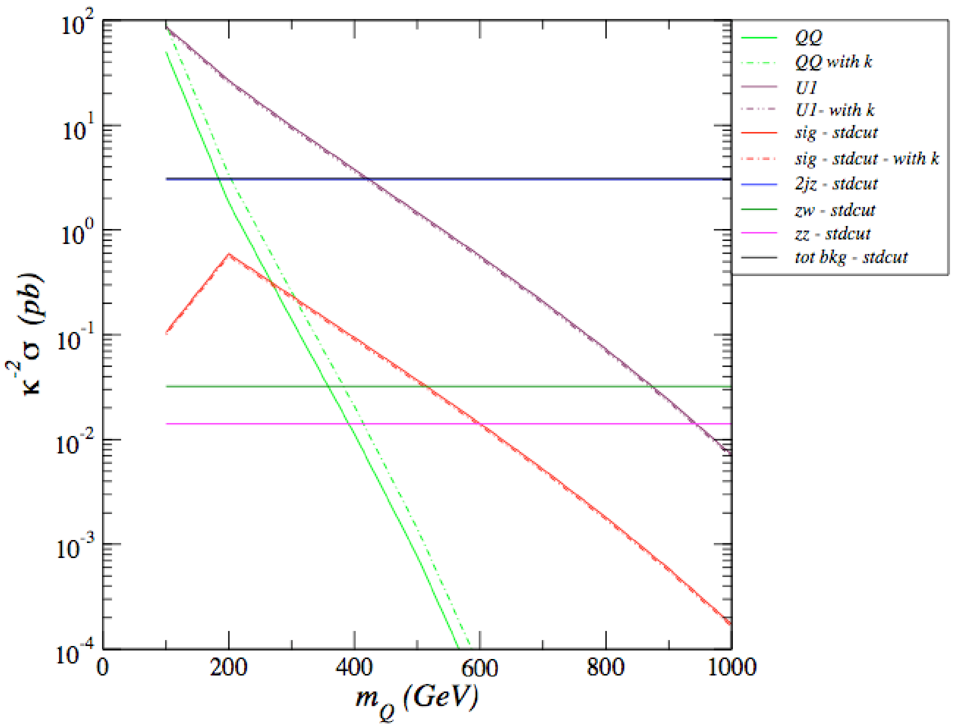


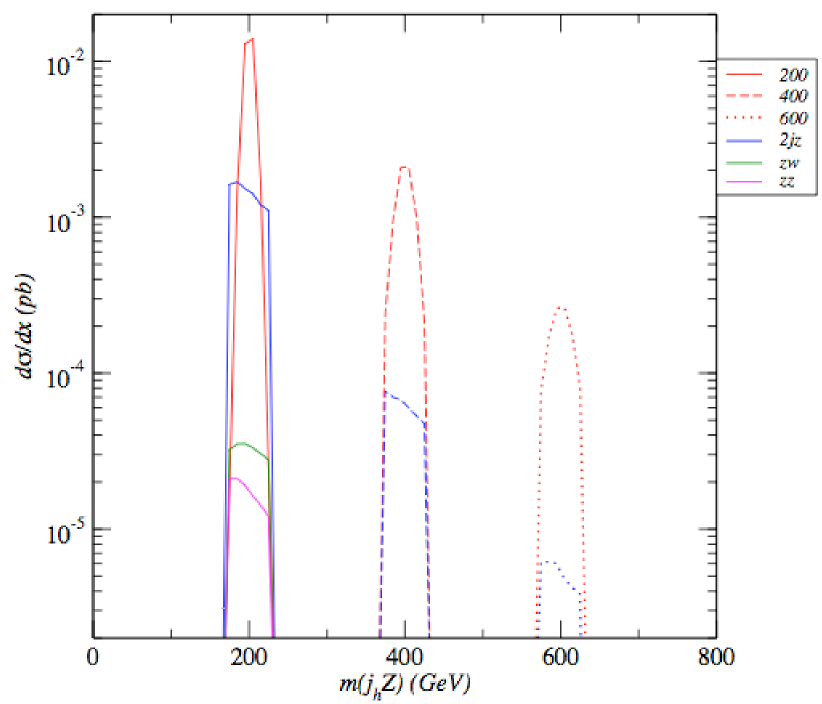


NC Channels

$$p_T(j_2) > \frac{m_{D_1}}{4} \qquad \Delta R_{jj} > 1.5 \qquad m_Q - 30 < m(j_h Z) < m_Q + 30$$

$$0.5 < |\eta(j_1)| < 3.0 \qquad \Delta R_{j\ell} > 0.8$$

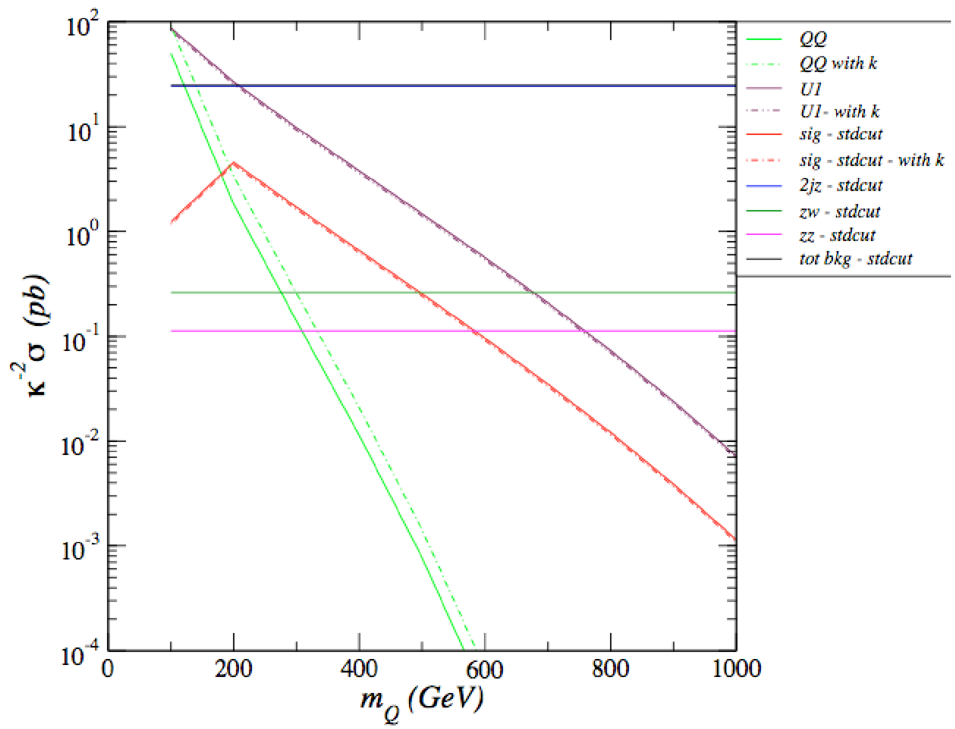


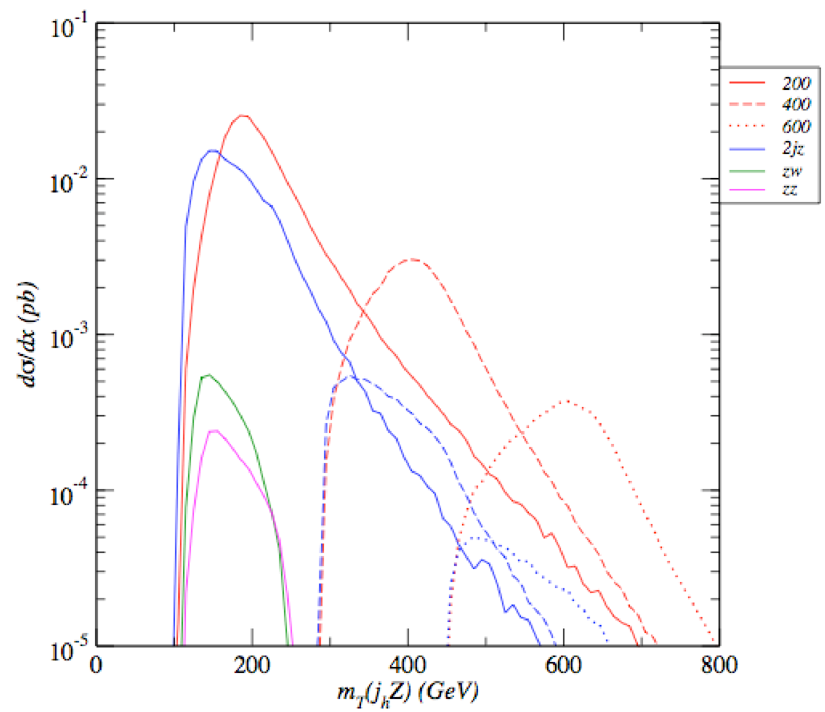


NC Channels

$$p_T(j_2) > \frac{m_{D_1}}{4} \qquad \Delta R_{jj} > 1.5 \qquad m_{D_1} - \frac{1}{4} m_{D_1} < m_T(j_2 W)$$

$$0.5 < |\eta(j_1)| < 3.0 \qquad \Delta R_{j\ell} > 0.8 \qquad m_{D_1} + 50 GeV > m_T(j_2 W)$$





$$m_T^2(j_2 Z) = [p_T^{j_2} + \sqrt{m_Z^2 + (\vec{p}_T^{\,Z})^2}]^2 - (\vec{p}_T^{\,j_2} + \vec{p}_T^{\,Z})^2$$

channels	Basic cuts (9)	High p_T (10)	m_Q (11)
CC $D \to W^{\pm}q$	1.49×10^{3}	1.09×10^{3}	9.06×10^{2}
CC $U \to W^{\pm}q$	3.08×10^{2}	2.19×10^{2}	1.81×10^{2}
$W^{\pm} + 2j$	6.81×10^{4}	5.54×10^{2}	1.27×10^{2}
$W^{\pm}W^{\mp}(\to 2j)$	1.50×10^{3}	9.32	8.59×10^{-1}
$W^{\pm}Z(\to 2j)$	2.41×10^{2}	2.99	3.15×10^{-1}
single top: $W^{\pm}b\ j$	3.58×10^{2}	1.34	-
NC $D \to Z(\to \ell\ell)q$	7.06×10^{1}	4.96×10^{1}	4.92×10^{1}
NC $U \to Z(\to \ell\ell)q$	1.78×10^{2}	1.27×10^{2}	1.26×10^{2}
$Z(\to \ell\ell) + 2j$	6.06×10^{3}	5.89×10^{1}	7.46
$Z(\to \ell\ell)W^{\pm}(\to 2j)$	6.42×10^{1}	4.64×10^{-1}	6.12×10^{-2}
$Z(\to \ell\ell)Z(\to 2j)$	2.83×10^{1}	3.65×10^{-1}	3.61×10^{-2}
NC $D \to Z(\to \nu\nu)q$	2.47×10^{2}	1.74×10^{2}	1.44×10^{2}
NC $U \to Z(\to \nu\nu)q$	6.24×10^{2}	4.44×10^{2}	3.68×10^{2}
$Z(\to \nu\nu) + 2j$	2.45×10^{4}	2.62×10^{2}	6.91×10^{1}
$Z(\to \nu\nu)W^{\pm}(\to 2j)$	2.62×10^{2}	1.95	1.82×10^{-1}
$Z(\to \nu\nu)Z(\to 2j)$	1.13×10^{2}	1.65	2.16×10^{-1}

Current Constraints

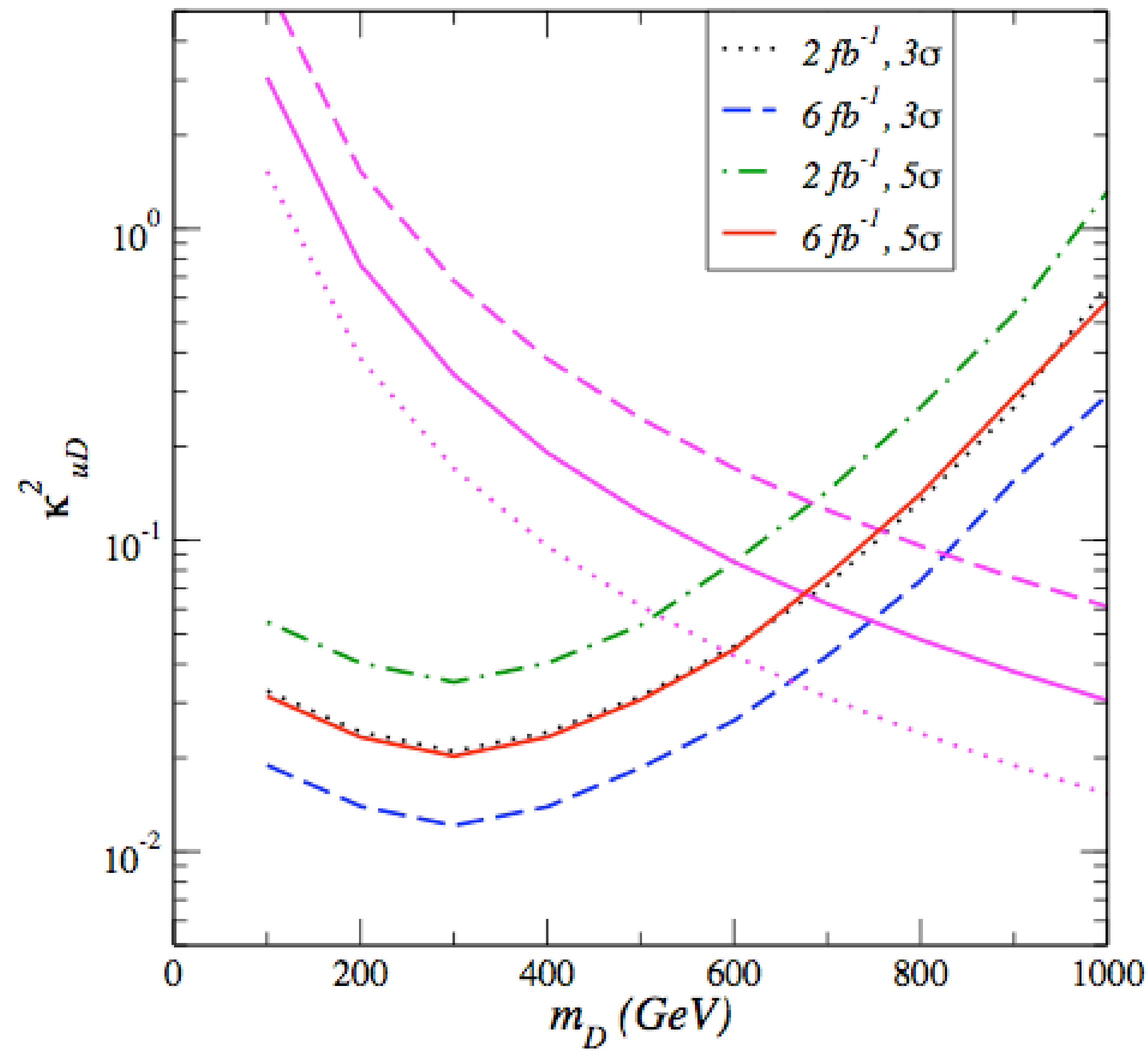
- Searches for extra quarks
  - Limits on *b`* are around 250 GeV from *1* fb^{-1} data
  - Limits are from $b` \rightarrow b\,Z$ mode
  - No $b` \rightarrow Wj$ mode analysis available

http://www-cdf.fnal.gov/physics/exotic/exotic.html

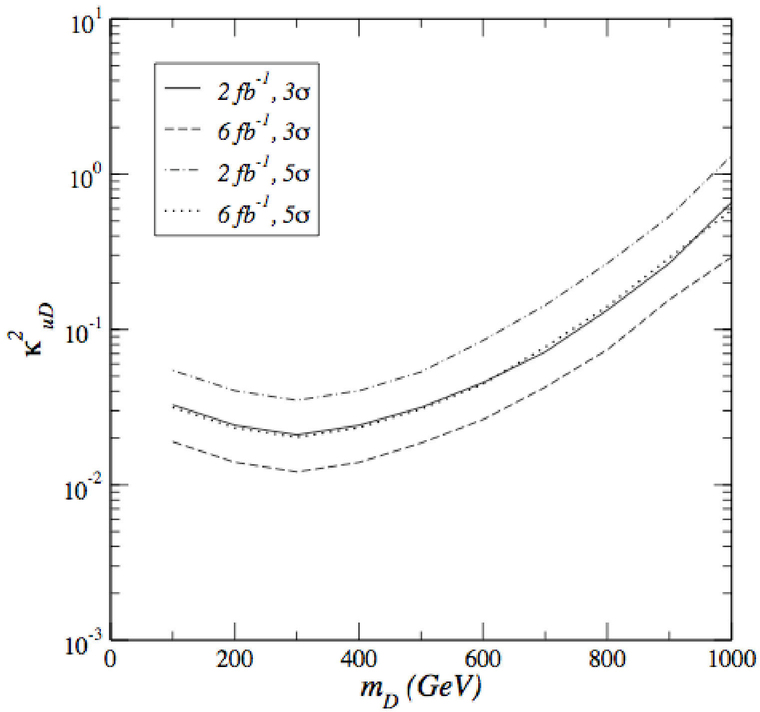
- Limits on a *t`* $(\rightarrow Wb)$ are 265 GeV with about *1* fb^{-1}

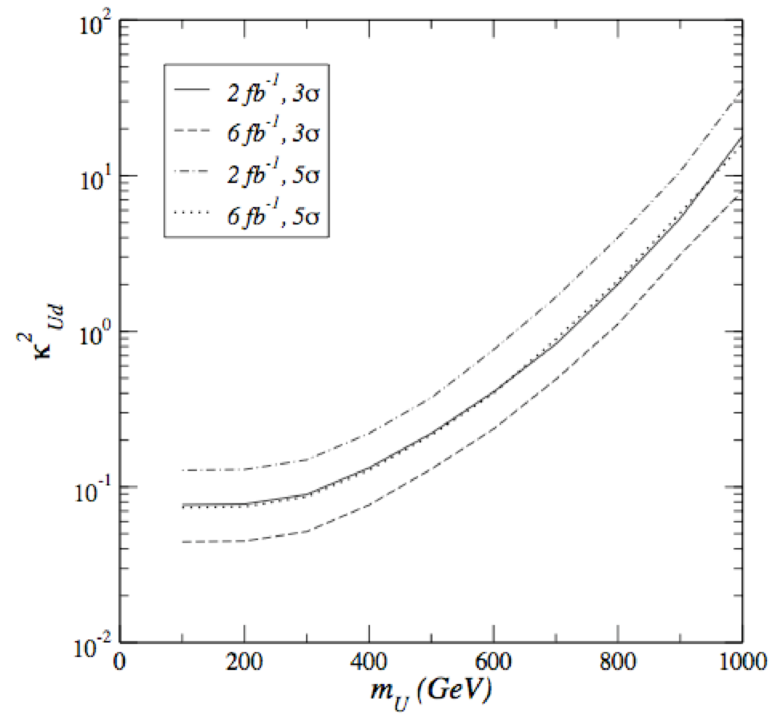
http://www-cdf.fnal.gov/physics/new/top/top.html

Sensitivity at Tevatron

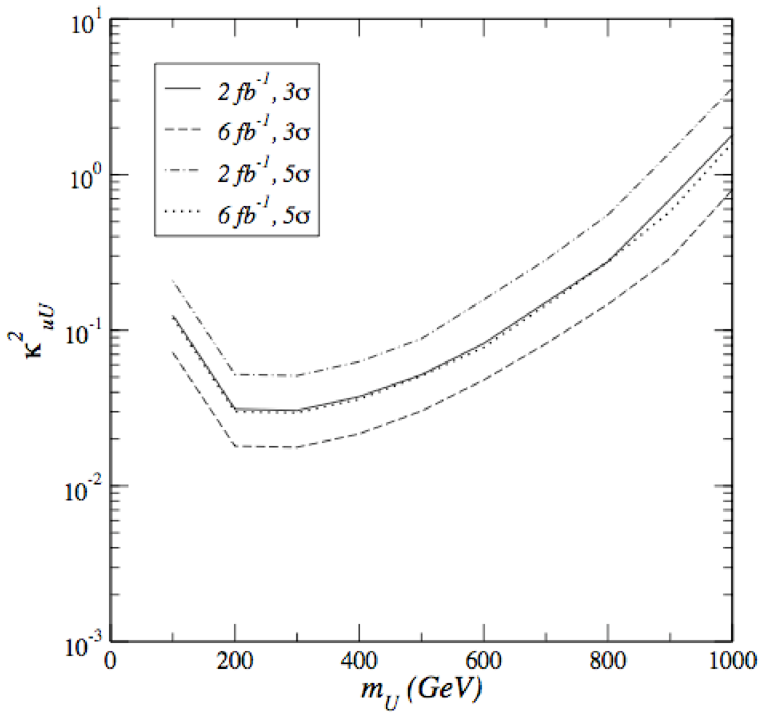


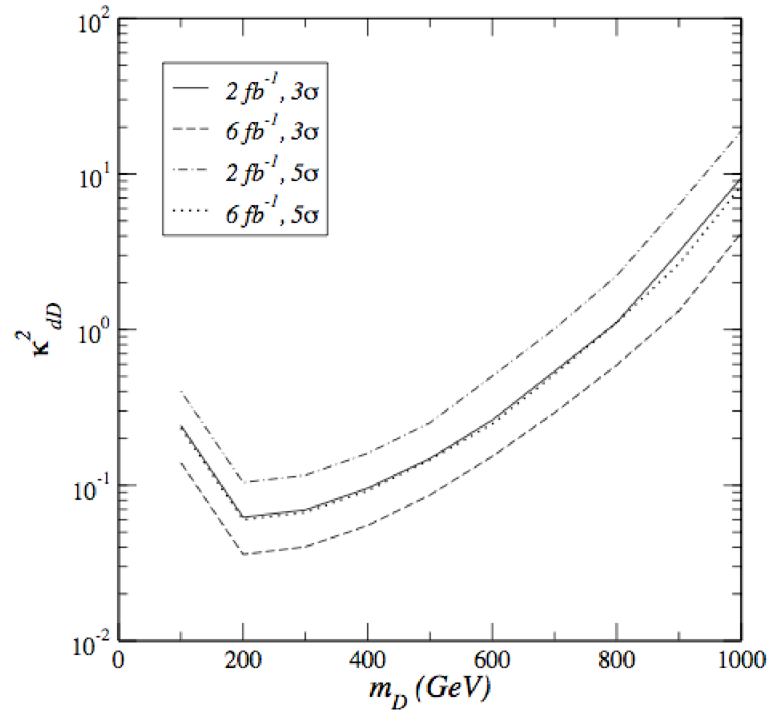
Sensitivity - Charged Currents





Sensitivity - Neutral Currents

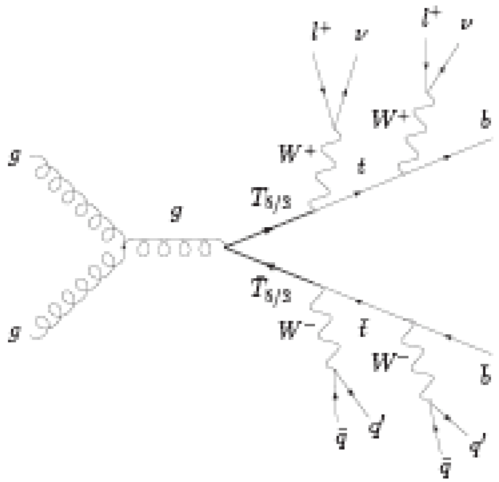


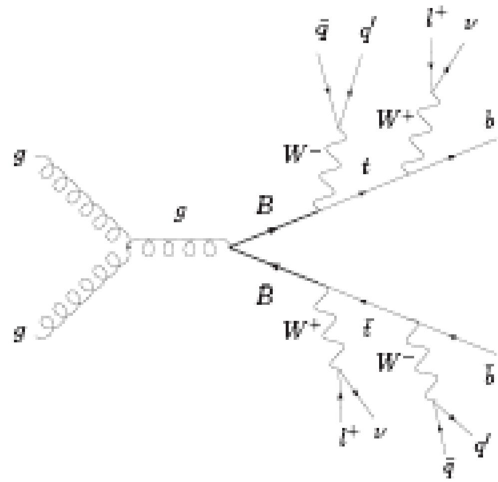


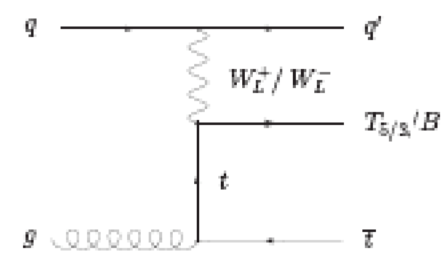
Further analysis in progress

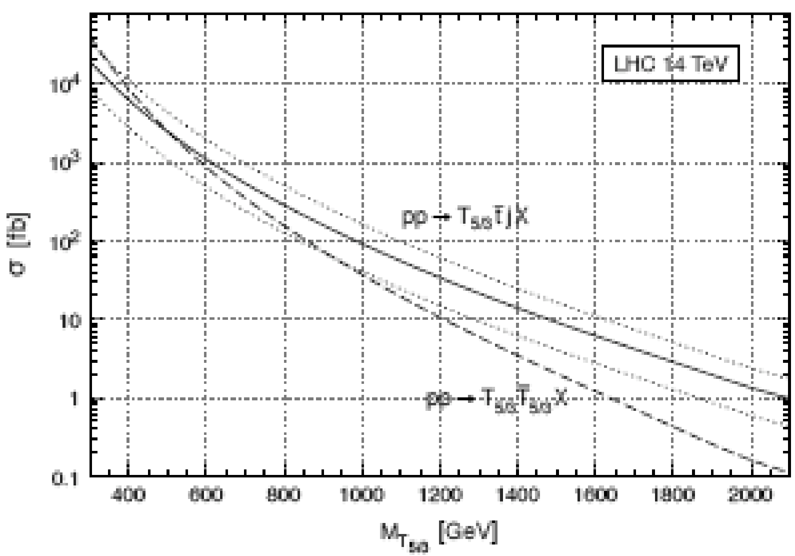
- Sensitivity at LHC - similar study but different challenges
- Low/Intermediate mass and High mass
- Heavy quarks that mix with second and third generations
  - c-tagging, third generation bkg
- Studies including ISR/FSR, showering on going
- Quarsk with exotic charges (5/3) - reconstruct charge of exotic quark via same sign leptons

Further analysis in progress



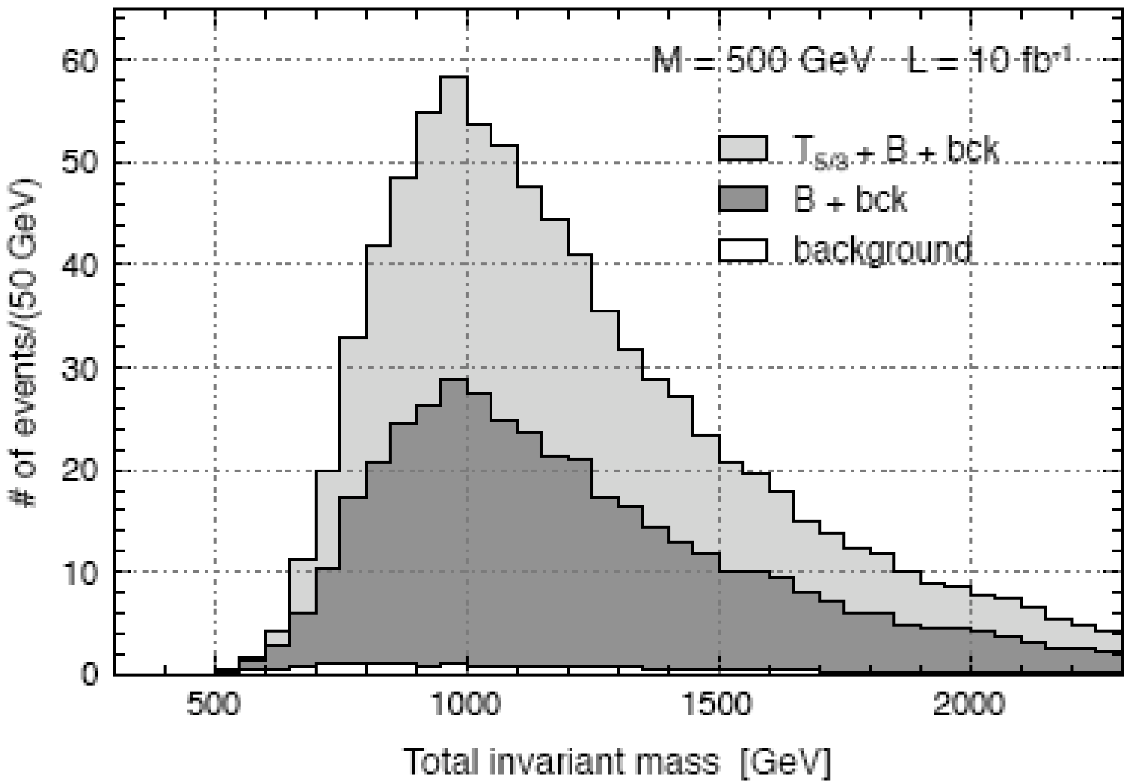






Contino, Servant '08

Further analysis in progress



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Conclusions

- Considered single production of heavy quarks with arbitrary coupling
- Single production has enhanced sensitivity compared to QCD pair production
- Can probe heavy quark mass up to 800 GeV at the Tevatron
- Enhanced sensitivity at LHC plus exotic charge quarks
- Heavy quarks can be found in many new physics scenarios

  Example: Light Kaluza-Klein quarks in Randall-Sundrum models

We can still discover new physics at the Tevatron!

Supplementary Slides

$Q^{(m)}$	U	D	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
isospin	0	0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1
hypercharge	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{7}{6}$	$-\frac{5}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$

$$\mathcal{L}^Z = -\frac{g}{2\cos\theta_W}\left(\bar{u}^i_L X^{uL}_{ij}\gamma^\mu u^j_L + \bar{u}^i_R X^{uR}_{ij}\gamma^\mu u^j_R\right.$$

$$\left. -\bar{d}^i_L X^{dL}_{ij}\gamma^\mu d^j_L - \bar{d}^i_R X^{dR}_{ij}\gamma^\mu d^j_R - 2\sin^2\theta_W J^\mu_{EM}\right) Z_\mu ,$$

$$\mathcal{L}^W = -\frac{g}{\sqrt{2}}(\bar{u}^i_L W^L_{ij}\gamma^\mu d^j_L + \bar{u}^i_R W^R_{ij}\gamma^\mu d^j_R)W^+_\mu + \text{h.c.},$$

$$\mathcal{L}^H = -\frac{1}{\sqrt{2}}(\bar{u}^i_L Y^u_{ij} u^j_R + \bar{d}^i_L Y^d_{ij} d^j_R)H + \text{h.c.},$$

$$X^{uL}_{ij} = \delta_{ij} - \frac{v^2}{\Lambda^2}V_{ik}(\alpha^{(1)}_{\phi q} - \alpha^{(3)}_{\phi q})_{kl}V^\dagger_{lj},$$

$$X^{uR}_{ij} = -\frac{v^2}{\Lambda^2}(\alpha_{\phi u})_{ij},$$

$$X^{dL}_{ij} = \delta_{ij} + \frac{v^2}{\Lambda^2}(\alpha^{(1)}_{\phi q} + \alpha^{(3)}_{\phi q})_{ij},$$

$$X^{dR}_{ij} = \frac{v^2}{\Lambda^2}(\alpha_{\phi d})_{ij},$$

$$W^L_{ij} = \tilde{V}_{ik}(\delta_{kj} + \frac{v^2}{\Lambda^2}(\alpha^{(3)}_{\phi q})_{kj}),$$

$$W^R_{ij} = -\frac{1}{2}\frac{v^2}{\Lambda^2}(\alpha_{\phi\phi})_{ij},$$

$$Y^u_{ij} = \delta_{ij}\lambda^u_j - \frac{v^2}{\Lambda^2}\left(V_{ik}(\alpha_{u\phi})_{kj} + \frac{1}{4}\delta_{ij}[V_{ik}(\alpha_{u\phi})_{kj} + (\alpha_{u\phi})^\dagger_{ik}V^\dagger_{kj}]\right),$$

$$Y^d_{ij} = \delta_{ij}\lambda^d_j - \frac{v^2}{\Lambda^2}\left((\alpha_{d\phi})_{ij} + \frac{1}{4}\delta_{ij}(\alpha_{d\phi} + \alpha^\dagger_{d\phi})_{ij}\right),$$

$Q^{(m)}$	$\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}$	$\frac{(\alpha^{(3)}_{\phi q})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{\phi u})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{\phi d})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{\phi \phi})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{u\phi})_{ij}}{\Lambda^2}$	$\frac{(\alpha_{d\phi})_{ij}}{\Lambda^2}$
U	$\frac{1}{4}V^\dagger_{ik}\frac{\lambda^{\prime(1)\dagger}_{ku}\lambda^{\prime(1)}_{ul}}{M_u^2}V_{lj}$	$-\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}$	–	–	–	$2\frac{(\alpha^{(1)}_{\phi q})_{ik}}{\Lambda^2}V^\dagger_{kj}\lambda^u_j$	–
D	$-\frac{1}{4}\frac{\lambda^{\prime(2)\dagger}_{iu}\lambda^{\prime(2)}_{uj}}{M_u^2}$	$\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}$	–	–	–	–	$-2\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}\lambda^d_j$
$\begin{pmatrix} U \\ D \end{pmatrix}$	–	–	$-\frac{1}{2}\frac{\lambda^{\prime(3u)\dagger}_{iu}\lambda^{\prime(3u)}_{uj}}{M_u^2}$	$\frac{1}{2}\frac{\lambda^{\prime(3d)\dagger}_{iu}\lambda^{\prime(3d)}_{uj}}{M_u^2}$	$-\frac{\lambda^{\prime(3u)\dagger}_{iu}\lambda^{\prime(3d)}_{uj}}{M_u^2}$	$-V^\dagger_{ik}\lambda^u_k\frac{(\alpha_{\phi u})_{kj}}{\Lambda^2}$	$\lambda^d_i\frac{(\alpha_{\phi d})_{ij}}{\Lambda^2}$
$\begin{pmatrix} X \\ U \end{pmatrix}$	–	–	$\frac{1}{2}\frac{\lambda^{\prime(4)\dagger}_{iu}\lambda^{\prime(4)}_{uj}}{M_u^2}$	–	–	$V^\dagger_{ik}\lambda^u_k\frac{(\alpha_{\phi u})_{kj}}{\Lambda^2}$	–
$\begin{pmatrix} D \\ Y \end{pmatrix}$	–	–	–	$-\frac{1}{2}\frac{\lambda^{\prime(5)\dagger}_{iu}\lambda^{\prime(5)}_{uj}}{M_u^2}$	–	–	$-\lambda^d_i\frac{(\alpha_{\phi d})_{ij}}{\Lambda^2}$
$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\frac{3}{16}V^\dagger_{ik}\frac{\lambda^{\prime(6)\dagger}_{ku}\lambda^{\prime(6)}_{ul}}{M_u^2}V_{lj}$	$\frac{1}{3}\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}$	–	–	–	$\frac{2}{3}\frac{(\alpha^{(1)}_{\phi q})_{ik}}{\Lambda^2}V^\dagger_{kj}\lambda^u_j$	$\frac{4}{3}\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}\lambda^d_j$
$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$	$-\frac{3}{16}V^\dagger_{ik}\frac{\lambda^{\prime(7)\dagger}_{ku}\lambda^{\prime(7)}_{ul}}{M_u^2}V_{lj}$	$-\frac{1}{3}\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}$	–	–	–	$-\frac{4}{3}\frac{(\alpha^{(1)}_{\phi q})_{ik}}{\Lambda^2}V^\dagger_{kj}\lambda^u_j$	$-\frac{2}{3}\frac{(\alpha^{(1)}_{\phi q})_{ij}}{\Lambda^2}\lambda^d_j$

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