Collider Signatures of Heavy Quarks

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arXiv:0708.xxxx - *AA, Marcela Carena, Tao Han, Jose Santiago*

arXiv:0708.xxxx - *Kaustubh Agashe, AA, Tao Han*

Outline

- Introduction of heavy quarks
- Signal and Background
- Current constraints
- Future analysis
- Conclusion

What we study

- Generic heavy quarks with arbitrary couplings

  LH only, RH only and both

$$\mathcal{L} \propto k_\ell \frac{g}{2\sqrt{2}}(1-\gamma_5) + k_r \frac{g}{2\sqrt{2}}(1+\gamma_5)$$

- 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
- Preliminary studies presented here for CC interactions of D_1 (with LH couplings only) at the Tevatron

Heavy Quarks in New Physics

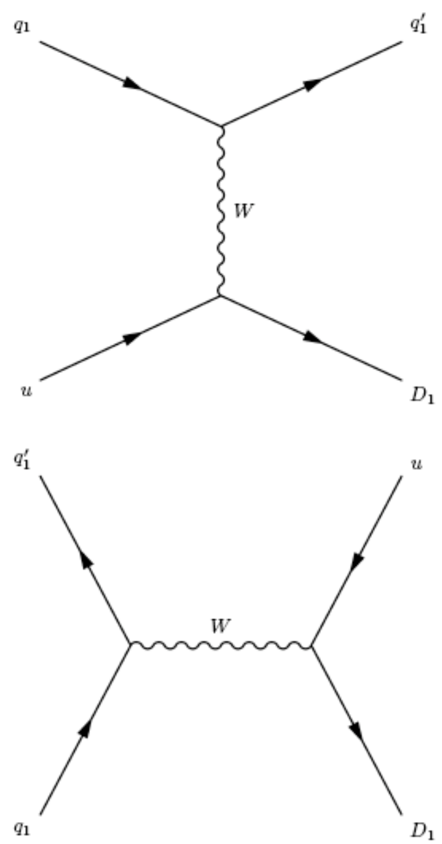
Warped extra dimensions

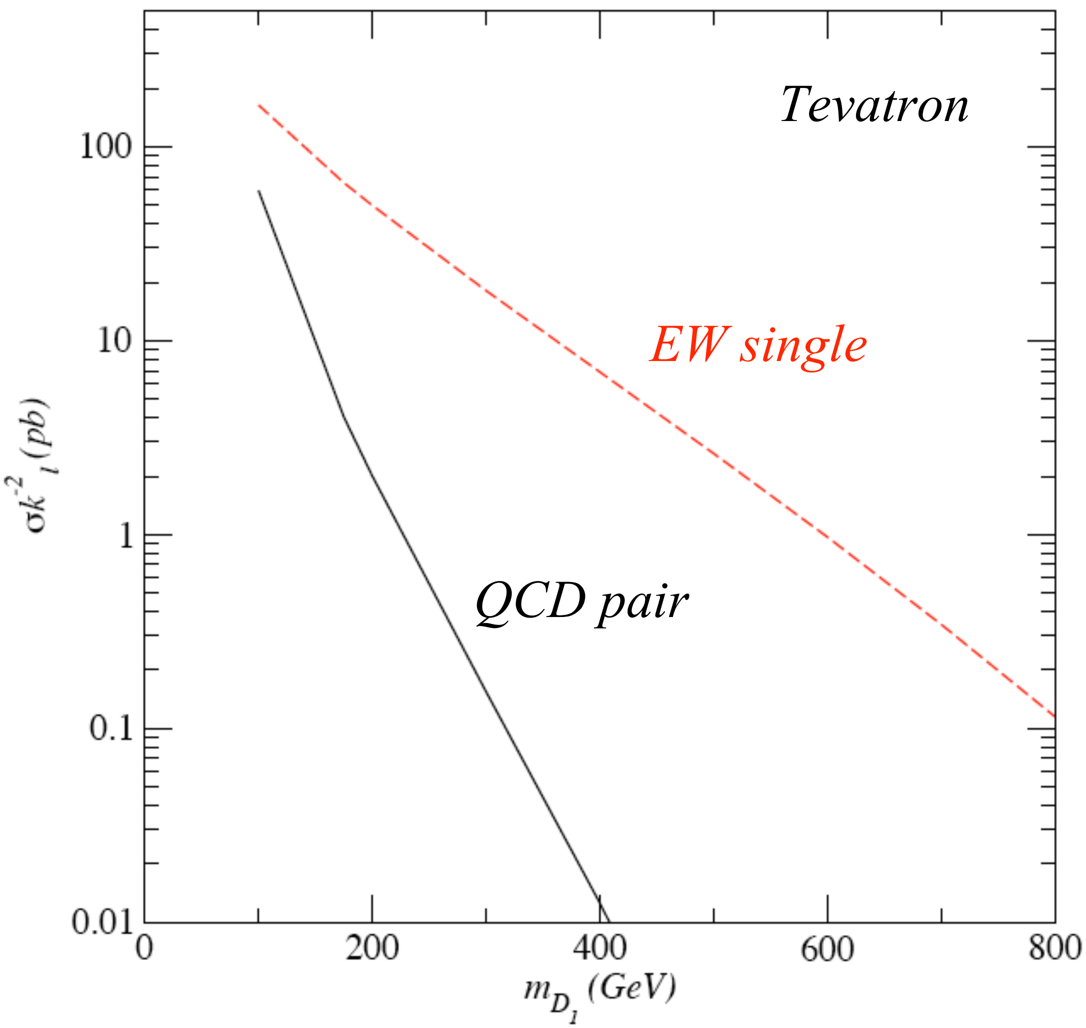
- Extend bulk gauge symmetry to custodially symmetric $SU(2)_L$x$SU(2)_R$ *Agashe, Delgado, May, Sundrum*
  - KK excitations of gauge bosons ~ few TeV
  - $SU(2)_R$ symmetric partners of RH quarks are light
- Custodial symmetry plus *L-R* symmetry protect b coupling
  - Bidoublets *Agashe, Contino, Da Rold, Pomarol*
- Higgs propagating in bulk - Gauge Higgs Unification model
  - Based on $SO(5)$x$U(1)_X$ broken to $SU(2)_L$x$SU(2)_R$x$U(1)_X$ on IR brane and $SU(2)_L$x$U(1)_Y$ on UV brane *Carena, Ponton, Santiago, Wagner*
- Warped GUTs *Agashe, Servant*
- ……. etc.

We study generic heavy quarks!

Signal Process: Production

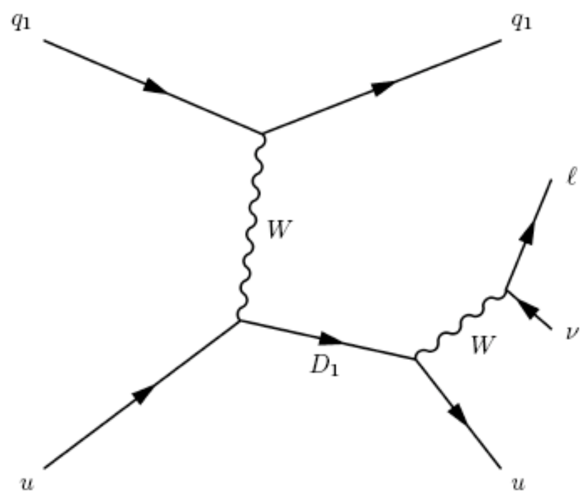
QCD pair production vs Electroweak single production

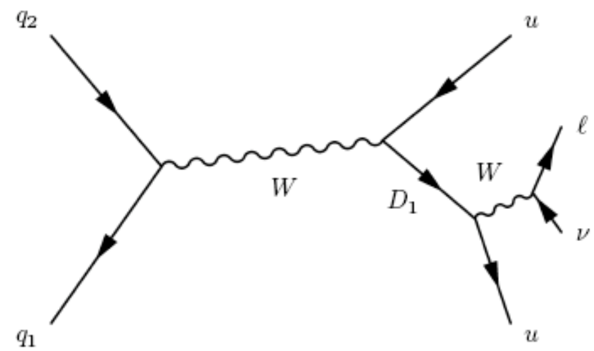




Signal Process: Decay

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





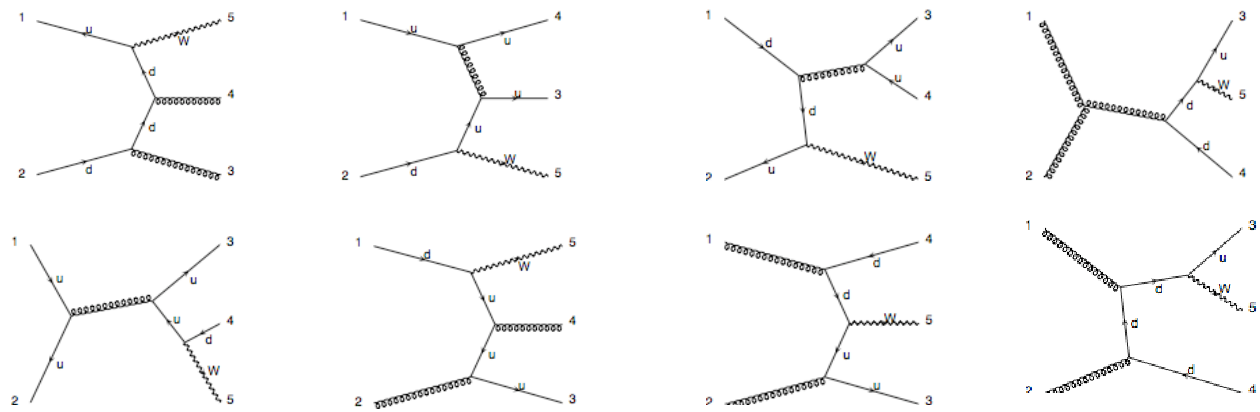
- Both D_1 and $\overline{D_1}$ considered
- Full spin correlation maintained
- Tevatron, $E_{cm} = 1.96$ TeV

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

Background Processes

Main Background:

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

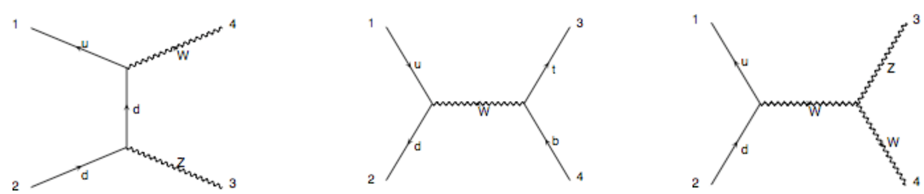


Other Background:

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:

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

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

$p_T(miss) > 15\ GeV$

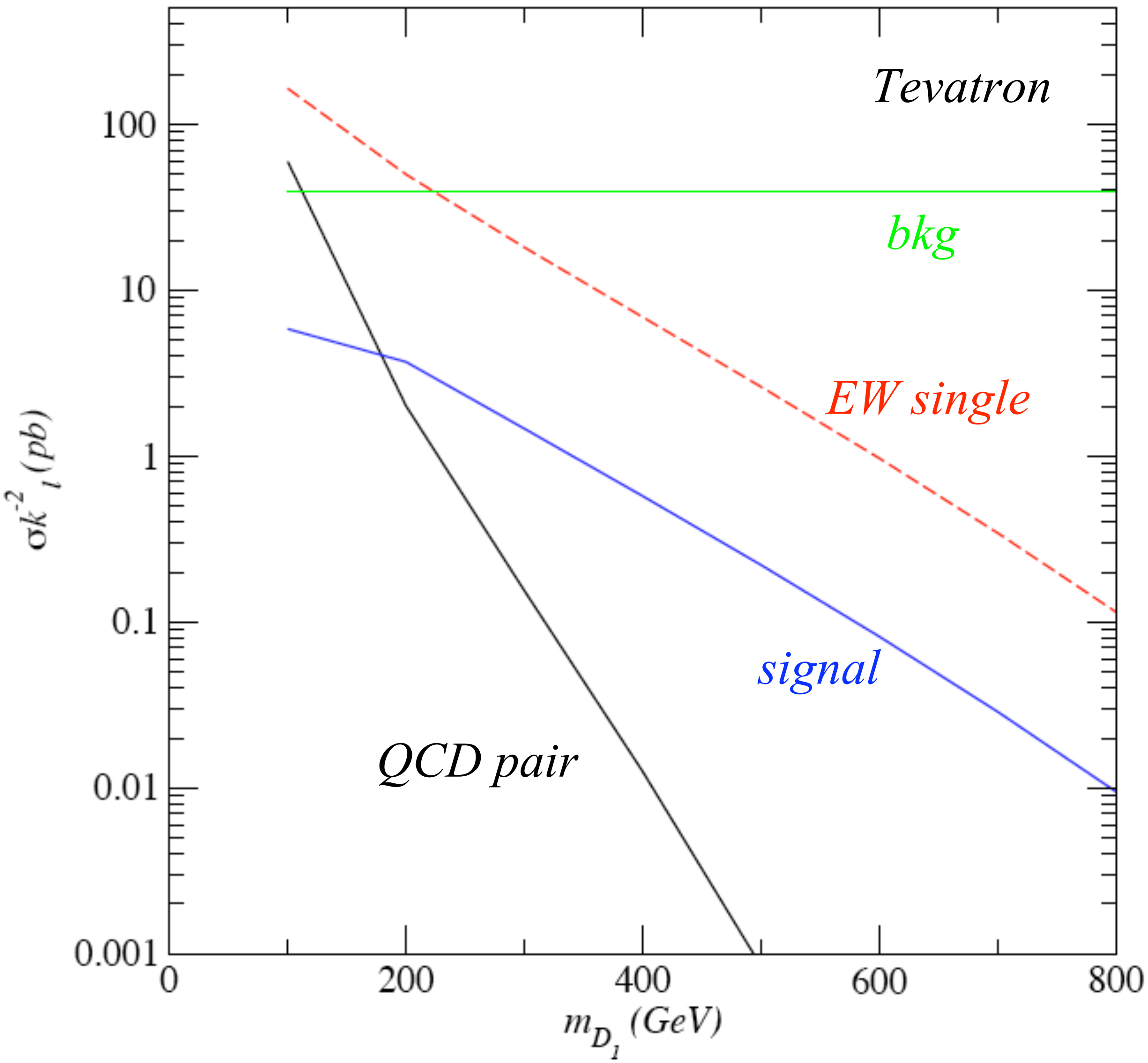
Smearing:

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

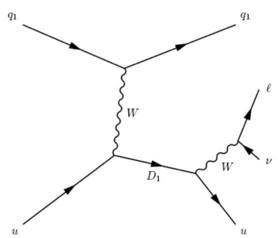
ECAL: $a = 13.5\%$ $\quad b = 1.5\%$

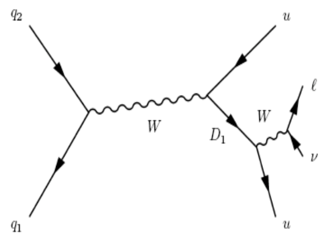
HCAL: $a = 75\%$ $\quad b = 3\%$

Signal vs Background



Signal vs Background Distributions



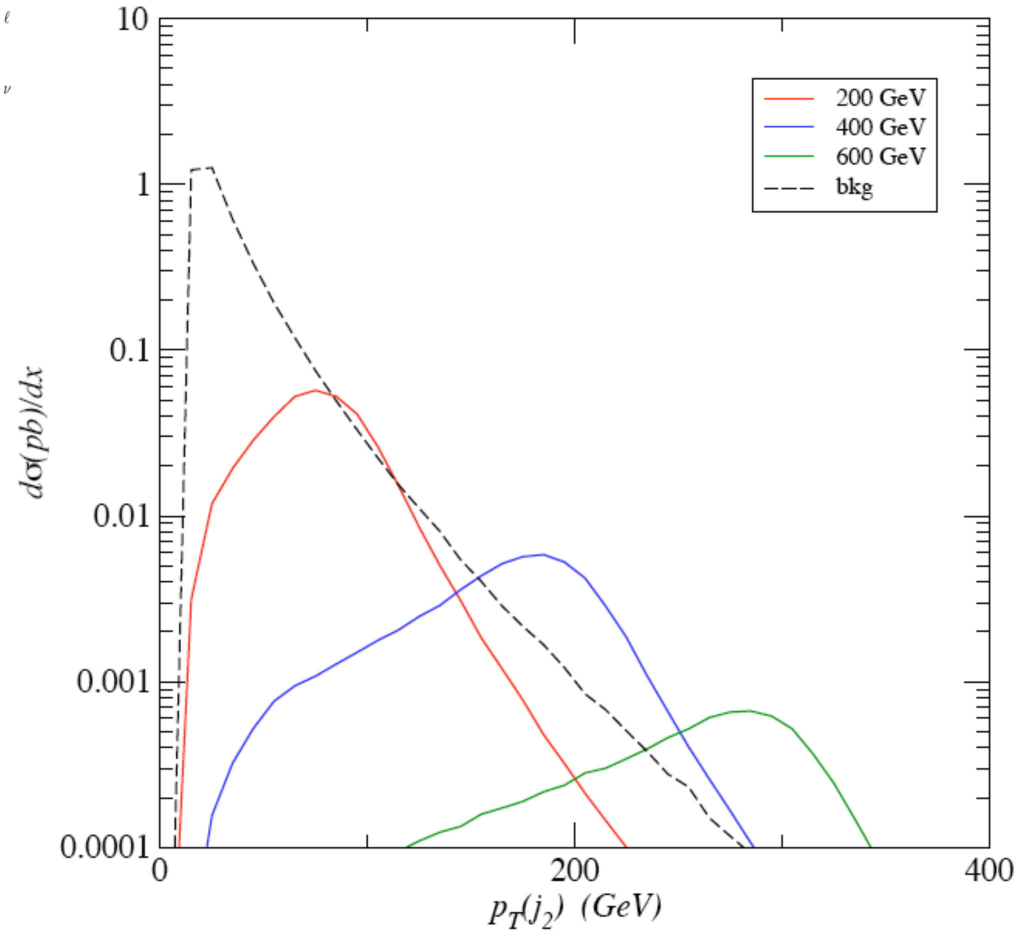


Improved Cuts:1

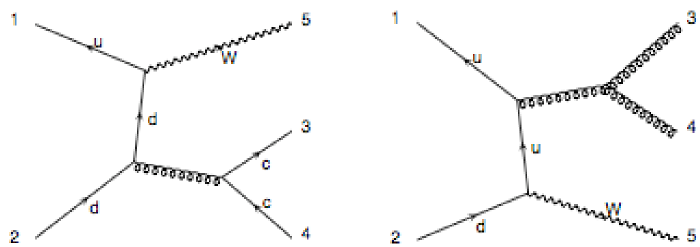
$$p_T(j_2) > \frac{m_{D_1}}{4}$$

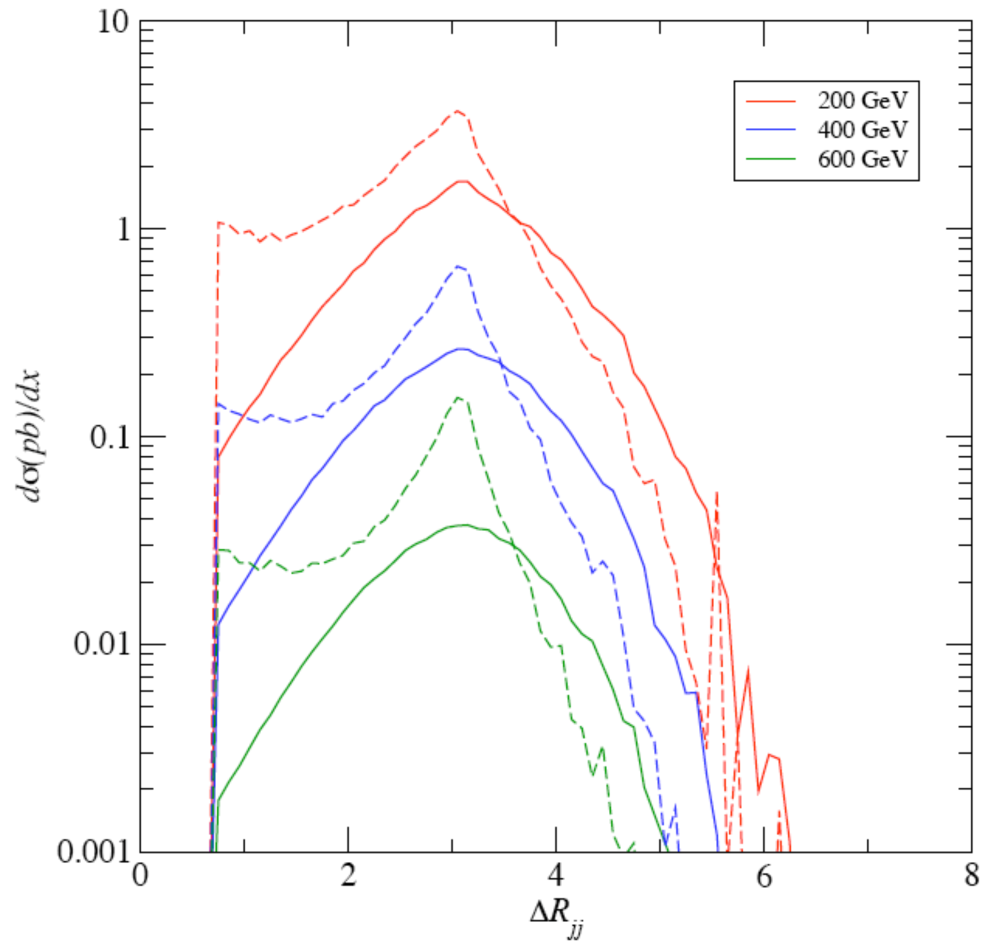
Signal efficiency:
~ 83 to 90%

Background efficiency:
~ 0.1 to 14%



Signal vs Background Distributions





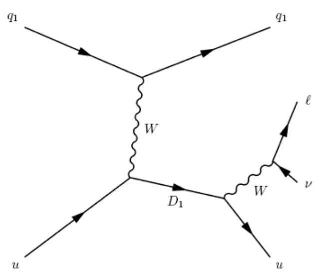
Improved Cuts: 2

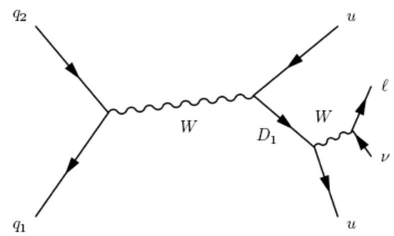
$$\Delta R_{jj} > 1.5$$

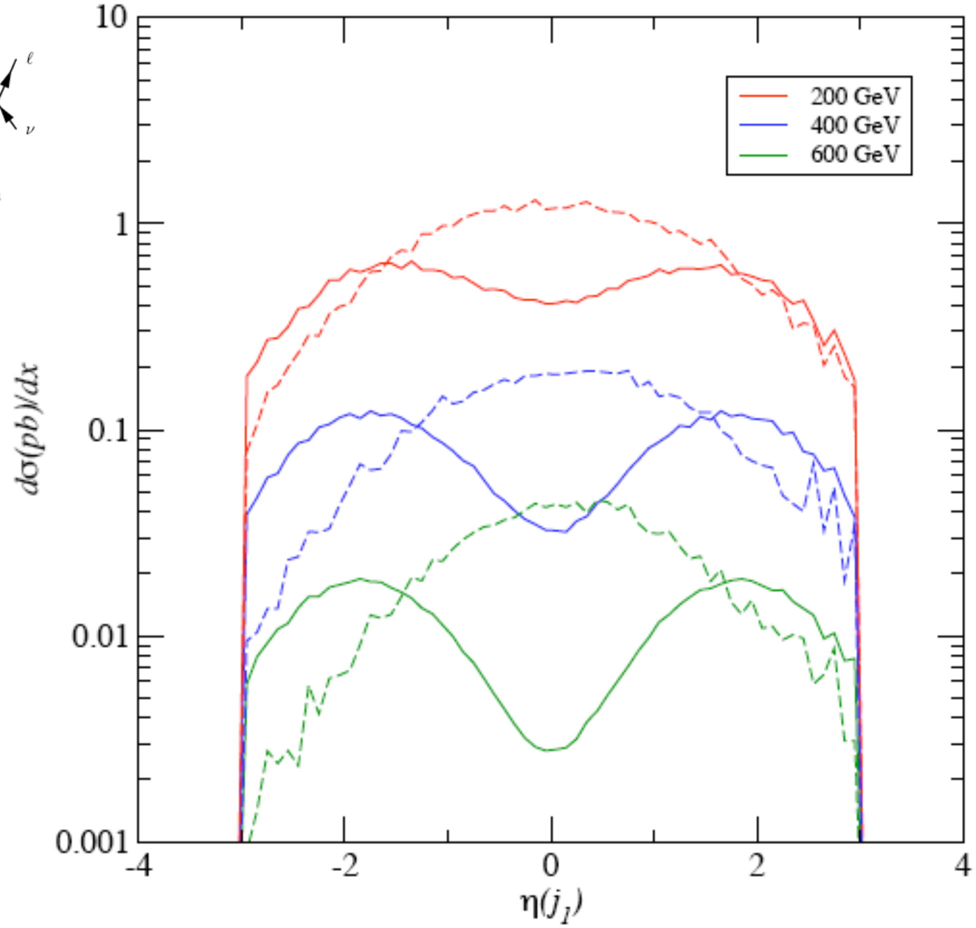
$$\Delta R_{j\ell} > 0.8$$

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

Signal vs Background Distributions







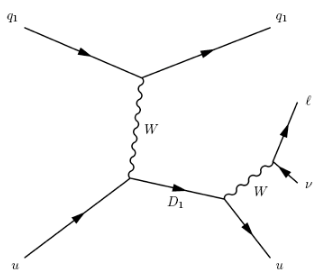
Improved Cuts: 3

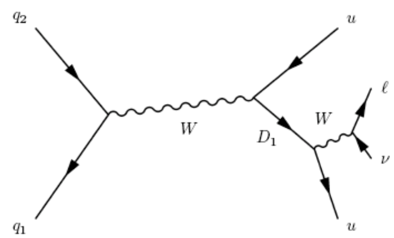
$$0.5 < |\eta(j_1)| < 3.0$$

Signal efficiency:
~ 85 to 96%

Background efficiency:
~ 64 to 72%

Signal vs Background Distributions



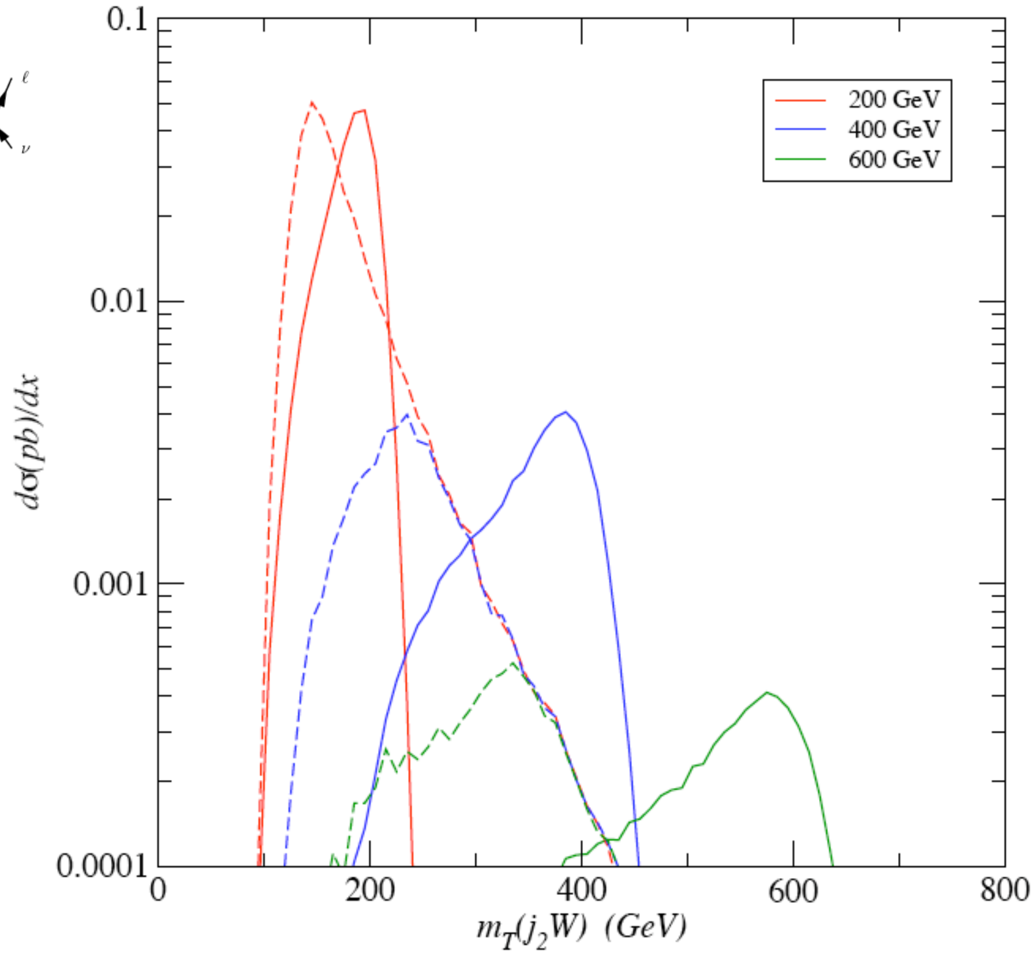


Improved Cuts: 4

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

$$m_{D_1} + \frac{1}{4} m_{D_1} > m_T(j_2 W)$$

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

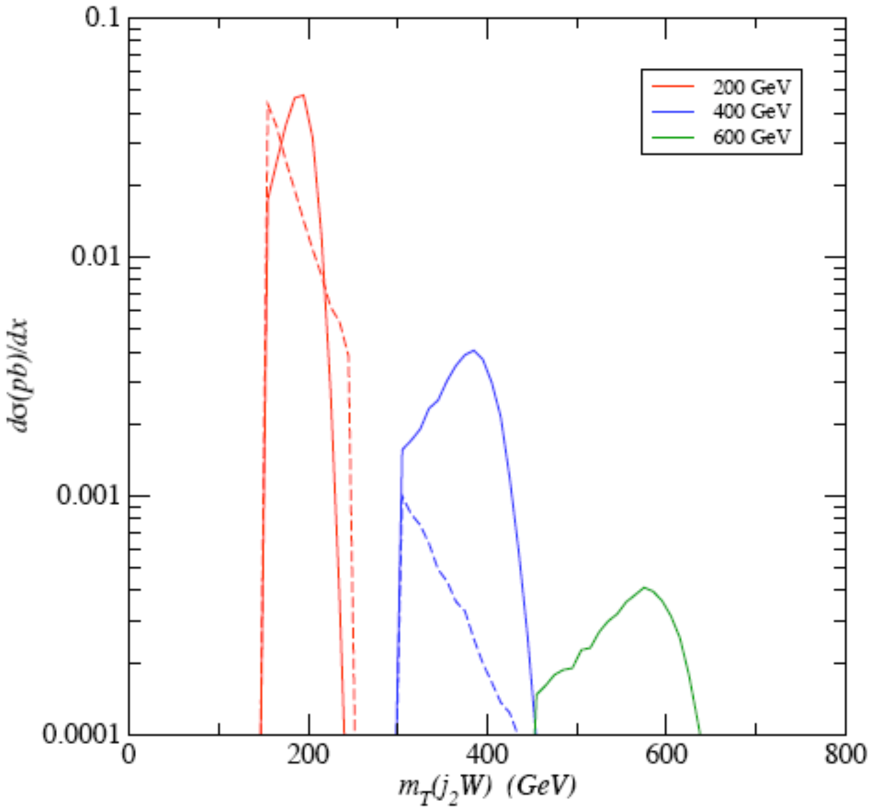


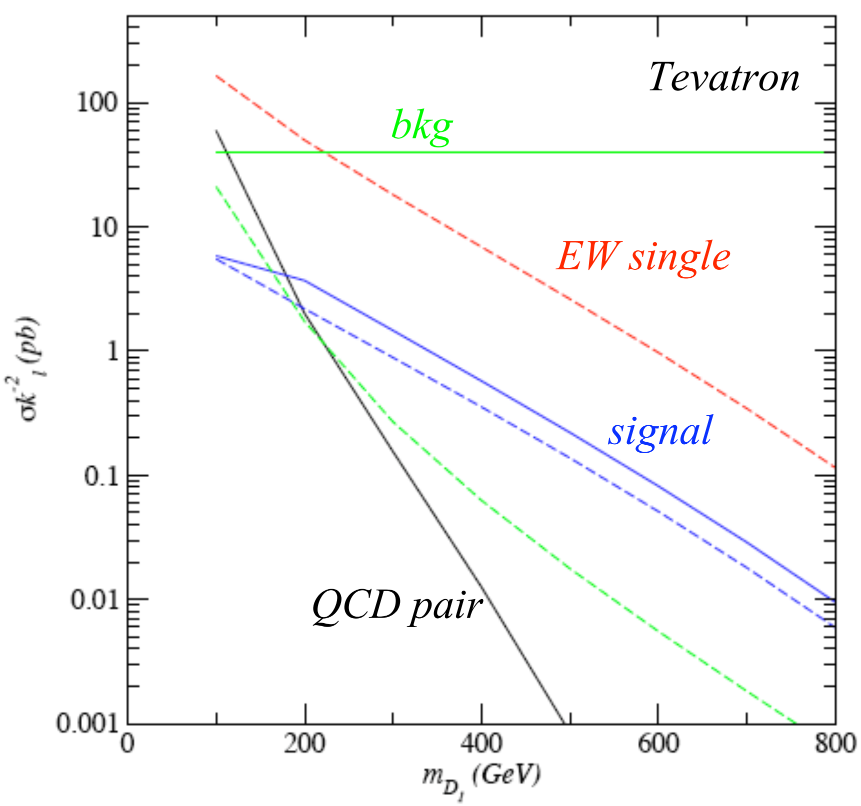
$$m_T^2(j_2 W) = [p_T^{j_2} + \sqrt{m_W^2 + (\vec{p}_T^{\,W})^2}]^2 - (\vec{p}_T^{\,j_2} + \vec{p}_T^{\,W})^2$$

Improved Cuts

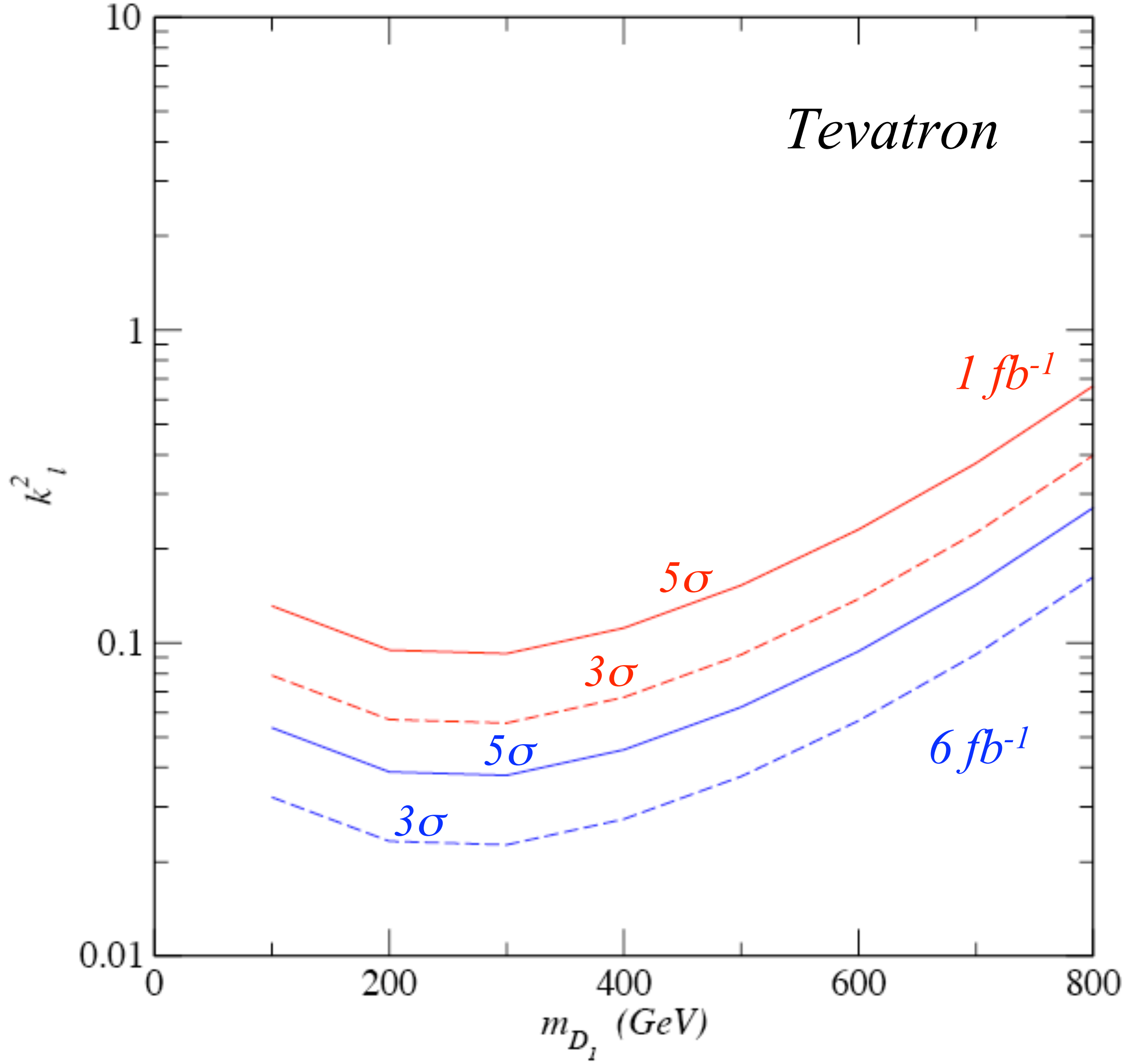
$$p_T(j_2) > \frac{m_{D_1}}{4} \qquad \Delta R_{jj} > 1.5 \qquad m_{D_1} - \frac{1}{4} m_{D_1} < m_T(j_2 W)$$

$$0.5 < |\eta(j_1)| < 3.0 \qquad \Delta R_{j\ell} > 0.8 \qquad m_{D_1} + \frac{1}{4} m_{D_1} > m_T(j_2 W)$$





Sensitivity at Tevatron



Current Constraints

- Searches for fourth generation
  - Limits on $b`$ are around 300 GeV from $1\ fb^{-1}$ data
  - Limits are from $b` \rightarrow b\,Z$ mode
  - No $b` \rightarrow Wj$ mode analysis available
- Searches for $W^{\pm}H(or\ X) \rightarrow l\,\nu\,2\bar{j}$
  - Limits on $\sigma.BR(H(or\ X)\rightarrow bb)$
  - Limits on H(or X)

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

- Limits on a $t`\ (\rightarrow Wb)$ are 265 GeV with about $1\ fb^{-1}$
  - Applicable for third generation*(b)*, results here for D_1

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

Further analysis in progress

- Consider RH couplings and generic LH + RH scenarios
- Electron as well as muon channel
- Heavy quarks that mix with second and third generations
- Study sensitivity at the LHC
- NC process - $2j + l^+ l^-$ channel.

  Better efficiency - two leptons

  Better reconstruction - no missing energy

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
- Heavy quarks can be found in many new physics scenarios

  Example: Light Kaluza-Klein quarks in Randall-Sundrum models with custodial symmetry

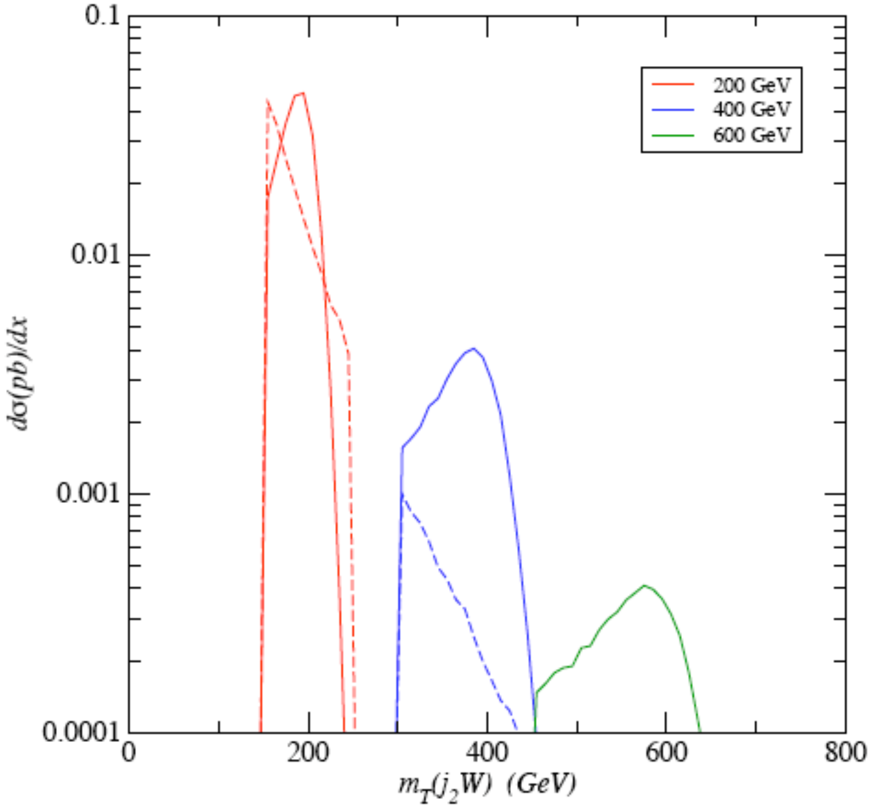
We can still discover new physics at the Tevatron!

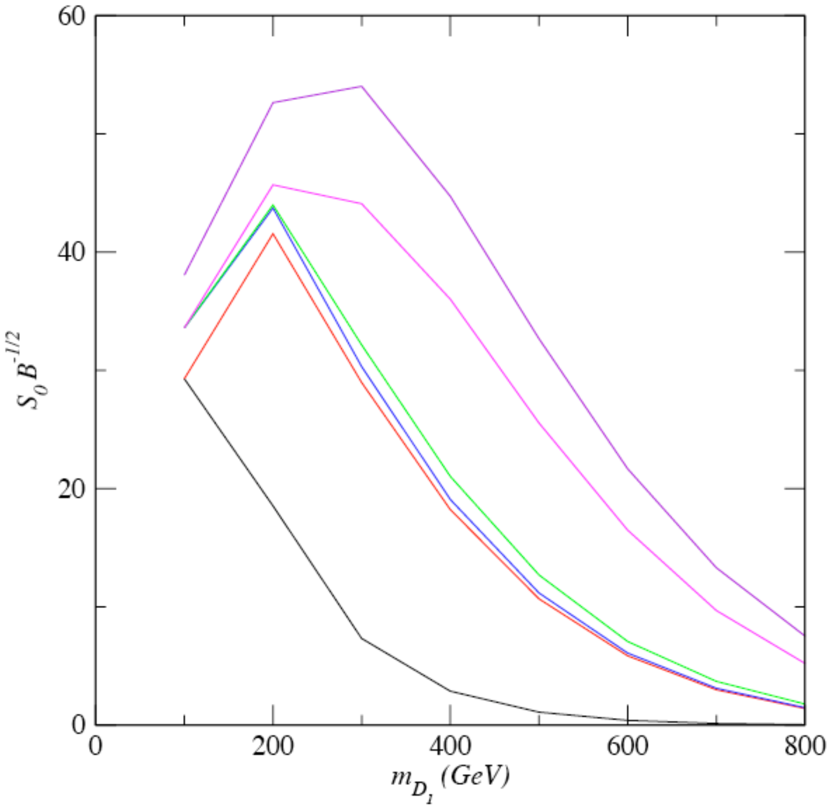
Supplementary Slides

Improved Cuts

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

$$0.5 < |\eta(j_1)| < 3.0 \qquad \Delta R_{j\ell} > 0.8 \qquad m_{D_1} + \frac{1}{4} m_{D_1} > m_T(j_2 W)$$





Example: warped extra dimension

- Warped extra dimension models address gauge hierarchy problem
- Background geometry a slice of AdS space with curvature scale k
- Due to AdS warping exponential hierarchy between mass scales at two ends of extra dimension generated
- Original set up all SM fields are localized on IR brane
- Leads to large FCNC and proton decay
- SM fields propogate in the bulk and Higgs localized on IR brane - attractive mechanism for Yukawa structure and prevents excessive FCNCs.
- Constraints from precision electroweak data

Heavy Quarks in New Physics

- Extend bulk gauge symmetry to a custodially symmetric $SU(2)_L \times SU(2)_R$
- Reduces tree level contribution to T parameter
- Gauge bosons with masses ~ *3 TeV*
- RH quarks included in doublets under $SU(2)_R$ symmetry
- $SU(2)_R$ symmetric partners can be light (*RH* top-bottom)
- This mode mixes with bottom quark and induces corrections to *Zbb* coupling
- Strong constraints on these models

Agashe, Delgado, May, Sundrum

Heavy Quarks in New Physics

- *Gauge-Higgs Unification* - Higgs field is a pNGB that arises as component along extra dimensions of gauge fields of broken symmetries
- Higgs field corresponds to zero mode of A_5 gauge boson along the broken direction of $SO(5)/O(4)$
- $SO(4) \mathrm{x} U(1)_X$ broken to $SU(2)_L$ x $SU(2)_R \mathrm{x} U(1)_X$ on *IR* brane and $SU(2)_L \mathrm{x} U(1)_Y$ on *UV* brane.
- Light higgs and light fermions predicted

Carena, Ponton, Santiago, Wagner

$$\xi^i_{1L} \sim Q^i_{1L} = \begin{pmatrix} \chi^{u_i}_{1L}(-,+) & q^{u_i}_L(+,+) \\ \chi^{d_i}_{1L}(-,+) & q^{d_i}_L(+,+) \end{pmatrix} \oplus u'^i_L(-,+) ,$$

$$\xi^i_{2R} \sim Q^i_{2R} = \begin{pmatrix} \chi^{u_i}_{2R}(+,-) & q'^{u_i}_R(+,-) \\ \chi^{d_i}_{2R}(+,-) & q'^{d_i}_R(+,-) \end{pmatrix} \oplus u^i_R(+,+) ,$$

$$\xi^i_{3R} \sim T^i_{1R} = \begin{pmatrix} \psi'^i_R(-,+) \\ U'^i_R(-,+) \\ D'^i_R(-,+) \end{pmatrix} \oplus T^i_{2R} = \begin{pmatrix} \psi''^i_R(-,+) \\ U''^i_R(-,+) \\ D^i_R(+,+) \end{pmatrix} \oplus Q^i_{3R} = \begin{pmatrix} \chi^{u_i}_{3R}(-,+) & q''^{u_i}_R(-,+) \\ \chi^{d_i}_{3R}(-,+) & q''^{d_i}_R(-,+) \end{pmatrix}$$

Q_i bidoublet under $SU(2)_L$ x $SU(2)_R$
$SU(2)_L$ vertically,
$SU(2)_R$ horizontally
T_1 and T_2 transform as (3,1) and (1,3) under $SU(2)_L$ x $SU(2)_R$
ui and *u'i* singlets
i-1,2,3 generations

Heavy Quarks in New Physics

- 16 of *SO(10)* with extra states assigned (-+) BC
- One 16 of *SO(10)* for each SM: Q_L -(u_L, d_L), u_R, d_R, $L_L = (e_L, \nu_L)$, e_R, ν_R
- One component of $SU(2)_R$ has zero mode other does not - split $SU(2)_R$ components. Similarly for leptons.

$$\mathbf{16_{u_R}} = \begin{pmatrix} u_R \\ \tilde{d}_R \\ e'_R \\ \nu'_R \\ L'_L \\ Q'_L \end{pmatrix}, \mathbf{16_{d_R}} = \begin{pmatrix} \tilde{u}_R \\ d_R \\ e'_R \\ \nu'_R \\ L'_L \\ Q'_L \end{pmatrix}, \mathbf{16_{e_R}} = \begin{pmatrix} u'_R \\ d'_R \\ e_R \\ \tilde{\nu}_R \\ L'_L \\ Q'_L \end{pmatrix}, \mathbf{16_{\nu_R}} = \begin{pmatrix} u'_R \\ d'_R \\ \tilde{e}_R \\ \nu_R \\ L'_L \\ Q'_L \end{pmatrix}, \mathbf{16_{Q_L}} = \begin{pmatrix} Q_L \\ L'_L \\ u'_R \\ d'_R \\ e'_R \\ \nu'_R \end{pmatrix}, \mathbf{16_{L_L}} = \begin{pmatrix} Q'_L \\ L_L \\ u'_R \\ d'_R \\ e'_R \\ \nu'_R \end{pmatrix}$$

Agashe, Servant

Heavy Quarks in New Physics

- Custodial symmetry with discrete *L-R* symmetry can protect *Zbb* coupling
- Bidoublets under $SU(2)_L$ x $SU(2)_R$
- Consistent with precision EW data
- Gauge bosons with masses accessible at LHC

Agashe, Contino, Da Rold, Pomarol