Heavy Quarks above the top

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Interplay of Collider and Flavour Physics
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Atre, Carena, Han, J.S., Phys. Rev. **D** (*in press*) [arXiv:0806.966]

The Big Question

- How is electroweak symmetry breaking realized in nature?
  - The answer is around the corner!!
  - A very good candidate is a composite Higgs
    - Compositeness can explain the "large" Hierarchy
    - PNGB nature can explain the "little" Hierarchy
  - Calculable models from warped extra dimensions
    - EWSB, EWPT, Flavour "reasonably" under control (difficult to escape few % fine-tuning in minimal models)

Realistic Composite Higgs

- A composite Higgs suggests a composite top
  - Large corrections to T and Zbb unless protected
  - A natural framework can be obtained with custodial symmetry and fermions in bidoublets

Agashe, Delgado, May, Sundrum 03

Agashe, Contino, Da Rold, Pomarol 06

$$Y = \frac{7}{6} \qquad \frac{1}{6}$$

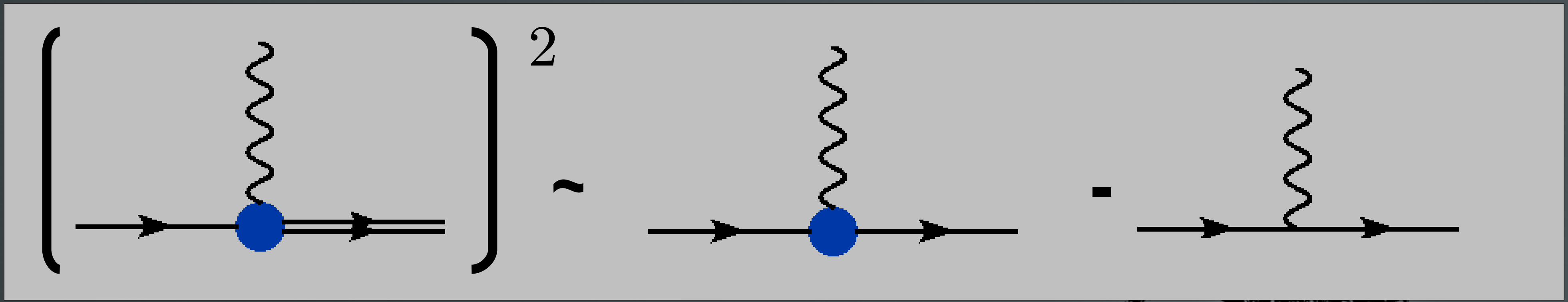
$$\begin{pmatrix} \chi^u_{\frac{5}{3}} & q^u_{\frac{2}{3}} \\ \chi^d_{\frac{2}{3}} & q^d_{-\frac{1}{3}} \end{pmatrix} \sim (2,2) \text{ under } SU(2)_L \times SU(2)_R$$

New quarks above the top

- New vector-like quarks that mix with SM quarks can be produced:
  - In pairs: QCD production
    - large (but strong suppression at high masses)
    - model independent, no low energy constraints

New quarks above the top

- New vector-like quarks that mix with SM quarks can be produced:
  - Singly: EW production
    - smaller for low masses, larger for heavy quarks
    - model dependent, production cross section constrained by EWPT and flavour experiments



New quarks above the top

- Can we have large mixing with valence quarks without violating EWPT and Flavour? YES!!
  - Degenerate doublets of hypercharges 1/6 and 7/6 that mix only with u_R, in the basis of diagonal up Yukawas

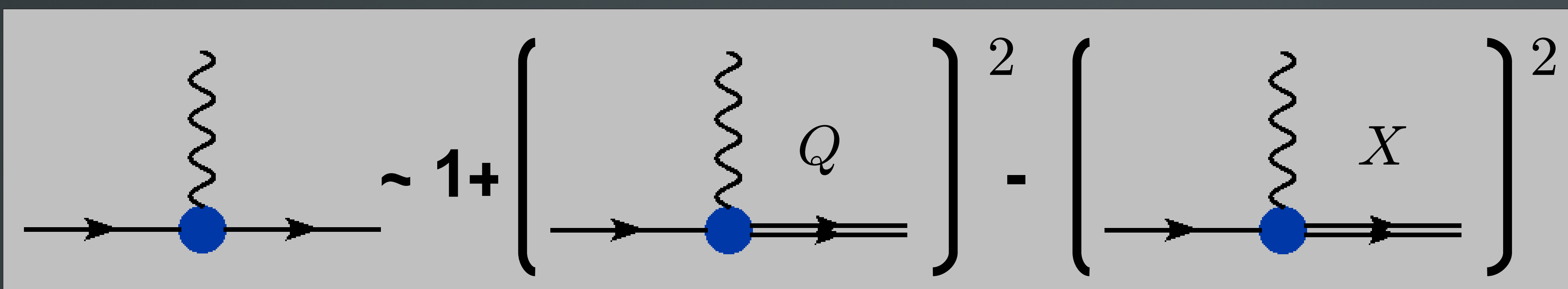
$$\mathcal{L} = \mathcal{L}_{\mathrm{K}} - \Big[\lambda_u^i \bar{q}_L^{(0)i} \tilde{\varphi} u_R^{(0)i} + \lambda_d^j V_{ij} \bar{q}_L^{(0)i} \varphi d_R^{(0)j}$$

$$+ \lambda_Q (\bar{Q}_L^{(0)} \tilde{\varphi} + \bar{X}_L^{(0)} \varphi) u_R^{(0)}$$

$$+ m_Q (\bar{Q}_L^{(0)} Q_R^{(0)} + \bar{X}_L^{(0)} X_R^{(0)}) + \mathrm{h.c.} \Big]$$

New quarks above the top

- How can it work?
  - The same cancellation that protects Zbb

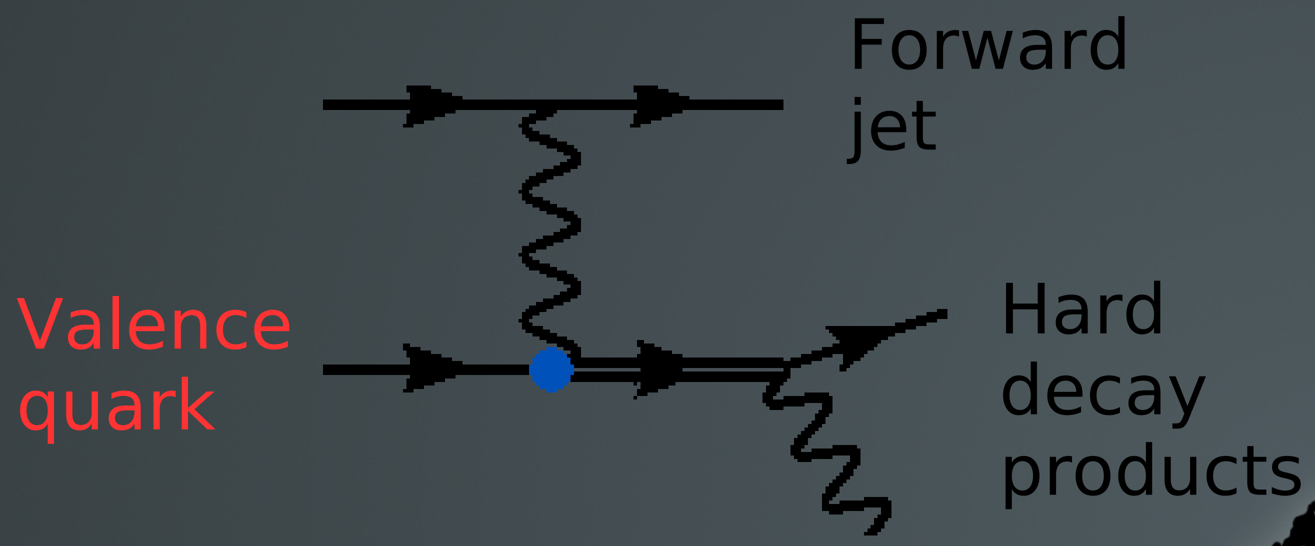


$$\sim 1 + \left(\frac{\lambda_Q v}{m_Q}\right)^2 - \left(\frac{\lambda_X v}{m_X}\right)^2$$

- They can be large!!

New quarks above the top

- Why single production?
  - Large (unconstrained) coupling to valence quarks
  - Distinctive kinematics



New quarks above the top

- Model independent analysis
  - Assume two new quarks U, D (charge 2/3, -1/3)
  - Arbitrary couplings to valence quarks

$$\mathcal{L}_{\rm int} = \frac{g}{\sqrt{2}} W_\mu^+ (\kappa_{uD} \bar{u}_R \gamma^\mu D_R + \kappa_{dU} \bar{d}_R \gamma^\mu U_R)$$

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

$$\kappa_{qQ} = \tilde{\kappa}_{qQ} \frac{v}{m_Q}$$

New quarks above the top

- Analysis classified by final state

$$l^{\pm}\ \not{E}_T\ + jj \qquad (W \to l\nu)$$

$$l^{+}l^{-} + jj \qquad (Z \to l^{+}l^{-})$$

$$\not{E}_T + jj \qquad (Z \to \bar{\nu}\nu)$$

$$(l = e, \mu \quad \text{here})$$

New quarks above the top

- Model independent analysis
  - Parametrize cross section (narrow width approx.)

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

Encode model dependence

Stripped off couplings (depends on kinematics)

New quarks above the top

- Model independent analysis
  - Parametrize cross section (narrow width approx.)

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

$$S_D^{CC} \equiv \left(\tilde{\kappa}_{uD}^2 + \frac{\sigma_{\text{prod}}^{NC}}{\sigma_{\text{prod}}^{CC}} \; \tilde{\kappa}_{dD}^2 \right) \; Br(D \to qW)$$

$$S_D^{NC} \equiv \left(\tilde{\kappa}_{dD}^2 + \frac{\sigma_{\text{prod}}^{CC}}{\sigma_{\text{prod}}^{NC}} \; \tilde{\kappa}_{uD}^2 \right) \; Br(D \to qZ)$$

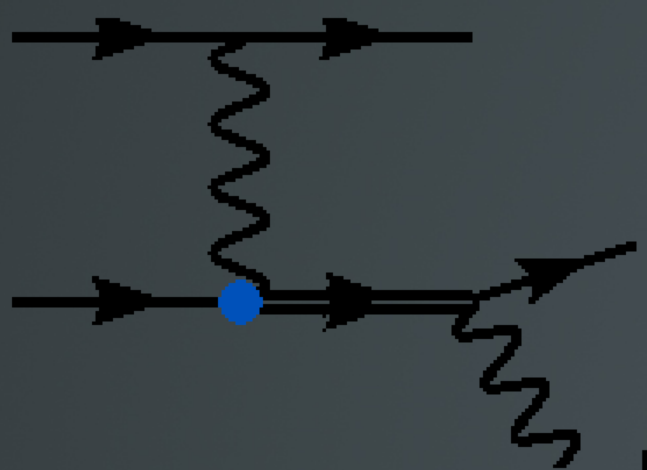
Tevatron Analysis

New quarks above the top

- Main kinematical features

Forward soft jet
(pT ~ $M_V/2$)

Good discrimination

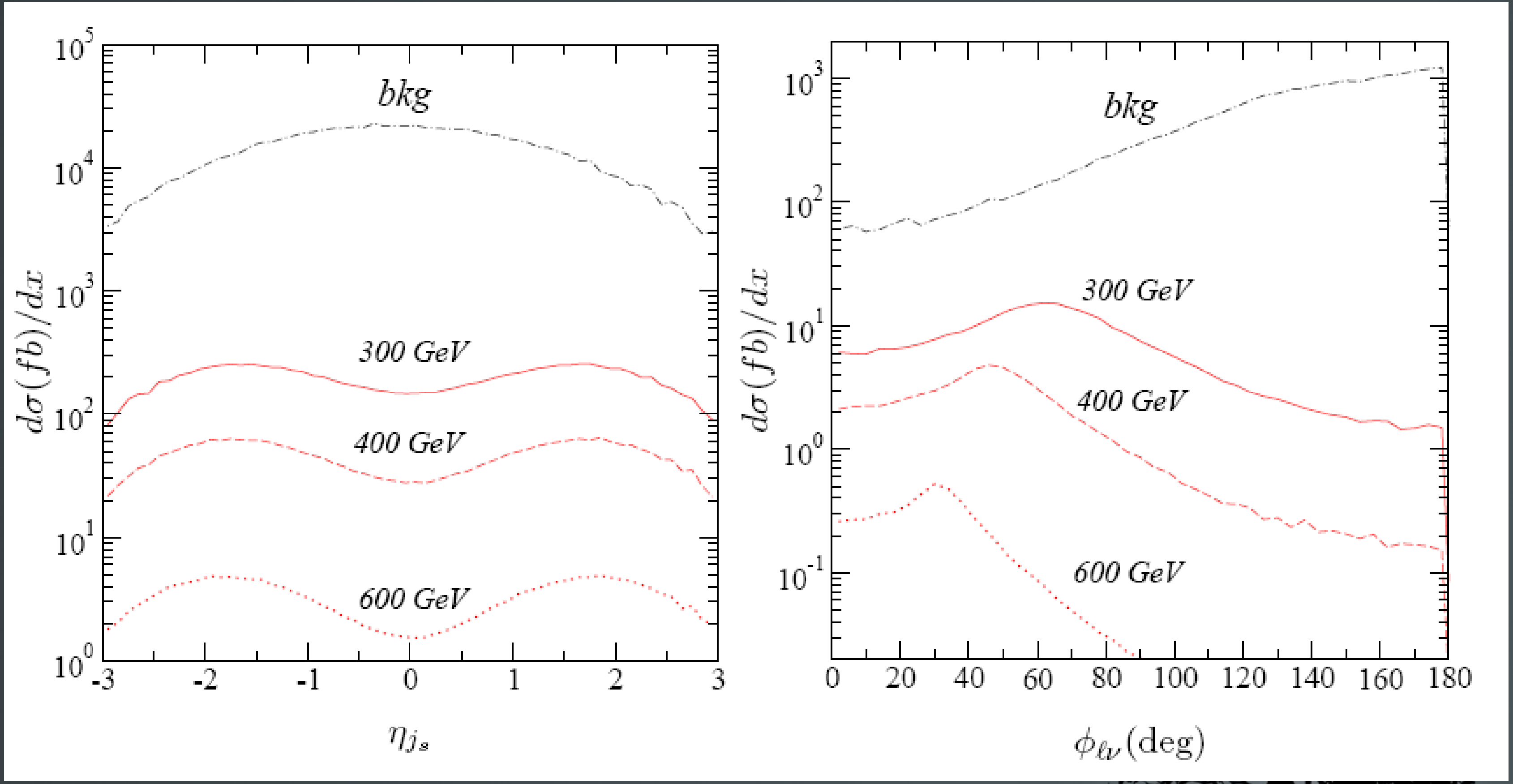


Hard jet $p_T \sim \sqrt{1 - \frac{m_V^2}{m_Q^2}} \frac{m_Q}{2}$

Hard V (collimated
decay products)

New quarks above the top

- Main kinematical features



New quarks above the top

- Cut based analysis
  - Basic cuts

    $$p_T(j, l, \not{E}_T) > 15 \text{ GeV}$$

    $$|\eta(l)| < 2 \quad |\eta(j)| < 3$$

  - Improved cuts

    $$p_T(j_h) > \frac{1}{4} m_Q \quad p_T(W/Z) > \frac{1}{5} m_Q$$

    $$0.5 < |\eta_{j_s}| < 3.0 \quad \Delta R(jj, jl) > 1.5,\ 0.8$$

    $$+ \text{ cut on } \phi_{l\nu, ll}$$

New quarks above the top

- Cut based analysis
  - Mass reconstruction

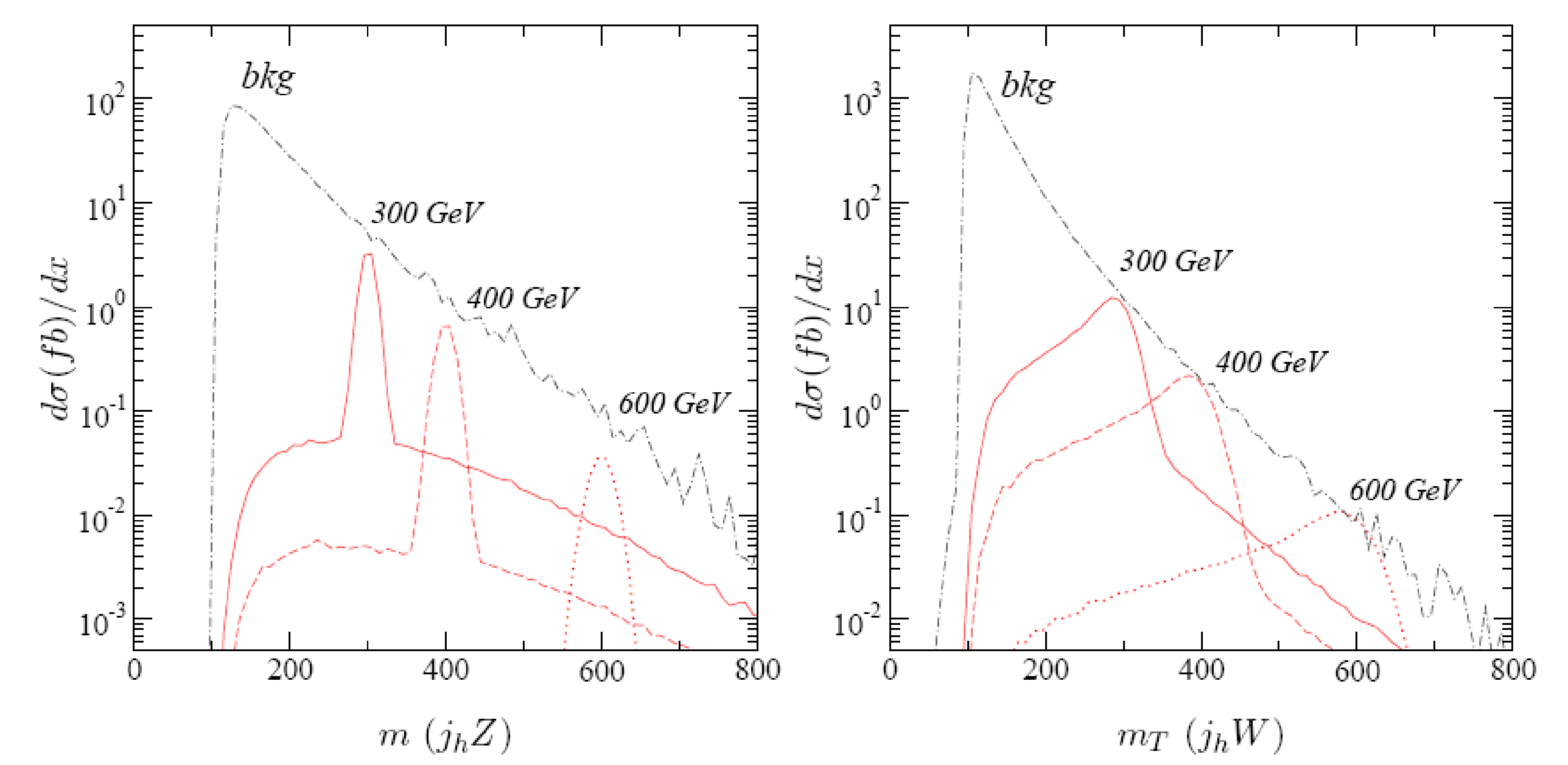
$$m_Q - 30\ \text{GeV} < M(j_h Z) < m_Q + 30\ \text{GeV}$$

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

$$M_T^2 = \left(\sqrt{p^2_{T\,W,Z} + M^2_{W,Z}} + p_{T\,j_h} \right)^2 - (\vec{p}_{T\,W,Z} + \vec{p}_{T\,j_h})^2$$

New quarks above the top

- Cut based analysis
  - Mass reconstruction

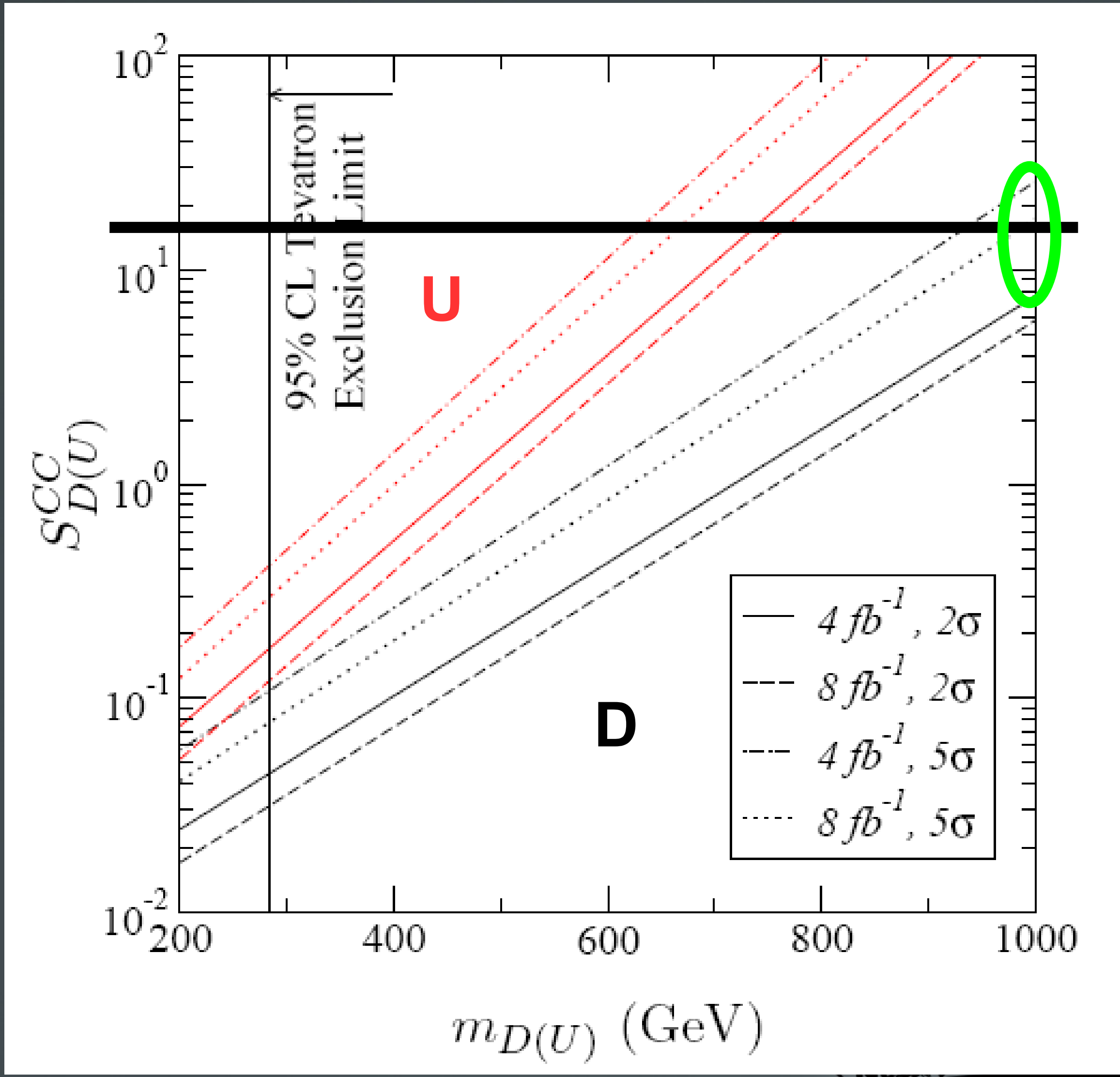


New quarks above the top

- Simulations:
  - We have performed a partonic analysis of signal and background with smeared momenta
  - Cross-checked at selected points with pythia+PGS
    - $\lesssim 7\%$ from hadronization/detector simulation
    - $\lesssim 20\%$ from ISR/FSR + reducible backgrounds

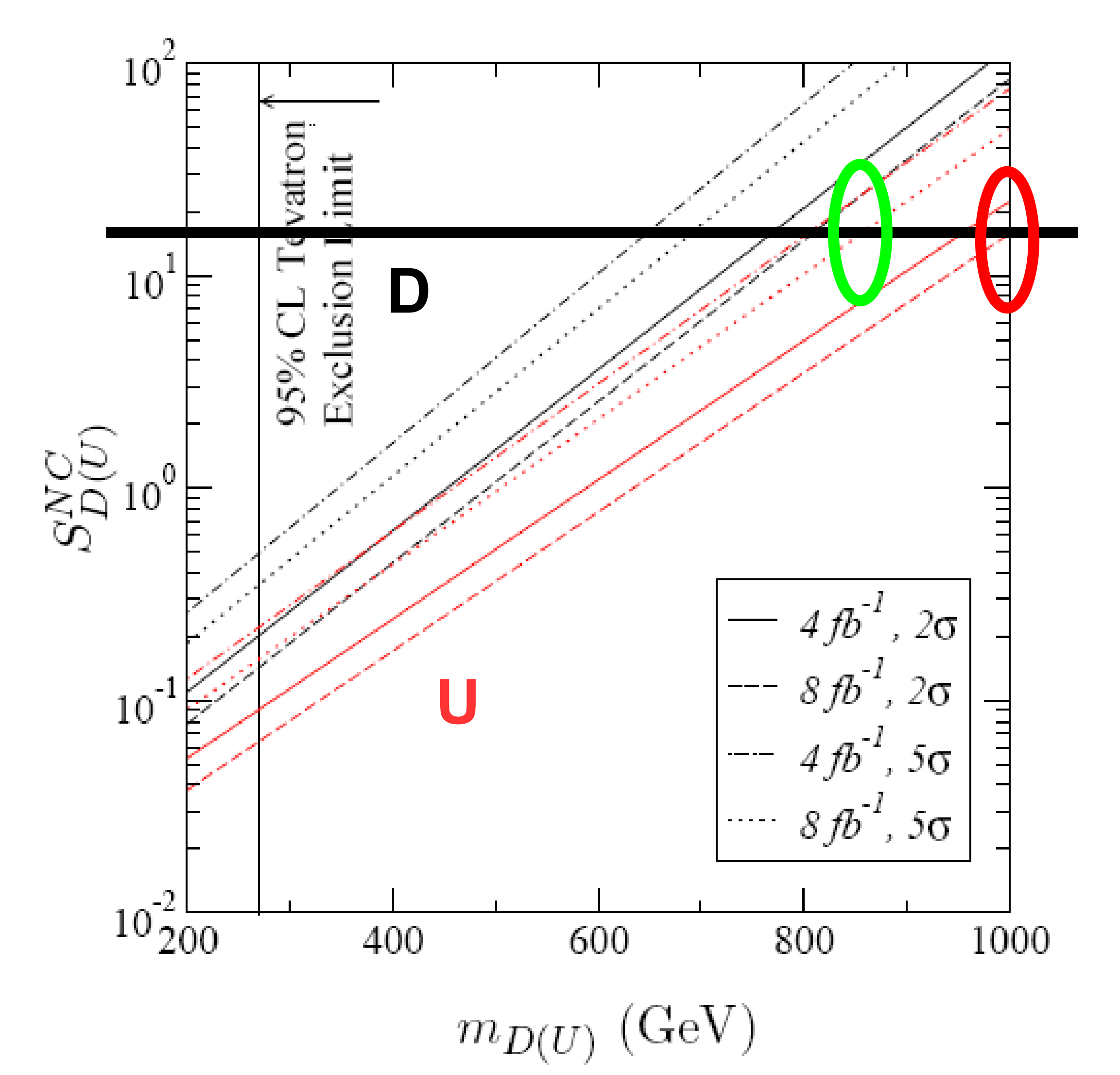
New quarks above the top

- Results:
  - CC channel



New quarks above the top

- Results:
  - NC channel



Conclusions and outlook

- New exciting collider and flavor phenomenology from composite Higgs models
- New quarks with strong mixing to valence quarks allowed by EWPT and Flavour data
- Great reach potential through single production at the Tevatron $m_Q \lesssim \text{TeV}$
- LHC analysis in progress

Backup Slides

New quarks above the top

- Single production and decay
  - The spectrum is fixed for degenerate doublets in terms of λ_Q and m_Q

State	q^-	q^+	q^d	χ^u
Electric Charge	$2/3$	$2/3$	$-1/3$	$5/3$
Coupling to u_R				
CC			$\frac{-g}{\sqrt{2}}\frac{v}{m_Q}\lambda_Q$	$\frac{-g}{\sqrt{2}}\frac{v}{m_Q}\lambda_Q$
NC	$\frac{-g}{\sqrt{2}c_W}\frac{v}{m_Q}\lambda_Q$			
Yukawa		$\sqrt{2}\lambda_Q$		

New quarks above the top

- How can it work?
  - The same cancellation that protects Zbb
  - Gauge and Yukawa SM couplings get corrections suppressed by the mass of the up quark

$$W^L_{ud_i} \approx V_{ud_i} \left[1 - \lambda_Q^2 \frac{v^2}{m_Q^2} \frac{m_u^2}{m_Q^2} \right] \sim 10^{-10}$$

$$W^R_{ud_i} = 0$$

- Controls single production

New quarks above the top

- Results:

$$m_Q = 400 \text{ GeV}$$

$$S_Q^{CC} = 1$$

$$\sigma \text{ (in fb}^{-1})$$

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	-

New quarks above the top

- Results:

$m_Q = 400$ GeV

$S_Q^{CC} = 1$

σ (in fb^{-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)	-	-

New quarks above the top

- Results:

$m_Q = 400$ GeV

$S_Q^{CC} = 1$

σ (in fb^{-1})

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

New quarks above the top

- Reach:

$\int \mathcal{L} dt$	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)

TABLE V: Tevatron sensitivity for $m_{D,U}$ (GeV).