Flavourful Production at Hadron Colliders

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Giudice, BMG, & Sundrum, 1105.3161, JHEP 1108 055

Motivation

What new physics could we see?

- The LHC will not see without looking.
- Highlight new theoretical paradigms.

Rules of the Game

- Mass $\lesssim$ TeV
- Large coupling to quarks/gluons
- Single production at LHC

Focus on scalar diquarks

- Yukawa interactions, $y^{ij}\phi q_i q_j$
- New window on flavour physics.
- Conflict with myriad flavour and *CP* constraints.

$\Delta F = 2$ FCNCs

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}
$(\bar{t}_L\gamma^\mu u_L)^2$	12		7.1×10^{-3}		$pp \to tt$

Isidori, Nir & Perez, 1002.0900

Consider a scalar diquark with quantum numbers $(3, 1, -\frac{4}{3})$ under $SU(3) \times SU(2) \times U(1)$.

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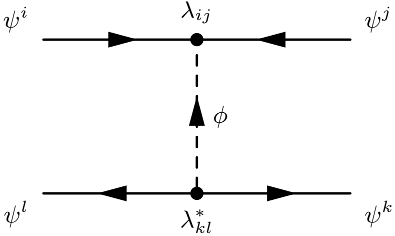
- It has a Yukawa coupling to a pair of u_Rs, with $(3, 1, +\frac{2}{3})$
- The colour indices are antisymmetric
- The flavour indices are antisymmetric

Theorem I: Flavour-changing processes involve all three generations.

Proof

- With one generation, the Yukawa coupling is zero
- With two generations, the Yukawa coupling is $\propto \varepsilon_{ij}$

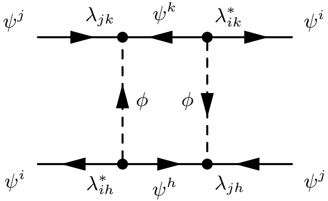
Corollary I.1: There are no $\Delta F = 2$ processes at tree-level.



Corollary I.2: Tree-level, flavour changing decays involve all 3 generations.

- e.g. $\bar{b}s\bar{s}d$
- Charmless, strangeless: $B \to \phi\phi$, $B \to \phi\pi$

Corollary I.3: One-loop $\Delta F = 1, 2$ diagrams involve all three generations



- Could imagine putting a large coupling anywhere.
- Can always get suppression
- Normal (23), inverted (12), or perverted (13) hierarchies

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Theorem II: No quark-diquark contributions to nucleon EDMs.

(Slick) Proof.

- With $g, g' = 0$, there are 3 phases and 3 re-phasings.
- EDMs at 3 loops or higher with $g, g' \neq 0$.

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Flavour/CP constraints allow a large coupling anywhere …

… and a large x-section at hadron colliders …

… provided there is a hierarchy.

Flavour philosophy.

Begin with the SM . . .

Curious pattern of masses and mixings.

Suggests a hierarchy in Yukawa couplings.

The Chiral Hierarchy

Ansatz:

- $\mathscr{L} = \Sigma_{i,j} - y^u_{ij}\epsilon^q_i\epsilon^u_j q_i H u^c_j - y^d_{ij}\epsilon^q_i\epsilon^d_j q_i H^c d^c_j$

e.g. Davidson, Isidori, & Uhlig, 0711.3376

- $\epsilon^q_3, \epsilon^u_3 \sim 1$
- $\implies V_{ub}/V_{cb} \sim V_{us}$

How could this pattern arise?

Hierarchical Yukawas

- E.g. extra dimensions
- E.g. Froggatt-Nielsen
- E.g. partial compositeness

e.g. Extra dimensions

- Scalars and fermions have extended wavefunctions in extra dimensions

Arkani-Hamed & Schmaltz, 9903417

- Put diquark and Higgs in different places

Bounds, M = TeV

Hierarchy	CKM-like	Chiral hierarchy
Inverted	$(\lambda_3^u)^2 \lesssim 10$ (D)	$(\lambda_3^u)^2 \lesssim 90$ (D)
Normal	$(\lambda_1^u)^2 \lesssim 0.03$ (D)	$(\lambda_1^u)^2 \lesssim 0.7$ (D)
Perverted	$(\lambda_2^u)^2 \lesssim 0.03$ (D)	$(\lambda_2^u)^2 \lesssim 0.7$ (D)
Inverted	$(\lambda_3^d)^2 \lesssim 2$ (B_d) $\lambda_3^d \lesssim 0.2$ $(B \to \phi\pi)$	$(\lambda_3^d)^2 \lesssim 0.06$ (K) $\lambda_3^d \lesssim 0.02$ $(B \to \phi\pi)$
Normal, Perverted	$(\lambda_{1,2}^d)^2 \lesssim 0.01$ (K) $\lambda_{1,2}^d \lesssim 0.2$ $(B \to \phi\pi)$	$(\lambda_{1,2}^d)^2 \lesssim 0.01$ (K) $\lambda_{1,2}^d \lesssim 0.02$ $(B \to \phi\pi)$

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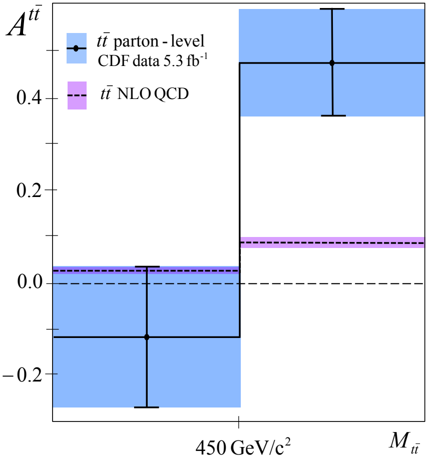
$$\lambda \geq O(1), M \sim \text{TeV}$$

Phenomenology of diquarks.

Top forward-backward asymmetry



CDF, 1101.0034

3.4σ

Top forward-backward asymmetry

- Several authors have proposed diquarks

Shu, Tait & Wang, 0911.3237

Dorsner & al., 0912.0972, 1007.2604

Gresham, Kim & Zurek, 1102.0018

Patel & Sharma, 1102.4736

Arnold & al., 0911.2225

Grinstein & al., 1102.3374

Ligeti, Schmaltz & Tavares, 1103.2757

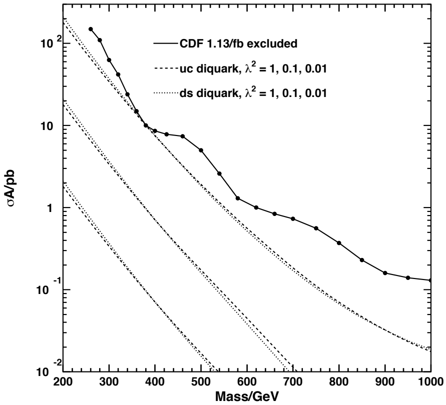
- Need $\lambda_{13} \sim$ few, mass $\lesssim$ *TeV*

D mixing: generic state would need mass $\geq$ 800 TeV!

Other pheno

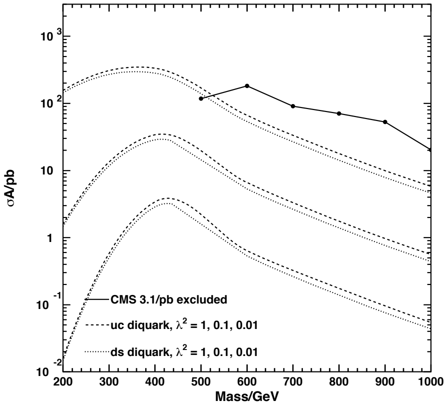
- Di-jet resonances
- Contact Interactions
- Heavy-light jet resonances
- Charm tagging
- Distinguishing qq from $q\bar{q}$ resonances @ LHC

Di-jet resonances CDF



CDF, 0812.4036

Di-jet resonances CMS



CMS, 1010.0203

Summary

- Anti-symmetrically coupled diquarks
- Flavour/CP safe
- LHC pheno.