LEPTOQUARKS AND LHC*

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2010 LHC DAYS IN SPLIT

Split, Croatia

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*I.D., Svjetlana Fajfer, Jernej F. Kamenik, Nejc Košnik, *Phys. Lett.* B 682:67-73, 2009, 0906.5585;
I.D., Svjetlana Fajfer, Jernej F. Kamenik, Nejc Košnik, *Phys. Rev.* D 81:055009, 2010, 0912.0972;
I.D., Svjetlana Fajfer, Jernej F. Kamenik, Nejc Košnik, 1007.2604.
I.D. and Pavel Fileviez Pérez, Nucl.Phys. B 723:53-76, 2005, hep-ph/0504276.

OUTLINE

•MOTIVATION

•CASE STUDY

(SCALAR LEPTOQUARKS IN GRAND UNIFIED MODELS)

•CONCLUSIONS

MOTIVATION

Leptoquarks[#] are ubiquitous in models of physics beyond the Standard Model!

They are inherent to any theory that treats quarks and leptons on the same footing.

- UNIFICATION THEORIES (PATI-SALAM[#], *SU*(5)…)
- R-PARITY VIOLATING SUSY MODELS;
- EXTENDED TECHNICOLOR MODELS

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LEPTOQUARKS ≡ QUALITATIVELY NEW PHYSICS!

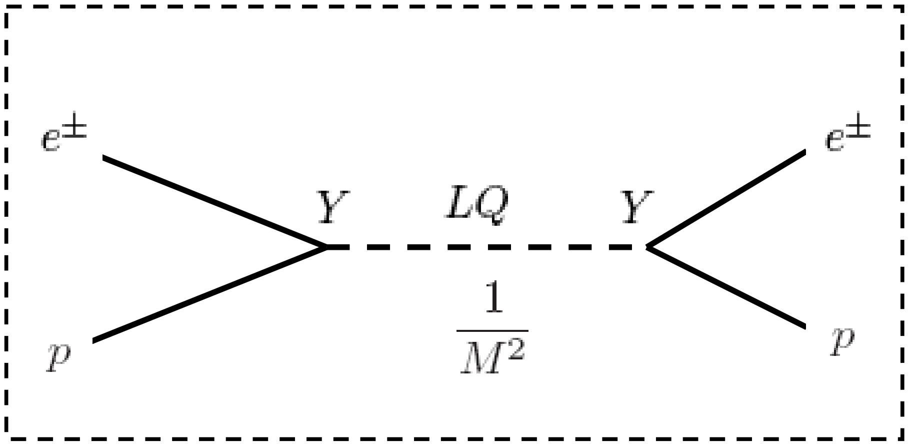
[#] J. C. Pati and A. Salam, *Phys. Rev.* D 10 275-289, 1974..

LEPTOQUARKS

Leptoquarks can be directly produced in colliders.

SINGLE PRODUCTION (ZEUS, HERA):

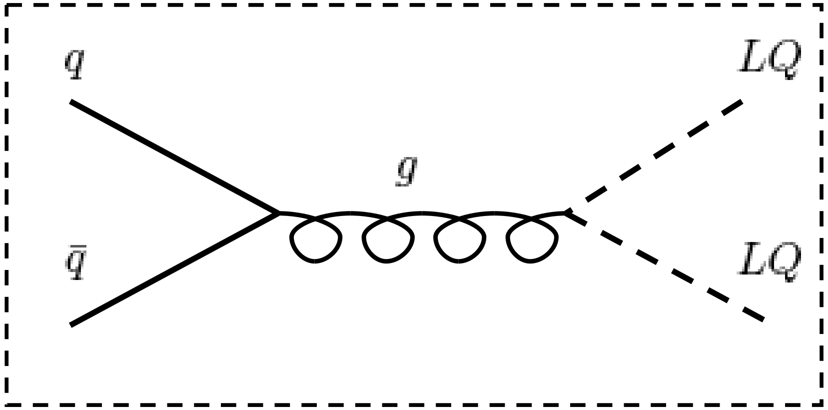
$$e^{\pm}p \to e^{\pm}p$$



$Y \equiv$ Yukawa coupling(s) $M \equiv$ Leptoquark mass

LEPTOQUARKS

PAIR PRODUCTION AT HADRON COLLIDERS[#]:



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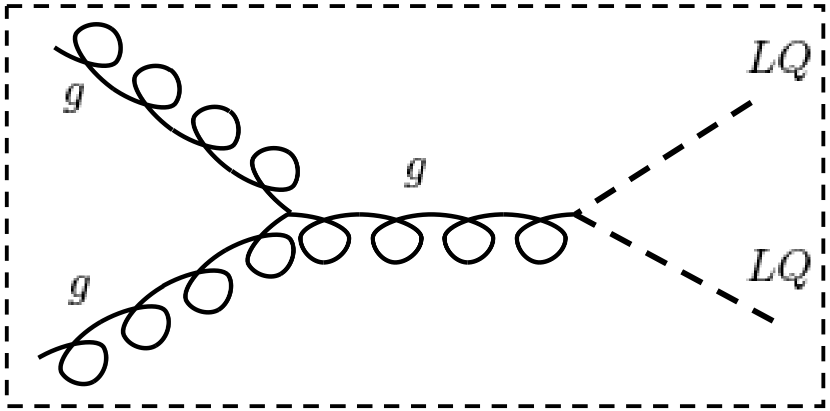

…

TEVATRON LIMITS:

	CDF[*]	DØ[‡]
1st	$m_{LQ} > 236\,\mathrm{GeV}$	$m_{LQ} > 292\,\mathrm{GeV}$
2nd	$m_{LQ} > 226\,\mathrm{GeV}$	$m_{LQ} > 316\,\mathrm{GeV}$

[*]DØ Collaboration, D0 Conference Note 5644-CONF (2008).
[‡]CDF Collaboration, A. Abulencia et al., *Phys. Rev.* D 73 (2006) 051102.

[#]ATLAS Collaboration (Shanti Wendler for the collaboration), PoS 2008LHC:015, 2008.
E. Del Nobilea, R. Franceschinib, D.Pappadopulob and A. Strumia, arXiv:0908.1567.

CASE STUDY

(LEPTOQUARKS IN AN *SU*(5)* SCENARIO)

FERMIONS OF THE STANDARD MODEL (SM):

LEPTONS

$$L_a \equiv (\mathbf{1}, \mathbf{2}, -1/2)_a = (\nu_a \quad e_a)^T$$

$$e_a^C \equiv (\mathbf{1}, \mathbf{1}, 1)_a$$

QUARKS

$$Q_a \equiv (\mathbf{3}, \mathbf{2}, 1/6)_a = (u_a \quad d_a)^T$$

$$u_a^C \equiv (\overline{\mathbf{3}}, \mathbf{1}, -2/3)_a$$

$$d_a^C \equiv (\overline{\mathbf{3}}, \mathbf{1}, 1/3)_a$$

$(\mathbf{10}^{\alpha\beta})_a$: e_a^C, Q_a, u_a^C

$(\overline{\mathbf{5}}_\alpha)_a$: L_a, d_a^C

$$a = 1, 2, 3 \qquad \alpha, \beta = 1, 2, 3, 4, 5$$

*H. Georgi and S.L. Glashow (1974).

FERMION MASSES

(SCALAR REPRESENTATIONS IN *SU*(5))

$\mathbf{10} \times \overline{\mathbf{5}} = \mathbf{5} \oplus \mathbf{45} \ : \ M_E, M_D$

$\overline{\mathbf{5}} \times \overline{\mathbf{5}} = \overline{\mathbf{10}} \oplus \overline{\mathbf{15}} \ : \ M_N$

$\mathbf{10} \times \mathbf{10} = \overline{\mathbf{5}} \oplus \overline{\mathbf{45}} \oplus \overline{\mathbf{50}} \ : \ M_U$

$\mathbf{5}$ | ~~$\mathbf{10}$~~ | $\mathbf{15}$ | $\mathbf{45}$ | ~~$\mathbf{50}$~~

$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\alpha)_j\mathbf{5}^*_\beta$

$(\overline{\mathbf{5}}_\alpha)_i(\overline{\mathbf{5}}_\beta)_j\mathbf{15}^{\alpha\beta}$

$(\mathbf{10}^{\alpha\beta})_i(\overline{\mathbf{5}}_\delta)_j\mathbf{45}^{*\,\delta}_{\alpha\beta}$

$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\gamma\delta})_j(\mathbf{5})^\epsilon$

$\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j(\mathbf{45})^{\delta\epsilon}_\zeta$

$i = 1, 2, 3$
FAMILY INDEX

$\alpha, \beta = 1, 2, 3, 4, 5$
GROUP INDICES

LEPTOQUARKS IN *SU*(5)

(THE SM DECOMPOSITION)

$$\mathbf{5} = (D, T)$$

$$D = (\mathbf{1}, \mathbf{2}, 1/2)$$

$$T = (\mathbf{3}, \mathbf{1}, -1/3)$$

$$\mathbf{15} = (\Phi_a, \Phi_b, \Phi_c)$$

$$\Phi_a = (\mathbf{1}, \mathbf{3}, 1)$$

$$\Phi_b = (\mathbf{3}, \mathbf{2}, 1/6)$$

$$\Phi_c = (\mathbf{6}, \mathbf{1}, -1/3)$$

$$\mathbf{45} = (\Delta_1, \Delta_2, \Delta_3, \Delta_4, \Delta_5, \Delta_6, \Delta_7)$$

$$\Delta_1 = (\mathbf{8}, \mathbf{2}, 1/2)$$

$$\Delta_2 = (\overline{\mathbf{6}}, \mathbf{1}, -1/3)$$

$$\Delta_3 = (\mathbf{3}, \mathbf{3}, -1/3)$$

$$\Delta_4 = (\overline{\mathbf{3}}, \mathbf{2}, -7/6)$$

$$\Delta_5 = (\mathbf{3}, \mathbf{1}, -1/3)$$

$$\Delta_6 = (\overline{\mathbf{3}}, \mathbf{1}, 4/3)$$

$$\Delta_7 = (\mathbf{1}, \mathbf{2}, 1/2)$$

(black line) ≡ Higgs doublet: D, Δ_7

(red line) ≡ *p* decay mediating leptoquark: T, Δ_3, Δ_5, Δ_6

(blue line) ≡ "genuine" leptoquark: Φ_b, Δ_4

LEPTOQUARKS IN *SU*(5)

(p DECAY MEDIATING LEPTOQUARK)

$\mathbf{5} = (D, T)$

$D = (\mathbf{1}, \mathbf{2}, 1/2)$

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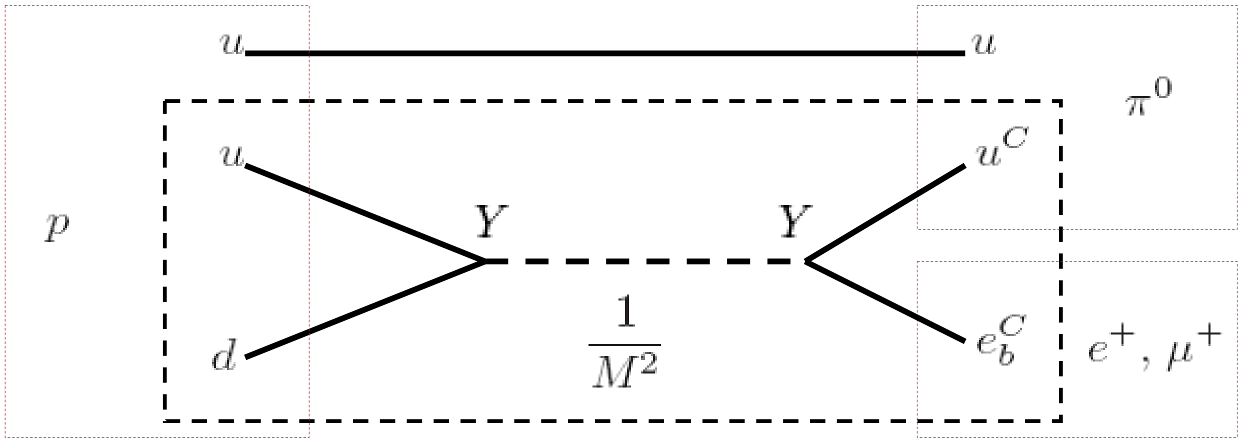
d=6 PROTON DECAY OPERATORS

(SCALAR CONTRIBUTIONS*)

PROTON DECAY MEDIATING LEPTOQUARKS SHOULD BE VERY HEAVY!

$$\Gamma_6 \sim \frac{Y^4}{M^4} m_p^5 \quad \Rightarrow \quad M \geq 10^{12}\,\mathrm{GeV}$$



$Y \equiv$ Yukawa coupling(s) $M \equiv$ Leptoquark mass

*S. Weinberg, *Phys. Rev.* D 22:1694, 1980.

EXPERIMENTAL RESULTS

(PROTON DECAY)

PROCESS	τ_p (10^{33} years)	
$p \to \pi^0 e^+$	8.2	*
$p \to \pi^0 \mu^+$	6.6	*
$p \to K^+ \bar{\nu}$	2.3	@
$p \to K^0 e^+$	1.0	@
$p \to K^0 \mu^+$	1.3	@
$p \to \eta e^+$	0.313	
$p \to \eta \mu^+$	0.126	
$p \to \pi^+ \bar{\nu}$	0.025	
⋮	⋮	
$p \to \pi^0 e^+$	10.1	¶

*[Super-Kamiokande Collaboration], arXiv:0903.0676.

@[Super-Kamiokande Collaboration], arXiv:hep-ex/0502026.

¶ www-sk.icrr.u-tokyo.ac.jp/whatsnew/new-20091125-e.html

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——— (blue) ≡ "genuine" leptoquark

GENUINE LEPTOQUARKS

(MINIMAL $SU(5)$ SCENARIO[#])

$$\mathbf{24} = (\Sigma_8, \underline{\Sigma_3}, \Sigma_{(3,2)}, \Sigma_{(\bar{3},2)}, \Sigma_{24})$$

$$\Sigma_8 = (\mathbf{8}, \mathbf{1}, 0)$$

$$\Sigma_3 = (\mathbf{1}, \mathbf{3}, 0)$$

$$\Sigma_{(3,2)} = (\mathbf{3}, \mathbf{2}, -5/6)$$

$$\Sigma_{(\bar{3},2)} = (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$$

$$\Sigma_{24} = (\mathbf{1}, \mathbf{1}, 0)$$

$$\mathbf{15} = (\underline{\Phi_a}, \underline{\Phi_b}, \Phi_c)$$

$$\mathbf{5}$$

$$(\mathbf{10})_a \qquad (\bar{\mathbf{5}})_a \qquad a = 1, 2, 3$$

There are only three degrees of freedom relevant for unification!

[#]I.D., Pavel Fileviez Pérez and Ricardo Gonzales Felipe, *Nucl. Phys*. B 747:312-327, 2006, hep-ph/0512068.
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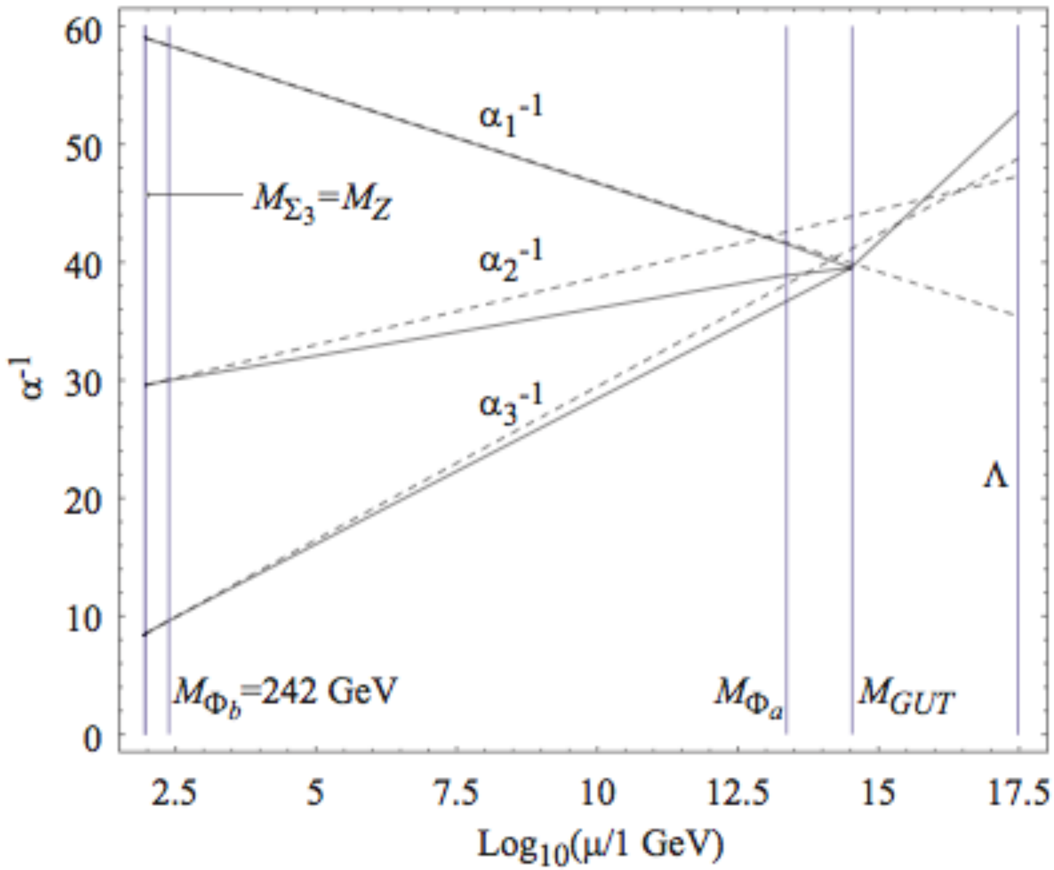
GENUINE LEPTOQUARK SCENARIO



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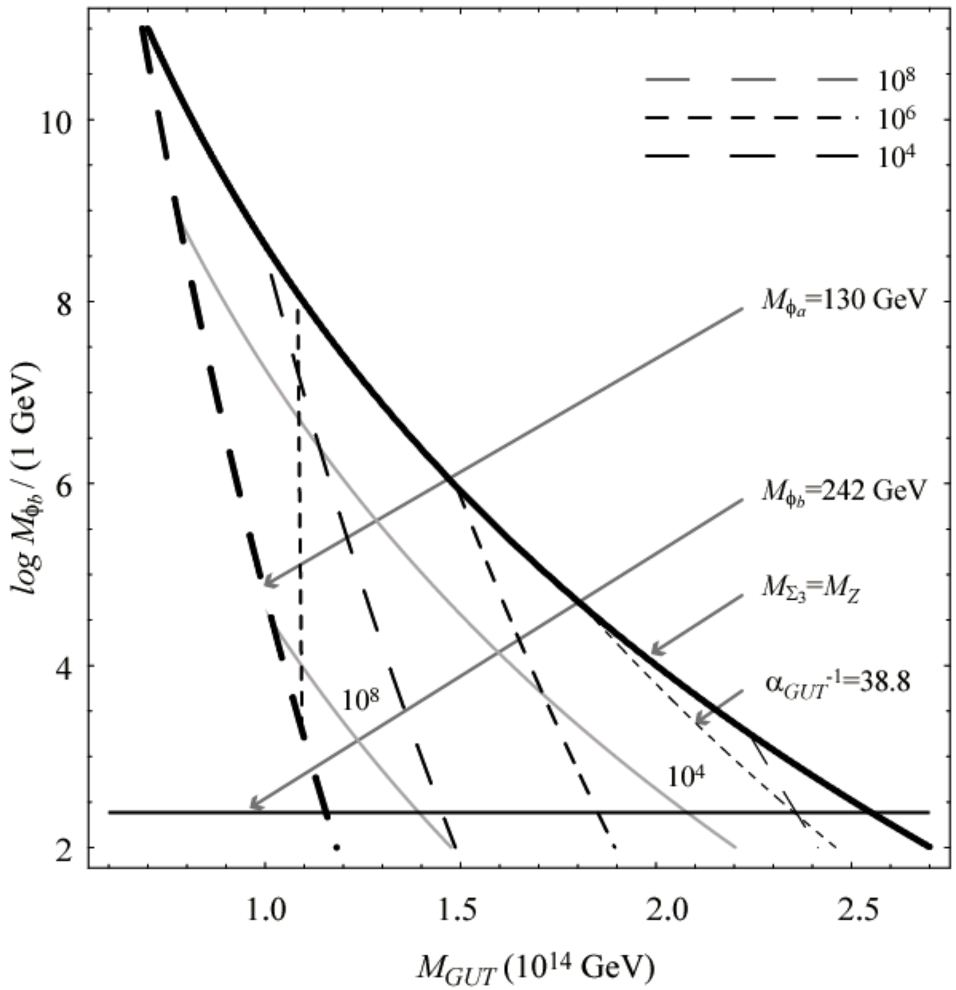

$$Y_{ij}\ d^T_{a\,i} C (\Phi^1_b)_a e_j$$

$$Y_{ij}\ d^T_{a\,i} C (\Phi^2_b)_a \nu_j$$

$$Y_{ij} \propto (M_N)_{ij}$$

I.D., Pavel Fileviez Pérez and Ricardo Gonzales Felipe, *Nucl. Phys*. B 747:312-327, 2006, hep-ph/0512068.
Pavel Fileviez Pérez, Tao Han, Tong Li, Michael J. Ramsey-Musolf, *Nucl. Phys.* B 819:139-176, 2009, arXiv:0810.4138.

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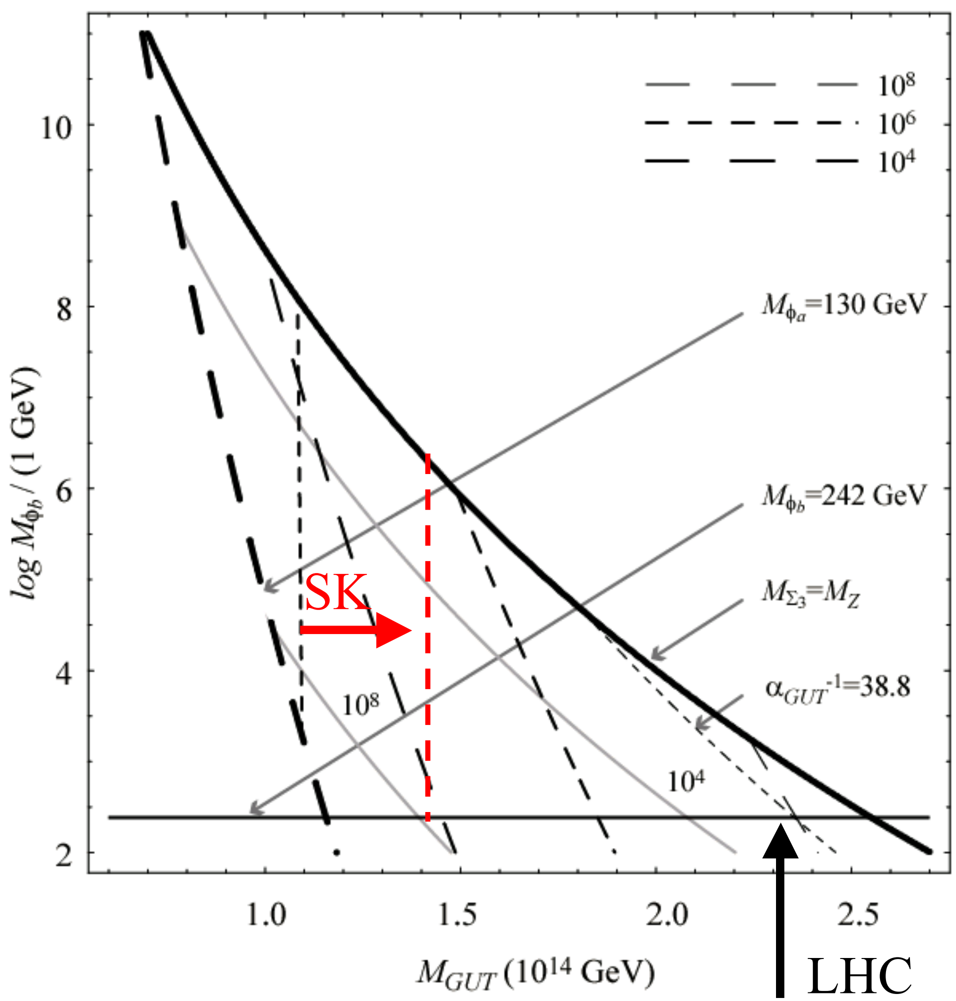

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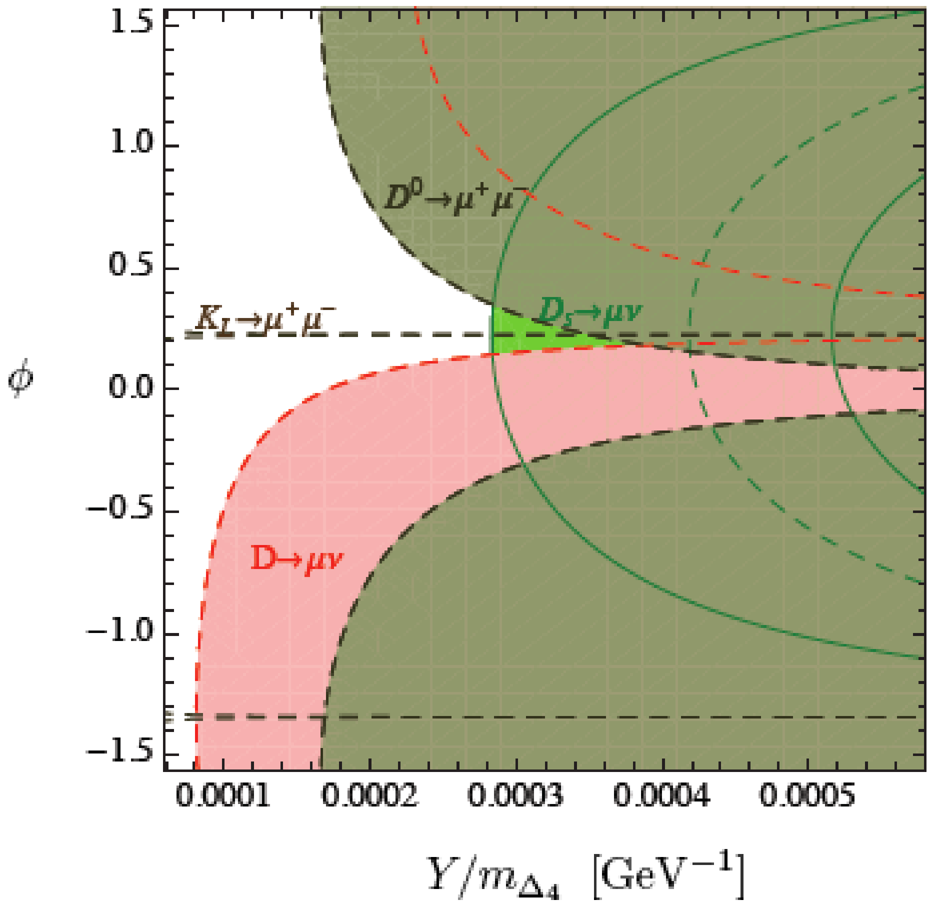
GENUINE LEPTOQUARKS*



STUDY# MOTIVATED BY DISCREPANCIES BETWEEN THE EXPERIMENTAL MEASUREMENTS OF LEPTONIC DECAY MODES OF D_s MESONS AND THE LATTICE RESULTS FOR THE RELEVANT f_{D_s} DECAY CONSTANT.

#B. A. Dobrescu and A. S. Kronfeld, Phys. Rev. Lett. 100, 241802 (2008), 0803.0512.

*I.D., Svjetlana Fajfer, Jernej F. Kamenik, Nejc Košnik, *Phys. Lett.* B 682:67-73, 2009, 0906.5585.
Belle Collaboration (M. Petric et al.), Phys. Rev. D 81:091102, 2010, 1003.2345.

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≡ Higgs doublet (black underline: D, Δ_7)

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≡ “genuine” leptoquark (blue underline: Φ_b, Δ_4)

LEPTOQUARKS IN *SU*(5)

COUPLINGS OF Δ_6 ARE FIXED BY GROUP THEORY!

$$\frac{g_6^{ij}}{2}\epsilon_{abc}u^{C\,T}_{i\,a}Cu^{C}_{b\,j}\Delta_{6\,c}$$

$$(Y)_{ij}e^{C\,T}_{i}Cd^{C}_{a\,j}\Delta^{*}_{6\,a}$$

$$g_6^{ij} = -g_6^{ji}$$

WHAT IF Δ_6 IS LIGHT?

LEPTOQUARKS

CONSTRAINTS ON g_6^{ij} ORIGINATE FROM
THE UP-QUARK PHENOMENOLOGY!

$m_{\Delta_6} = 400\,\mathrm{GeV}$

$|g_6^{13}| = 1.9$ → $t\,\bar{t}$ FORWARD-BACKWARD (FB) ASYMMETRY AT TEVATRON

$|g_6^{23}| \leq 0.0033$ → $D^0 - \bar{D}^0$ MIXING CONSTRAINTS

$|g_6^{12}| \leq 0.042$ → SINGLE t PRODUCTION CROSS-SECTION AT TEVATRON

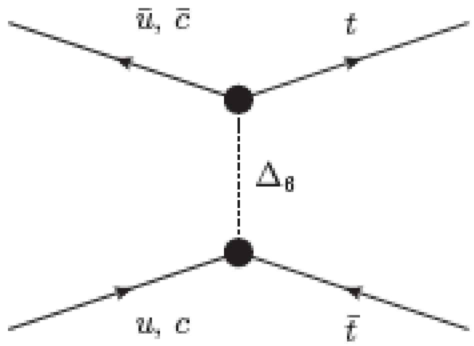
FORWARD-BACKWARD ASYMMETRY

SIMULTANEOUS FIT TO THE INTEGRATED CROSS SECTION $\sigma^{\exp}$ AND A_{FB}

$$A_{FB}^{\exp} - A_{FB}^{SM} = (14.2 \pm 6.9)\%$$

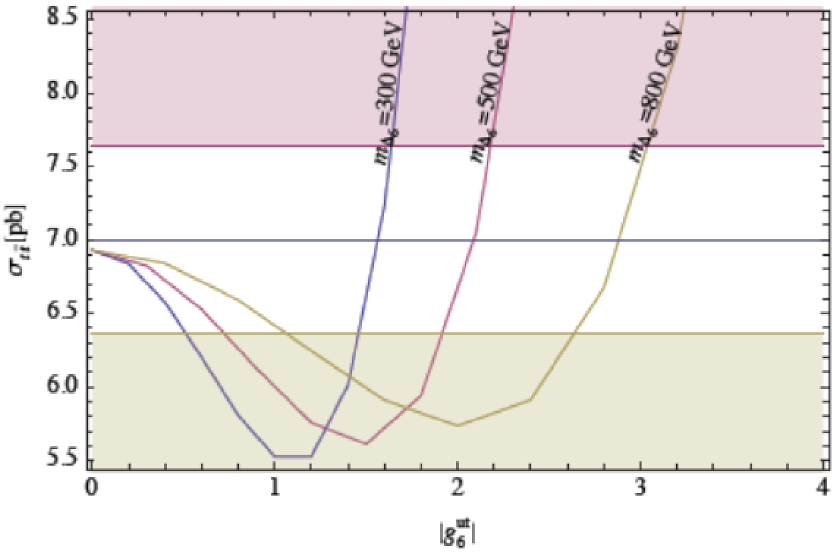
$$\sigma^{\exp} = 7.0 \pm 0.6\,\mathrm{pb}$$

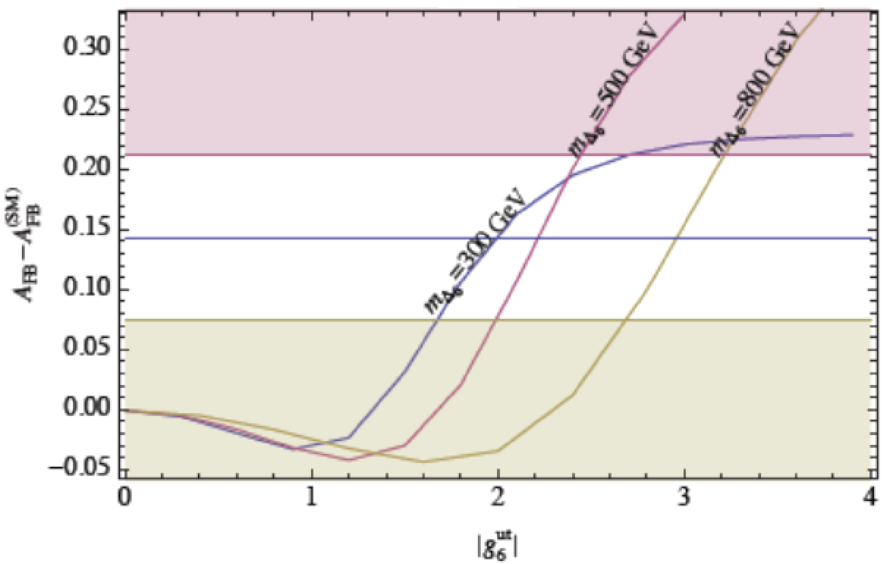
$$|g_6^{13}| = 0.9(2) + 2.5(4)\frac{m_{\Delta_6}}{1\,\mathrm{TeV}}$$



LEADING CONTRIBUTIONS TO $t\,\bar{t}$ PRODUCTION CROSS SECTION AND A_{FB} AT TEVATRON.

FORWARD-BACKWARD ASYMMETRY



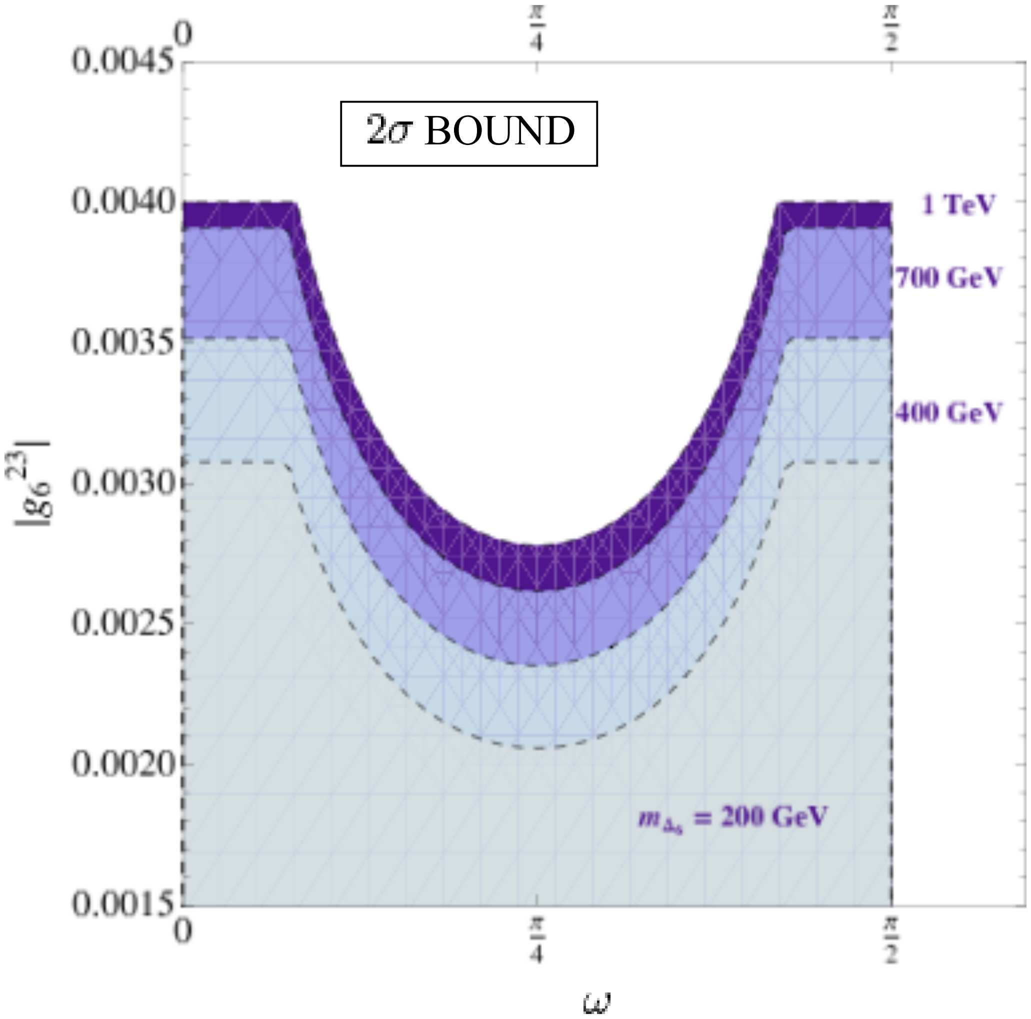


Examples of the $t\bar{t}$ hadronic cross-section and the forward-backward asymmetry at Tevatron including Δ_6. The shaded regions are outside one sigma experimental bound. Our study implies:

$$m_{\Delta_6} \geq 300\,\text{GeV}$$

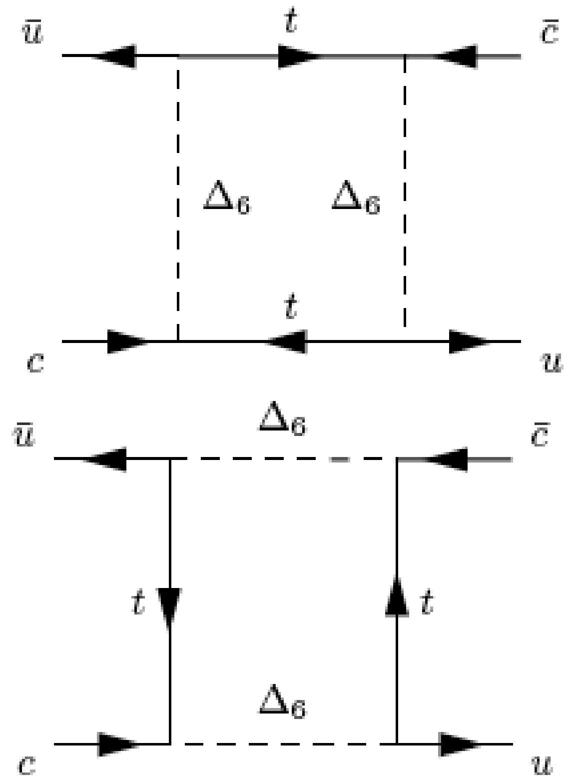
$$|g_6^{13}| = 0.9(2) + 2.5(4)\frac{m_{\Delta_6}}{1\,\text{TeV}}$$

$D^0 - \bar{D}^0$ MIXING CONSTRAINTS



$\omega \equiv$ RELATIVE PHASE BETWEEN g_6^{13} AND g_6^{23}

$(g_6^{13} g_6^{23*})^2$ CONTRIBUTIONS TO $|\Delta C| = 2$:



$m_{\Delta_6} = 400\,\text{GeV}$

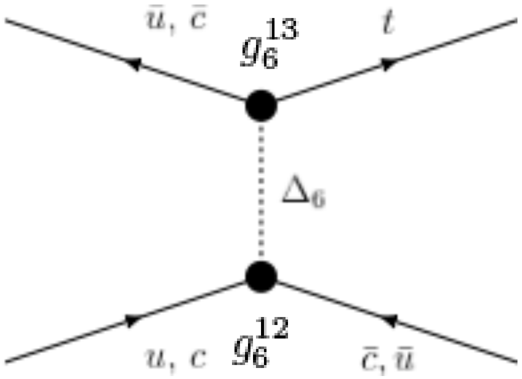
$|g_6^{23}| \leq 0.0033$

SINGLE *t* PRODUCTION CROSS-SECTION

THE SINGLE *t* PRODUCTION IS SENSITIVE TO THE PRODUCT $|g_6^{12} g_6^{13*}|$.

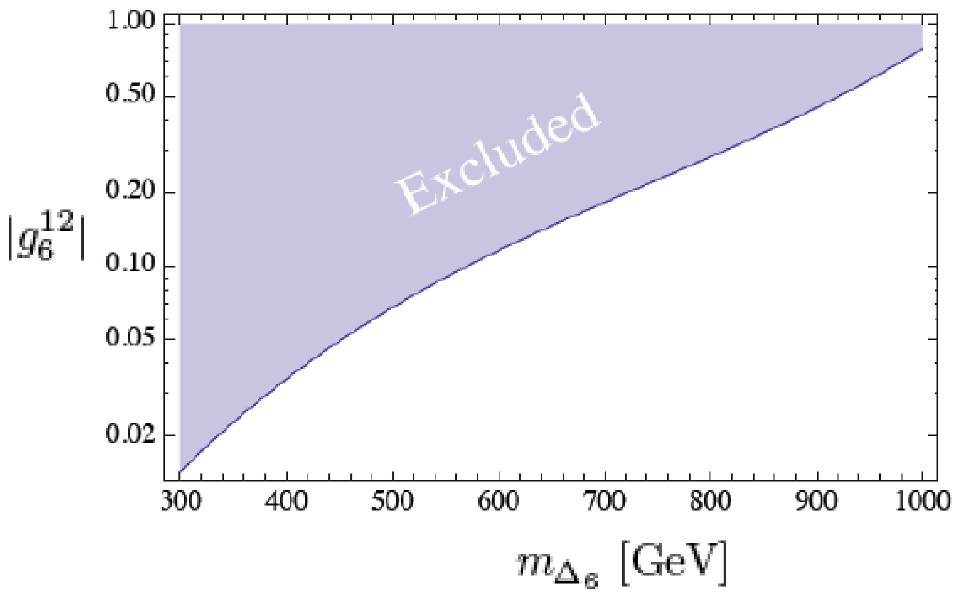
TEVATRON RESULT: $\sigma_{1t} = 2.76^{+0.58}_{-0.47}\,\mathrm{pb}$

WE REQUIRE: $\sigma_{1t}^{\Delta_6} \leq 1\,\mathrm{pb}$

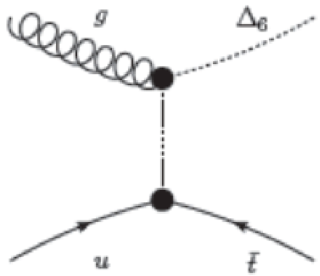


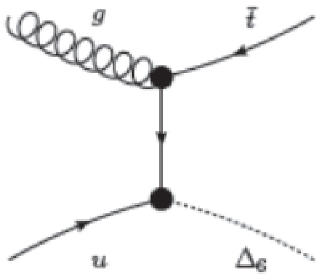
$m_{\Delta_6} = 400\,\mathrm{GeV}$

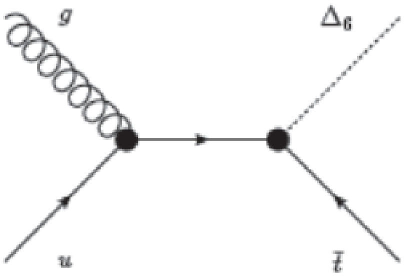
$|g_6^{12}| \leq 0.042$

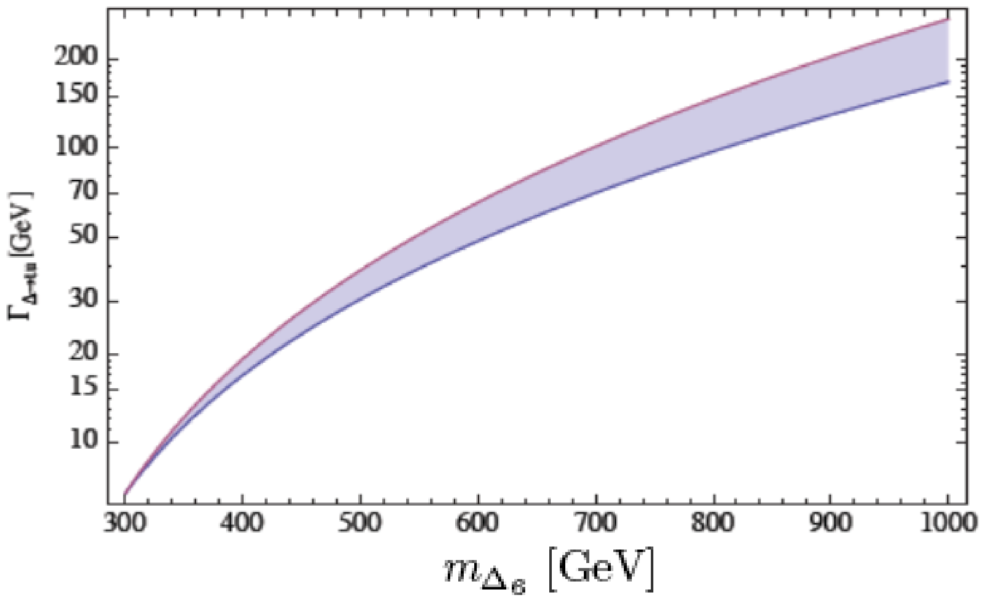


SEARCH STRATEGIES AT HADRON COLLIDERS







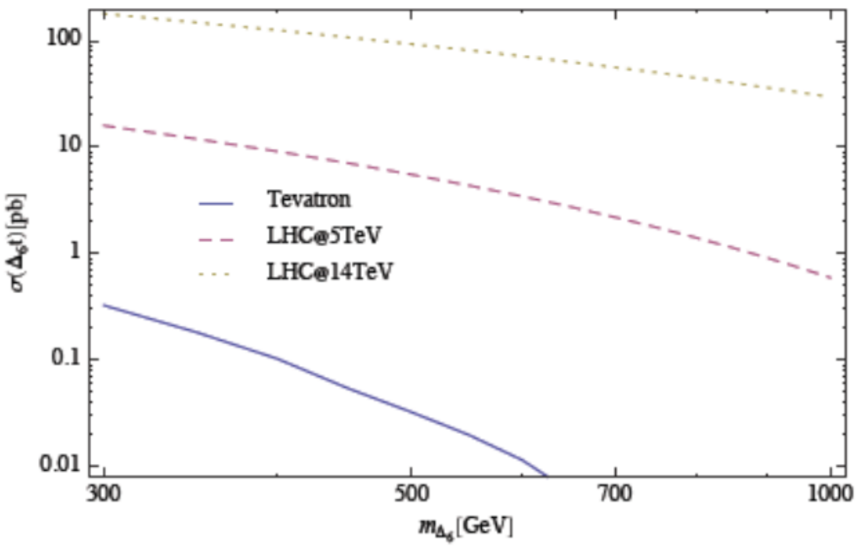


DEPENDENCE OF THE DECAY WIDTH ON Δ_6 MASS

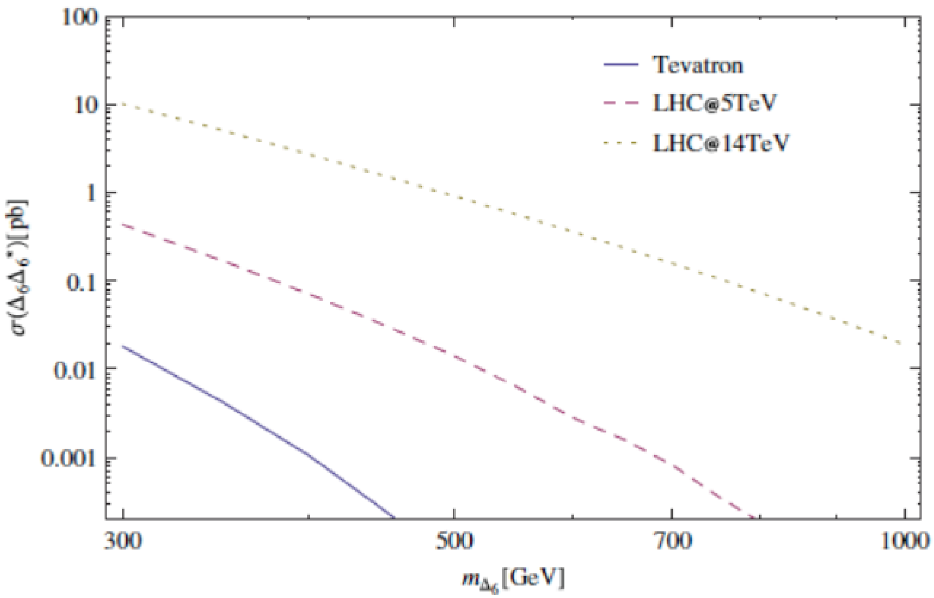
$$\sigma^{\Delta_6}_{t\bar{t}+j} \approx (\sigma_{t\Delta_6^*} + \sigma_{\bar{t}\Delta_6}) \times Br(\Delta_6 \to tu)$$

$$\Gamma(\Delta_6 \to tu) = \frac{|g_6^{13}|^2 (m_{\Delta_6}^2 - m_t^2)^2}{16\pi m_t^3}$$

Δ_6 PRODUCTION



HADRONIC PRODUCTION AT LHC AND TEVATRON



Δ_6 WOULD APPEAR AS A RESONANCE IN THE INVARIANT MASS OF A TOP AND ONE HARD JET.

BACK TO GRAND UNIFIED THEORIES

$\mathbf{5}$	$\mathbf{45}$
$(Y_2')_{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\gamma\delta})_j(\mathbf{5})^\epsilon$	$(Y_2)^{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j\mathbf{45}^{\delta\epsilon}_\zeta$

$$M_U = \left[4(Y_2'^T + Y_2')v_5 - 8(Y_2^T - Y_2)v_{45}\right]/\sqrt{2}$$

VACUUM EXPECTATION VALUES:

$$\langle \mathbf{5}\rangle^5 = \sqrt{2}v_5$$

$$\langle \mathbf{45}\rangle_1^{51} = \langle \mathbf{45}\rangle_2^{52} = \langle \mathbf{45}\rangle_3^{53} = \sqrt{2}v_{45}$$

$$2|v_5|^2 + 48|v_{45}|^2 = v^2$$

$$v = 246\,\mathrm{GeV}$$

THE UP-QUARK SECTOR

$$4S' = U^\dagger M_U^{diag} + M_U^{diag} U^*$$

$$4A' = U^\dagger M_U^{diag} - M_U^{diag} U^*$$

$$S'(= \sqrt{2} U_R^\dagger (Y_2'^T + Y_2') U_R^* v_5)$$

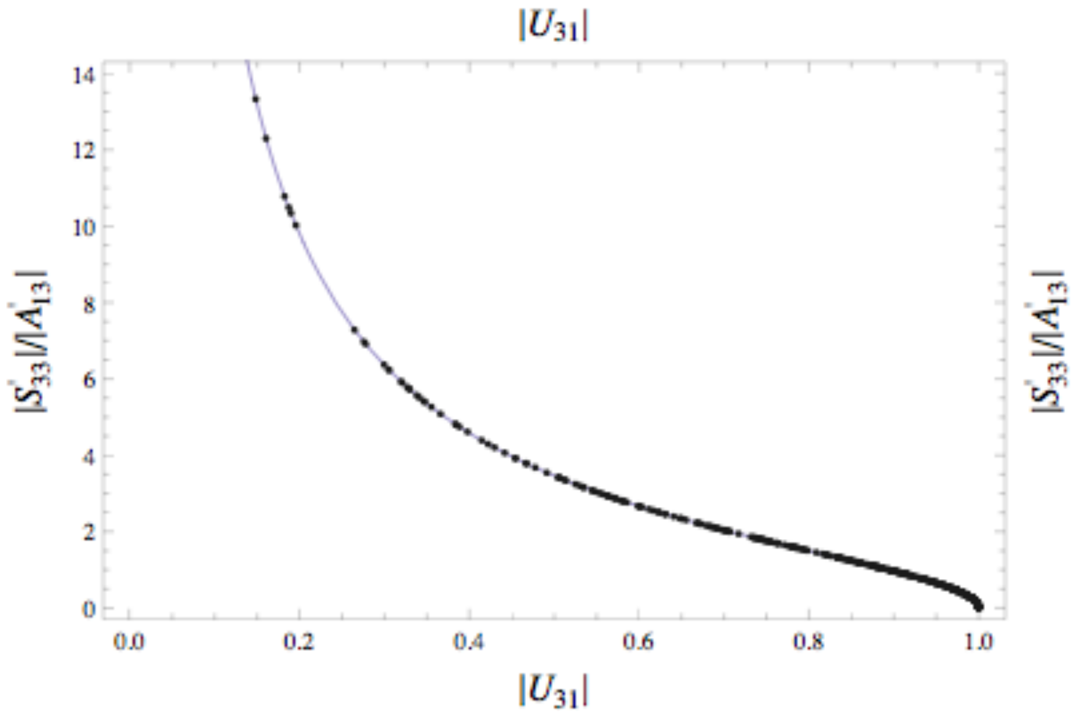
UNIFICATION SCALE RELATION:

$$\boxed{A' = g_6 v_{45}}$$

$$U = \tilde{V}_{CKM} U_R$$

$$|S'_{13}| = |A'_{13}| \qquad |S'_{33}|/|A'_{13}| \approx 2\sqrt{1 - |U_{31}|^2}/|U_{31}|$$

THE UP-QUARK SECTOR



$$|U_{31}| = \frac{4|g_6^{13}|v_{45}}{m_t}$$

EVERY ENTRY OF THE UP-QUARK MASS MATRIX CAN BE DESCRIBED IN TERMS OF ONE PARAMETER $|U_{31}|$.

$|U_{31}|$ OR v_{45} CAN BE CONSTRAINED BY THE DOWN-QUARK AND CHARGED LEPTON SECTOR!

CONCLUSIONS

Scalar leptoquarks appear naturally in theories of (grand) unification.

In certain minimal scenarios their mass could be directly accessible by Tevatron and/or LHC.

Genuine leptoquarks, at first sight, look more phenomenologically viable as candidates for New Physics. But…

<u>CONCLUSIONS</u>

The Δ_6 scenario offers a possibility to explain FB asymmetry in top pair production at Tevatron, without spoiling the SM prediction for the cross section.

The best strategy for the experimental search for the Δ_6 state would be to study the spectrum of the $t\bar{t}$ + jet production and search for resonances in the invariant mass of the light jet together with t or t.

Δ_6 can help us to decipher a pattern of the up-quark Yukawa mass matrix.

THANK YOU!

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