Scalar diquark in $t\bar{t}$ production and constraints on Yukawa sector of grand unified theories

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Outline

1. Forward-backward asymmetry in $t\bar{t}$ production and a color triplet diquark Δ
2. Diquark couplings of Δ in up-quark processes
3. Leptoquark induced processes: $\Delta \ell d$
4. Light Δ in GUT setting

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- Cross section measurements at Tevatron ($\sqrt{s} = 1.96$ TeV)

$$\sigma_{t\bar{t}}^{\rm exp} = 7.50 \pm 0.48 \text{ pb}$$

[CDF exp,2009]

$$\sigma_{t\bar{t}}^{SM} = (6.30 \pm 0.19^{+0.31}_{-0.23}) \text{ pb}$$

[Ahrens et al, 2010]

$$\sigma_{t\bar{t}}^{SM} = (7.46^{+0.66}_{-0.80}) \text{ pb}$$

[Langenfeld et al, 2009]

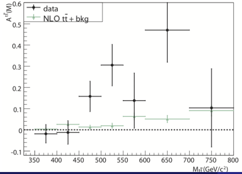
Th and exp in good agreement.

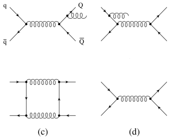
- Forward-backward asymmetry ($t\bar{t}$ frame)

$$A_{FB}(m_{t\bar{t}}) = \frac{N(\Delta y > 0, m_{t\bar{t}}) - N(\Delta y < 0, m_{t\bar{t}})}{N(\Delta y > 0, m_{t\bar{t}}) + N(\Delta y < 0, m_{t\bar{t}})}, \qquad \Delta y = y_t - y_{\bar{t}}$$

[CDF, Phys.Rev.,D83]	NLO QCD	
$A_{FB} = 0.158 \pm 0.075$	0.058 ± 0.009	(1.3σ)
$A_{FB}^{\rm M_{t\bar{t}}>450\ GeV} = 0.475 \pm 0.114$	0.088 ± 0.013	(3.4σ)
$A_{FB}^{\rm \vert\Delta y\vert>1} = 0.611 \pm 0.256$	0.123 ± 0.008	(1.9σ)

See previous talks by CDF and D0





$\mathcal{O}(\alpha_s^3)$ interference between tree-level $q\bar{q} \to t\bar{t}$ and two-gluon exchange [Kühn, Rodrigo]

- warped models Djouadi et al, Bauer et al
- Extra gauge bosons
  - W' Cheung et al
  - Z' Murayama et al
  - asymmetric left-right W' Barger et al
- s-channel axigluons Kühn et al, Frampton et al, Chivukula et al
- R-parity violating MSSM Cao et al
- t-channel color triplets, sextets Shu et al, Arhrib et al
- colored unparticles Chen et al

⋮

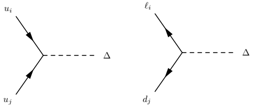
For reviews, see Gresham et al, PRD83; Aguilar-Saavedra,Pérez-Victoria,1107.0841

... and talk by Susanne Westhoff

Yukawa couplings of $\Delta = (\bar{3}, 1, 4/3)$

Yukawa couplings of Δ to $u\bar{u}$ or $\bar{\ell}\bar{d}$ pairs

$$\mathcal{L}_\Delta = \frac{g_{ij}}{2}\,\epsilon_{abc}\,\bar{u}_{ia} P_L u^C_{jb}\,\Delta_c + Y_{ij}\,\bar{e}_i P_L d^C_{ja}\,\Delta^*_a$$



(Couples to R-handed fermions)

- Antisymmetric color contraction $\bar{3} \otimes \bar{3} \otimes \bar{3}$ enforces antisymmetry in diquark couplings $g_{ij} = -g_{ji}$

$$\epsilon_{abc}\,\bar{u}_{ia} u^C_{ib} = 0$$

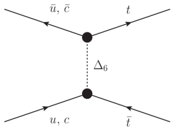
- Leptoquark couplings Y are arbitrary
- g and Y, when both present, violate baryon and lepton number
- Dimension-6 operator mediating proton decay is absent

$$\sim \frac{1}{m^2_\Delta} g_{ij} Y_{kl} \bar{u}_i \bar{u}_j \bar{e}_k \bar{d}_l$$

$$m_\Delta > \begin{cases} 384\ \text{GeV} & ;\quad \text{1st generation leptoquark} \\ 394\ \text{GeV} & ;\quad \text{2nd generation leptoquark} \end{cases}$$ [ATLAS]

- Contributions to $t\bar{t}$ in the u-channel via g_{ut}

Partonic cross-section (u-channel mediation)

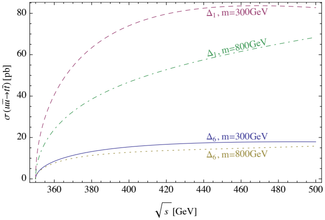


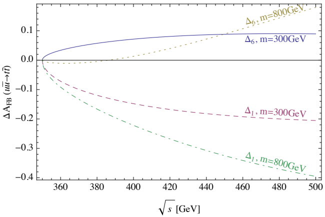
$$\frac{d\sigma^{q\bar{q}}(\hat{s})}{d\hat{t}} = \frac{d\sigma^{q\bar{q}}_{SM}(\hat{s})}{d\hat{t}} \underbrace{- \frac{\alpha_s |g_{qt}|^2}{9\hat{s}^3} \frac{m_t^2 \hat{s} + (m_t^2 - \hat{u})^2}{m_\Delta^2 - \hat{u}}}_{\Delta\times\text{SM interference term}} + \frac{|g_{qt}|^4}{48\pi\hat{s}^2} \frac{(m_t^2 - \hat{u})^2}{(m_\Delta^2 - \hat{u})^2}$$

$$\hat{t} = (p_u - p_t)^2$$

$$\hat{u} = (p_{\bar{u}} - p_t)^2$$

- Partonic cross section and global FBA





- Mild enhancement of σ by Δ
- Δ enhances A_{FB} well above threshold

- Convolute partonic distribution with PDFs

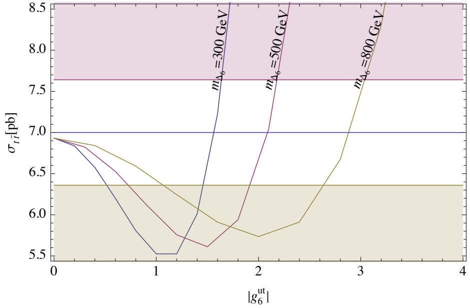
$$\frac{d\sigma(s)}{dt} = \sum_{p,p'=q,g} \int_{x_0}^{1} dx_1 \int_{x_0}^{1} dx_2 x_1 x_2 \frac{d\sigma^{pp'}(\hat{s})}{d\hat{t}} f_p(x_1) f_{p'}(x_2)$$

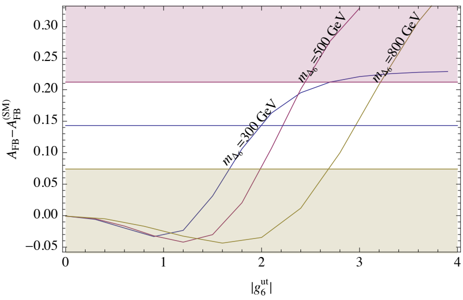
$$\hat{s} = x_1 x_2 s, \qquad \hat{t} = x_1 x_2 (t - m_t^2) + m_t^2$$

$$\frac{d\sigma(s)}{d\cos\theta} = \frac{s\sqrt{1 - 4m_t^2/\hat{s}}}{2} \frac{d\sigma(s)}{dt(\cos\theta)}$$

$$t(\cos\theta) = -s(1 - \cos\theta\,\beta_t)/2 + m_t^2$$

- We use CTEQ5 PDFs and rescale our results in each bin of $m_{t\bar{t}}$ so that our LO QCD results match with the reference NLO QCD [Frederix, Maltoni]

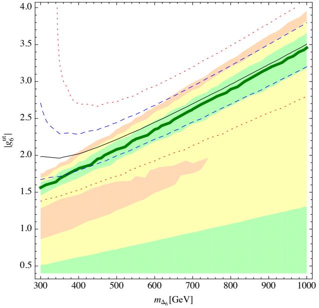




- Mass m_Δ and coupling g_{ut} are positively correlated

Δ in $t\bar{t}$ production

Correlating g_{ut} and m_Δ



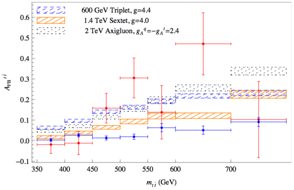
- Green contour = 1σ agreement with $\sigma_{t\bar{t}}$
- Blue dashed line = 1σ A_{FB}

From $t\bar{t}$ production constraints (global A_{FB})

$$|g_{ut}| = 0.9(2) + 2.5(4)\frac{m_\Delta}{1\ \mathrm{TeV}}$$

Perturbativity only for light Δ.

Tension in the high $m_{t\bar{t}}$ region. [Gresham et al, PRD83]



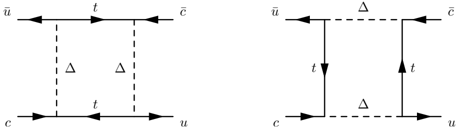
Need large coupling, $g_{ut} \sim \mathcal{O}(1)$. Together with other couplings g_{ct}, g_{uc} FCNC effects in the up-quarks are possible.

Outline

D–$\bar{D}$ mixing

[Doršner, Fajfer, Kamenik, NK, PRD82]

- Only $g_{ut}g_{ct}^*$ contributes because of antisymmetry of g — pure short distance diagrams



$$\mathcal{H}_{\rm eff} = C_6 Q_6, \qquad Q_6 = (\bar{u}_R\gamma^\mu c_R)(\bar{u}_R\gamma_\mu c_R),$$

$$C_6(m_\Delta) = \frac{(g_{ut}g_{ct}^*)^2 h(m_t^2/m_\Delta^2)}{64\pi^2 m_\Delta^2}, \qquad h(x) = \frac{-x^2+2x\log x+1}{(1-x)^3}.$$

- Rich data on D–$\bar{D}$ mixing

HFAG 2010

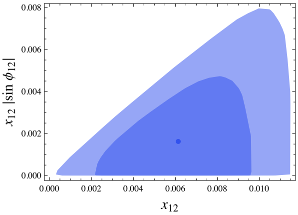
$$x = (0.59\pm0.20)\%, \qquad y = (0.81\pm0.13)\%,$$
$$|q/p| = 0.98^{+0.15}_{-0.14}, \qquad \phi = -0.051^{+0.112}_{-0.115}.$$

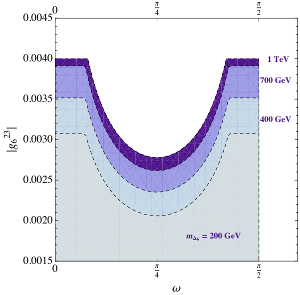
$$|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle$$
$$x = \frac{m_H - m_L}{\Gamma}$$
$$M_{12}/\Gamma_{12} \equiv -|M_{12}/\Gamma_{12}|e^{i\phi}$$

- CP violating phase in mixing is small, consistent with the SM
- Prediction of x is long-distance dominated in the SM

- Δ only contributes to M_{12}
- Fit of x_{12} and ϕ_{12} observables [$x_{12} \equiv 2|M_{12}|/\Gamma$, $\phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$], assuming $x_{12} < x_{12}^{\rm exp}$ [Gedalia et al]
- 2σ upper bounds

$$x_{12} < 9.6 \times 10^{-3}, \qquad x_{12}|\sin\phi_{12}| < 4.4 \times 10^{-3}$$

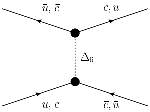




$\omega = \arg(g_{ct}/g_{ut})$

- Using the known value of g_{ut}:

Phase dependent bound from ϕ constraint, g_{ct} is of order $\lesssim 10^{-3}$

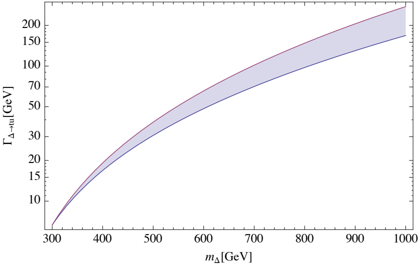


+ crossed diagrams

$$\hat{s} = (p_{\bar{u}} + p_u)^2$$
$$\hat{t} = (p_u - p_c)^2$$
$$\hat{u} = (p_{\bar{u}} - p_c)^2$$

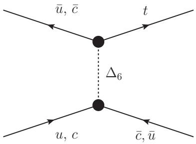
$$\frac{d\sigma^{u\bar{u}\to c\bar{c}}(\hat{s})}{d\hat{t}} = \frac{d\sigma^{u\bar{u}\to c\bar{c}}_{SM}(\hat{s})}{d\hat{t}} + \frac{|g_{uc}|^4}{48\pi\hat{s}^2}\frac{\hat{u}^2}{\left(m_\Delta^2 - \hat{u}\right)^2 + \Gamma_\Delta^2} - \frac{\alpha_s |g_{uc}|^2}{9\hat{s}^3}\frac{\hat{u}^2\left(m_\Delta^2 - \hat{u}\right)}{\left(m_\Delta^2 - \hat{u}\right)^2 + \Gamma_\Delta^2}$$

We regularize on-shell poles by Δ width



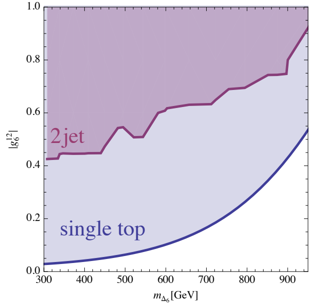
$$\Gamma(\Delta \to t q_i) = \frac{|g_{it}|^2 \left(m_\Delta^2 - m_t^2\right)^2}{16\pi m_\Delta^3}$$

- Comparable to exp. bin size in dijet invariant mass
- Compare hadronic cross section against CDF measured spectrum [CDF,0812.4036]



$$\frac{d\sigma^{u\bar{u}\to t\bar{c}}}{d\hat{t}} = -\frac{|g_{ut}^* g_{uc}|^2}{48\pi\hat{s}^2}\frac{(\hat{s}+\hat{t})\hat{u}}{(\hat{u}-m_\Delta^2)^2+\Gamma_\Delta^2}$$

$$+\ \text{s–channel}$$



- Conservative approach: compare only Δ contribution with the experimental error of the cross section $\sigma_{1t} = 2.76^{+0.58}_{-0.47}$ pb [CDF]

We require $\Delta\sigma_{1t} < 1$ pb at 95% CL

Coupling g_{uc} of the order $\lesssim 0.1$.

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Δ as a leptoquark

Introduction

- $\Delta = (\bar{3}, 1, 4/3)$ couples to down-quark and leptons

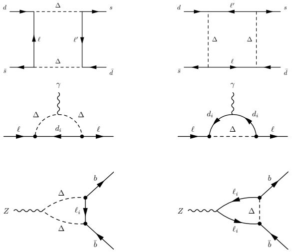
$$Y_{ij}\, \bar{\ell}_i P_L d^C_{ja}\, \Delta^*_a \qquad \text{right-handed fermions}$$

- Affected processes at tree-level

$$\mathcal{H}^{\Delta}_{d_i \bar{d}_j \to \ell^-_a \ell^+_b} = \frac{Y_{aj} Y^*_{bi}}{2 m^2_\Delta} (\bar{\ell}_a \gamma^\mu P_R \ell_b)(\bar{d}_j \gamma_\mu P_R d_i)$$

  - LFV meson decays to leptons, semileptonic decays
    $K^0 \to \ell\ell'$, $B_{d(s)} \to \ell\ell'$, $B \to X_s \ell^+ \ell^-$
  - μ–e conversion on nuclei
  - semileptonic LFV τ decays
    $\tau \to e\pi^0$, $\tau \to e K_S, \ldots$

- Loop processes:
  - ϵ_K, Δm_s, Δm_d, $\boxed{\sin 2\beta_s}$, $\sin 2\beta$
  - anomalous magnetic moments
    $\boxed{(g-2)_\mu}$, $(g-2)_e$
  - LFV radiative decays
    $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$
  - Decay width of $Z \to b\bar{b}$



Enough observables to overconstrain unknown complex parameters Y_{ij}

$$\mathcal{A}^\mu \equiv -ie\bar{u}(p', s')\Gamma^\mu u(p, s)\,,$$
$$\Gamma^\mu = F_1\gamma^\mu + \frac{F_2}{2m_\mu} i\sigma^{\mu\nu} q_\nu + F_3\sigma^{\mu\nu} q_\nu\gamma_5 + F_4(2mq^\mu + q^2\gamma^\mu)\gamma_5$$
$$a_\mu = (g-2)_\mu/2 = F_2(q^2 = 0)$$

- SM (QED + hadronic vacuum polarization + weak) Vs. experiment

$$a_\mu^{\rm exp} = 1.16592080(63) \times 10^{-3} \qquad \text{[Bennet et al]}$$
$$a_\mu^{\rm SM} = 1.16591793(68) \times 10^{-3} \qquad \text{[Jegerlehner]}$$
$$\Rightarrow \quad \delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.87 \pm 0.93) \times 10^{-9}$$

- Δ loops provide $a_\mu^\Delta > 0$:

$$a_\mu^\Delta = \frac{3m_\mu^2}{16\pi^2 m_\Delta^2} \sum_{i=d,s,b} |Y_{\mu i}|^2 \left[Q_\Delta f_\Delta(x_i) + Q_d f_d(x_i)\right], \qquad x = m_{d_i}^2/m_\Delta^2.$$

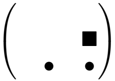
Can Δ explain the $(g-2)_\mu$ anomaly?

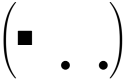
Inputs

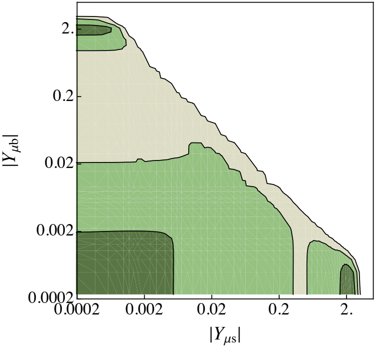
- Upper bounds (LFV processes, rare decays) + nontrivial constraints (e.g. a_μ, ϵ_K, $\sin 2\beta$)
- Global fit of 31 observables with 9 moduli and 9 phases of Y_{ij} couplings (+4 CKM parameters)

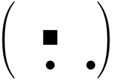
- $\chi^2 = 3.5$ (@10 degrees of freedom)

$$|Y^{(1\sigma)}| \in \begin{pmatrix} < 1.3\times 10^{-6} & < 2.2\times 10^{-4} & < 6.4\times 10^{-3} \\ < 4.2\times 10^{-3} \cup [1.8, 2.6] & < 4.2\times 10^{-3} \cup [1.8, 2.5] & < 1.7\times 10^{-3} \cup [1.8, 2.5] \\ < 4.9\times 10^{-3} & < 0.39 & < 0.41 \end{pmatrix}$$

 $\longrightarrow$

 $\longrightarrow$



$\longleftarrow$ 

$(g-2)_\mu$ tension is relaxed and requires large element in the second row.

CP violating phase in B_s–$\bar{B}_s$ mixing or $\Delta\Gamma_s$ stay at the SM level.

Recapitulation

Scalar $\Delta = (\bar{3}, 1, 4/3)$ can explain the observed A_{FB} excess in $t\bar{t}$

- Provided its mass is around 500 GeV and coupling to ut is large:

$$|g_{ut}| = 0.9(2) + 2.5(4)\frac{m_\Delta}{1\ \mathrm{TeV}}$$

Remaining diquark couplings have to be small

- D–$\bar{D}$ mixing measurements imply $g_{ct} \lesssim 4 \times 10^{-3}$
- Single-top production cross section implies $g_{uc} \lesssim 10^{-1}$

$$g \sim \begin{pmatrix} & \bullet & \blacksquare \\ \bullet & & \\ \blacksquare & & \end{pmatrix}$$

Leptoquark side of Δ can explain the muon magnetic moment

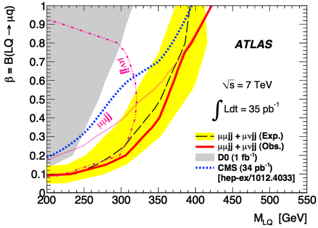
- While keeping rates of LFV and FCNCs below the observed level.
- It is a second generation leptoquark and decays as $\Delta \to \mu d, \mu s, \mu b$.

$$Y \sim \begin{pmatrix} & & \\ \blacksquare & & \\ & \bullet & \bullet \end{pmatrix} \text{ or } \begin{pmatrix} & & \\ & \blacksquare & \\ & \bullet & \bullet \end{pmatrix} \text{ or } \begin{pmatrix} & & \\ & & \blacksquare \\ & \bullet & \bullet \end{pmatrix}$$

Direct searches and mass constraints

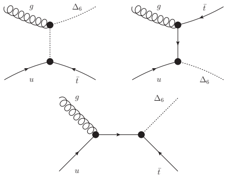
Pair production

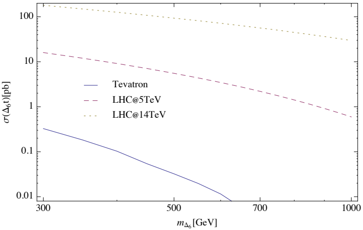
- LEP bound: $m_\Delta > 105$ GeV
- ATLAS 2nd-gen. LQ: $m_\Delta > 380$ GeV for $\mathcal{B}(\Delta \to \mu q) > 0.7$ (estimated from g_{ut}, $Y_{\mu q}$)
  [poster by Carolina Deluca], [1104.4481]



Associated production with t or μ

- LHC cross sections of $\Delta\bar{t}$ are comparable to $t\bar{t}$ production





Perturbativity bound from $(g-2)_\mu$

$$\sum_{i=d,s,b} |Y_{\mu i}|^2 = (6.45 \pm 2.09) \times \frac{m_\Delta^2}{(400\ \mathrm{GeV})^2}$$

From $Y_{\mu i} < \sqrt{4\pi}$ it then follows

$$m_\Delta \lesssim 560\ \mathrm{GeV}$$

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Non-SUSY SU(5) should contain 5 and 45 scalar representations to provide viable fermion masses (to avoid additional fermionic reps or nonrenormalizable operators) [Georgi,Glashow]

$$\begin{aligned} 5 &= (\Psi_D, \Psi_T) = (1,2,1/2) \oplus (3,1,-1/3) \\ 24 &= (\Sigma_8, \Sigma_3, \Sigma_{(3,2)}, \Sigma_{(\bar{3},\bar{2})}, \Sigma_{24}) \\ 45 &= (\Delta_1, \ldots, \Delta_6, \Delta_7), \qquad \Delta_6 = \Delta \end{aligned}$$

- 24 breaks SU(5)
- Matter fermions reside in 10_i and $\bar{5}_i$ representations, $i = 1,2,3$

$$10_i = (1,1,1) \oplus (\bar{3},1,-2/3) \oplus (3,2,1/6), \qquad \bar{5}_i = (1,2,-1/2) \oplus (\bar{3},1,1/3)$$

- Fermionic $24_F = (\rho_8, \rho_3, \ldots)$ in order to have type I+III seesaw ν masses
- 45 contains scalars, which contribute to $t\bar{t}$ production at tree-level, and is present in many GUT models

Yukawa couplings of 45 to matter

$$(Y_1)_{ij}(10^{\alpha\beta})_i(\bar{5}_\delta)_j 45^{*\delta}_{\alpha\beta}, \qquad \epsilon_{\alpha\beta\gamma\delta\epsilon}(Y_2)_{ij}(10^{\alpha\beta})_i(10^{\zeta\gamma})_j 45^{\delta\epsilon}_{\zeta}$$

Proton decay and unification

The most pressing constraints are

- unification of couplings at M_{GUT}
- proton stability, $\tau_{p\to\pi^0 e^+} > 8.2\times 10^{33}\mathrm{yr}$: M_{GUT} should not be too low, as well as masses of particles mediating proton decay

$$\Gamma \approx \frac{m_p}{f_\pi^2}\frac{\pi}{4}A_L^2|\alpha|^2(1+D+F)^2\frac{\alpha_{GUT}^2}{m_{X,Y}^4}[A_{SR}^2+4A_{SL}^2] \qquad \gamma_{L(R)i} = (23(11)/20, 9/4, 2)$$

$$A_{SL(R)} = \prod_{i=1,2,3}\prod_{I}^{M_Z\le m_I\le M_{GUT}}\left[\frac{\alpha_i(m_{I+1})}{\alpha_i(m_I)}\right]^{\gamma_{L(R)i}/(\sum_J^{M_Z\le m_J\le m_I} b_{iJ})}$$

- Ψ_T, Δ_3, and Δ_5 should be heavier than 10^{12} GeV
- ρ_8 must be above 10^6 GeV to accomodate BBN constraints

- We find that range $m_\Delta \in [300\ \mathrm{GeV}, 1\ \mathrm{TeV}]$ is consistent with unification and proton stability. [backup]
- Increase of proton lifetime by factor of 6 would rule out this scenario.

Yukawa sector

Mass terms:

$$\begin{aligned} M_D &= -Y_1 v_{45}^* - \frac{1}{2} Y_3 v_5^* \\ M_E &= 3 Y_1{}^T v_{45}^* - \frac{1}{2} Y_3^T v_5^* \\ M_U &= 2\sqrt{2}(Y_2 - Y_2^T) v_{45} - \sqrt{2}(Y_4 + Y_4^T) v_5 \end{aligned}$$

Phenomenologically well known couplings:

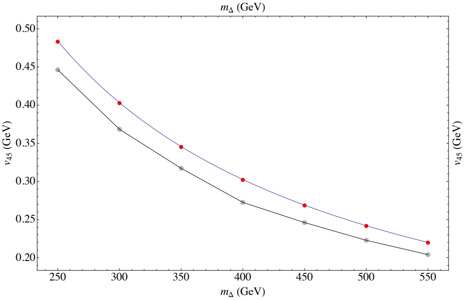
$$Y = E_R^\dagger Y_1 D_R^*$$
$$g = 2\sqrt{2} U_R^\dagger (Y_2 - Y_2^T) U_R^*$$

Going to a flavor basis, where rotations CKM and PMNS matrices stem from rotations in u_L and ν_L sector:

$$\begin{aligned} E_R^\dagger M_D^{diag} &= (-\frac{1}{2} E_R^\dagger Y_3 D_R^* v_5 - Y v_{45}), \\ M_E^{diag} D_R^* &= (-\frac{1}{2} E_R^\dagger Y_3 D_R^* v_5 + 3 Y v_{45}), \end{aligned}$$

$$E_R^\dagger M_D^{diag} - M_E^{diag} D_R^* = -4 Y v_{45}$$

- We apply the constraint on scale $m_{GUT} = 10^{16}$ GeV.
- Randomize unitary matrices E_R and D_R and test if obtained Y is compatible with phenomenological constraints



$$Y_3 \in \begin{pmatrix} < 5.2 \times 10^{-6} & < 1.2 \times 10^{-4} & < 2.0 \times 10^{-3} \\ < 4.5 \times 10^{-7} & < 1.3 \times 10^{-4} & [0.6, 2.3] \times 10^{-3} \\ < 3.6 \times 10^{-5} & [3.2, 3.5] \times 10^{-3} & 1.7 < \times 10^{-3} \end{pmatrix}.$$

Conclusions

Scalar $(\bar{3}, 1, 4/3)$

- As a diquark, it can satisfy both A_{FB} and $\sigma_{t\bar{t}}$ constraints in $t\bar{t}$ production, if g_{ut} is ≈ 2.
- As a leptoquark, it provides positive contribution to $(g-2)_\mu$, if $Y_{\mu q}$ are large.

Complementary constraints

- D–$\bar{D}$ mixing and single-top production require $g_{uc} \lesssim 0.1$ and $g_{ut} \lesssim 0.001$
- LFV and FCNCs in the down-quark and charged lepton processes together with $(g-2)_\mu$ guarantee that μ is coupled strongly to exactly one of the down quarks $Y_{\mu q}$.

$$Y \sim \begin{pmatrix} \blacksquare & & \\ & \bullet & \bullet \end{pmatrix} \text{ or } \begin{pmatrix} & \blacksquare & \\ & \bullet & \bullet \end{pmatrix} \text{ or } \begin{pmatrix} & & \blacksquare \\ & \bullet & \bullet \end{pmatrix}$$

Direct observation prospects

- Second generation leptoquark, $\Delta \to \mu q$, or $\Delta \to ut$
- Mass already constrained to a narrow window $m_\Delta = 380 - 560\ \mathrm{GeV}$

Present in realistic GUT framework

- Member of scalar 45-dimensional representation of $SU(5)$.
- Y, g are, together with v_{45}, responsible for mass matrices of u, d, and ℓ
- Phenomenological constraints on Y result in fixed, small, value of $v_{45} \sim 0.1\ \mathrm{GeV}$

Backup

The most pressing constraints are

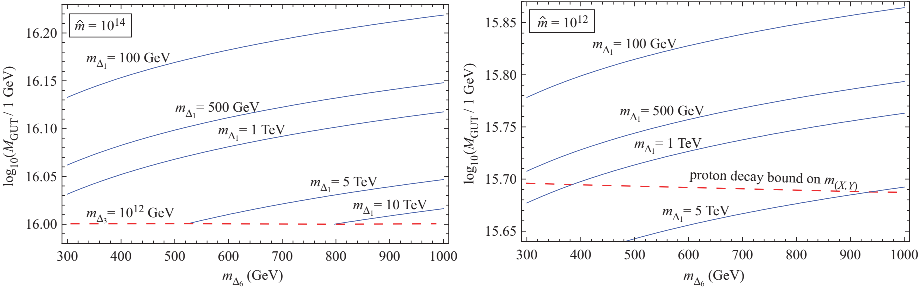
- unification of couplings at M_{GUT}
- proton stability, $\tau_{p\to\pi^0 e^+} > 8.2\times 10^{33}\mathrm{yr}$: M_{GUT} should not be too low, as well as masses of particles mediating proton decay

$$\Gamma \approx \frac{m_p}{f_\pi^2}\frac{\pi}{4}A_L^2|\alpha|^2(1+D+F)^2\frac{\alpha_{GUT}^2}{m_{X,Y}^4}[A_{SR}^2+4A_{SL}^2] \qquad \gamma_{L(R)i} = (23(11)/20, 9/4, 2)$$

$$A_{SL(R)} = \prod_{i=1,2,3}\prod_{I}^{M_Z\le m_I\le M_{GUT}}\left[\frac{\alpha_i(m_{I+1})}{\alpha_i(m_I)}\right]^{\gamma_{L(R)i}/(\sum_J^{M_Z\le m_J\le m_I} b_{iJ})}$$

- Ψ_T, Δ_3, and Δ_5 should be heavier than 10^{12} GeV
- ρ_8 must be above 10^6 GeV to accomodate BBN constraints

We determine upper bound on M_{GUT} for $m_\Delta \in [300\ \mathrm{GeV}, 1\ \mathrm{TeV}]$, while requiring unification and satisfying the above constraints.



$$\hat{m} \equiv m_{\rho_8}/m_{\rho_3}$$

- Also the octet Δ_1 must be light $\Rightarrow$ need to suppress Y_1
- Whole region $m_\Delta \in [300 \text{ GeV}, 1 \text{ TeV}]$ would be excluded if proton lifetime was larger by factor 6

Proton decay and unification