Signatures of light color scalars in low-energy phenomenology

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Alex-Fest: "Colour meets Flavour: QCD and quark
flavour physics”, 13-14 Oct. 2011, Siegen,

Outline

I GUT and light scalars;

II Flavor physics constraints on colored weak singlet scalar;

- Forward-backward asymmetry in $t\bar{t}$ production and diquark couplings of colored weak singlet scalar Δ;
- Diquark couplings in up-quark sector;
- Constraints on leptoquark down-quarks and lepton phenomenology;
- Role of $(g-2)_\mu$;
- Search for light Δ;

III Mass-matrices texture within SU(5) GUT.

Based on:

I.Doršner, S.F. J.F. Kamenik and N. Košnik, 0912.0972 ;
0906.5585; 1007.2604 ;
J. Drobnak, I.D., S.F., JFK, N.K. 1107.5393.

I GUT and light scalars

Inclusion of 45 Higgs representation SU(5) GUT

Higgs in 45 modifies: $M_E^T = -3M_D$

Both are needed:
Higgses in 5 and 45!

$$\mathbf{45_H = (\Delta_1, \Delta_2, \Delta_3, \Delta_4, \Delta_5, \Delta_6, \Delta_7) = (8, 2, 1/2) \oplus (\overline{6}, 1, -1/3) \oplus (3, 3, -1/3) \oplus (\overline{3}, 2, -7/6) \oplus (3, 1, -1/3) \oplus (\overline{3}, 1, 4/3) \oplus (1, 2, 1/2)}$$

Δ_3, Δ_4, Δ_5 excluded by experimental results from K and D (I. Doršner, S.F, N. Košnik, J.F. Kamenik, (2009)

Is unification possible with some of light scalars in 45?

Yes!

I.Doršner, S.F. J.F. Kamenik and N. Košnik, 0906.5585; 1007.2604 ;

Unification possible with 2 light scalars: Δ_1 and Δ_6.
Bounds from proton decay lifetime lead to a possibility for GUT:
if e.g. m(Δ_6) ≈ 400 GeV, then m(Δ_1) ≈1000 GeV;

II Flavor physics constraints on colored weak singlet scalar

Indication for new physics in flavor physics

exp. result ⟷ SM prediction

1) Forward-backward asymmetry in top - anti-top production at Tevatron;

2) CP phase in B_s system;

3) Muon anomalous magnetic moment.

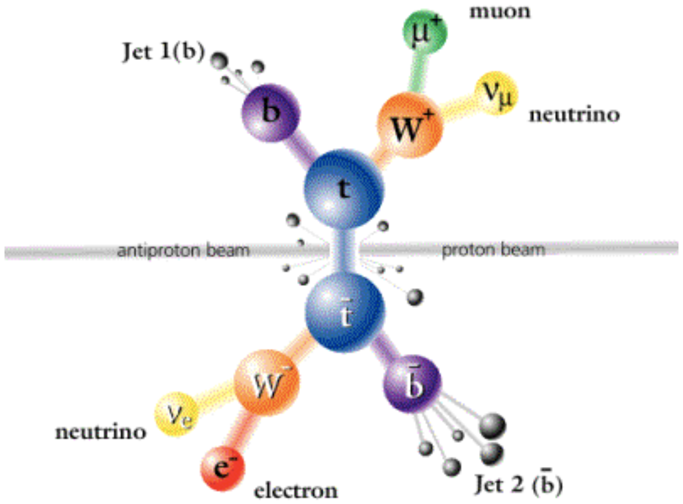
Forward-backward asymmetry in $t\bar{t}$ production and Δ

Cross section measurements at Tevatron

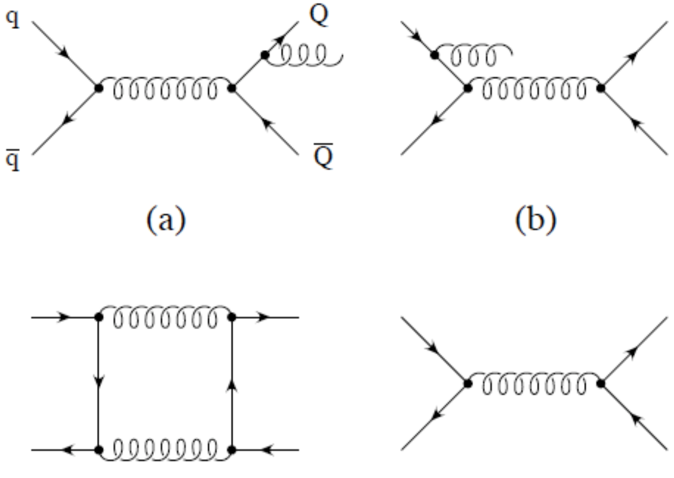
$(\sqrt{s} = 1.96 \text{ TeV})$

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

[CDF note 9913,2009]



SM prediction and experimental result agrees!



(a) (b)

(c) (d)

$$\sigma_{t\bar{t}}^{SM} = (7.22^{+0.31}_{-0.47}{}^{+0.71}_{-0.55}) \text{ pb}$$

[Beneke et al, 2011]

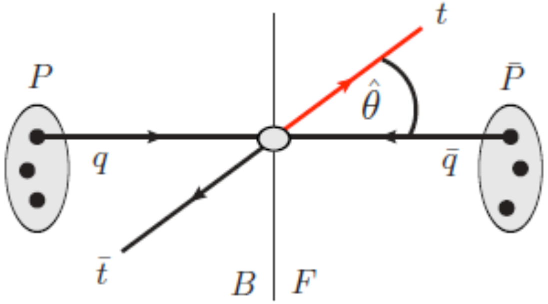
$$\sigma_{t\bar{t}}^{SM} = (6.30 \pm 0.19^{+0.31}_{-0.23}) \text{ pb}$$

[Ahrens et al, 2010]

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

[Langenfeld et al, 2009]

Forward-backward asymmetry in double top production at Tevatron



$$A^t_{FB} = \frac{N_t(F) - N_t(B)}{N_t(F) + N_t(B)}$$

$M_{t\bar{t}}$ dependence of A_{FB}

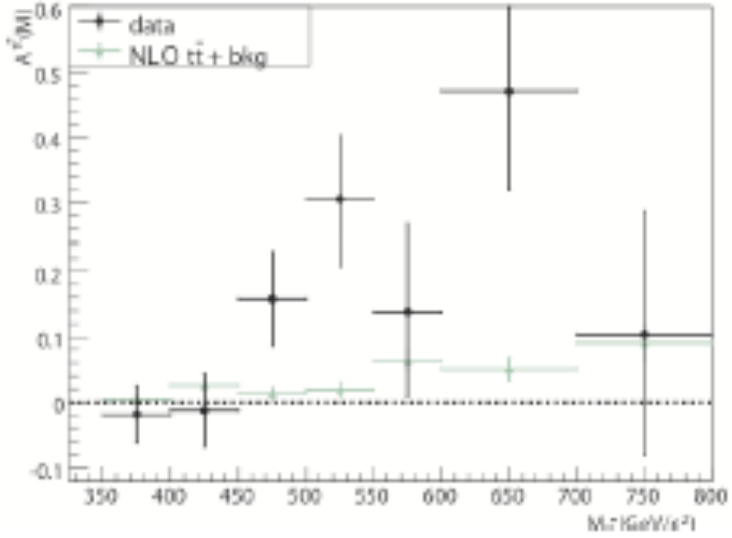
SM A_{FB} at NNLO QCD

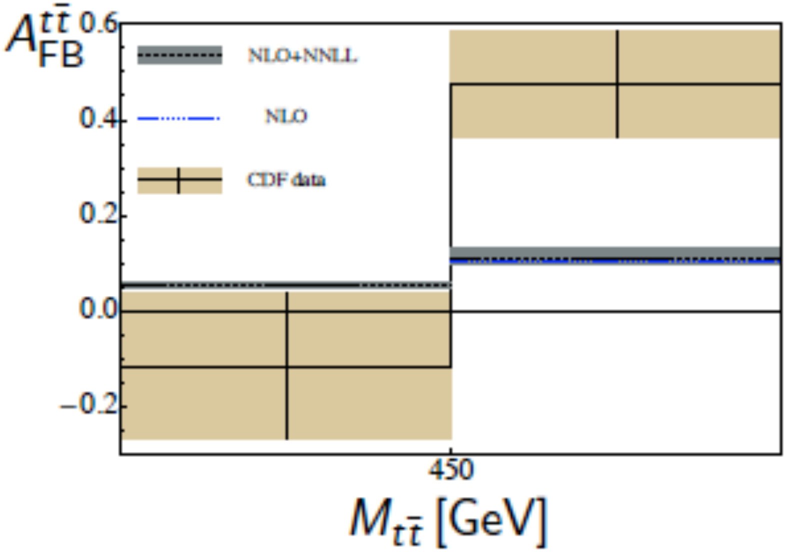
$$A^t_{FB} = \begin{cases} 0.158 \pm 0.072 \pm 0.017 \ \ (CDF) \\ 0.42 \pm 0.15 \pm 0.05 \ \ (CDF) \\ 0.196 \pm 0.060^{+0.018}_{-0.026} \ \ (D0) \end{cases}$$

$$(7.24^{+1.04+0.20}_{-0.67-0.27}) \cdot 10^{-2}$$

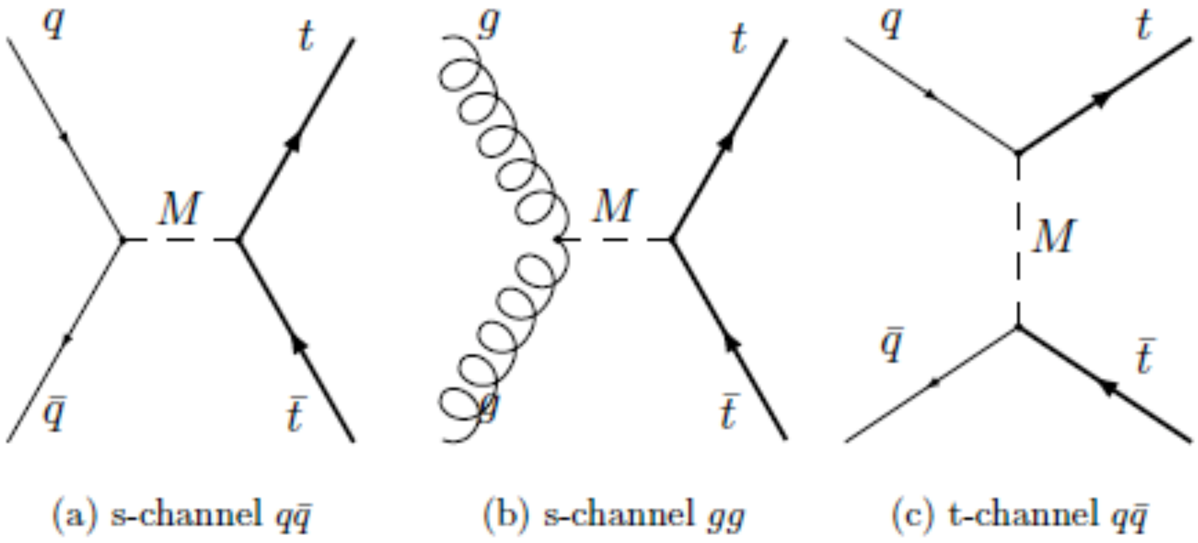
V. Ahrens et al, 2011;

$$A^t_{FB} \simeq 0.200 \pm 0.047$$





Many attempts to explain it : new particles either in s or t (u) channel



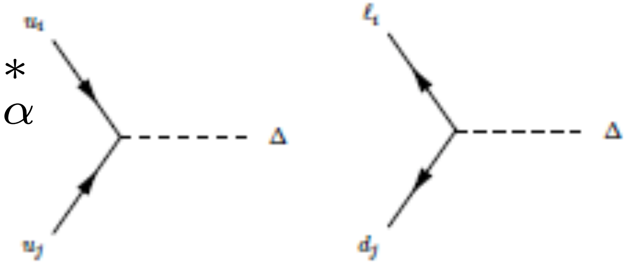
(a) s-channel $q\bar{q}$ (b) s-channel gg (c) t-channel $q\bar{q}$

- Z' $M_{Z'} \approx 160\,\mathrm{GeV}$
- Kaluza – Klein gluon excitation;
- Axigluons;
- W';
- Randall-Sundrum model;
- color triplet;
- color sextet;
- colored Higgs etc….

For review see
Gresham et al. , 1103.3501;
Aguilar-Saavedra, Perez-Victoria,
1107.0841; KJ.F. Kamenik et al.,
1107.5257; S. Westhoff, 11083341;

Color triplet exchange $\Delta = (\bar{3}, 1, 4/3)$

$$\mathcal{L}_\Delta = \frac{g_{ij}}{2}\epsilon^{\alpha\beta\gamma}\bar{u}_{i\alpha}P_L u^C_{j\beta}\Delta_\gamma + Y_{ij}\bar{l}_i P_L d^C_{j\alpha}\Delta^*_\alpha$$



violate baryon and lepton number

right-handed fermions

absence of dimension 6 tree level proton decay amplitude

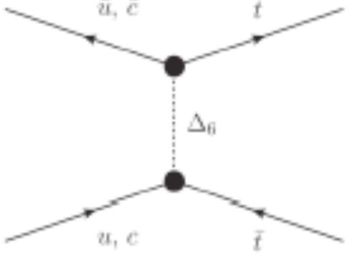
$$\sim \frac{1}{m_\Delta^2} g_{ij} Y_{kl} \bar{u}_i \bar{u}_j \bar{e}_k \bar{d}_l$$

ATLAS searches

$$m_\Delta > \begin{cases} 384\ \mathrm{GeV} \\ 394\ \mathrm{GeV} \end{cases}$$

1 generation leptoquark
2 generation leptoquark

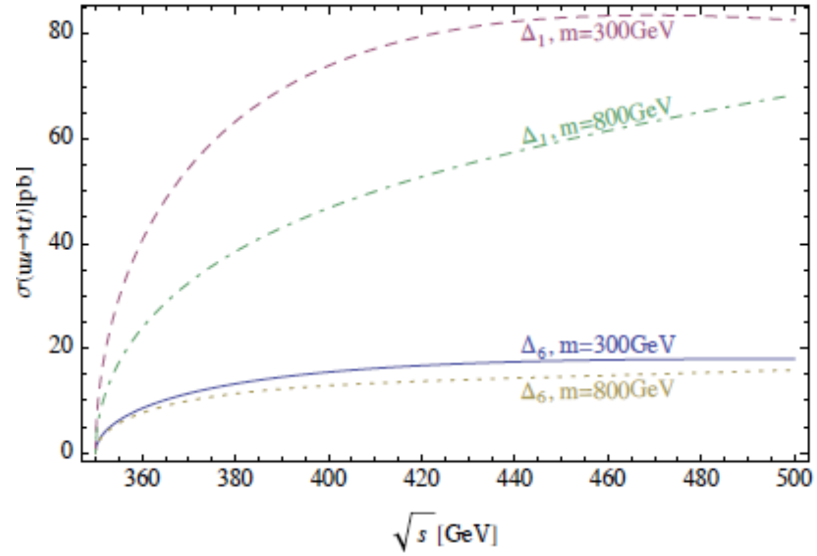
A_{FB} at Tevatron and Δ exchange in u-channel

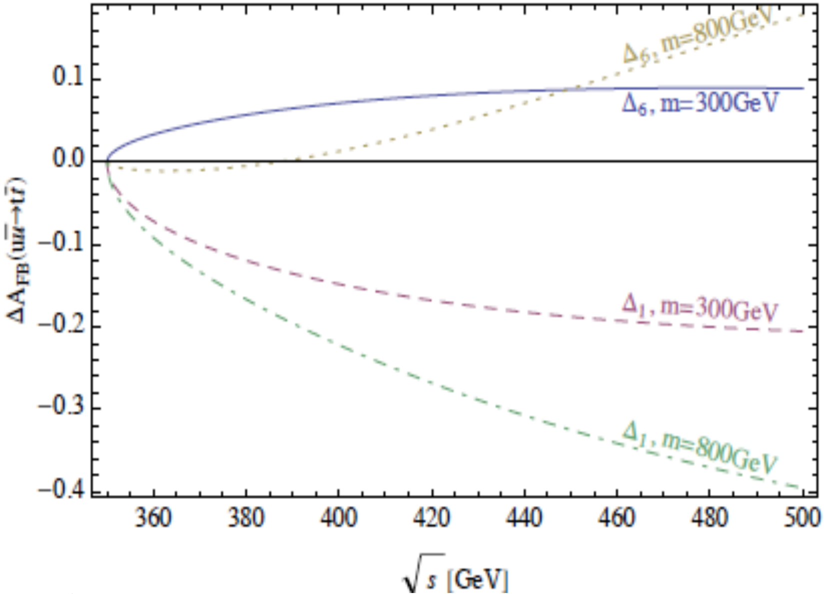


$$\frac{d\sigma^{q\bar q}(\hat s)}{d\hat t} = \frac{d\sigma^{q\bar q}_{SM}(\hat s)}{d\hat t} \underbrace{\boxed{-\frac{\alpha_s|g_{qt}|^2}{9\hat s^3}\,\frac{m_t^2\hat s+(m_t^2-\hat u)^2}{m_\Delta^2-\hat u}}}_{\Delta\times\mathrm{SM\ interference\ term}} + \frac{|g_{qt}|^4}{48\pi\hat s^2}\,\frac{(m_t^2-\hat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

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

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

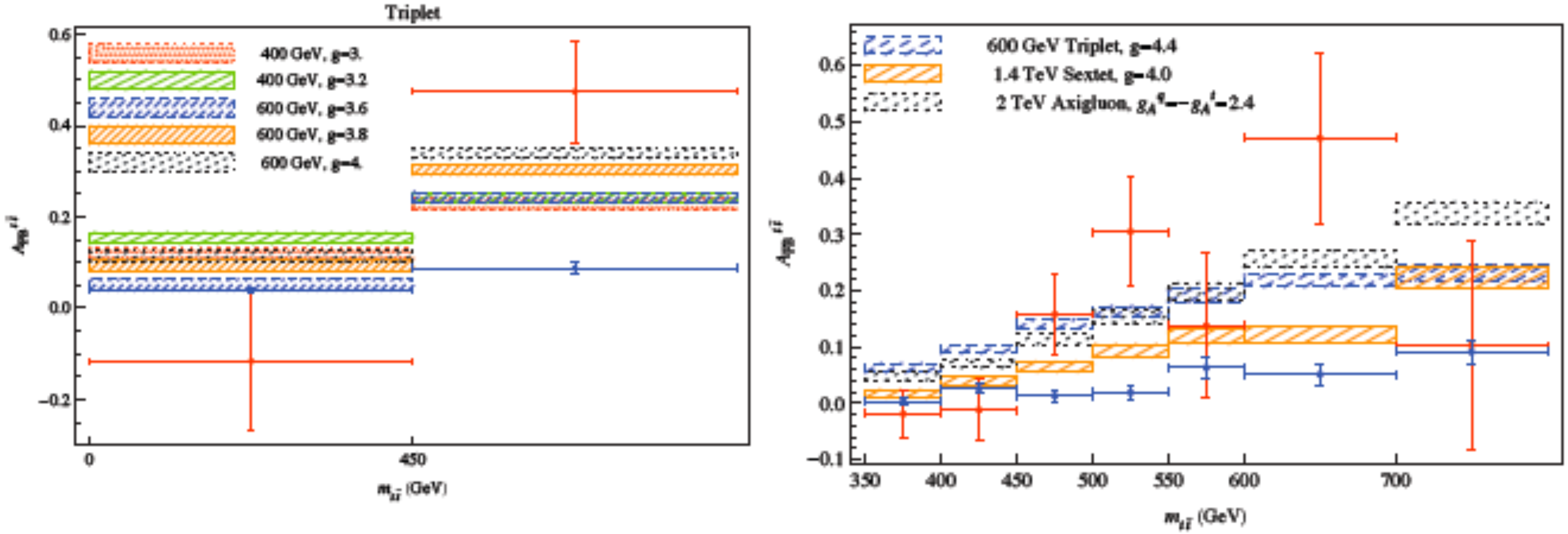




moderate increase of σ by Δ, while it enhances A_{FB}

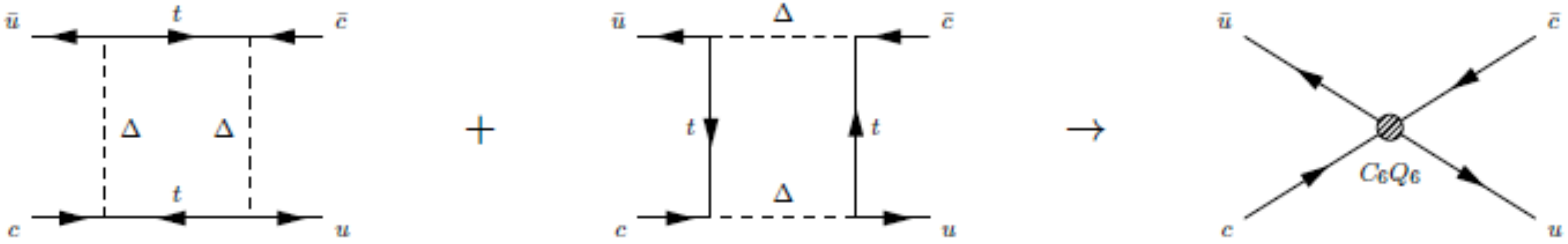
best fit value for $\boxed{|g_{ut}| = 0.9(2) + 2.5(4)\frac{m_\Delta}{1\ \mathrm{TeV}}}$

preferred value
$m_\Delta \approx 400$ GeV



from M. Gresham et al., 1103.3501

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



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

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

Δ contributes to $M_{12} = \langle D^0 | \mathcal{H}_{\rm eff} | \bar{D}^0 \rangle / (2m_D)$

$|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle$

$$x_{12} = \frac{2|M_{12}|}{\Gamma}, \qquad y_{12} = \frac{|\Gamma_{12}|}{\Gamma}, \qquad \phi_{12} = \arg(M_{12}/\Gamma_{12})$$

$$x = \frac{m_H - m_L}{\Gamma}$$

HFAG 2010
$$\left\{ \begin{array}{c} x = 90.59 \pm 0.20)\%, \;\; y = (0.81 \pm 0.13)\% \\ |q/p| = 0.98^{+0.15}_{-0.14}, \;\; \Phi = -0.051^{+0.1112}_{-0.115}. \end{array} \right\}$$

- in SM CP violating phase consistent with 0;
- x is in SM prediction range- long distance contribution dominant!

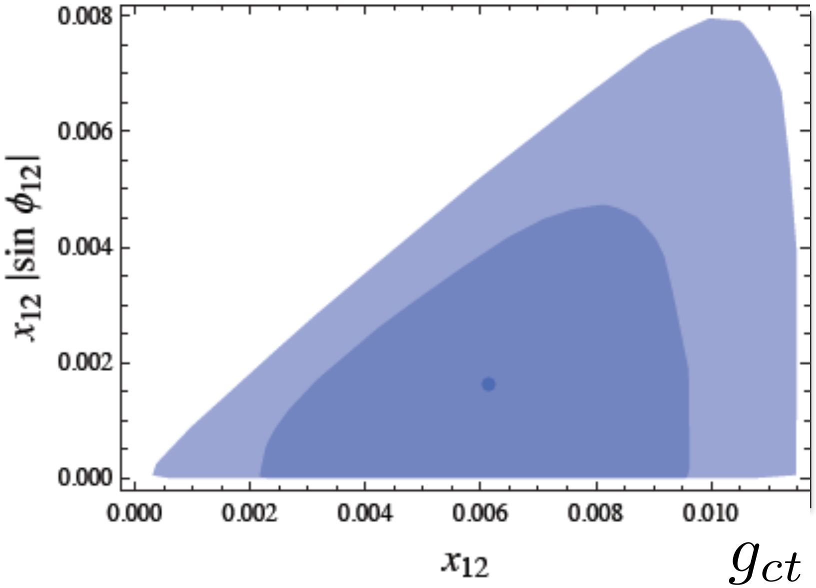
We use following relations (Gedalia et al. (2009), Grossman et al, (2009))

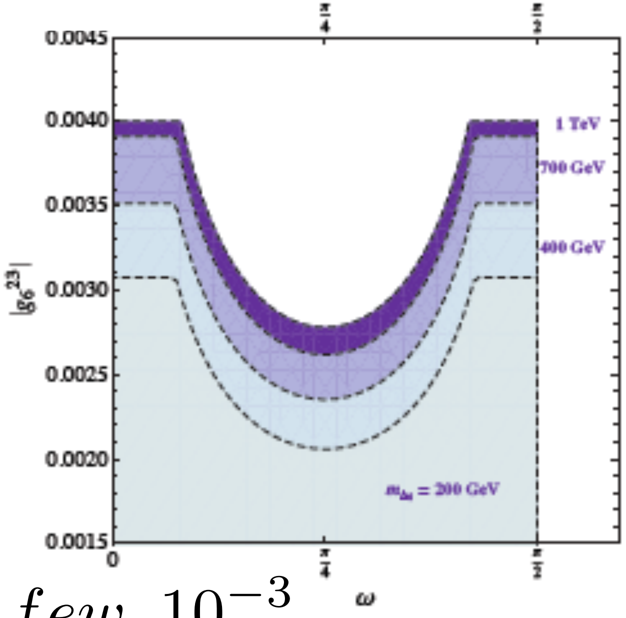
$$x_{12}^2 = \frac{\left(|q/p|^2+1\right)^2 x^2 + \left(1-|q/p|^2\right)^2 y^2}{4|q/p|^2},$$

$$\sin^2\phi_{12} = \frac{\left(1-|q/p|^4\right)^2 \left(x^2+y^2\right)^2}{16|q/p|^4 x^2 y^2 + \left(1-|q/p|^4\right)^2 \left(x^2+y^2\right)^2}.$$

Imaginary part of M_{12} is accessible in the product

$$x_{12}\sin\phi_{12} = \frac{2\,\mathrm{Im}M_{12}}{\Gamma},$$





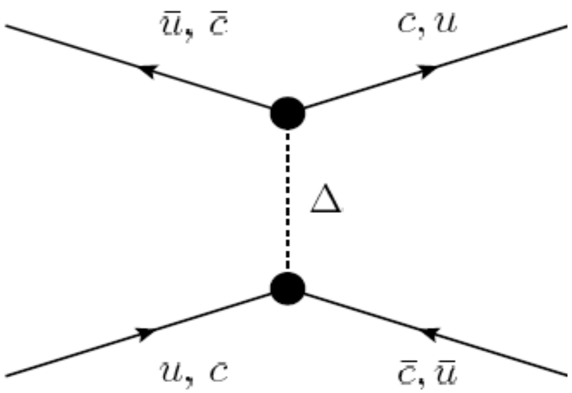
$\omega = \arg(g_{ct}/g_{ut})$

$g_{ct} \le few\ 10^{-3}$

Bounds on g_{uc}

- CDF search for resonances in the mass-spectrum of the di-jets;
- single top production cross-section measurements at Tevatron.

di-jet



u-channel exchange

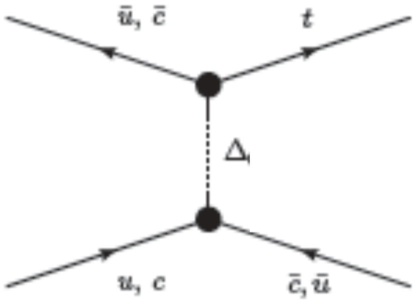
$$\frac{d\sigma_6^{u\bar{u}\to c\bar{c}}(\hat{s})}{d\hat{t}} = \frac{d\sigma_{SM}^{u\bar{u}\to c\bar{c}}(\hat{s})}{d\hat{t}} + \frac{|g_6^{12}|^4}{48\pi\hat{s}^2}\frac{\hat{u}^2}{(m_{\Delta_6}^2-\hat{u})^2+\Gamma_{\Delta_6}^2} - \frac{\alpha_s|g_6^{12}|^2}{9\hat{s}^3}\frac{\hat{u}^2\,(m_{\Delta_6}^2-\hat{u})}{(m_{\Delta_6}^2-\hat{u})^2+\Gamma_{\Delta_6}^2},$$

crossing symmetry for the rest of the processes

$u\bar{c}\to u\bar{c}$, $c\bar{u}\to c\bar{u}$, $uc\to uc$ and $\bar{u}\bar{c}\to\bar{u}\bar{c}$

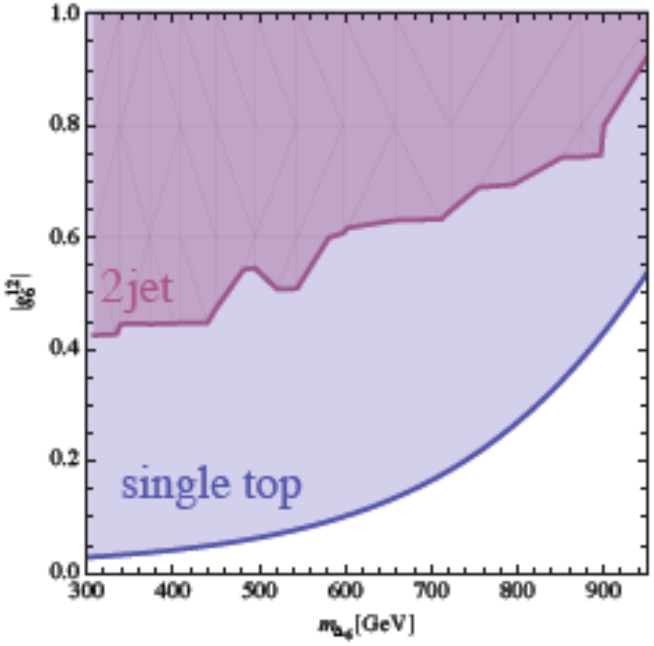
Hadronic di-jet production invariant mass spectrum
(programs: CTEQ5 set of PDFs)

Single top production



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

$$+\ \text{s–channel}$$



we require

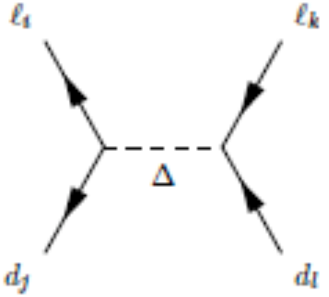
$$\Delta\sigma 1t \leq 1\ \ pb\ \ at\ \ 95\%\ \ CL$$

$$g_{ut} \sim 0.1$$

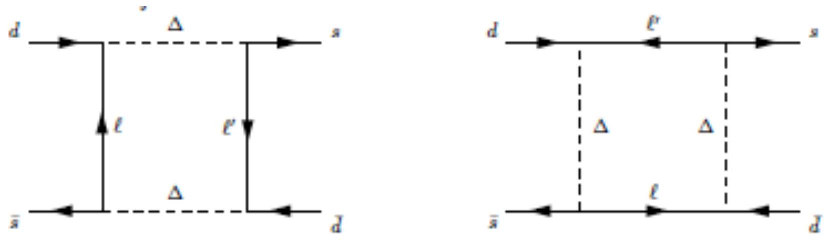
Down-quarks and leptons interactions with Δ

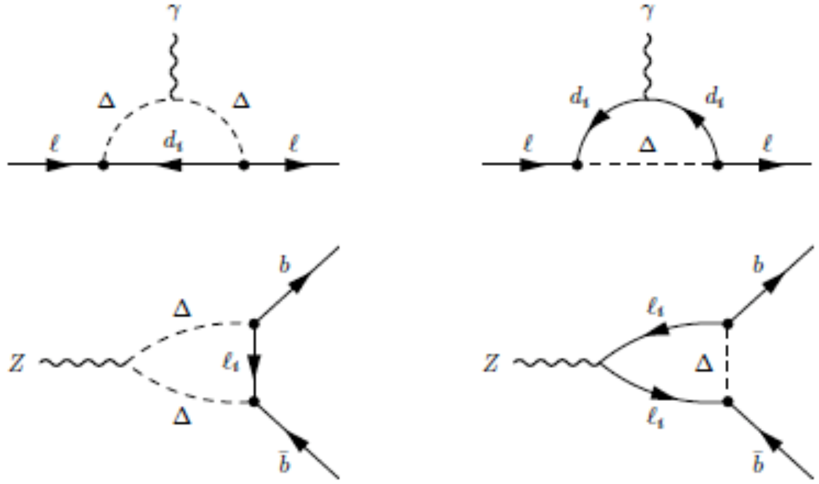
$$\mathcal{L}_\Delta = Y_{ij}\bar{l}_i P_L d_{ja}\Delta^*_a$$

$$\Big\downarrow$$



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





Enough variables to (over)constrain Y

Constraints at tree level

- LFV meson decays to leptons, semileptonic decays

$K^0 \to \ell\ell'$, $B_{d(s)} \to \ell\ell'$,
$B \to X_s \ell^+ \ell^-$, $B \to K(\pi)\ell\ell'$

- μ–e conversion in nuclei
- LFV decays of τ

$\tau \to e\pi^0$, $\tau \to eK_S, \ldots$

Loop processes

- K and B physics

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

$\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$

- decays of $Z \to b\bar{b}$

Anomalous lepton magnetic moment

$$\mathcal{A}^\mu \equiv -ie\bar{u}(p',s')\Gamma^\mu u(p,s)\,,$$

$$\Gamma^\mu = F_1\gamma^\mu + \frac{F_2}{2m_\mu} i\sigma^{\mu\nu} q_\nu + F_3\sigma^{\mu\nu} q_\nu\gamma_5 + F_4(2mq^\mu + q^2\gamma^\mu)\gamma_5$$

$$a_\mu = (g-2)_\mu/2 = F_2(q^2=0)$$

SM: QED + hadronic vacuum polarization + weak corrections

$$a_\mu^{\rm exp} = 1.16592080(63)\times 10^{-3} \qquad \text{[Bennet et al]}$$

$$a_\mu^{\rm SM} = 1.16591793(68)\times 10^{-3} \qquad \text{[Jegerlehner]}$$

$$\Rightarrow \quad \delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.87 \pm 0.93)\times 10^{-9}$$

Δ provides $a_\mu^\Delta > 0$

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

Puzlle: does Δ provide missing part of a_μ and hides effects in LFV and FCNC?

CP phase in B_s system

$\Delta M_s \equiv M_{sH} - M_{sL}$ very accurately measured

$$\Delta\Gamma_s \equiv \Gamma_{sL} - \Gamma_{sH}$$

$\Delta M_s = (17.73 \pm 0.05)\,\mathrm{ps}^{-1}$ $\quad (\Delta M_s)_{\mathrm{SM}} = (17.3 \pm 2.6)\,\mathrm{ps}^{-1}$

-

$$B_s \to J/\psi\phi$$

$(\phi^s_{J/\psi\phi})_{\mathrm{SM}} = \arg\left[\frac{(V^*_{ts}V_{tb})^2}{(V^*_{cs}V_{cb})^2}\right] = (-2.1 \pm 0.1)^\circ$ $\quad (\Delta\Gamma_s)_{\mathrm{SM}} = (0.087 \pm 0.021)\,\mathrm{ps}^{-1}$

slight tension SM and experimental results

CDF and D0 $\quad \phi^s_{J/\psi\phi} = (-32 \pm 18)^\circ \quad \Delta\Gamma_s = (0.097 \pm 0.032)\,\mathrm{ps}^{-1}$ at 68% CL

LHCb $\quad \phi^s_{J/\psi\phi} = (1.7 \pm 10.0)^\circ\,, \quad \Delta\Gamma_s = (0.123 \pm 0.030)\,\mathrm{ps}^{-1}\,.$

Global fit of leptoquark couplings

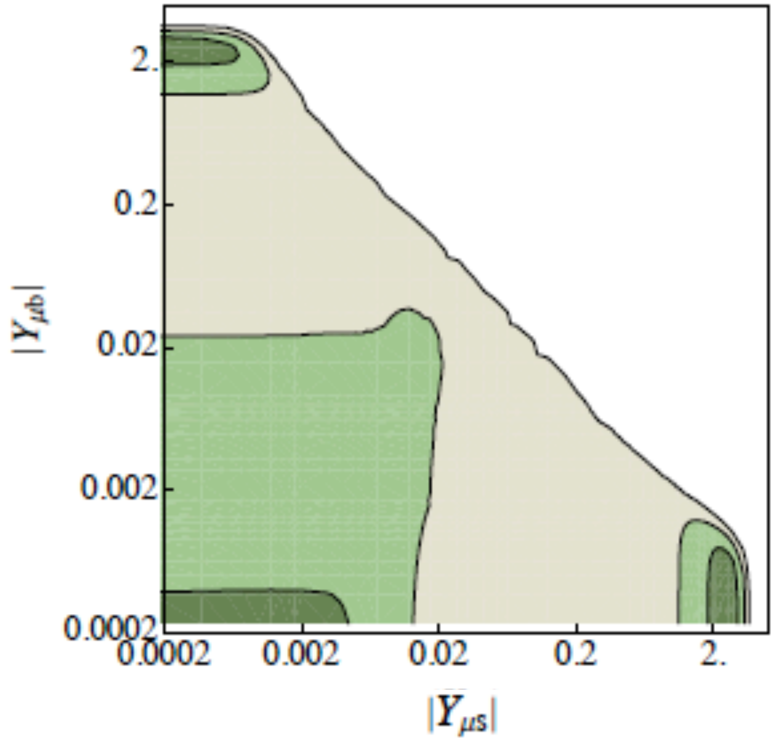
Inputs

- upper bounds (LFV processes, rare decays) + nontrivial constraints (a_μ , ε_K, $\sin(2\beta)$);
- global fit of 31 observables with 9 moduli and 9 phases of Y (+ 4 CKM parameters)
- $\chi^2 = 3.6$ (@13 degrees of freedom)

$$|Y^{(1\sigma)}| \in \begin{pmatrix} < 1.4 \times 10^{-6} & < 8.7 \times 10^{-5} & < 4.1 \times 10^{-4} \\ < 3.6 \times 10^{-3} \cup [2.1, 2.9] & < 3.6 \times 10^{-3} \cup [2.1, 2.9] & < 6.2 \times 10^{-4} \cup [2.2, 2.8] \\ < 5.6 \times 10^{-3} & < 8.1 \times 10^{-3} & < 9.6 \times 10^{-3} \end{pmatrix}$$

$$\begin{pmatrix} & & \blacksquare \\ \bullet & \bullet & \bullet \end{pmatrix} \longrightarrow$$

$$\begin{pmatrix} \blacksquare & & \\ \bullet & \bullet & \bullet \end{pmatrix} \longrightarrow$$

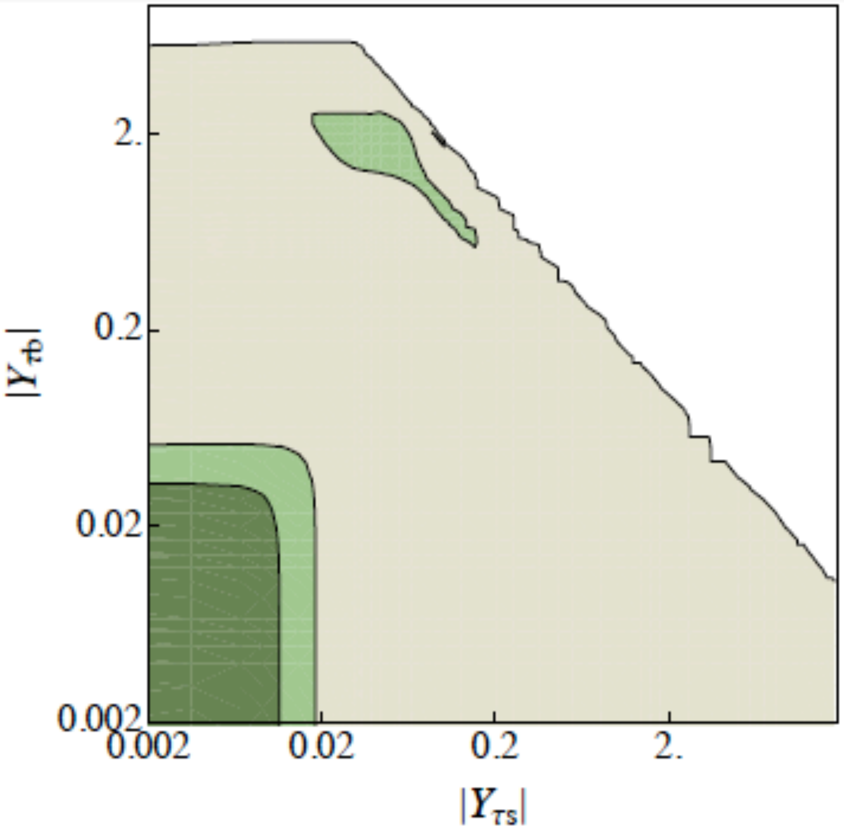


$$\longleftarrow \begin{pmatrix} & \blacksquare & \\ \bullet & \bullet & \bullet \end{pmatrix}$$

$(g\text{-}2)_\mu$ requires one large matrix element in the second row

B_s system

CP violating phase in B_s - $\bar{B}_s$ mixing or $\Delta\Gamma_s$ remains at the SM level!

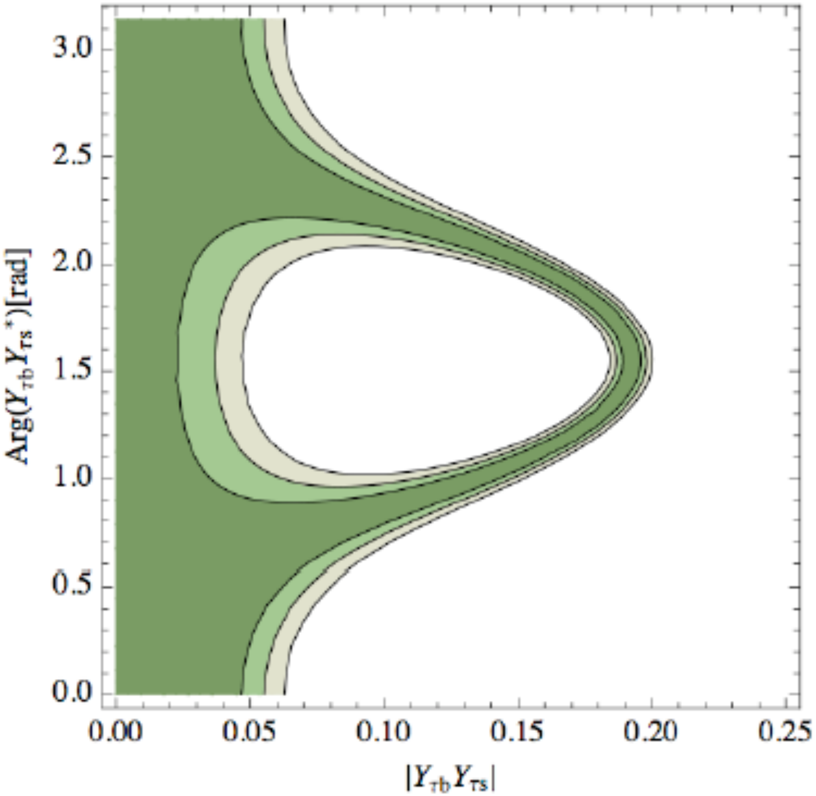


$$|Y_{\mu s} Y_{\mu b}| < 0.0015\,(0.0021)$$

$$|Y_{\tau s} Y_{\tau b}| < 1.2 \times 10^{-4}\,(4.3 \times 10^{-3})$$

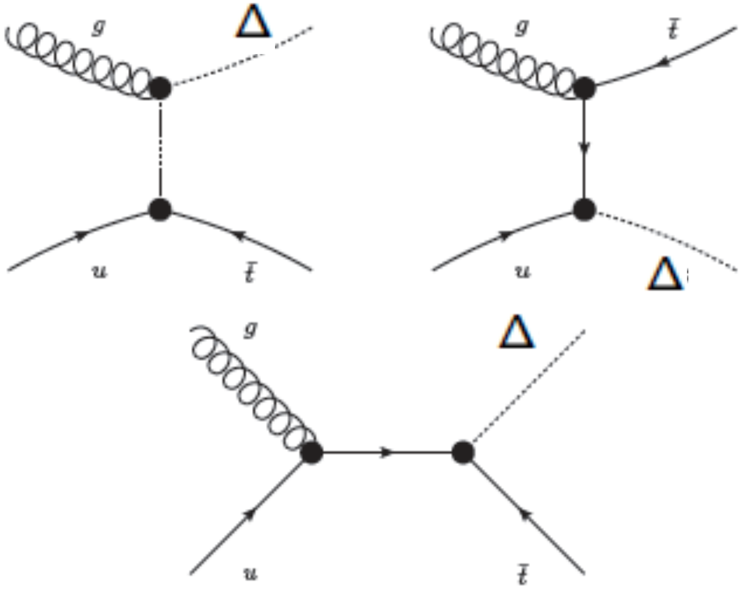
Negligible in comparison with $|V_{tb}V_{ts}|$

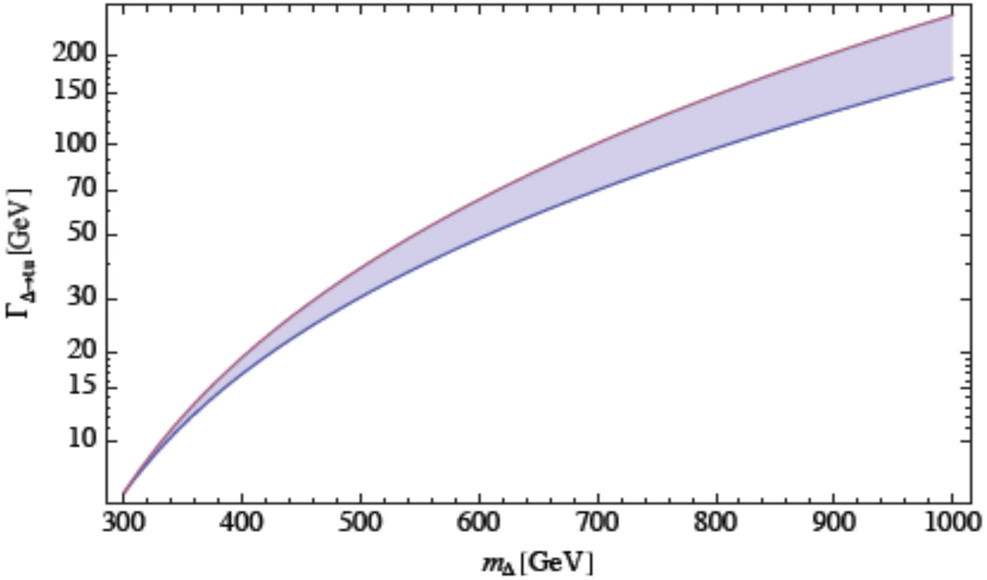
If one does not take into account constraints from $(g\text{-}2)_\mu$
(Dighie et al, 2011, Haisch and Bobeth 2011) one can get explanation of large β_s.



Although, constraint on $Y_{\tau b}Y^*_{\tau s}$are relaxed and dominated by Δm_s and $\Delta m_s/\Delta m_d$. However, $|Y_{\tau b}Y_{\tau s^*}| \sim 0.2$ can be reached, et the expense of fine tuning the phase $Arg(Y_{\tau b}Y_{\tau s^*})$. The right destructive interference with SM contribution to $\Delta m_{s,d}$ cannot be reached.

Search strategies at LHC



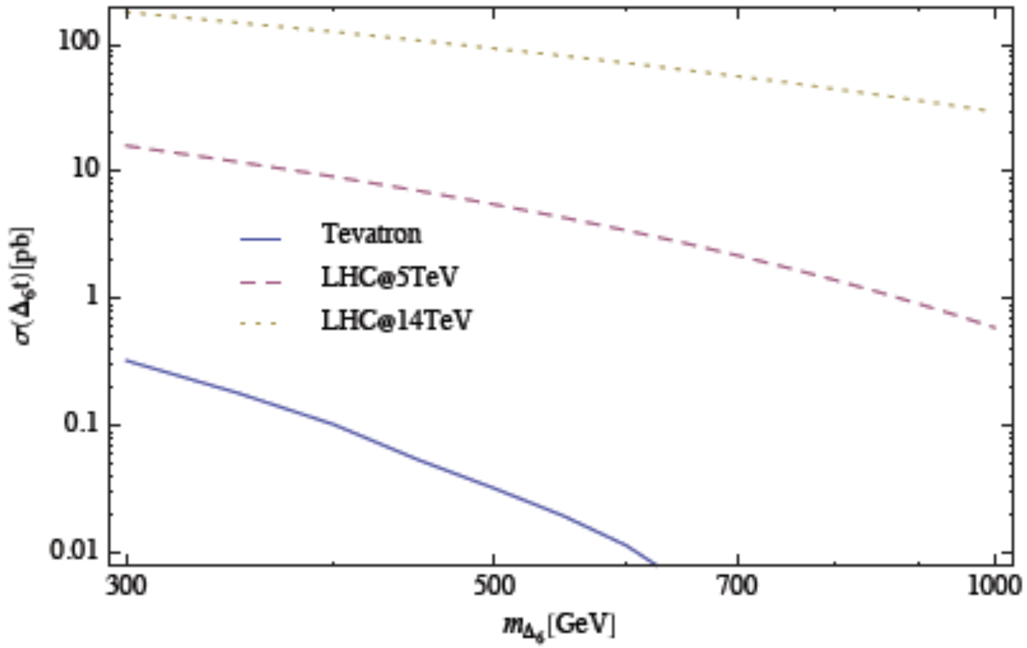


Dependence of the decay width on the Δ mass .

$$\Gamma(\Delta \to ut) = \frac{|g_{ut}|^2 (m_\Delta^2 - m_t^2)^2}{16\pi m_\Delta^3}$$

$$\sigma_{t\bar{t}+j} \simeq (\sigma_{t\Delta^*} + \sigma_{\bar{t}\Delta}) \times BR(\Delta \to ut)$$

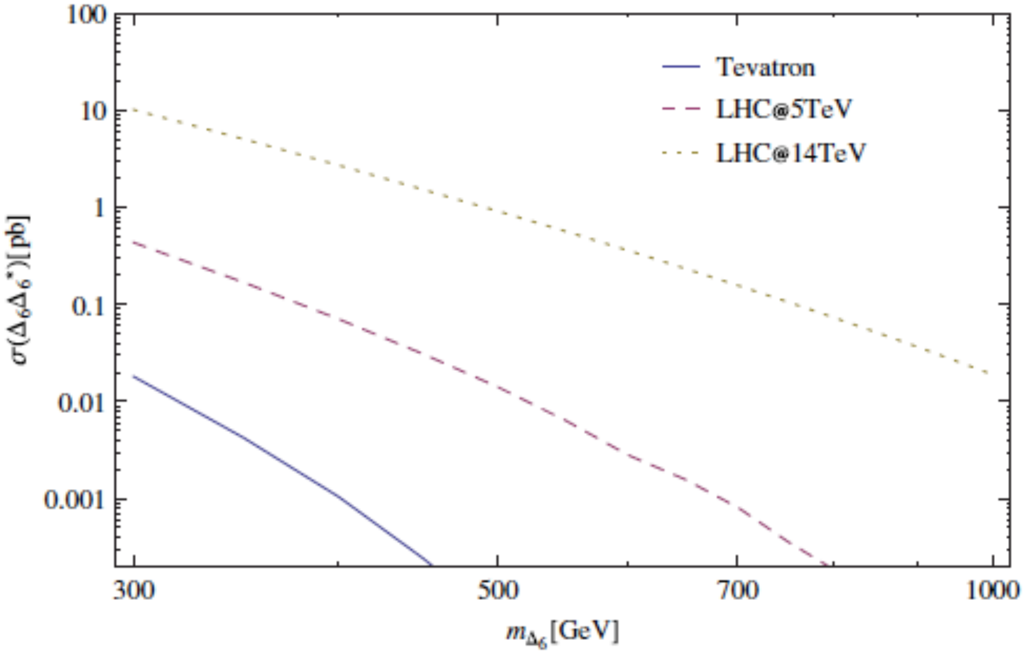
Δ can be produced at hadron colliders:



Hadronic production at LHC and Tevatron

Pair production

$$q\bar{q} \rightarrow \Delta\Delta^*$$
$$gg \rightarrow \Delta\Delta^*$$



Δ would appear as a resonance in the invariant mass of a top and one hard jet.

Constraints on anti-symmetric Yukawa couplings

$$V_{\mathbf{45}}^{\text{matter}} = (Y_1)^{ij}(\mathbf{10}^{\alpha\beta})_i(\bar{\mathbf{5}}_\delta)_j \mathbf{45}^{*\delta}_{\alpha\beta} + (Y_2)^{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\zeta\gamma})_j \mathbf{45}^{\delta\epsilon}_{\zeta}$$

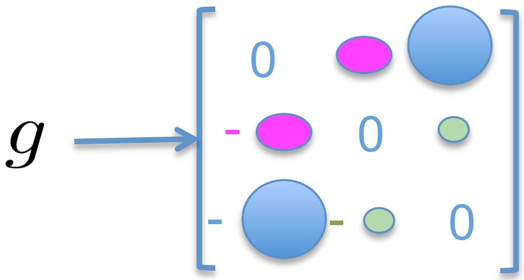
$$\mathcal{L}_\Delta = \frac{g_{ij}}{2}\epsilon^{\alpha\beta\gamma}\bar{u}_{i\alpha}P_L u^C_{j\beta}\Delta_\gamma + Y_{ij}\bar{l}_i P_L d^C_{j\alpha}\Delta^*_\alpha$$

$$g_{ij} = 2\sqrt{2}[U_R^\dagger((Y_2)_{ij} - (Y_2)_{ji})U_R^*] \qquad g_{ij} = -g_{ji}$$

Results

Matrix which makes transformation from the weak to the mass basis

Our constraints on Yukawa come from the up- quark phenomenology



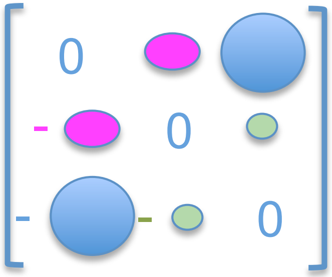
$$M_U = \left[4(\underbrace{Y_2'^T + Y_2'}_{\text{symmetric}})v_5 - 8(\underbrace{Y_2^T - Y_2}_{\text{anti-symmetric}})v_{45}\right]/\sqrt{2},$$

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

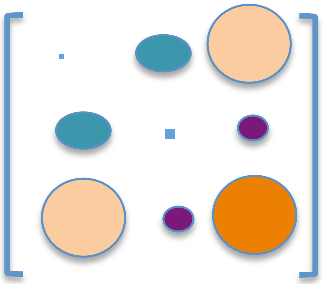
diagonal up-quark mass matrix

Lopsided structure of the mass matrix!

$A' \sim$



$S' \sim$

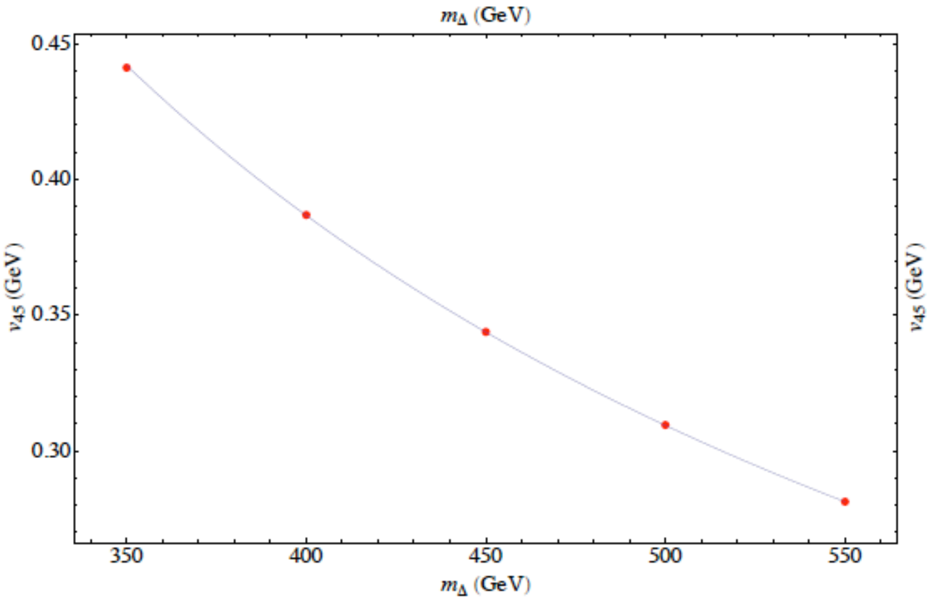


Down quarks and charged leptons

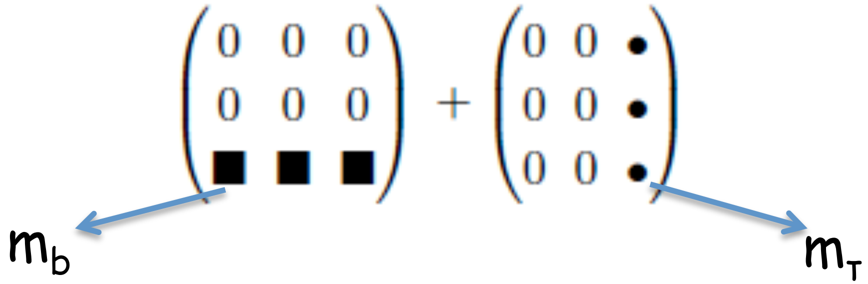
$$
\begin{aligned}
M_D &= -Y_1 v_{45}^* - \frac{1}{2} Y_3 v_5^*, \\
M_E &= 3Y_1^T v_{45}^* - \frac{1}{2} Y_3^T v_5^*, \\
M_U &= 2\sqrt{2}(Y_2 - Y_2^T) v_{45} - \sqrt{2}(Y_4 + Y_4^T) v_5
\end{aligned}
$$

diagonalization of mass matrices
at unification scale

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



generic form of this equation



$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix} + \begin{pmatrix} 0 & 0 & \bullet \\ 0 & 0 & \bullet \\ 0 & 0 & \bullet \end{pmatrix}$$

Numerical study: impossible to
generate single satisfactory solution!

Conclusions and outlook

- Forward-backward asymmetry in $t\bar{t}$ production can be explained by exchange of Δ;

- Contribution of Δ to muon anomalous magnetic moment is positive for large $Y_{\mu q}$;

- $D^0 - \bar{D}^0$ mixing and single top production impose $g_{uc} \sim 0.1$
  $g_{ct} \sim 0.001$;

- LFV and FCNCs in the down-quark and charged lepton processes together with $(g-2)_\mu$ lead to texture :

$$Y \sim \begin{pmatrix} 0 & 0 & 0 \\ \blacksquare & 0 & 0 \\ \bullet & \bullet & \bullet \end{pmatrix}, \quad \begin{pmatrix} 0 & 0 & 0 \\ 0 & \blacksquare & 0 \\ \bullet & \bullet & \bullet \end{pmatrix}, \quad \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \blacksquare \\ \bullet & \bullet & \bullet \end{pmatrix}$$

- Direct search: second generation leptoquark
  $\Delta \to \mu q \quad \Delta \to ut \qquad m_\Delta \simeq 380 - 600 \ \text{GeV}$

- low energy phenomenology fixed the Yukawa couplings;

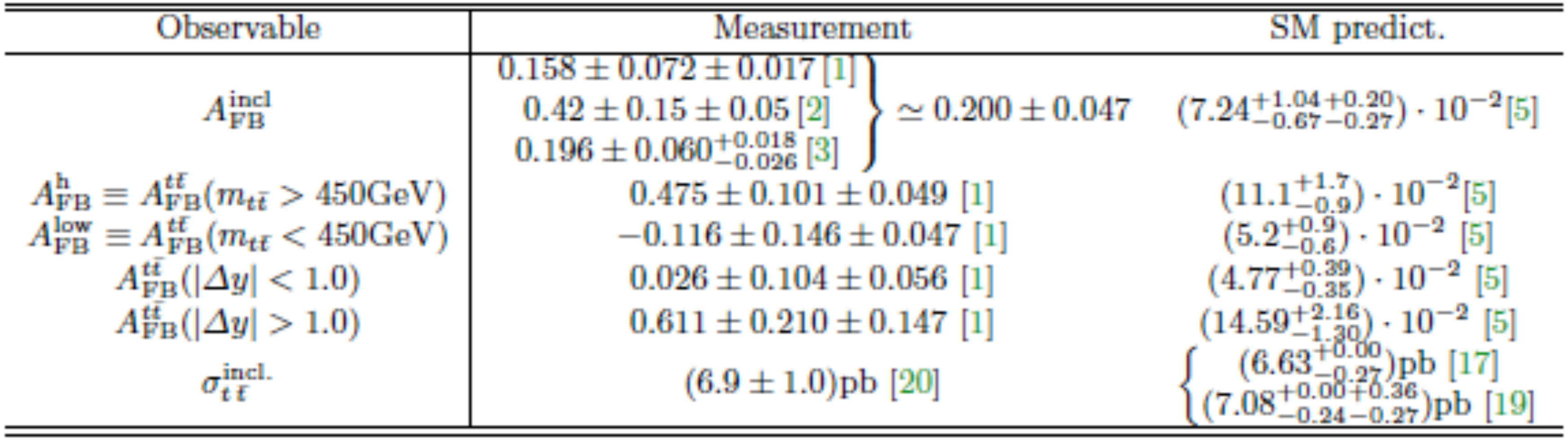
- we determined texture of the up quark mass matrix;

- we showed that symmetric scenario for the Yukawa couplings of leptoquarks to down-quarks and charged leptons is not compatible with the constraints due to the presence of light Δ;

- other scenario: *e.g.* SO(10) with 120, 126 and 10….

Alex, best wishes!

from J.F. Kamenik, J. Shu, J. Zupan, 2011 summary



Observable	Measurement	SM predict.
$A_{\rm FB}^{\rm incl}$	$0.158 \pm 0.072 \pm 0.017$ [1] $0.42 \pm 0.15 \pm 0.05$ [2] $0.196 \pm 0.060^{+0.018}_{-0.026}$ [3] $\simeq 0.200 \pm 0.047$	$(7.24^{+1.04+0.20}_{-0.67-0.27}) \cdot 10^{-2}$[5]
$A_{\rm FB}^{\rm h} \equiv A_{\rm FB}^{t\bar t}(m_{t\bar t} > 450{\rm GeV})$	$0.475 \pm 0.101 \pm 0.049$ [1]	$(11.1^{+1.7}_{-0.9}) \cdot 10^{-2}$[5]
$A_{\rm FB}^{\rm low} \equiv A_{\rm FB}^{t\bar t}(m_{t\bar t} < 450{\rm GeV})$	$-0.116 \pm 0.146 \pm 0.047$ [1]	$(5.2^{+0.9}_{-0.6}) \cdot 10^{-2}$ [5]
$A_{\rm FB}^{t\bar t}(\lvert\Delta y\rvert < 1.0)$	$0.026 \pm 0.104 \pm 0.056$ [1]	$(4.77^{+0.39}_{-0.35}) \cdot 10^{-2}$ [5]
$A_{\rm FB}^{t\bar t}(\lvert\Delta y\rvert > 1.0)$	$0.611 \pm 0.210 \pm 0.147$ [1]	$(14.59^{+2.16}_{-1.30}) \cdot 10^{-2}$ [5]
$\sigma_{t\bar t}^{\rm incl.}$	(6.9 ± 1.0)pb [20]	$(6.63^{+0.00}_{-0.27})$pb [17] $(7.08^{+0.00+0.36}_{-0.24-0.27})$pb [19]

[1] V. Ahrens et al. 2011 (CDF);
[2] Y. Takeuchi et al., (CDF), (2011);
[3] V.M. Abazov et al, (D0), (2011);
[5] V. Ahrens et al, 2011;
[17] V. Ahrens et al, 2
[19] N. Kidonakis, 2011;
[20] V. Ahrens et al. 2009 (CDF),

- CKM contributions are fixed from tree level measurements (insensitive to Δ)

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.97425(22) & 0.2252(9) & 3.89(44) \times 10^{-3} \\ 0.23(11) & 1.023(36) & 4.06(13) \times 10^{-2} \end{pmatrix}$$

- performing fit without Δ $\chi^2_{\min} = 13.1 = 9.5_{(g-2)_\mu} + 2.2_{\mathrm{CKM}} + 1.2_{\Delta m_s} + \cdots$

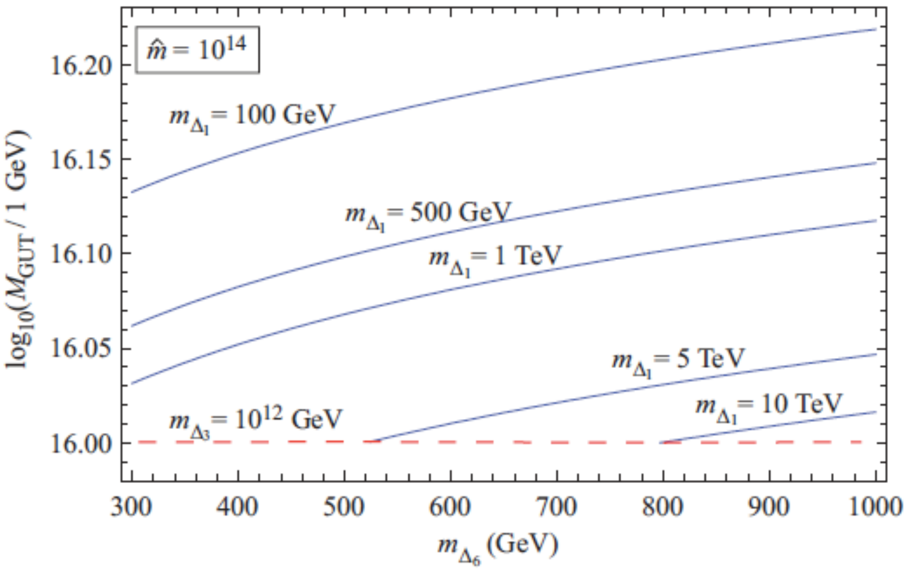
$$\begin{aligned} \lambda &= 0.22538(65)\,, \\ A &= 0.7994(260)\,, \\ \rho &= 0.124(70)\,, \\ \eta &= 0.407(52)\,, \end{aligned}$$

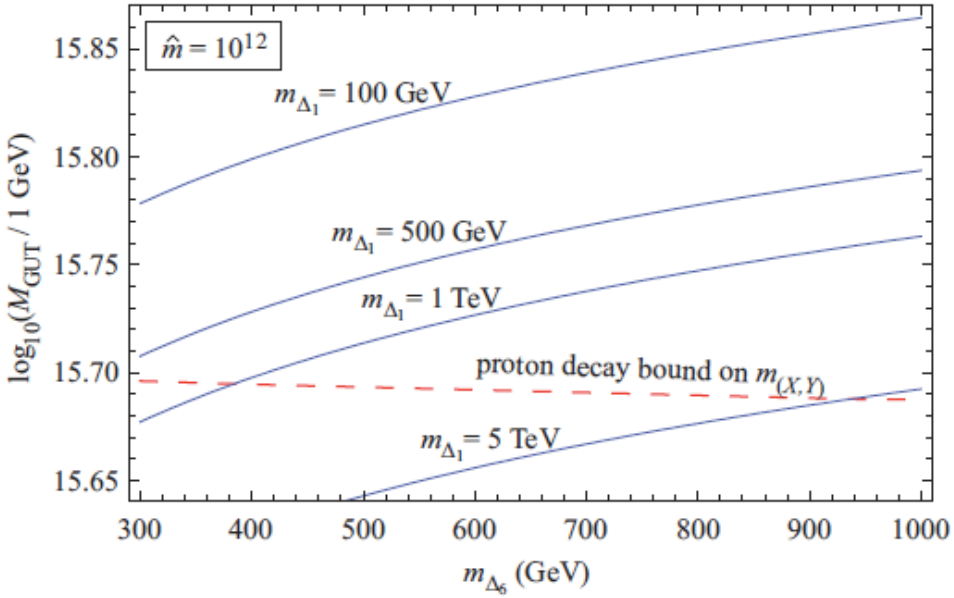
- $(g\text{-}2)_\mu$ is at 3 σ and some inherent tension at CKM

decay mode	90 % C.L. exp. bound on $\mathcal{B}$	$1\,\sigma$ upper bound in units $(m_\Delta/400\ \mathrm{GeV})^4$
$B_d \to e^- e^+$	8.3×10^{-8}	$\left\|Y_{eb}Y^*_{ed}\right\|^2 < 4.4$
$B_d \to \mu^- \mu^+$	4.2×10^{-9}	$\left\|Y_{\mu b}Y^*_{\mu d}\right\|^2 < 5.0 \times 10^{-6}$
$B_d \to \tau^- \tau^+$	4.1×10^{-3}	$\left\|Y_{\tau b}Y^*_{\tau d}\right\|^2 < 1.3 \times 10^{-2}$
$B_s \to e^- e^+$	2.8×10^{-7}	$\left\|Y_{eb}Y^*_{es}\right\|^2 < 10.1$
$B_s \to \mu^- \mu^+$	1.2×10^{-8}	$\left\|Y_{\mu b}Y^*_{\mu s}\right\|^2 < 1.1 \times 10^{-5}$
$B_d \to e^\mp \mu^\pm$	6.4×10^{-8}	$\left\|Y_{eb}Y^*_{\mu d}\right\|^2 + \left\|Y_{\mu b}Y^*_{ed}\right\|^2 < 1.6 \times 10^{-4}$
$B_d \to \mu^\mp \tau^\pm$	2.2×10^{-5}	$\left\|Y_{\mu b}Y^*_{\tau d}\right\|^2 + \left\|Y_{\tau b}Y^*_{\mu d}\right\|^2 < 2.2 \times 10^{-4}$
$B_d \to \tau^\mp e^\pm$	2.8×10^{-5}	$\left\|Y_{\tau b}Y^*_{ed}\right\|^2 + \left\|Y_{eb}Y^*_{\tau d}\right\|^2 < 2.7 \times 10^{-4}$
$B_s \to e^\mp \mu^\pm$	2.0×10^{-7}	$\left\|Y_{eb}Y^*_{\mu s}\right\|^2 + \left\|Y_{\mu b}Y^*_{es}\right\|^2 < 3.4 \times 10^{-4}$

decay mode	90 % C.L. exp. bound on $\mathcal{B}$	$1\,\sigma$ upper bound in units $(m_\Delta/400\ \text{GeV})^4$
$B^+ \to \pi^+\ell^-\ell^+$	4.9×10^{-8}	$\lvert Y_{eb}Y^*_{ed}\rvert^2 + \lvert Y_{\mu b}Y^*_{\mu d}\rvert^2 < 3.0 \times 10^{-7}$
$B^+ \to \pi^+e^\pm\mu^\mp$	1.7×10^{-7}	$\lvert Y_{eb}Y^*_{\mu d}\rvert^2 + \lvert Y_{\mu b}Y^*_{ed}\rvert^2 < 1.1 \times 10^{-6}$
$B^+ \to K^+e^\pm\mu^\mp$	9.1×10^{-8}	$\lvert Y_{eb}Y^*_{\mu s}\rvert^2 + \lvert Y_{\mu b}Y^*_{es}\rvert^2 < 4.3 \times 10^{-7}$
$B^+ \to K^+\tau^\pm\mu^\mp$	7.7×10^{-5}	$\lvert Y_{\tau b}Y^*_{\mu s}\rvert^2 + \lvert Y_{\mu b}Y^*_{\tau s}\rvert^2 < 5.7 \times 10^{-4}$

decay mode	90 % C.L. exp. bound on $\mathcal{B}$	$1\,\sigma$ upper bound in units $(m_\Delta/400\ \text{GeV})^4$
$\tau \to e\pi^0$	8.0×10^{-8}	$\lvert Y_{ed}Y^*_{\tau d}\rvert^2 < 1.9 \times 10^{-4}$
$\tau \to \mu\pi^0$	1.1×10^{-7}	$\lvert Y_{\mu d}Y^*_{\tau d}\rvert^2 < 2.7 \times 10^{-4}$
$\tau \to eK_S$	3.3×10^{-8}	$\lvert Y_{ed}Y^*_{\tau s} - Y_{es}Y^*_{\tau d}\rvert^2 < 3.2 \times 10^{-5}$
$\tau \to \mu K_S$	4.0×10^{-8}	$\lvert Y_{\mu d}Y^*_{\tau s} - Y_{\mu s}Y^*_{\tau d}\rvert^2 < 4.0 \times 10^{-5}$
$\tau \to \mu\eta$	6.5×10^{-8}	$\lvert 0.69\, Y_{\mu d}Y^*_{\tau d} - Y_{\mu s}Y^*_{\tau s}\rvert^2 < 1.3 \times 10^{-4}$





Unification is possible if Δ_6 and Δ_1 are both relatively light.
We varied all relevant masses from 100 GeV to GUT scale .

Comment: If the partial lifetime of proton $p \to \pi^0 e^+$ is improved by factor 6 then $300\mathrm{GeV} \leq m_{\Delta_6} \leq 1\mathrm{TeV}$ will be excluded.

Pair production

- LEP bound $m_\Delta > 105\ \text{GeV}$
- ATLAS 2nd-gen. LQ: $m_\Delta > 380\ \text{GeV}$

$BR(\Delta \to \mu q) > 0.7$

(estimated from $g_{ut},\ Y_{\mu q}$ (1104.4481))