Light colored scalars and the up quarks phenomenology

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Outline

Motivation – experimental puzzles for NP

Phenomenological constraints on new physics

NP scenario: colored scalars

GUT model accommodates colored scalars

Predictions for Yukawa sector

Search strategies for colored scalar;

Conclusions and perspective.

Based on:
Ilja Dorsner, Svjetlana Fajfer, Jernej F. Kamenik, Nejc Kosnik:Phys.Rev.D81:055009,2010; Phys.Lett.B682,67,2009;
S.F. and N. Kosnik, Phys.Rev.D79:017502,2009;
I.D., S.F., JFK, N.K.,Phys. Rev.D82:094015,2010;
J. Drobnak, I.D., S.F., JFK, N.K. work in progress.

Third quark generation and recent experimental results

Experimental results differ from the Standard Model calculations (2 - 3 σ effect)

I Forward-backward asymmetry in double top production at Tevatron

$$A_{FB}^{exp} = 0.15 \pm 0.050 \pm 0.024$$
$$A_{FB}^{SM} \simeq 5\%$$

II B_s system: $\Delta M_s \equiv M_{sH} - M_{sL}$ measured very accurately

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

disagreement SM and experiment

$$\beta_s^{J/\psi\phi(\mathrm{SM})} = -\mathrm{Arg}\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right) = 0.01818 \pm 0.00085$$

should be compared with $\beta_s^{J/\psi\phi} \simeq 0.38$

(CDF and D0 – anomalous like-sign di-muon charge asymmetry)

Forward backward asymmetry in the top pair production at Tevatron

- top quark is the heaviest fundamental fermion;
- top quark mass is important for constraints of the Higgs boson mass and the electroweak symmetry breaking ;
- production of top quarks in pairs offers an important probe of strong interactions;

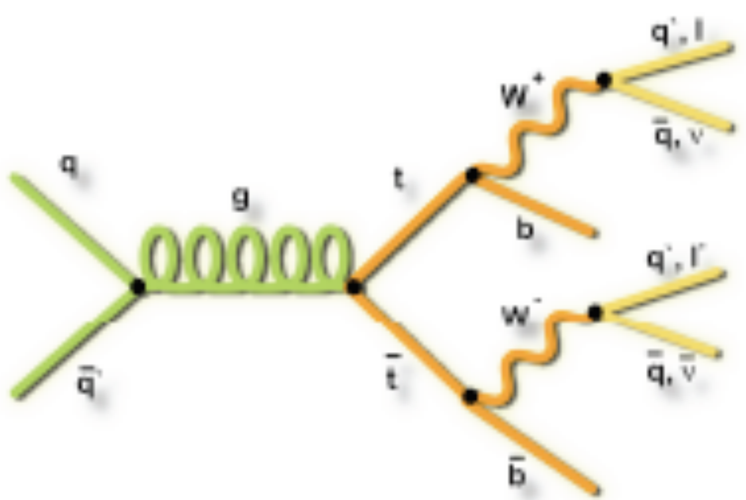
Discovery: Fermilab Tevatron collider (1995)

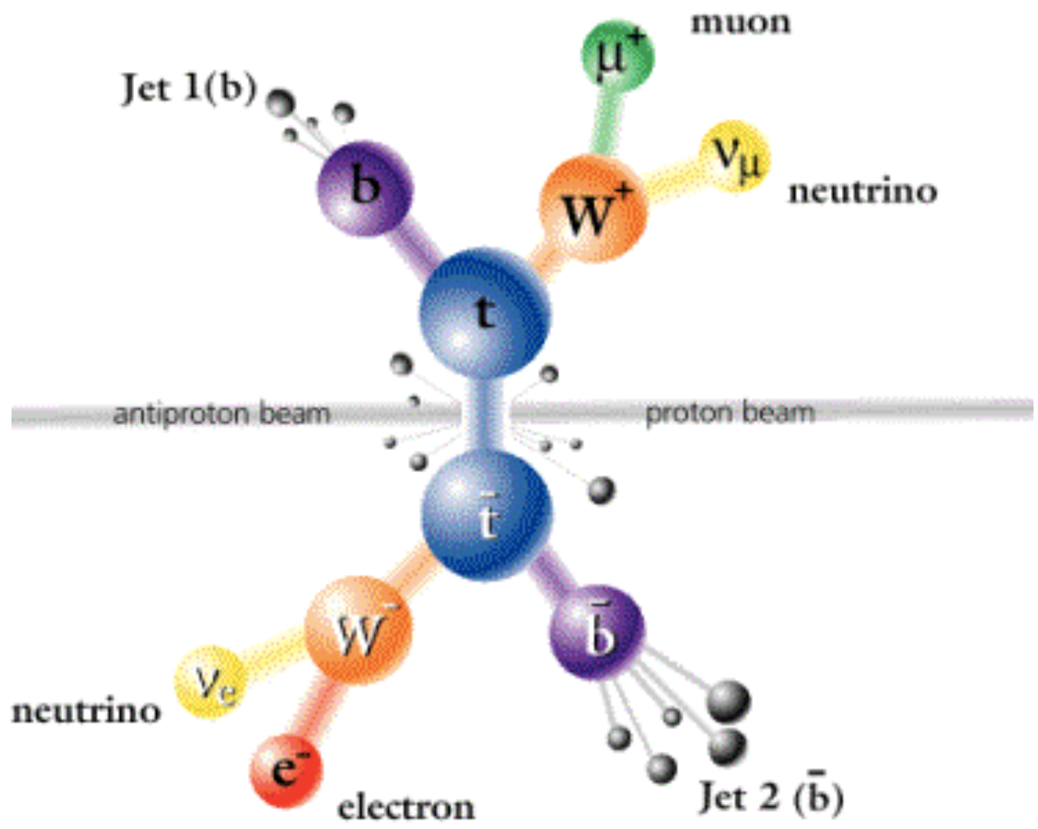
$$q\bar{q} \to t\bar{t} \;\; \& \;\; gg \to t\bar{t}$$

$$Q = \frac{2}{3}$$

$$m_t = 173.1 \pm 1.3 \;\; GeV$$

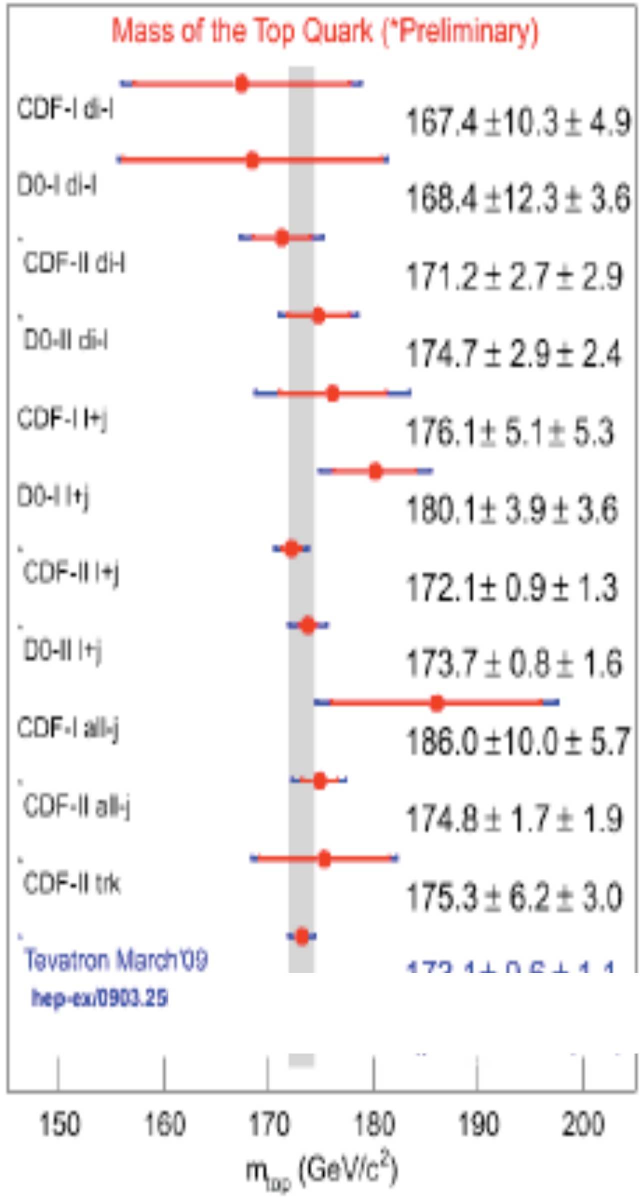
Double top production at Tevatron





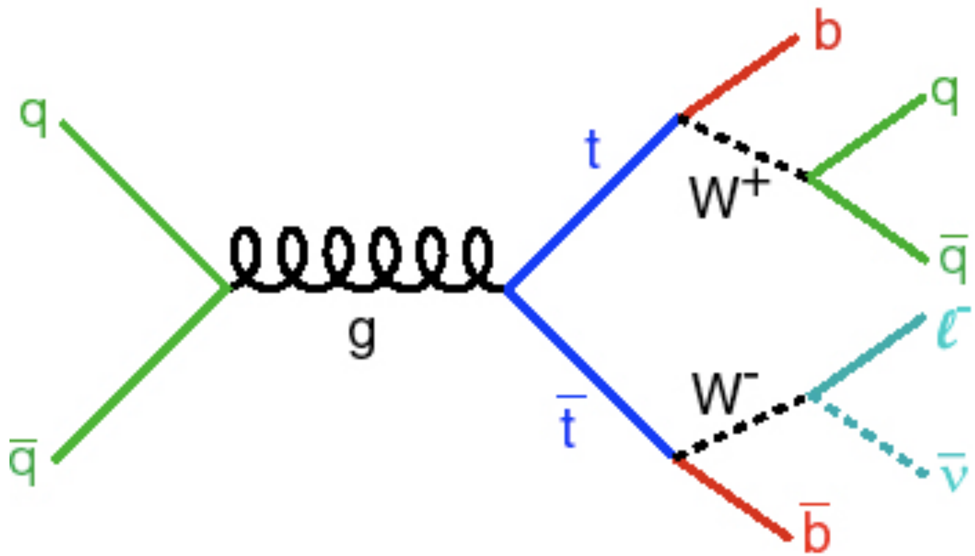
Tevatron results:

The precise measurement of the top quark mass : how one can gain from the electroweak precision observables by improving the experimental precision.

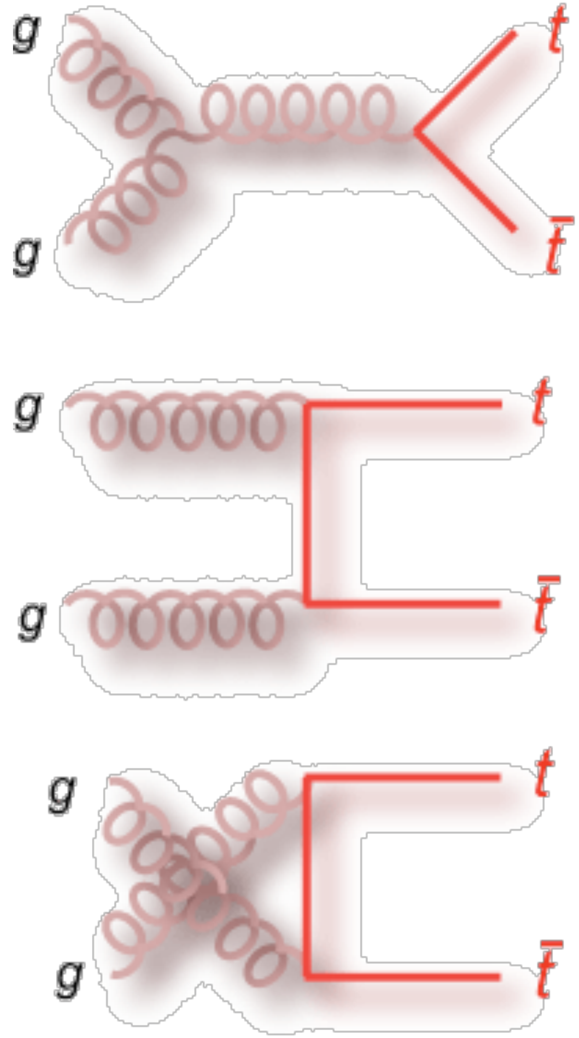


Production:
- double top production;
- single top production.

At Tevatron dominant production mechanism



~85%



~ 15 %

At LHC: the opposite situation - gg dominant (90%) !

Forward-backward asymmetry in double top production

$$A_{FB} = 0.19 \pm 0.09^{stat} \pm 0.02^{syst} (0.9 fb^{-1} \quad D0 \quad 0712.0851)$$

$$A_{FB} = 0.17 \pm 0.07^{stat} \pm 0.04^{syst} (1.9 fb^{-1} \quad CDF \quad 0806.2472)$$

$$A_{FB} = 0.193 \pm 0.065^{stat} \pm 0.024^{syst} (3.2 fb^{-1} \quad D0 \quad 9724, \quad 17 March 2009)$$

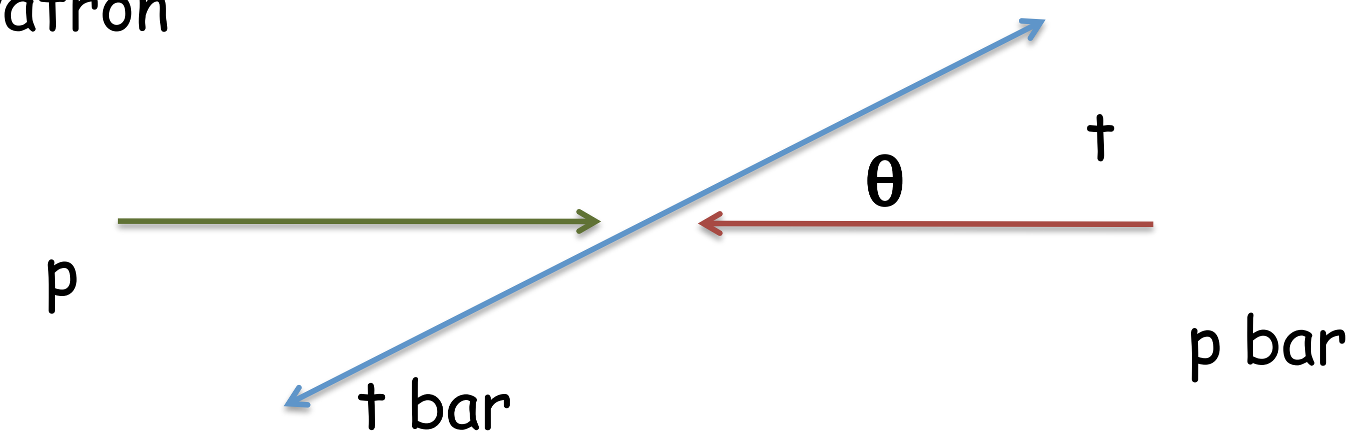
$$A_{FB} = 0.150 \pm 0.050^{stat} \pm 0.024^{syst} (5.3 fb^{-1} \quad A.Eppig, \quad ICHEP, \quad July \quad 2010)$$

Standard model predicts: $A_{FB} = 0.05 \pm 0.08$ (2σ effect)

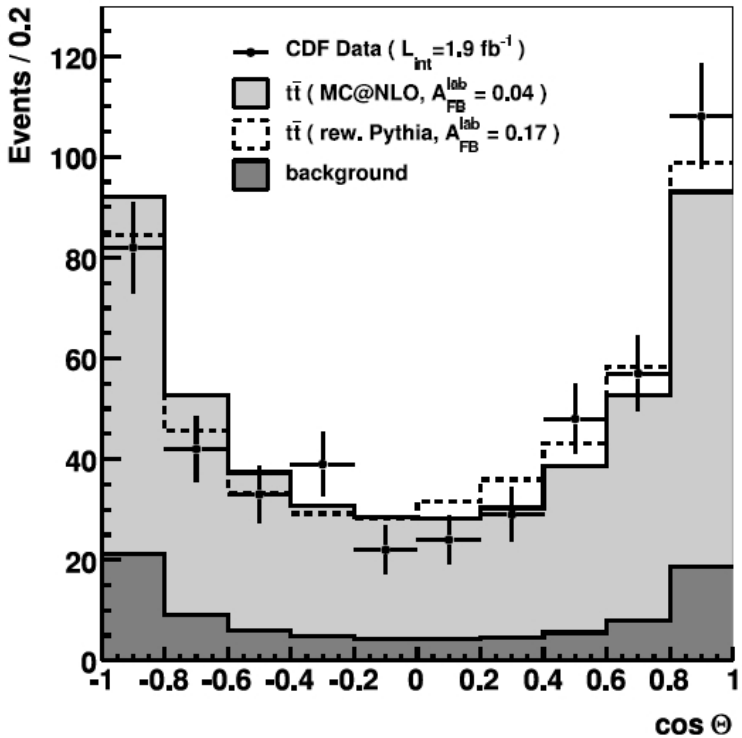
However, the production cross section agrees with Standard Model prediction.

Difficult to explain within SM! NEW PHYSICS?

Tevatron



$$A_{FB} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}$$

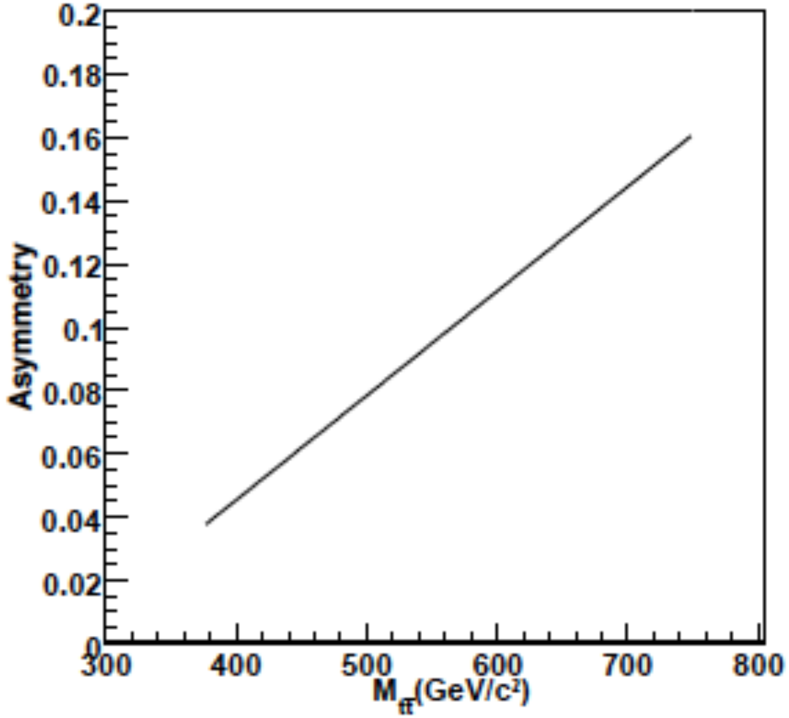


Assuming CP

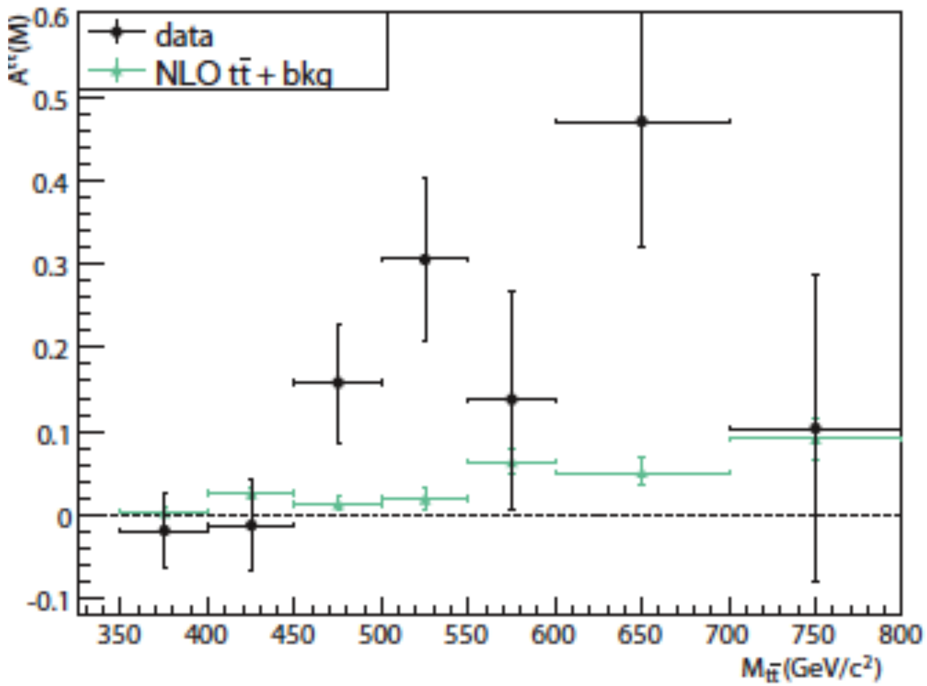
$$N_{\bar{t}} = N_t(\bar{p})$$

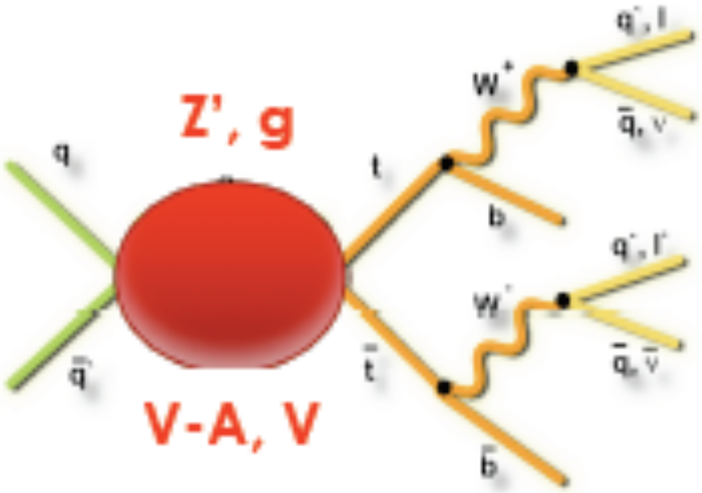
Recent CDF measurement- arXive:1101.0034[hep-ex]
Forward-backward asymmetry and its rapidity and mass dependence

For $M_{t\bar{t}} \leq 450\ \mathrm{GeV}$ $A^{t\bar{t}} = 0.475 \pm 0.114$



$M_{t\bar{t}}$-dependence of $A^{t\bar{t}}$ according to MCFM.

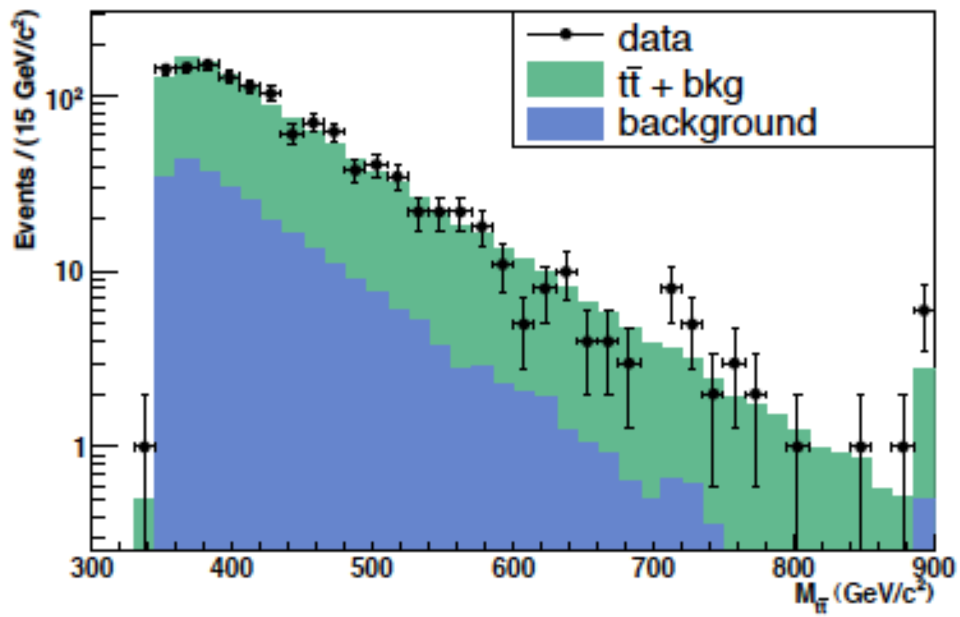


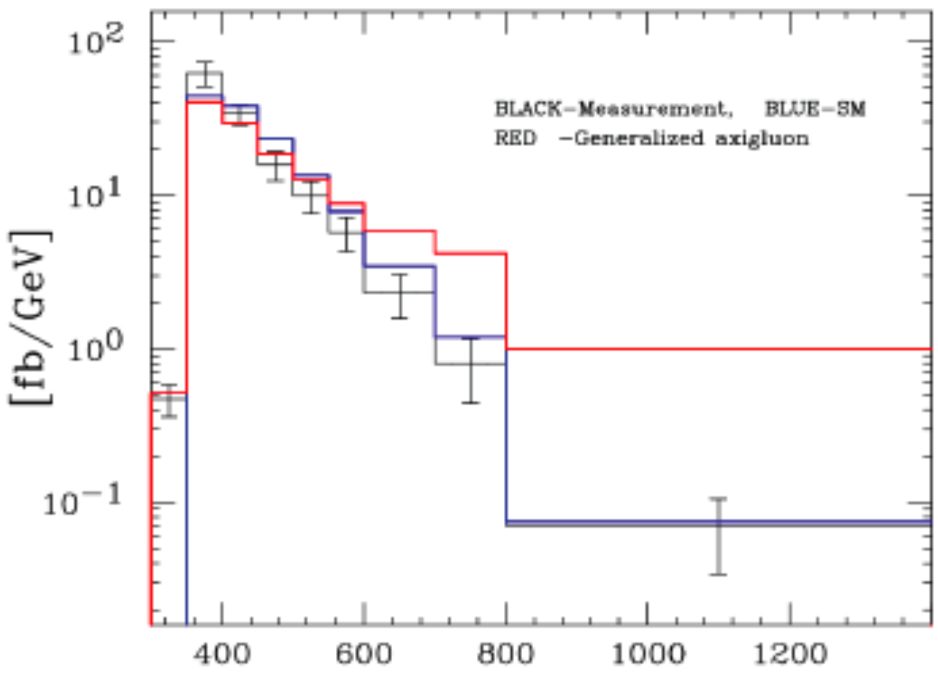


Many attempts to explain it (more than 40 papers):

-Z', $M_{Z'} \approx 160\,\mathrm{GeV}$ Jung et al, 2009;
- Kaluza – Klein gluon excitation with the mass of around 3 TeV, Djuadi et al. 2009;
- Axigluons (mass in the range 0.6 - 1.4 TeV) Ferreira and Rodrigo,2009, Chivikula et al. , 2010, showed that Bd oscillations exclude this model explaining FBA);
- W', Cheung et al, 2009;
- M. Bauer et al, Randall-Sundrum model, 2010.
-V.Barger et al., 2011;
-E.Berger et al, 2011;
-J. Cao et al, 2011;
-B. Bhattacherjee et al.;

Difficulty with differential cross section!





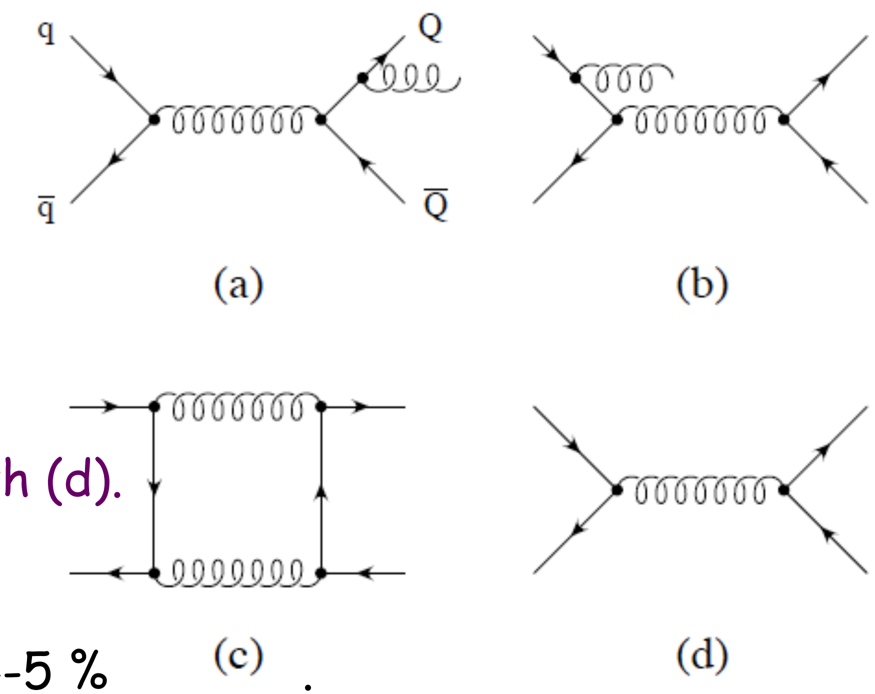
Models reproducing AFB have difficulty in obtaining differential cross-section in agreement with the experimental result.

Standard Model and FBA

-Kühn and Rodrigo, 1998

The origin of FB asymmetry in QCD:
interference of (a) with (b) and (c) with (d).

The effect should be of the order 4-5 %



- Ahrens et al, 2010
NLO+NNLL; FB asymmetry excess cannot be explained

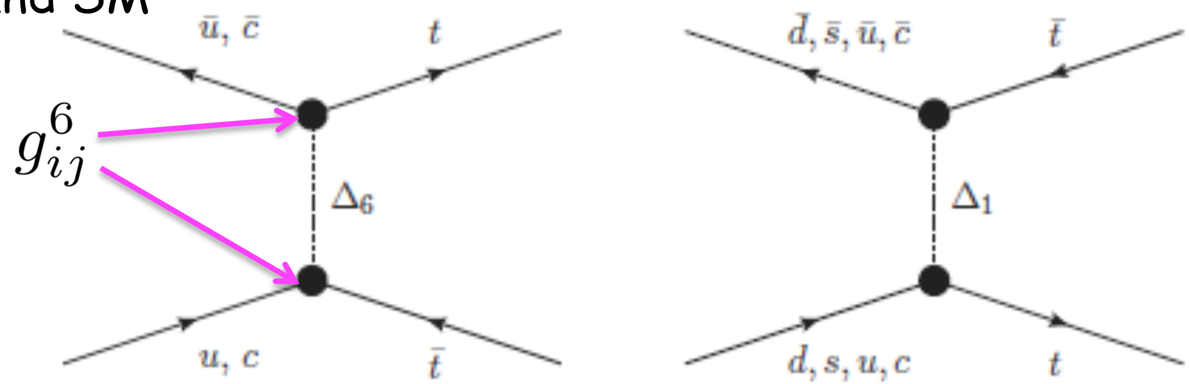
- Boughzel and Petriello, 2010, NLO in top pair production +color octet scalars;

The $t\bar{t}$ production cross-section and the forward-backward asymmetry and colored scalars

Our assumption SM + NP

$$\mathcal{L}(\Delta_6) = g^6_{ij}\epsilon_{abc}\bar{u}_{ia}P_L u^c_{jb}\Delta^c_6$$

Interference of NP and SM



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

$$\Delta_6 = (\bar{3}, 1, \frac{4}{3})$$

This state interacts with up-quarks and independently with down-quarks and charged leptons:

$$\mathcal{L}_{\Delta_6} = \sqrt{2}[(Y_2)_{ij} - (Y_2)_{ji}]\epsilon_{abc}\bar{u}_{ia}P_L u^c_{jb}\Delta^c_6 + (Y_1)^{ij}\bar{e}_i P_L d^c_{ja}\Delta^{a*}_6 + \text{H.c.}$$

$$g^6_{ij} = 2\sqrt{2}[U^\dagger_R((Y_2)_{ij} - (Y_2)_{ji})U^*_R] \qquad g^6_{ij} = -g^6_{ji}$$

Matrix which makes transformation from the weak to the mass basis

Only phenomenological constraints on new physics in the up-quark sector are considered:

- forward –backward asymmetry in the double top production at Tevatron;
- charm physics;
- constrains from di-jets production and single top production atTevatron;
- predictions for rare top quark decays.

Using partonic distribution functions

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

$$\frac{d\sigma(s)}{d\theta} = \frac{s\beta_t}{2} \frac{d\sigma(s)}{dt(\theta)}$$

we have to sum over all quark and gluon contribution

the polar angle of the $t\bar{t}$ production

Simultaneous fit to the integrated cross section and AFB

$$A_{FB}^{t\bar{t}}(s) = \frac{\int_0^1 d\theta[d\sigma(s)/d\theta] - \int_{-1}^0 d\theta[d\sigma(s)/d\theta]}{\sigma_{t\bar{t}}(s)}$$

$$\sigma_{t\bar{t}}(s) = \int_{-1}^{1} d\theta[d\sigma(s)/d\theta].$$

$$\sigma_{t\bar{t}}^{exp} = 7.0 \pm 0.6 \text{ pb}$$

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

$$\Delta_1 = (8, 2, 1/3)$$

The colored triplet scalar is not the only possible state. Color octet scalar (weak doublet) might interact with up and down quarks and in principle contribute to double top production:

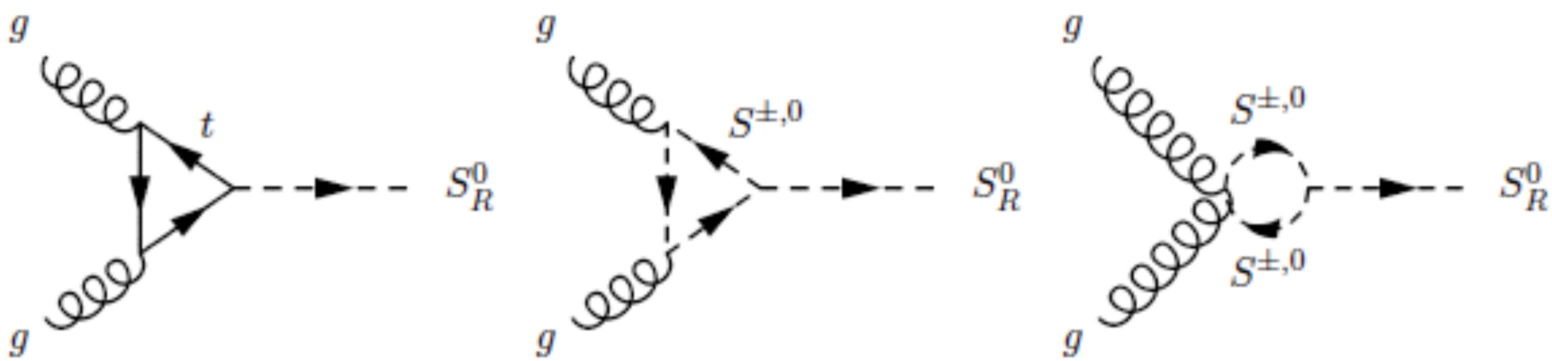
$$\mathcal{L}(\Delta_1) = g^1_{ij}\left(-\bar{u}_{Ria} T^A_{ab} u_{Ljb} \Delta_1^{0A} + \bar{u}_{Ria} T^A_{ab} d_{Ljb} \Delta_1^{+A}\right)$$

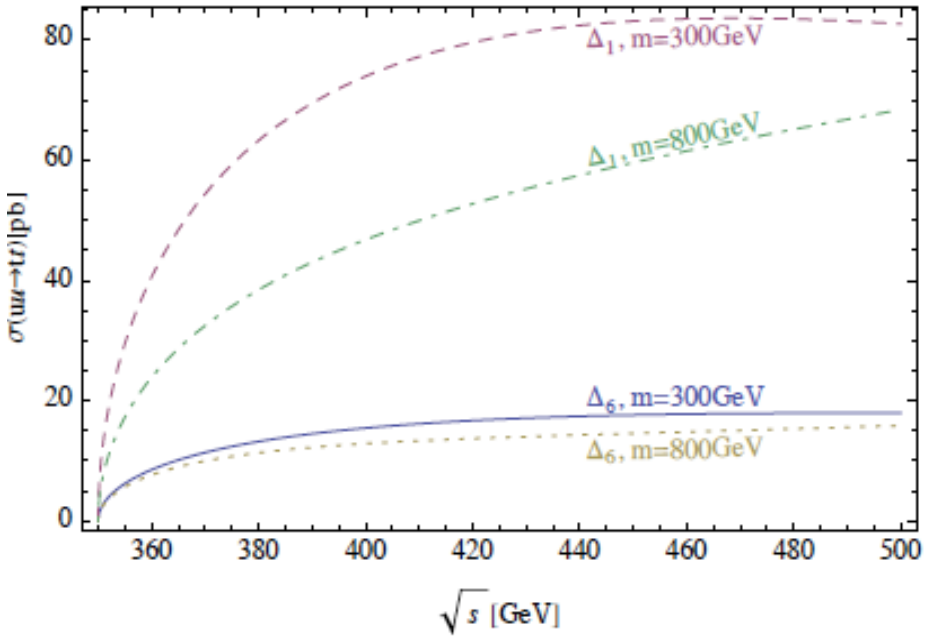
$$\Delta_1^a = \begin{bmatrix} \Delta_1^{a,+} \\ \Delta_1^{a,0} \end{bmatrix}$$

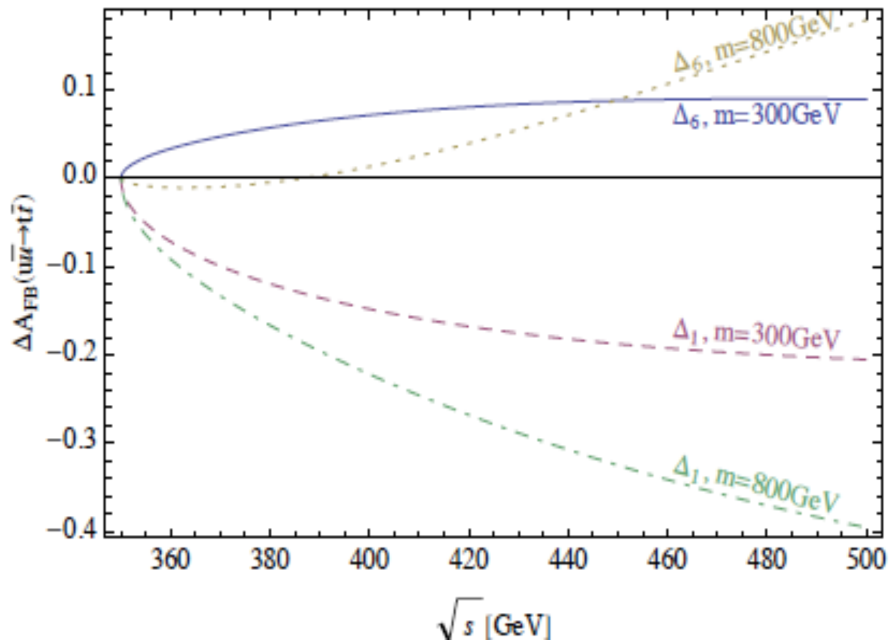
$a = 1, ..., 8$

Many papers on color octets (Manohar and Wise, 2006; Gersham and Wise, 2007; Burgess et al, 2009; P.F. Perez and Wise, 2009_

In principle, they can be produced at LHC:



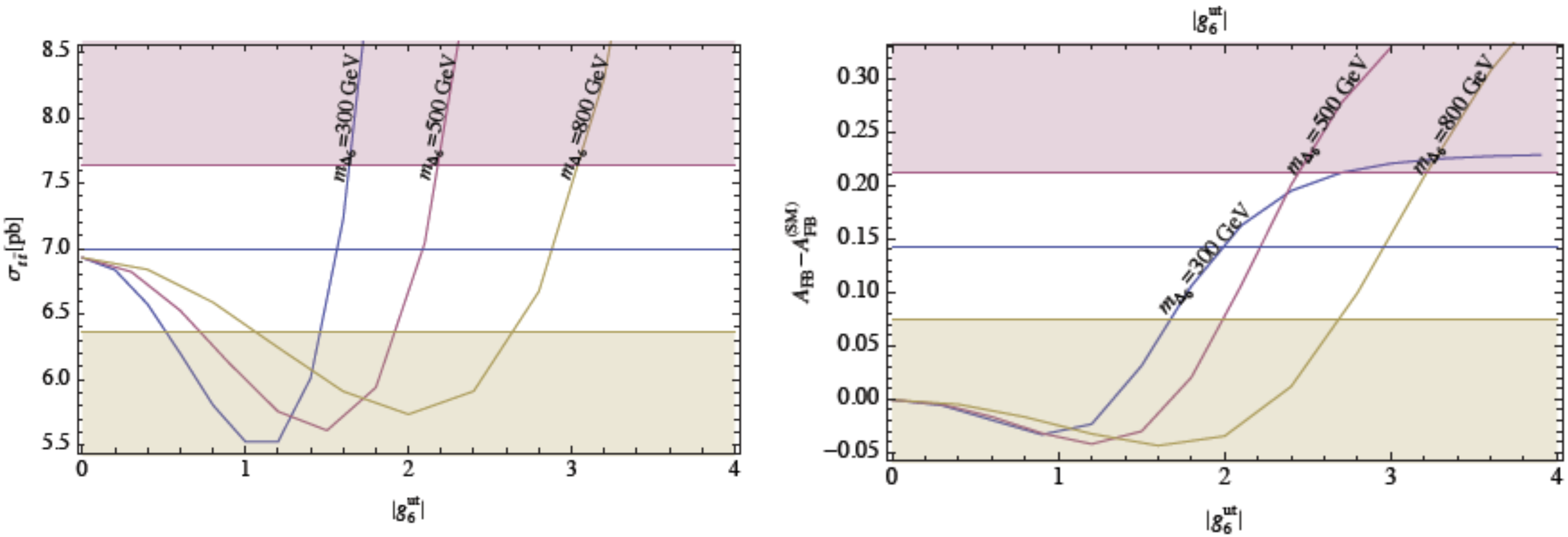




The colored octet scalars at the partonic level cannot induce large positive AFB. The contributions of Δ_1 interfere constructively with the SM amplitude resulting in big enhancement in the cross section.

The Δ_6 gives moderate increase in the cross section and gives positive AFB, while AFB is negative for Δ_1.

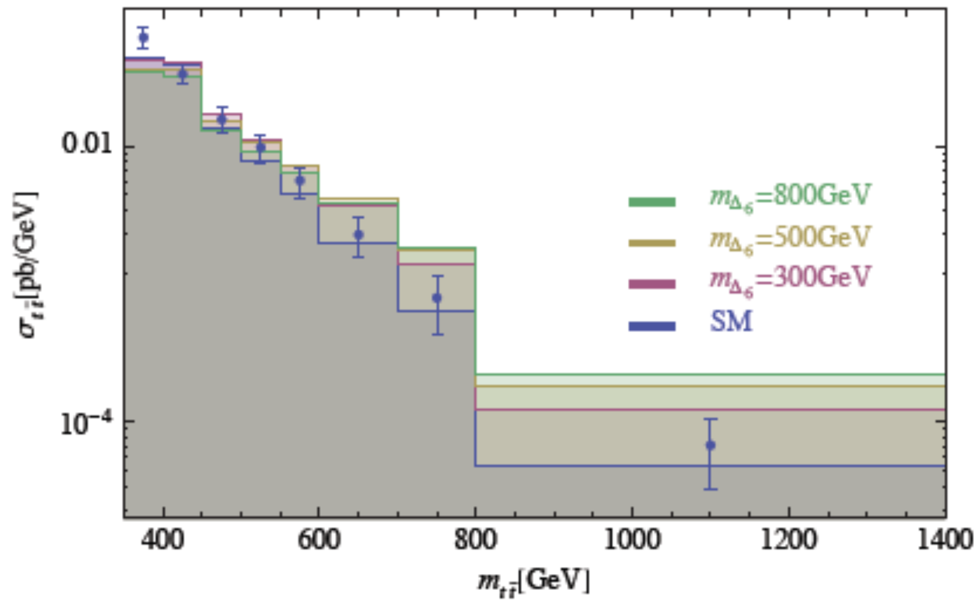
The contribution of Δ_1 should be suppressed compared to the one coming from Δ_6 .

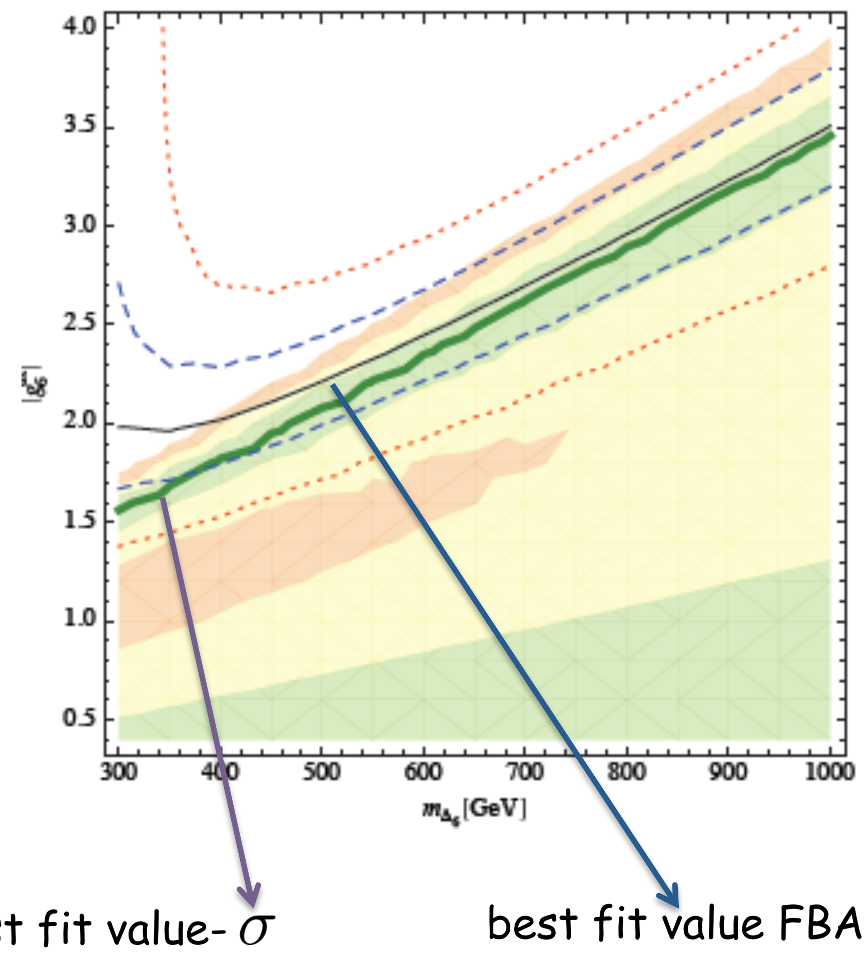


Examples of the hadronic $t\bar{t}$ cross-section and the forward-backward asymmetry at Tevatron including Δ_6. The shaded regions are outside one sigma experimental bound. Our study implies:

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

best fit value for $$g_{13}^6 = 0.9(2) + 2.5(4)\frac{m_{\Delta_6}}{1\ TeV}$$





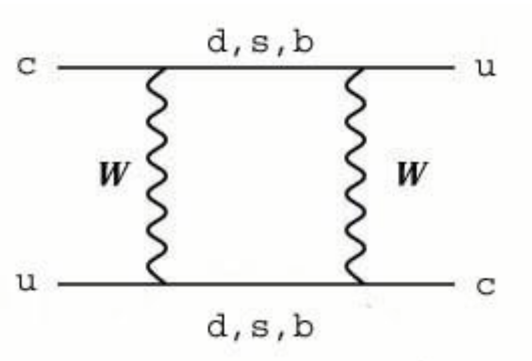
The contribution of colored singlet to the $m_{t\bar{t}}$ invariant mass spectrum in $t\bar{t}$ production at Tevatron (left). Constraints on the parameter space of Δ_6 .
Green, yellow and orange denote 68%, 95%, 99% confidence level regions in the production cross section.
FBA are bounded by blue dashed (68 % C.L.) red dotted (95% C.L.)

Remaining up quarks: c and u

Most restrictive for FCNC : $D^0 - \bar{D}^0$

The neutral D meson system is the only one created out of the up-type quarks.

Standard model



- intermediate down-type quarks
- due to CKM contribution of b
- quark negligible;
- in the SU(3) limit 0;
- long distance contributions important;

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle, \qquad |D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

$$< D^0|\mathcal{H}|\bar{D}^0 >= M_{12} - \frac{i}{2}\Gamma_{12}$$

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

Gedalia, Grossman, Nir, Peres, 2009; Golowich, Petrov, Pakvasa, 2007, 2009; Bigi, Buras et al., 2009

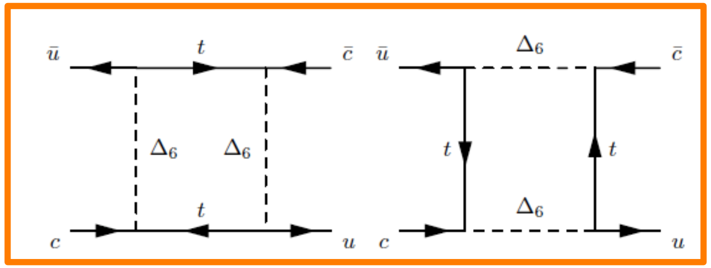
Latest HFAG average, assumes no direct CP violation

$$x = (0.59 \pm 0.20)\%, \qquad y = (0.81 \pm 0.13)\%,$$
$$|q/p| = 0.98^{+0.15}_{-0.14}, \qquad \phi = -0.051^{+0.112}_{-0.115}.$$

Models of new physics in $\Delta C = 2$

- additional gauge bosons; → left-right model ; horizontal symmetries etc.;
- additional scalars; → two-Higgs doublet models, leptoquarks;
- additional fermions; → e.g. 4th generation, vector-like quarks; mirror fermions;
- additional dimensions; → UED, warped ED;
- additional symmetries; → SUSY: MSSM, split susy;

Charm quark processes with Δ_6



Effective Hamiltonian is evolved down to charm scale (following Golowich et al,2009)

$$\mathcal{H}(\mu = m_{\Delta_6}) = C_6(m_{\Delta_6}) Q_6, \qquad Q_6 = (\bar{u}_R \gamma^\mu c_R)(\bar{u}_R \gamma_\mu c_R)$$

Wilson coefficient

$$C_6(m_{\Delta_6}) = \frac{(g_6^{13} g_6^{23*})^2 h(m_{\Delta_6}^2/m_t^2)}{32\pi^2 m_t^2}, \qquad h(x) = \frac{x^2 - 2x\log x - 1}{(x-1)^3}$$

$$\langle D^0 | (\bar{u}_R \gamma^\mu c_R)\,(\bar{u}_R \gamma_\mu c_R) | \bar{D}^0 \rangle = \frac{2}{3} m_D^2 f_D^2 B_D$$

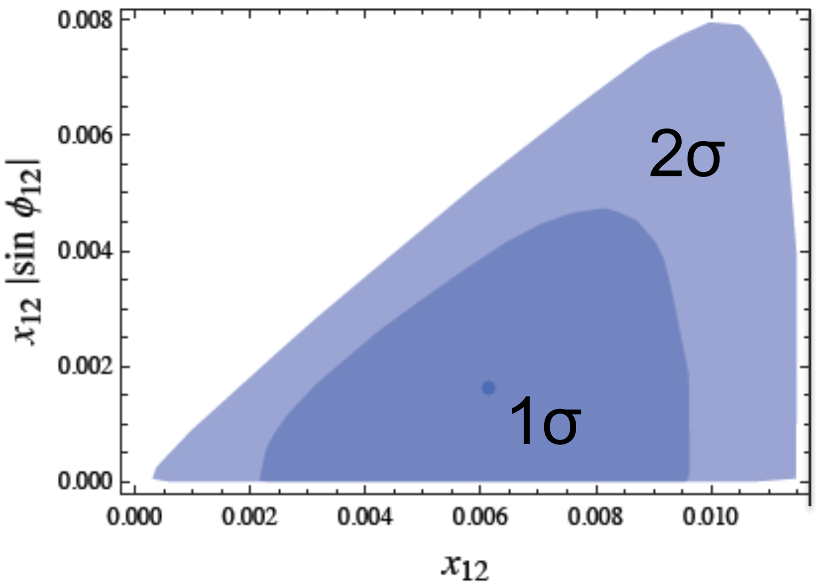
We use following relations (Gedalia et al. (2009), Grossman et al, (2009))

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

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

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

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



Our reslut

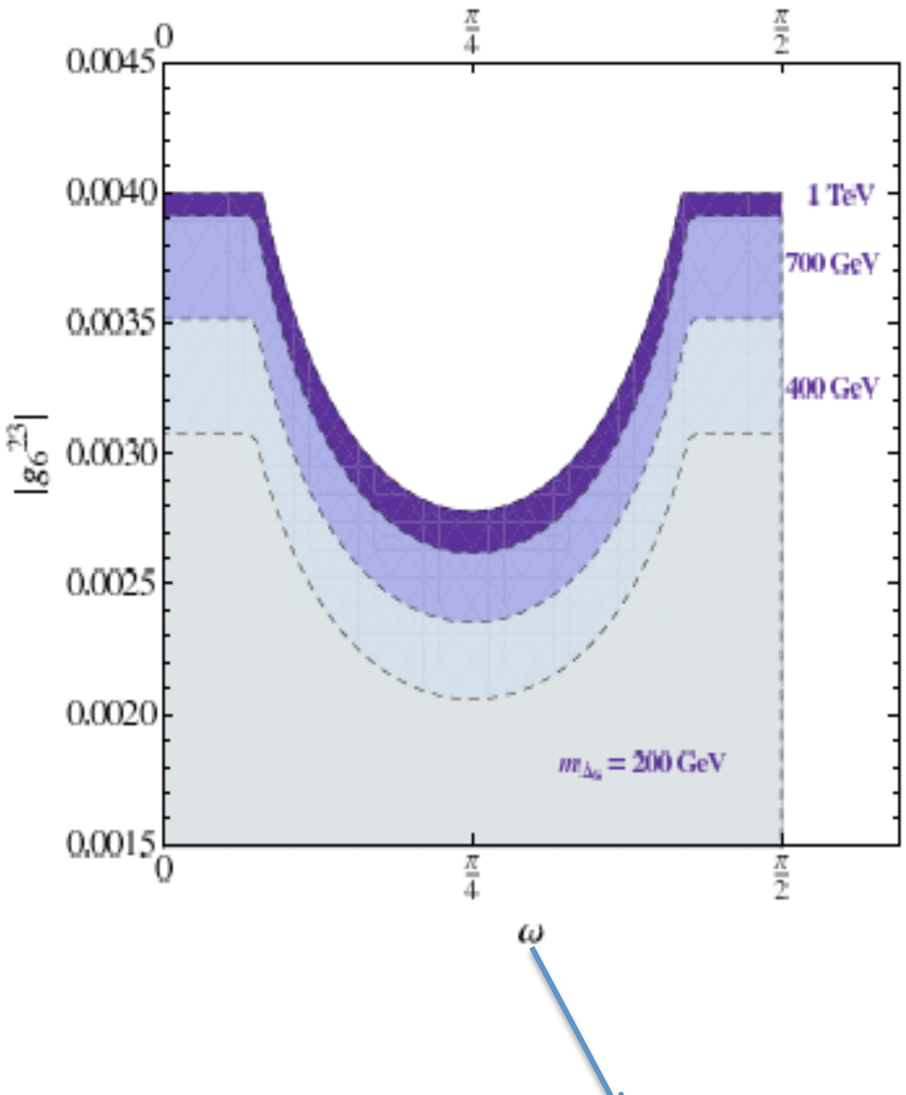
(95% C.L.)

$$x_{12} < 9.6\cdot 10^{-3}$$

$$x_{12}|sin\Phi_{12}| < 4.4\cdot 10^{-3}$$

$$\mathrm{Im}\left[(g_6^{13} g_6^{23*})^2\right] = |g_6^{13}|^2 |g_6^{23}|^2 \sin(2\,\omega)$$

CP violating phase comes from the relative phase between (ut) and (ct) couplings



relative phase between
g^6_{13} and g^6_{23}

Bound on imaginary part of the Wilson coefficient is the dominant constraint, except for in the region close $\omega = 0$ or $\pi/2$

$m_{\Delta_6} < 1$ TeV:

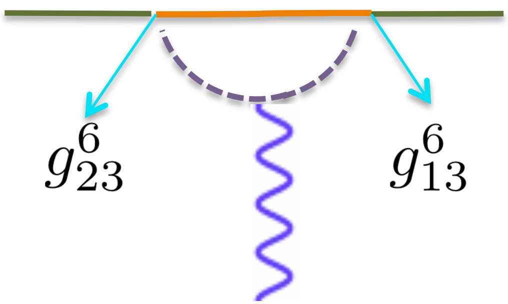
$|g_6^{23}| < 0.0038,$

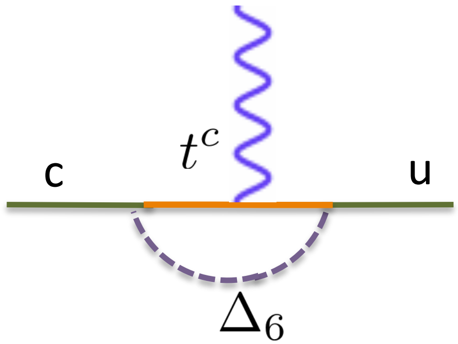
(regardless of phase)

Impact on the charm FCNC rare decays

$$c \longrightarrow u\gamma$$

- from charm meson oscillation bound on g_{23}^{6}
- from top quark forward-backward asymmetry g_{13}^{6}





$$\mathcal{H}^{c\to u\gamma} = \frac{g_6^{13} g_6^{23*} f(m_{\Delta_6}^2/m_t^2)}{6m_t^2} \times \frac{e m_c}{(4\pi)^2} (\bar{u}_R \sigma^{\mu\nu} c_L) F_{\mu\nu}$$

$$f(x) = \frac{2x^3 + 3x^2 - 6x^2 \log x - 6x + 1}{(x-1)^4}$$

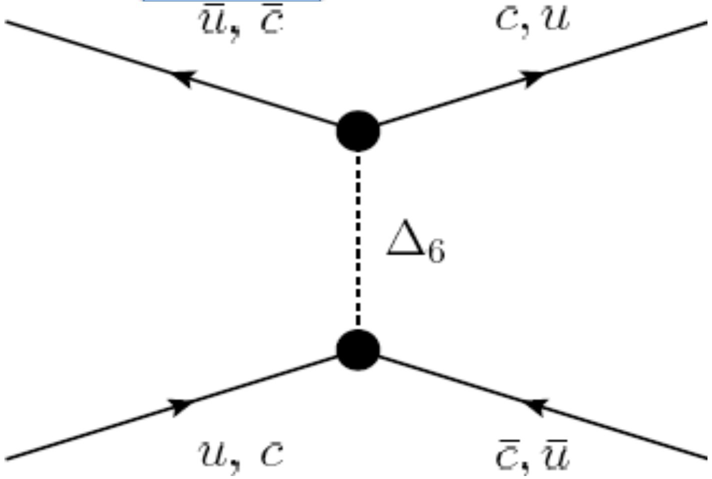
$$\Gamma^{c\to u\gamma}/\Gamma_{D^0} \lesssim 10^{-10}$$

Bounds on g_6^{12} coupling

They can be determined from :

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

di-jet



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

Partonic contribution:
u-channel exchange

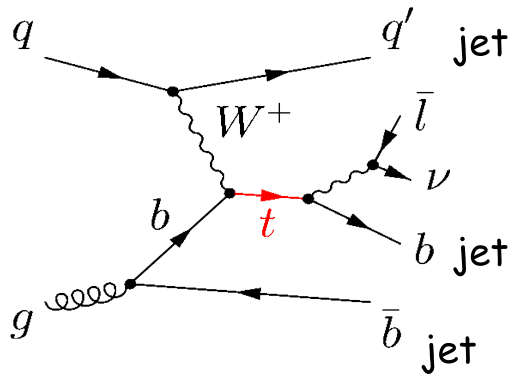
With help of crossing symmetry one can get cross-sections for the rest of the processes

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

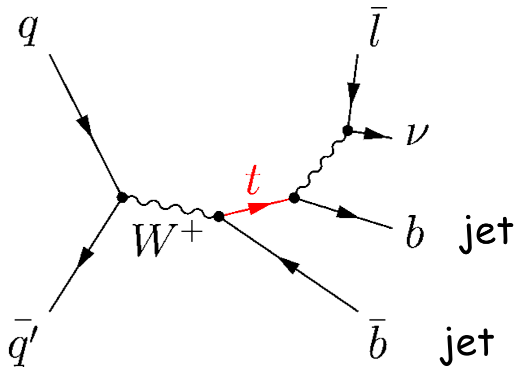
Hadronic di-jet production invariant mass spectrum computed convoluting the LO QCD partonic differential cross-section including the tree level Δ_6 contributions (CTEQ5 set of PDFs)

Single top production at Tevatron

First observation of single top event in 2009 (CDF and D0);



t channel

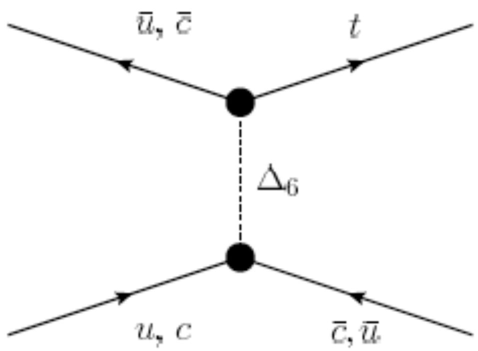


s channel

Single top is produced by the weak interaction
(contrary to double top anti- top which are produced by the strong interaction)

Single top production cross-section

$$\frac{d\sigma^{u\bar{u}\to t\bar{c}}}{d\hat{t}} = -\frac{|g_6^{13*}g_6^{12}|^2}{48\pi\hat{s}^2}\frac{(\hat{s}+\hat{t})\hat{u}}{(\hat{u}-m_{\Delta_6}^2)^2+\Gamma_{\Delta_6}^2}$$



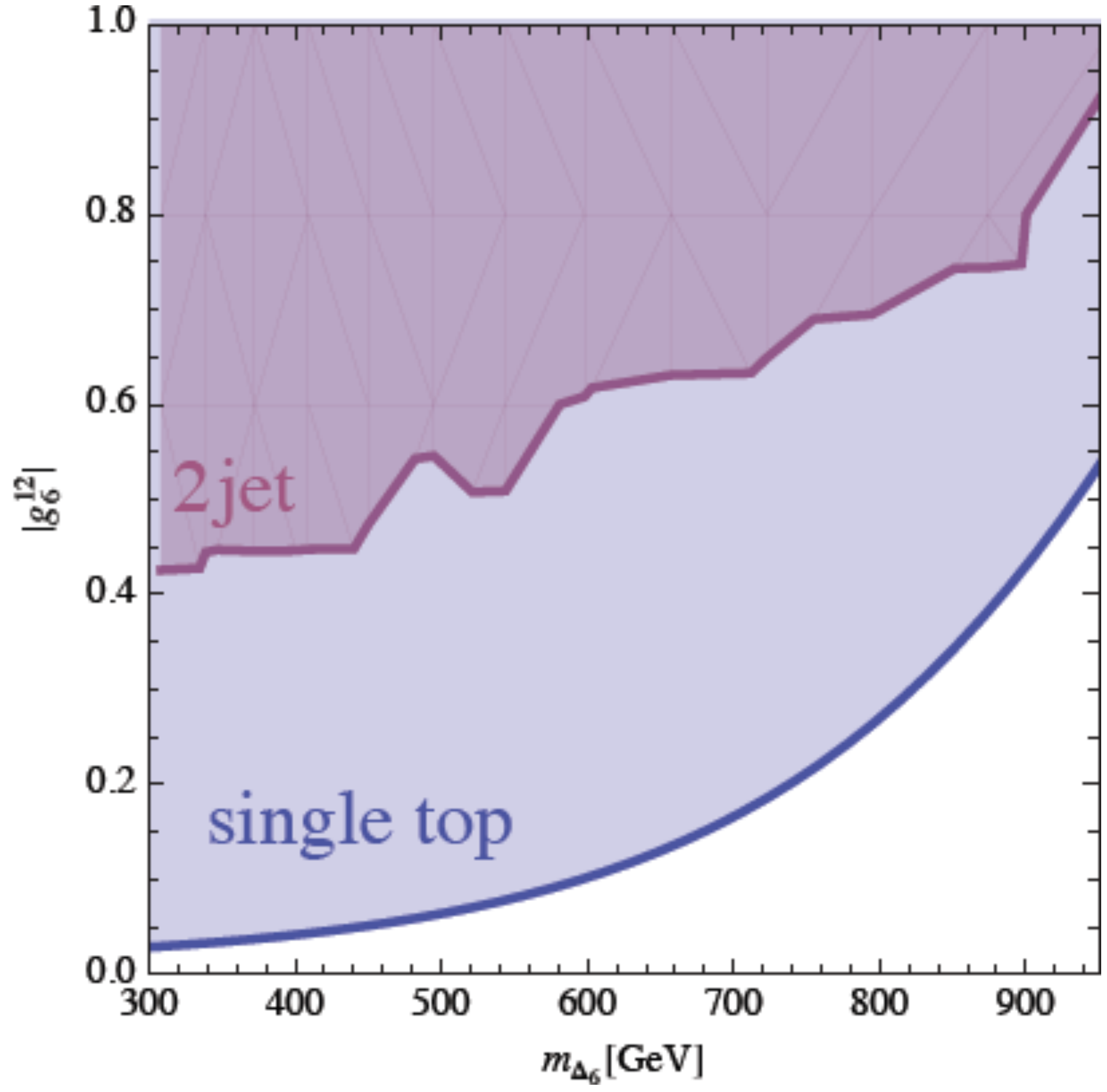
$$\hat{s} = (p_{\bar{u}} + p_u)^2,\ \hat{t} = (p_u - p_t)^2,\ \hat{u} = (p_{\bar{u}} - p_t)^2$$

using crossing symmetry one gets $uc \to tu$

We compare NP contribution with the experimental error on the combined Tevatron result for the total single-top cross-section

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

$$\sigma_{1t} = 2.76^{+0.58}_{-0.47}\ \text{pb}$$

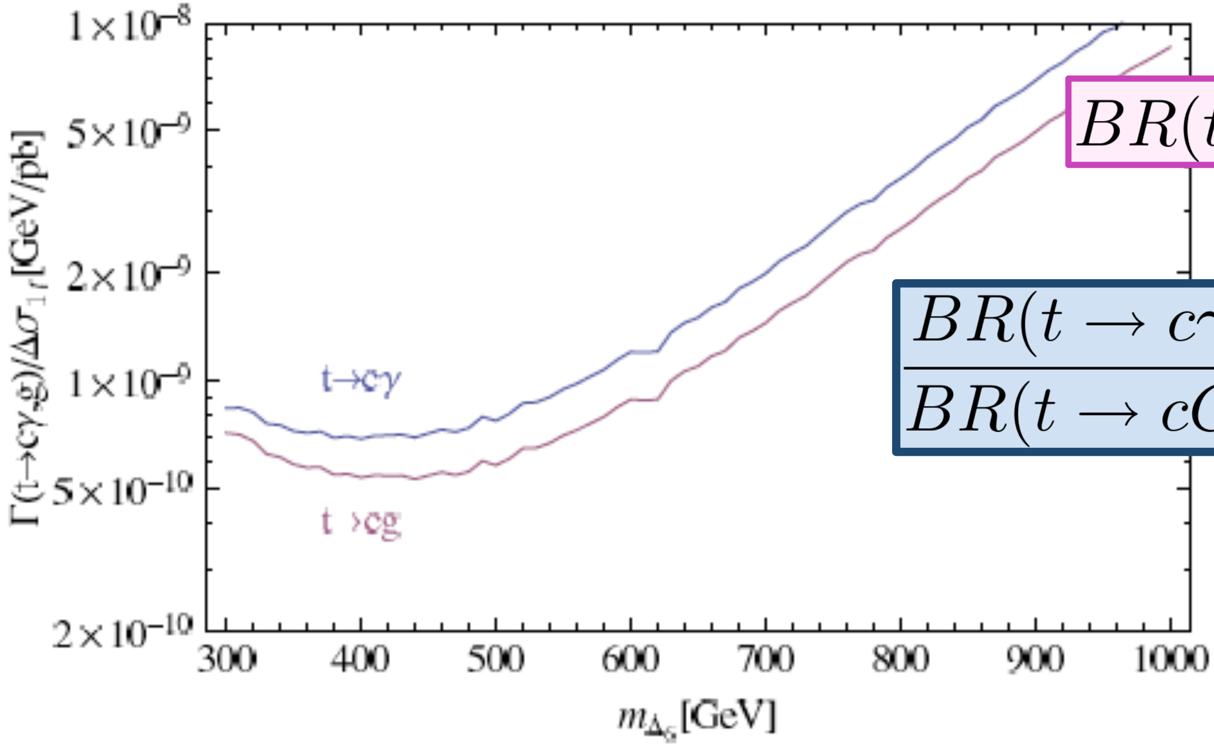


Bounds on g_6^{uc} from di-jets and single top production

FCNC top quark decays

$$\Gamma^{t\to c\gamma} = \frac{\alpha |g_6^{12} g_6^{13}|^2 m_t}{2304\pi^4} \left[F^\gamma(m_{\Delta_6}^2/m_t^2)\right]^2$$

$$\Gamma^{t\to cG} = \frac{\alpha_S |g_6^{12} g_6^{13}|^2 m_t}{768\pi^4} \left[F^G(m_{\Delta_6}^2/m_t^2)\right]^2$$



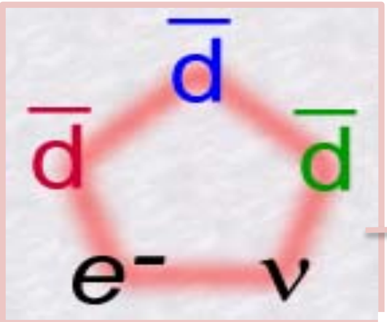
$BR(t \to cG) \sim 10^{-9}$

$$\frac{BR(t \to c\gamma)}{BR(t \to cG)} = (30 - 40)\%$$

Can colored triplet scalar state appear within some of SM extensions?

GUT models contain such a state in an extended SU(5), SO(10).

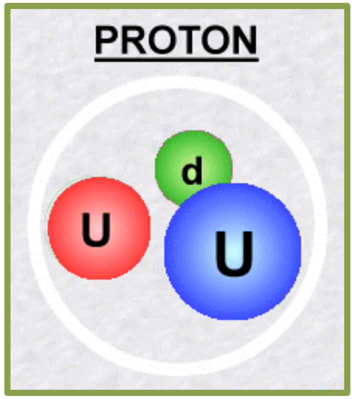
Georgi-Glashow (1974) proposed $SU(5) \longrightarrow SU(3) \times SU(2) \times U(1)$



Matter fields are in representation

5 and $\overline{10}$

Unifications of the strong, weak and electromagnetic interactions occurs at the scale 10^{16} GeV.



Proton might decay:
Current experimental limit

$\tau_p > 10^{33}$ years

Inclusion of 45 Higgs representation

$$M_E^T = M_D$$

In GUT there is a problem with masses of charged fermions at the GUT scale

$$m_\tau / m_b = m_\mu / m_s = m_e / m_d$$

Solutions:
- extra vectorlike fermions;
- higher dimensional operators (45);

Higgs in 45 modifies:

$$M_E^T = -3M_D$$

Both are needed: Higgses in 5 and 45!

45 representation should be part of any simple renormalizable SU(5) GUT without SUSY.

In 45 Higgs representation there are many new scalars

Experimental results from K and D phenomenology almost exclude presence of these light state at low energies, Dorsner, S.F, N. Kosnik, J.F. Kamenik, (2009)

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

$$(\mathbf{8}, \mathbf{2}, \mathbf{1/2}) \oplus (\overline{\mathbf{6}}, \mathbf{1}, -\mathbf{1/3}) \oplus (\mathbf{3}, \mathbf{3}, -\mathbf{1/3}) \oplus (\overline{\mathbf{3}}, \mathbf{2}, -\mathbf{7/6}) \oplus (\mathbf{3}, \mathbf{1}, -\mathbf{1/3}) \oplus (\overline{\mathbf{3}}, \mathbf{1}, \mathbf{4/3}) \oplus (\mathbf{1}, \mathbf{2}, \mathbf{1/2})$$

colored scalars

- "genuine" leptoquark interacts always with one lepton and one quark;
- colored scalars might interact with two quarks only

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

- role of leptoquark with down-like quarks
- role of diquarks with the up-like quarks

Is unification possible with the light colored scalars ?

At one loop level, two equations should be satisfied:

Unification conditions:

$$\frac{B_{23}}{B_{12}} = \frac{5}{8}\frac{\sin^2\theta_W - \alpha/\alpha_3}{3/8 - \sin^2\theta_W} = 0.716 \pm 0.005,$$

$$B_{12} = \frac{16\pi}{5\alpha}(3/8 - \sin^2\theta_W) = 184.9 \pm 0.2.$$

$$B_{ij} = B_i - B_j$$

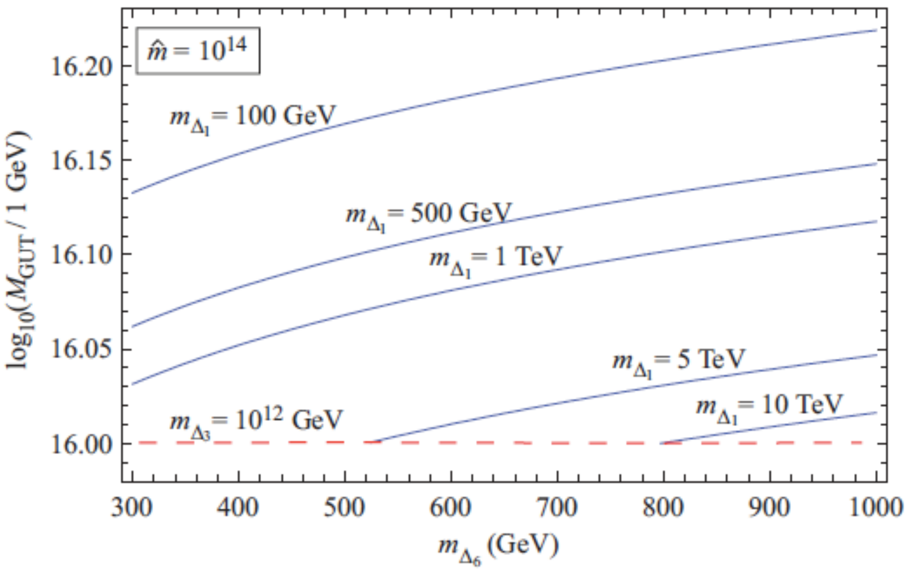
$$B_i = \sum_I b_{iI} \ln M_{GUT}/m_I$$

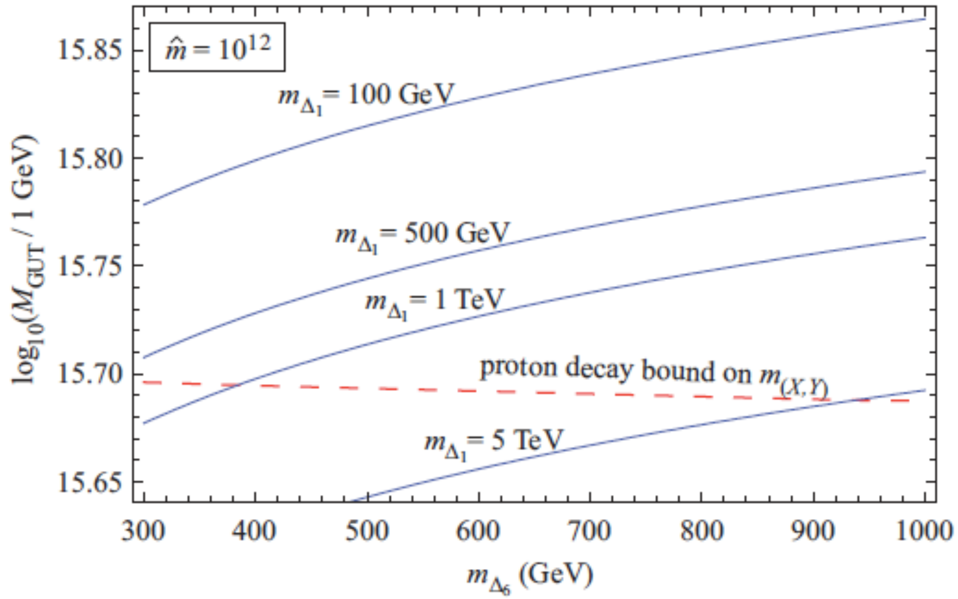
Experimental constraints:

$$\alpha_3 = 0.1176 \pm 0.0020,\ \alpha^{-1} = 127.906 \pm 0.019 \qquad (M_Z \leq m_I \leq M_{GUT})$$

$$\sin^2\theta_W = 0.23122 \pm 0.00015$$

experimental result on proton lifetime: $\tau(p \to \pi^0 e^+) > 8.2 \times 10^{33}$ Y





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 $300\text{GeV} \leq m_{\Delta_6} \leq 1\text{TeV}$ will be excluded.

Proton decay and colored triplet scalar

Δ_6 innocuous for proton decay at the tree level ;
(dangerous mixing with Higgs doublet from 5 avoided due to scalars 24)

Neutrino masses:

In addition to 5, 45, 24 scalars one 15 scalars needed for the neutrino masses type II seesaw. Problem: GUT scale to low being around $10^{13}\,\mathrm{GeV}$.

Our scenario: neutrino masses generated by seesaw combination type I and type III with the new fermions in adjoint representation (Bajc and Senjanović ,2008, Dorsner and Mocinou , 2009), instead of representation 15.

Constraints on anti-symmetric Yukawa couplings

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

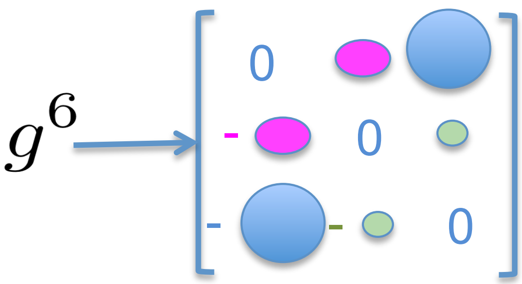
$$\mathcal{L} = (Y_1)_{ij} e_i^{cT} C d^c_{aj} \Delta^*_{6a} + \sqrt{2}[(Y_2)_{ij} - (Y_2)_{ji}]\epsilon_{abc} u_i^{aT} C u^c_{bj} \Delta_{6c}$$

$$g^6_{ij} = 2\sqrt{2}[U_R^\dagger((Y_2)_{ij} - (Y_2)_{ji})U_R^*] \qquad g^6_{ij} = -g^6_{ji}$$

U_R: Matrix which makes transformation from the weak to the mass basis

Results

Our constraints on Yukawa come from the up- quark phenomenology



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

$$|g^6_{13}| = 1.8$$

$$|g^6_{23}| \leq 0.0043$$

$$|g^6_{12}| \leq 0.03$$

Higgs in 5 interacts with matter fields as $\epsilon_{\alpha\beta\gamma\delta\epsilon}(Y_2')_{ij}(\mathbf{10}^{\alpha\beta})_i(\mathbf{10}^{\gamma\delta})_j(\mathbf{5})^{\epsilon}$

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

symmetric anti-symmetric

$\langle\mathbf{5}\rangle = v_5/\sqrt{2}$ and $\langle\mathbf{45}\rangle_1^{15} = \langle\mathbf{45}\rangle_2^{25} = \langle\mathbf{45}\rangle_3^{35} = v_{45}/\sqrt{2}$

$|v_5|^2 + |v_{45}|^2 = v^2$ $v = 246\,\mathrm{GeV}$

Y_2' and Y_2 are 3 x 3 Yukawa matrices at GUT scale

in the basis where down-quark mass matrix is diagonal one can separate

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

diagonal up-quark mass matrix

$$U = \tilde{V}_{CKM} U_R \qquad \tilde{V}_{CKM} = U_1 V_{CKM} U_2$$

CKM matrix including 5 additional phases at GUT scale contained on U_1 and U_2

$$A' = 2\sqrt{2} U_R^\dagger (Y_2 - Y_2^T) U_R^* v_{45}$$

arbitrary unitary matrix

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

at GUT scale, while constraints on g_6 are obtained at low energies

If we run g_6 constraints and relevant fermion masses and their mixing parameters from electroweak to the GUT scale we would have $A' = g_6 v_{45}$

This relations lets us deduce generic properties of the symmetric contribution S' and pinpoint the texture of the up-quark Yukawa couplings.

basic points of our analysis are

- M_U^{diag} is very hierarchical matrix
- $|g_6^{13}| >> |g_6^{23}|, |g_6^{12}|$, fixed by AFB
- unitarity of U_R

interesting consequences

$$\left.\begin{array}{l}|A'_{13}| \\ |S'_{13}|\end{array}\right\} \simeq |U_{31}| m_t \qquad |S'_{13}| = |A'_{13}|$$

$|U_{31}|/v_{45}$ is a constant for a given m_{Δ_6}

Numerical study of A′ and S′

We have generated 10^8 random points in the nine-dimensional space of the unitary matrix U for different values $m_{\Delta_6} = 200, 400, 700, 1000\,\mathrm{GeV}$

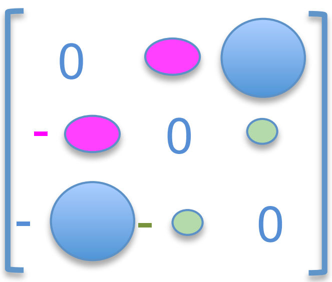
- A′ dominated by $|A'_{13}|$ and then S′ also has $|S'_{13}|$ much larger then the other matrix elements;
- there are analytic correlations between all entries of S′ and A′ except $|S'_{23}|$
- the underlying Yukawa structure of the up-sector exhibit dependence on 45 vev ;
- phenomenological constraints on the form of A′ put limitation on the allowed form of S′ , $|S'_{12}|, |S'_{13}|, |S'_{33}|$ and $|S'_{11}|/|S'_{22}|$ are tied to $|U_{31}|$;

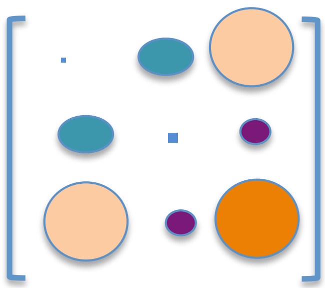
The form of M_U is lopsided!

$$\boxed{M_{GUT} = 1.1 \times 10^{16}\,\text{GeV}}$$

	$m_{\Delta_6} = 400\,\text{GeV}$	$m_{\Delta_6} = 1\,\text{TeV}$
$\lvert A'_{12}\rvert/m_t$	$[2.9 \times 10^{-7}, 8.0 \times 10^{-4}]$	$[1.1 \times 10^{-6}, 8.2 \times 10^{-4}]$
$\lvert A'_{13}\rvert/m_t$	$[3.7 \times 10^{-2}, 2.5 \times 10^{-1}]$	$[1.8 \times 10^{-2}, 2.5 \times 10^{-1}]$
$\lvert A'_{23}\rvert/m_t$	$[1.4 \times 10^{-5}, 5.6 \times 10^{-4}]$	$[1.4 \times 10^{-5}, 5.1 \times 10^{-4}]$
$\lvert S'_{11}\rvert/m_t$	$[2.2 \times 10^{-9}, 4.0 \times 10^{-6}]$	$[5.3 \times 10^{-9}, 3.9 \times 10^{-6}]$
$\lvert S'_{12}\rvert/m_t$	$[2.6 \times 10^{-7}, 8.1 \times 10^{-4}]$	$[6.5 \times 10^{-7}, 8.2 \times 10^{-4}]$
$\lvert S'_{13}\rvert/m_t$	$[3.7 \times 10^{-2}, 2.5 \times 10^{-1}]$	$[1.8 \times 10^{-2}, 2.5 \times 10^{-1}]$
$\lvert S'_{22}\rvert/m_t$	$[5.9 \times 10^{-5}, 1.7 \times 10^{-3}]$	$[1.0 \times 10^{-4}, 1.6 \times 10^{-3}]$
$\lvert S'_{23}\rvert/m_t$	$[1.7 \times 10^{-5}, 2.2 \times 10^{-3}]$	$[3.2 \times 10^{-5}, 2.1 \times 10^{-3}]$
$\lvert S'_{33}\rvert/m_t$	$[1.2 \times 10^{-3}, 4.9 \times 10^{-1}]$	$[3.3 \times 10^{-3}, 5.0 \times 10^{-1}]$

Lopsided structure of the mass matrix!

$A' \sim$ 

$S' \sim$ 

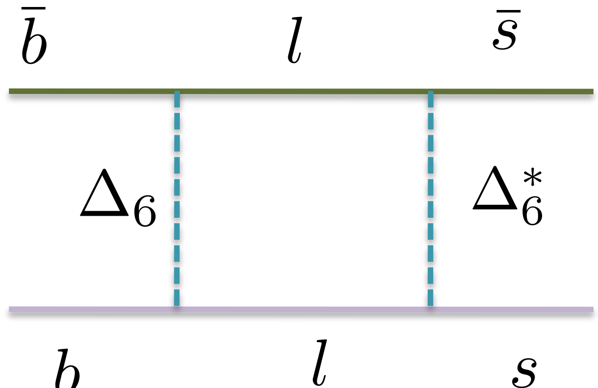
Down-quarks and colored scalar

$$\mathcal{L}(\Delta_6) = Y_1^{ik} \bar{d}_k^c P_R l_i \Delta_6 + h.c.$$

Work in progress!

$$K^0 - \bar{K}^0, B_d^0 - \bar{B}_d^0, B_s^0 - \bar{B}_s^0,$$

Dighe et al. (2010), AFB in Bs, anomalous dimuon charge asymmetry;
Saha et al. (2010), bounds from oscillations and rare decays;

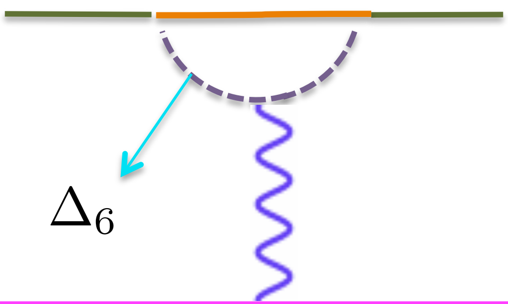


$$K^0 - \bar{K}^0 \to \sum_l Y_1^{l1} Y_1^{l2*} \sim 3.5 \times 10^{-3},$$

$$B_d^0 - \bar{B}_d^0 \to \sum_l Y_1^{l1} Y_1^{l3*} \sim 0.012,$$

$$B_s^0 - \bar{B}_s^0 \to \sum_l Y_1^{l2} Y_1^{l3*} \sim 0.02.$$

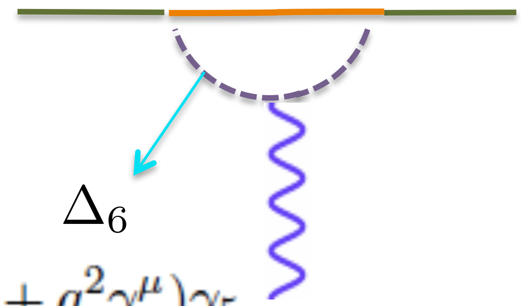
Lepton's anomalous magnetic moments



$$|Y_1^{23}| = (1.7 \pm 0.5) \times 4\pi \frac{m_\Delta}{10^{4.5} m_\mu}$$

$$|Y_1^{13}| < 1.7 \times 4\pi \frac{m_\Delta}{10^{6.5} m_e}$$

Lepton's anomalous magnetic moments



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

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

anomalous magnetic moment

$$a_\mu^{\rm exp} = 1.16592080(63) \times 10^{-3}$$
$$a_\mu^{\rm SM} = 1.16591793(68) \times 10^{-3}.$$

$$\delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (287 \pm 91) \times 10^{-11}$$

$$a_\mu = \frac{3m_\mu^2}{16\pi^2 m_\Delta^2}|Y_1^{23}|^2\left[Q_\Delta f_\Delta(x) + Q_b f_b(x)\right], \qquad x = m_b^2/m_\Delta^2$$

$$|Y_1^{23}| = (1.7 \pm 0.5) \times 4\pi\frac{m_\Delta}{10^{4.5}m_\mu}$$

$\delta a_e = 2.8 \times 10^{-13}$ for electron

$$|Y_1^{13}| < 1.7 \times 4\pi\frac{m_\Delta}{10^{6.5}m_e}$$

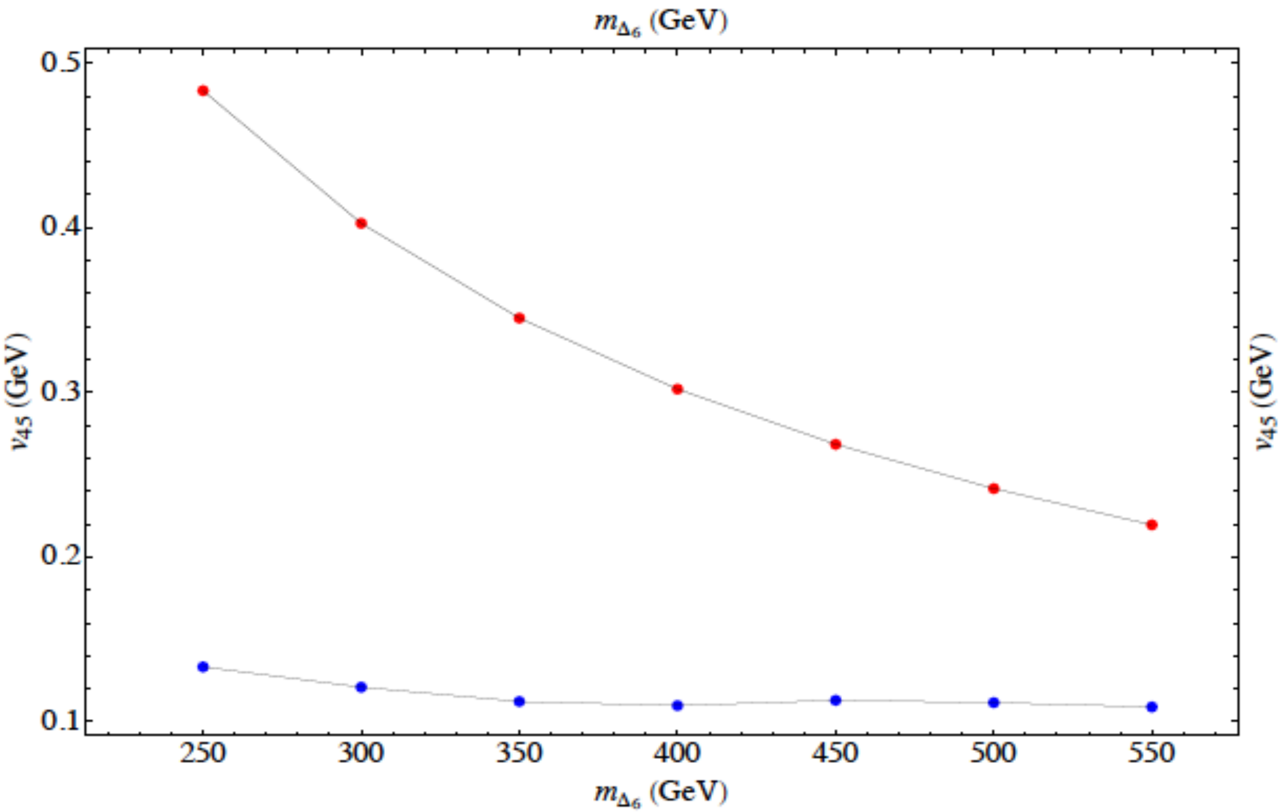
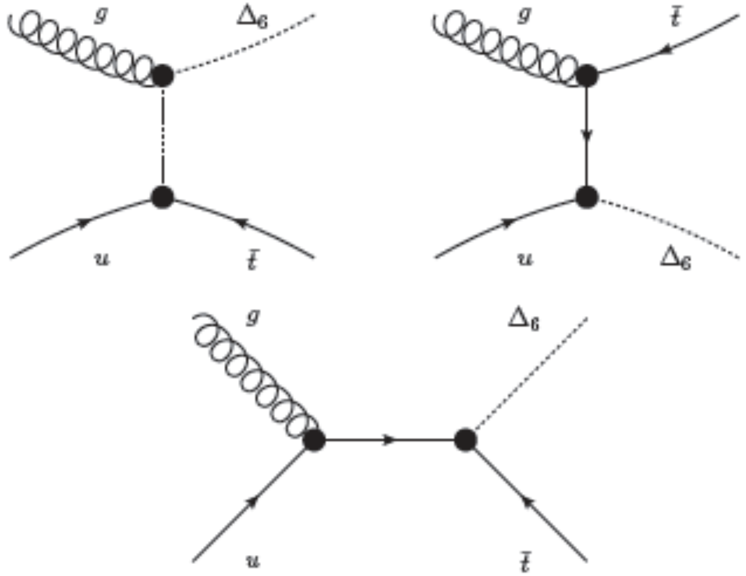
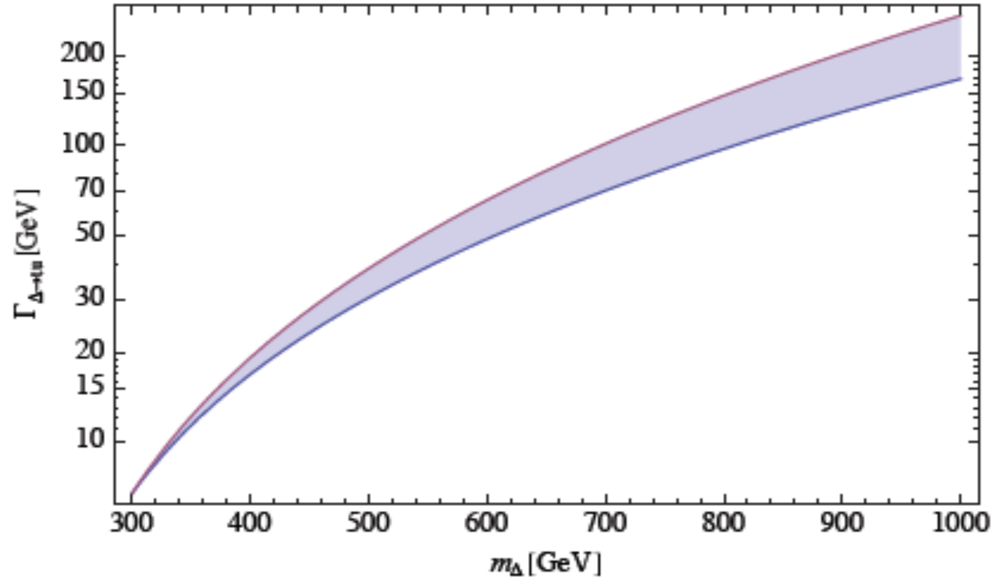


FIG. 1: Upper and lower bound on v_{45} as a function of m_{Δ_6}.

$$M_D^{diag} = (-\frac{1}{2}Y_2 v_5 - Y_4 v_{45})D_R^*,$$
$$M_E^{diag} = (-\frac{1}{2}Y_2^T v_5 + 3Y_4^T v_{45})E_R^*,$$

Search strategies at hadron colliders



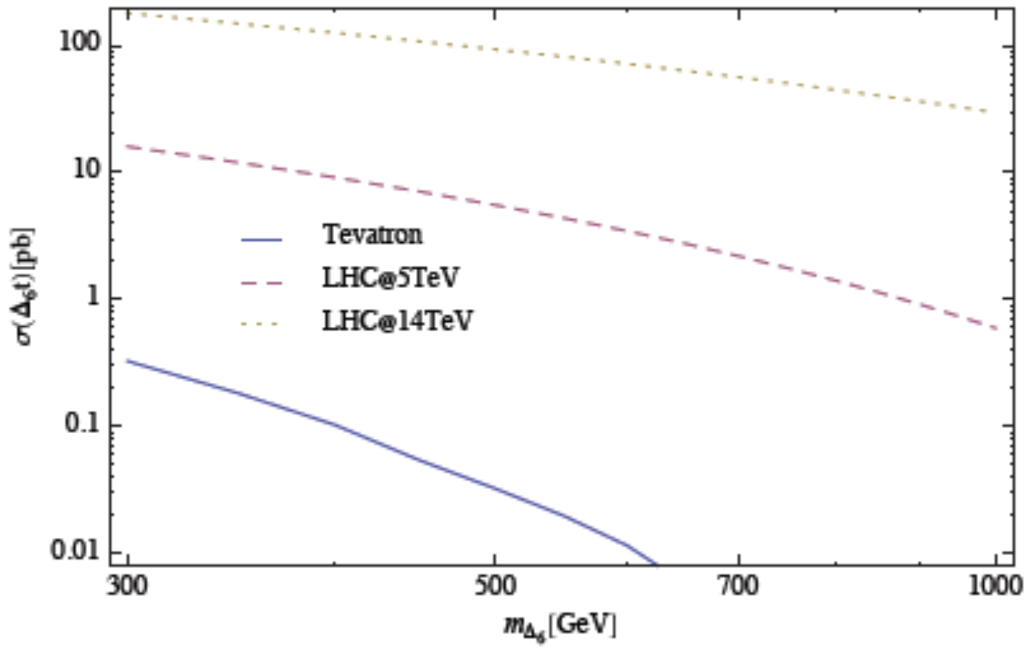


Dependence of the decay width on the Δ_6 mass .

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

$$\Gamma(\Delta_6 \to tu) = \frac{|g_6^{ut}|^2 \left(m_{\Delta_6}^2 - mt^2\right)^2}{16\pi m_{\Delta_6}^3}$$

Δ_6 can be produced at hadron colliders:

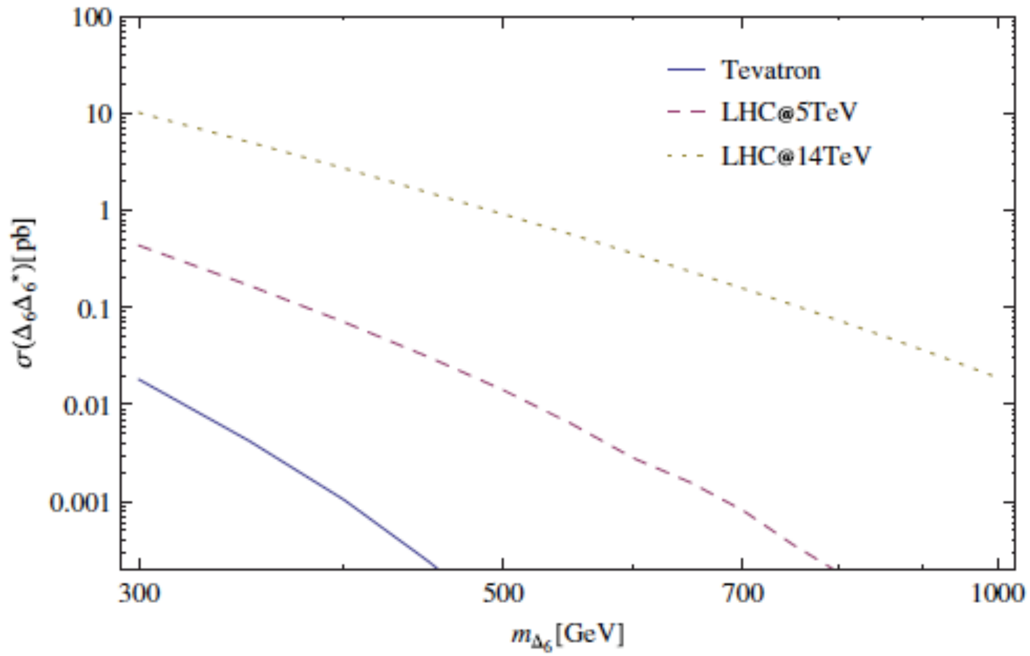


Hadronic production at LHC and Tevatron

Pair production

$$q\bar{q} \longrightarrow \Delta_6 \Delta_6^*$$

$$gg \longrightarrow \Delta_6 \Delta_6^*$$



Δ_6 would appear as a resonance in the invariant mass of a top and one hard jet.

Conclusions and perspective

- Model offers a possibility to explain FB asymmetry in top pair production at Tevatron, without spoiling the SM prediction for the cross section;

- $D^0 - \bar{D}^0$ system might constrain Yukawa couplings;

- Might help in understanding a pattern of Yukawa mass matrix for the up-quarks;

- Rather large coupling fixed by AFB in double top production implies that the up-quark mass matrix has lopsided texture;

- 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 top or anti-top.

- The study of Δ_6 role in the down-quark charged lepton interaction will offer inside in the texture of the down-quark mass matrix;