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Portoroz

Studying anomalous top-gluon couplings at Tevatron/LHC

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Collaboration with Kazumasa OHKUMA

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This talk is based on

Z.H. and K. Ohkuma,

Eur.Phys.J. C65 (2010), 127 and C71 (2011), 1535

What we have calculated is not very new .....

Eur. Phys. J. C (2010) 65: 127–135
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THE EUROPEAN
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Regular Article - Theoretical Physics

Search for anomalous top–gluon couplings at LHC revisited

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Abstract Through top quark pair productions at LHC, we study possible effects of nonstandard top–gluon couplings yielded by $SU(3) \times SU(2) \times U(1)$ invariant dimension-6 effective operators. We calculate the total cross section and also some distributions for $pp \to t\bar{t}X$ as functions of two anomalous-coupling parameters, i.e., the chromoelectric and chromomagnetic moments of the top, which are constrained by the total cross section $\sigma(p\bar{p} \to t\bar{t}X)$ measured at Tevatron. We find that LHC might give us some chances to observe sizable effects induced by those new couplings.

sume a new physics characterized by an energy scale Λ and write down $SU(3) \times SU(2) \times U(1)$-symmetric effective (nonrenormalizable) operators for the world below Λ. Those operators with dimension 6 were systematically listed in [2, 3]. Although we still have to treat several operators (parameters) even in this framework, but some of the operators given there were found to be dependent of each other through equations of motion [4]. This shows that we might be further able to reduce the number of independent operators, and indeed it was recently done in [5, 6].

In this effective-operator framework, not only elec-

But we believe what we have found is interesting .....

Eur. Phys. J. C (2011) 71: 1535
DOI 10.1140/epjc/s10052-010-1535-8

THE EUROPEAN PHYSICAL JOURNAL C

Addendum

Addendum to: Search for anomalous top–gluon couplings at LHC revisited

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Abstract In our latest paper "Search for anomalous top–gluon couplings at LHC revisited" in *Eur. Phys. J. C* **65** (2010), 127–135 (arXiv:0910.3049 [hep-ph]), we studied possible effects of nonstandard top–gluon couplings through the chromoelectric and chromomagnetic moments of the top

$$\mathcal{L}_{t\bar{t}g,gg} = -\frac{1}{2} g_s \sum_a \Big[\bar{\psi}_t(x)\lambda^a\gamma^\mu\psi_t(x)G^a_\mu(x) - \bar{\psi}_t(x)\lambda^a \frac{\sigma^{\mu\nu}}{m_t}(d_V + i d_A\gamma_5)\psi_t(x) G^a_{\mu\nu}(x)\Big]. \quad (1)$$

where g_s is the SU(3) coupling constant, and d_V and d_A correspond to the top chromomagnetic and chromoelectric moments, respectively. It is straightforward, though a bit

1. Introduction

Discovery of the top-quark (1994)

$\Downarrow$

We have now all the quarks and leptons required in the SM.

$$
\textit{First} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad \textit{Second} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \qquad \textit{Third} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}
$$

$$
\begin{pmatrix} u \\ d \end{pmatrix} \qquad\qquad \begin{pmatrix} c \\ s \end{pmatrix} \qquad\qquad \begin{pmatrix} t \\ b \end{pmatrix}
$$

However $\cdots$ still questions/problems :

t is the least-studied observed particle

- **Is the 3rd generation a simple copy of the 1st and 2nd ones ?**
- **Are there any New Physics effects in the top couplings ?**

New-physics search can be classified into two categories:

(1) Model-dependent analyses

$\cdots$ Precise calculations are possible

But, we get little result if the model is wrong!!

(2) Model-independent analyses

$\cdots$ " No-lose game" We can write some papers !

But We need to treat many parameters altogether

$\Longrightarrow$ Difficult to perform precise calculations

These two approaches should work complementary to each other

We performed model-independent studies of

possible anomalous top-quark interactions

at ILC.[♯1]

When we started those studies around 1995, we were thinking

ILC would be realized before LHC (and SSC), and

we would be able to study a lot about the top-quark, the Higgs-boson, and other particles in TeV world,

but · · · · · · , as you know.

So we decided to focus on Hadron Colliders.

[♯1] With B.Grzadkowski, J.Wudka, and K.O.

LHC (= The Large Hadron Collider):

The world largest hadron (proton + proton) collider.

Its circumference is about **27 km** (precisely 26.659 km),
with a total of 9300 magnets inside.

If everything had been fine,

we already would have had lots of data by now !

It may be too much to say this,
but even the Higgs might have been discovered !!?

$\Downarrow$

Let's stop crying over the past! What's done cannot be undone !

This machine is now working.

2. Framework

Our basic framework:

When we studied top-quark physics at ILC, we started from

the most general amplitude for $e\bar{e} \longrightarrow t\bar{t}$:

$$\Gamma_v^\mu = \frac{g}{2}\bar{u}(p_t)\Big[\gamma^\mu(A_v - B_v\gamma_5) + \frac{(p_t - p_{\bar{t}})^\mu}{2m_t}(C_v - D_v\gamma_5) + \frac{(p_t + p_{\bar{t}})^\mu}{2m_t}(E_v - F_v\gamma_5)\Big]v(p_t)$$

Here, $v = \gamma/Z$, g is the SU(2) gauge coupling constant.

Form factors $A_v \sim F_v$ are functions of q^2, but $q^2 = s$ is fixed.

$\Longrightarrow$ **We can treat them as constants.**

However, we cannot take this approach anymore for LHC physics,

since $q^2 = x_1 x_2 s$ is no longer a constant.

$\cdots$ We do not know their functional forms.

Therefore,

We assume <u>a new physics characterized by an energy scale Λ</u>, and <u>we have only SM particles below Λ</u>.

$\Downarrow$

Then, below Λ, heavy-boson-exchange effects will appear as non-renormalizable effective interactions.

For example, in the SM, W-boson-exchange effects

$\Longrightarrow$ Feynman-Gell-Mann type interaction

in phenomena far below M_W.

According to Buchmüller et al., three effective operators

$$\mathcal{O}_{uG\phi} = \sum_a [\, \bar{q}_L(x)\lambda^a\sigma^{\mu\nu}u_R(x)\tilde{\phi}(x)G^a_{\mu\nu}(x) \,]$$

$$\mathcal{O}_{qG} = \sum_a [\, \bar{q}_L(x)\lambda^a\gamma^\mu D^\nu q_R(x)G^a_{\mu\nu}(x) \,]$$

$$\mathcal{O}_{uG} = \sum_a [\, \bar{u}_R(x)\lambda^a\gamma^\mu D^\nu u_R(x)G^a_{\mu\nu}(x) \,]$$

contribute to strong interactions.

They produce top-pair production amplitudes which include

γ^μ, $\sigma^{\mu\nu}q_\nu$, $(p_i + p_j)^\mu$, q^μ terms, $\cdots\cdots$,

where $p_{i,j}$ and q are the top-quark i, j and gluon momenta.

Again so many unknown parameters !?

However two of them were shown not to be independent[♯2]

and we only need to take into account one operator

$$\mathcal{O}_{uG\phi} = \sum_a [\, \bar{q}_L(x)\lambda^a\sigma^{\mu\nu}u_R(x)\tilde{\phi}(x)G^a_{\mu\nu}(x)\,]$$

where $q = (t, b)$ and $u = t$.

Now

our starting Lagrangian becomes with unknown coefficient $C_{uG\phi}$ as

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm BSM}$$

$$\mathcal{L}_{\rm BSM} = \frac{1}{\Lambda^2}[\, C_{uG\phi}\mathcal{O}_{uG\phi} + C^*_{uG\phi}\mathcal{O}^\dagger_{uG\phi}\,]$$

[♯2] J.A. Aguilar-Saavedra, Nucl. Phys. B **812** (2009) 181 (arXiv:0811.3842 [hep-ph])

$$\mathcal{L}_{\rm BSM} = \frac{g_s}{2m_t}\sum_a [\, d_V \bar{\psi}_t(x)\lambda^a \sigma^{\mu\nu}\psi_t(x) + i\, d_A \bar{\psi}_t(x)\lambda^a\sigma^{\mu\nu}\gamma_5\psi_t(x)\,] G^a_{\mu\nu}(x).$$

Here,

$d_V \equiv \frac{\sqrt{2}vm_t}{g_s\Lambda^2}{\rm Re}(C_{uG\phi})$ and $d_A \equiv \frac{\sqrt{2}vm_t}{g_s\Lambda^2}{\rm Im}(C_{uG\phi})$

correspond to

the top chromomagnetic and chromoelectric moments,

and v is the Higgs vacuum expectation value ($= 246$ GeV)

A number of similar analyses have been performed
ever since more than a decade ago.

However, $\cdots$

- The couplings used there were not always the same.
- The precision of CDF/D0 data used there was not that high either.
- Focusing on $d_{V,A}$ exclusively was just an assumption.

We now know:

The analysis using the two moments is $\cdots$

the most general model-independent one.

Apart from QCD higher order corrections,
$q\bar{q} \longrightarrow g \longrightarrow t\bar{t}$ process is expressed by one Feynman diagram :

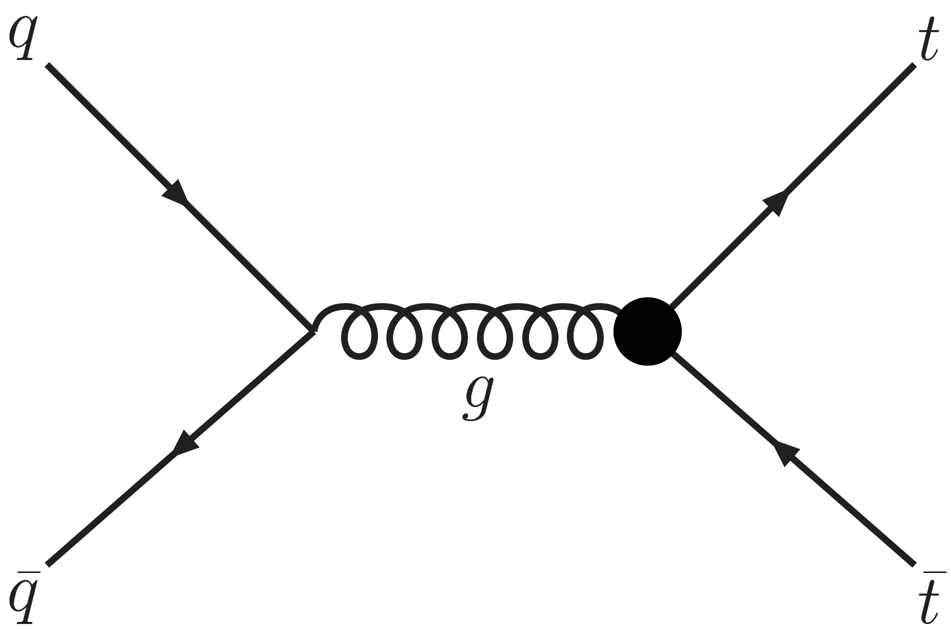

Figure 1: Feynman diagram of $q\bar{q} \longrightarrow t\bar{t}$. The bullet • expresses the vertex which includes the anomalous couplings.

The corresponding invariant amplitude is given by

$$\mathcal{M}_{q\bar{q}} = \frac{1}{4\hat{s}} g_s^2 \sum_a \bar{u}(p_t)\lambda^a \Gamma^\mu(q) v(p_{\bar{t}})\, \bar{v}(q_2)\lambda^a \gamma_\mu u(q_1),$$

where $q \equiv p_t + p_{\bar{t}}$, $\hat{s} \equiv q^2$, $[a]$ is the color label of the gluon,[♯3] and we defined $\Gamma^\mu(q)$ as

$$\Gamma^\mu(q) \equiv \gamma^\mu - \frac{2i\sigma^{\mu\nu}q_\nu}{m_t}(d_V + i d_A \gamma_5).$$

[♯3] Here (and hereafter) we do not show the color-component indices of u/v spinors, and also all the spin variables for simplicity.

On the other hand, $gg \longrightarrow t\bar{t}$ consists of four intermediate states:

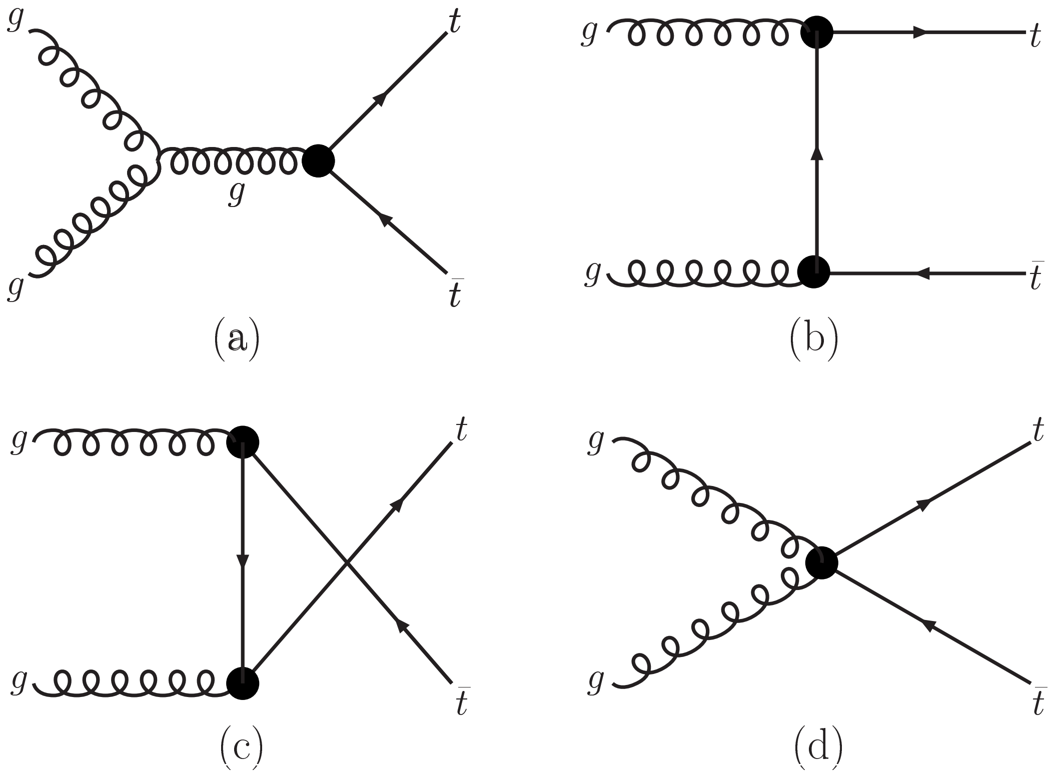

Figure 2: **Feynman diagrams of $gg \longrightarrow t\bar{t}$. The bullet • expresses the vertex which includes the anomalous couplings.**

The corresponding amplitudes are

$$\mathcal{M}_{gg} = \mathcal{M}_{gg}^{\rm a} + \mathcal{M}_{gg}^{\rm b} + \mathcal{M}_{gg}^{\rm c} + \mathcal{M}_{gg}^{\rm d},$$

$$\mathcal{M}_{gg}^{\rm a} = -\frac{g_s^2}{2\hat{s}} \sum_a \bar{u}(p_t)\lambda^a \Gamma^\mu(q) v(p_{\bar{t}})$$
$$\times\, i f_{abc}[\, 2q_{2\,\nu}\epsilon^\nu(q_1)\epsilon_\mu(q_2) - 2q_{1\,\nu}\epsilon_\mu(q_1)\epsilon^\nu(q_2)$$
$$+ (q_1 - q_2)_\mu \epsilon_\nu(q_1)\epsilon^\nu(q_2)\,]$$

$$\mathcal{M}_{gg}^{\rm b} = \frac{1}{4} g_s^2\, \bar{u}(p_t)\lambda^b\lambda^c \Gamma^\mu(q_1) \frac{1}{m_t - \not{k}_1} \Gamma^\nu(q_2) v(p_{\bar{t}})\, \epsilon_\mu(q_1)\epsilon_\nu(q_2)$$

$$\mathcal{M}_{gg}^{\rm c} = \frac{1}{4} g_s^2\, \bar{u}(p_t)\lambda^c\lambda^b \Gamma^\mu(q_2) \frac{1}{m_t - \not{k}_2} \Gamma^\nu(q_1) v(p_{\bar{t}})\, \epsilon_\nu(q_1)\epsilon_\mu(q_2)$$

$$\mathcal{M}_{gg}^{\rm d} = -g_s^2 \sum_a f_{abc} \bar{u}(p_t)\lambda^a \Sigma^{\mu\nu} v(p_{\bar{t}})\, \epsilon_\mu(q_1)\epsilon_\nu(q_2).$$

Here $k_1 \equiv p_t - q_1$, $k_2 \equiv p_t - q_2$, $[a]$ and $[b,\ c]$ are the color labels of the intermediate gluon and the incident gluons with momenta $q_1,\ q_2$,

$\epsilon(q_{1,2})$ are the incident-gluon polarization vectors, and

$$\Sigma^{\mu\nu} \equiv \frac{\sigma^{\mu\nu}}{m_t}(d_V + i d_A \gamma_5).$$

Differential cross sections in the parton-CM frame:

$$\frac{d\sigma_{q\bar{q}}}{dE_t^* d\cos\theta_t^*} = \frac{\beta_t^*}{16\pi\hat{s}}\delta(\sqrt{\hat{s}} - 2E_t^*)\left(\frac{1}{3}\right)^2 \sum_{\text{color}} \left(\frac{1}{2}\right)^2 \sum_{\text{spin}} |\mathcal{M}_{q\bar{q}}|^2,$$

$$\frac{d\sigma_{gg}}{dE_t^* d\cos\theta_t^*} = \frac{\beta_t^*}{16\pi\hat{s}}\delta(\sqrt{\hat{s}} - 2E_t^*)\left(\frac{1}{8}\right)^2 \sum_{\text{color}} \left(\frac{1}{2}\right)^2 \sum_{\text{spin}} |\mathcal{M}_{gg}|^2,$$

where quantities with "$*$" are those in the parton CM frame, $\beta_t^* \equiv |p_t^*|/E_t^* (= \sqrt{1 - 4m_t^2/\hat{s}})$ is the size of the top velocity.

$$\sum_{\text{color}}\sum_{\text{spin}}|\mathcal{M}_{q\bar{q}}|^2 = 16g_s^4\left[1-2(v-z)-8(d_V-d_V^2+d_A^2)+8(d_V^2+d_A^2)v/z\right],$$

$$\sum_{\text{color}}\sum_{\text{spin}}|\mathcal{M}_{gg}|^2 = \frac{32}{3}g_s^4\Big[(4/v-9)\,[\,1-2v+4z(1-z/v)-8d_V(1-2d_V)\,]$$

$$+4(d_V^2+d_A^2)\,[\,14(1-4d_V)/z+(1+10d_V)/v\,]$$

$$-32(d_V^2+d_A^2)^2(1/z-1/v-4v/z^2)\Big],$$

where $z \equiv m_t^2/\hat{s}$, $v \equiv (\hat{t}-m_t^2)(m_t^2-\hat{s}-\hat{t})/\hat{s}^2$, $\hat{t} \equiv (q_1-p_t)^2$.

The hadron cross sections are obtained by integrating the product of *the parton distribution functions* and *the parton cross sections in the hadron-CM frame* on the momentum fractions x_1 and x_2 carried by the partons.

3. Analysis I : Tevatron

The latest data of $t\bar{t}$ productions at Tevatron for $\sqrt{s} = 1.96$ TeV

$$\begin{aligned} \sigma_{\rm exp} &= 7.02 \pm 0.63 \text{ pb} \quad (\text{CDF}: \ m_t = 175 \text{ GeV}) \\ &= 8.18 \,{}^{+\,0.98}_{-\,0.87} \text{ pb} \quad (\text{D0}: \ m_t = 170 \text{ GeV}). \end{aligned}$$

The SM total cross section with QCD higher order corrections using the latest parton-distribution "CTEQ6.6M" (NNLO approximation)

$$\begin{aligned} \sigma_{\rm QCD} &= 6.73 \,{}^{+\,0.51}_{-\,0.46} \text{ pb} \quad (m_t = 175 \text{ GeV}) \\ &= 7.87 \,{}^{+\,0.60}_{-\,0.55} \text{ pb} \quad (m_t = 170 \text{ GeV}), \end{aligned}$$

We combine these errors with the above experimental ones as

$$\begin{aligned} \sigma_{\rm exp} &= 7.02 \,{}^{+\,0.81}_{-\,0.78} \text{ pb} \quad (\text{CDF}: \ m_t = 175 \text{ GeV}) \\ &= 8.18 \,{}^{+\,1.15}_{-\,1.03} \text{ pb} \quad (\text{D0}: \ m_t = 170 \text{ GeV}). \end{aligned}$$

We then compare the data with our total cross section:

$$\sigma(d_V, d_A) = \sigma_{\rm QCD}(\rm NNLO) + \Delta\sigma(d_V, d_A)$$

where $\Delta\sigma(d_V, d_A)$ is the non-SM contribution we computed.

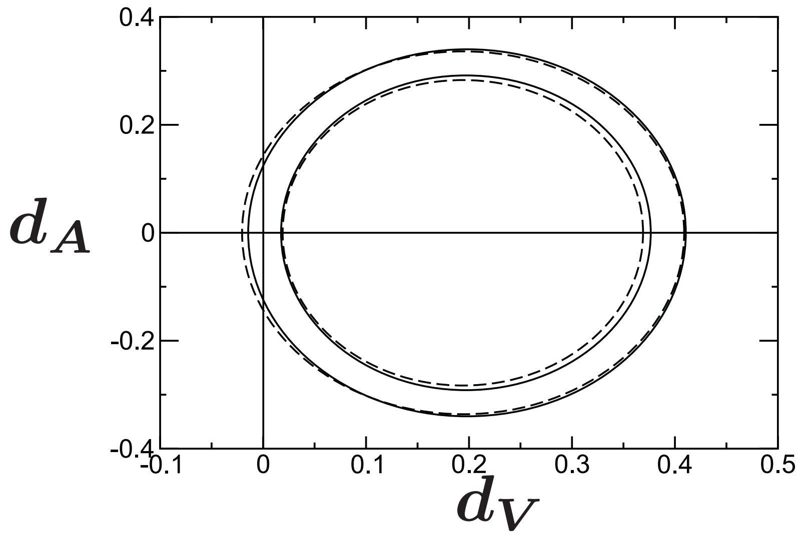

Figure 3: Experimentally allowed region for $d_{V,A}$. The region between two solid/dashed curves is from CDF/D0 data.

The more precise data we get, the narrower the allowed region becomes,

H O W E V E R

we won't be able to single out, e.g., the SM values $d_{V,A} = 0$

as long as we use Tevatron data alone,

and there is no inconsistency between CDF and D0 data.

4. Analysis II : LHC

At Tevatron, $q\bar{q}$ collisions dominate.

At LHC, gg collisions dominate.

So we will be able to get more interesting results from them.

However, $\cdots\cdots$

when we started this work, we had no LHC data yet.

Therefore we tried performing similar calculations,
assuming that we have

$$\sigma(\sqrt{s} = 10 \text{ TeV}) = 415 \pm 100 \text{ pb}$$
$$\sigma(\sqrt{s} = 14 \text{ TeV}) = 919 \pm 100 \text{ pb}$$

at LHC experiments.

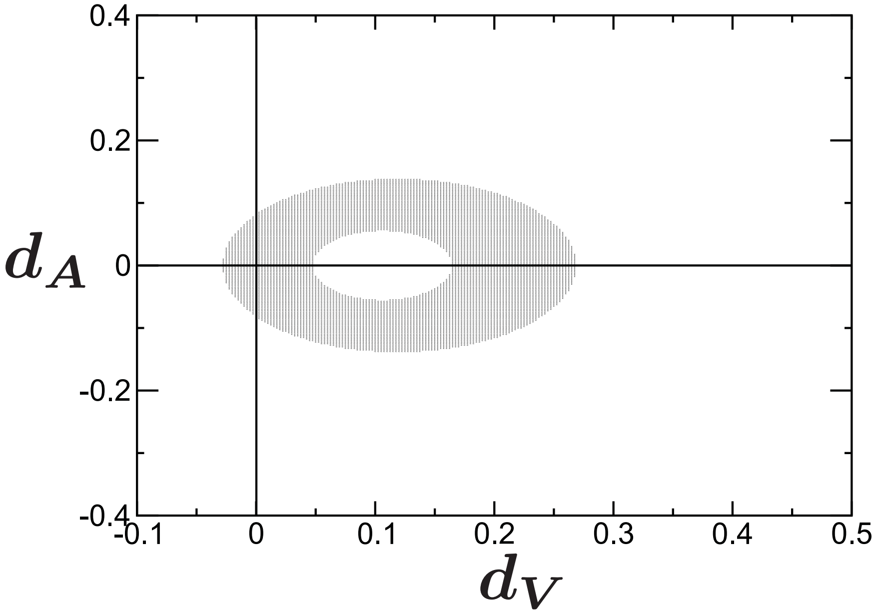

Figure 4: $\sqrt{s}$ =10 TeV

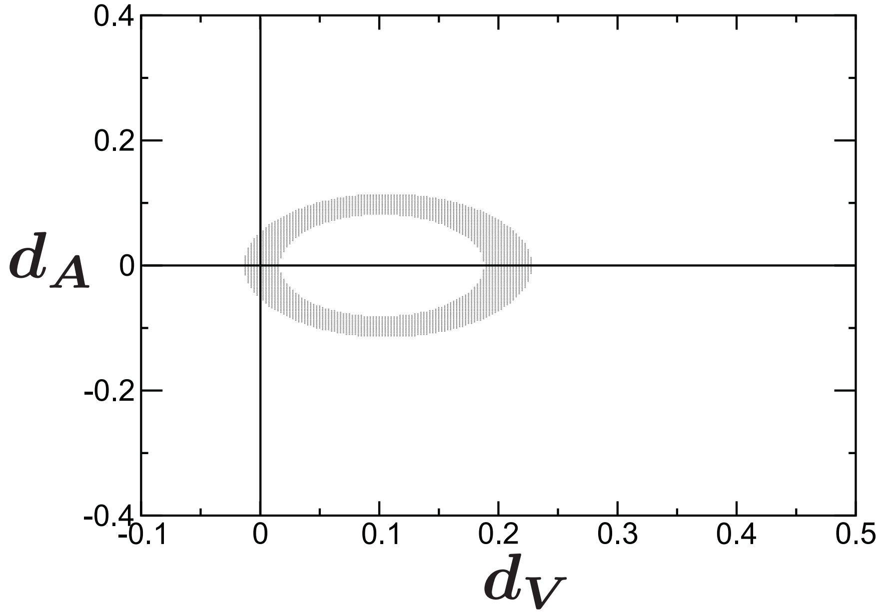

Figure 5: $\sqrt{s}$ =14 TeV

These are the allowed region for $d_{V,A}$ which LHC ($\sqrt{s}$ =10 and 14 TeV) might give us.

At first sight, it seems there is no big difference from the Tevatron results, but if we superpose them $\cdots\cdots$

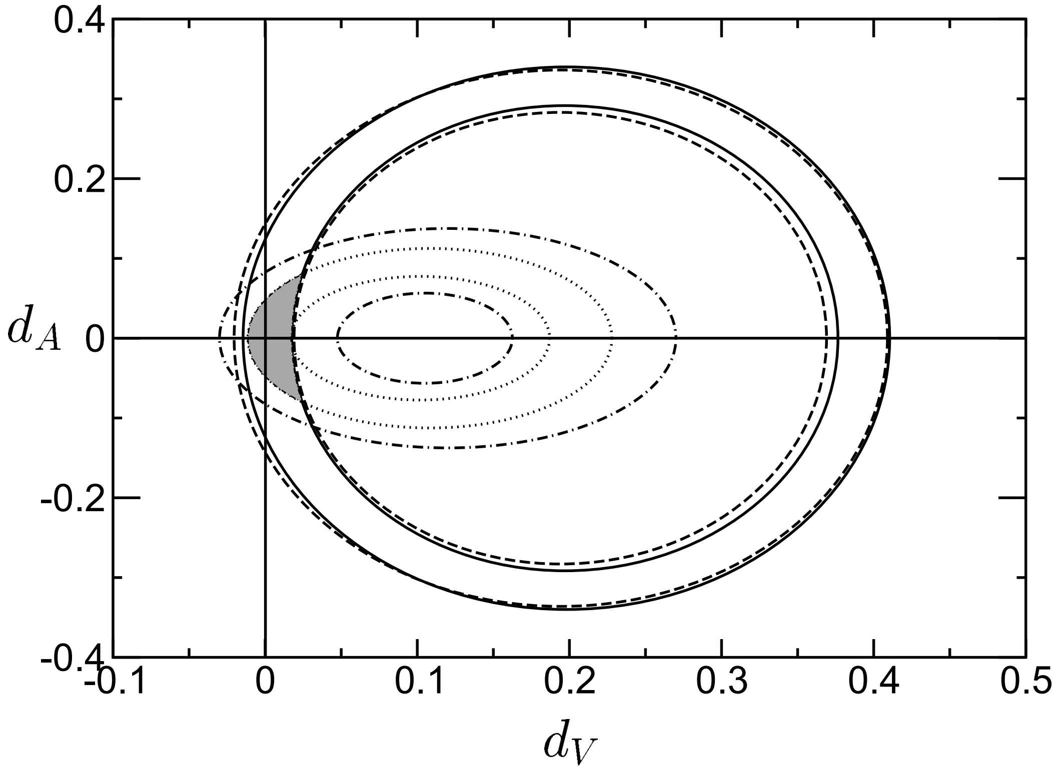

Figure 6: The $d_{V,A}$ region allowed by Tevatron and *assumed* LHC data (the shaded part).

They show that LHC will actually give a very good opportunity to perform precise analyses of top-gluon couplings.

In the end of 2010,

we have obtained R E A L LHC data :

- **CMS**

$$\sigma_{\rm exp} = 194 \pm 72 \pm 24 \pm 21 \ {\rm pb}$$

- **ATLAS**

$$\sigma_{\rm exp} = 145 \pm 31^{+42}_{-27} \ {\rm pb}$$

We have used the NNLO value for $\sigma_{\rm SM}$:

$$\sigma^{\rm NNLO}_{\rm SM} = 164.6^{+11.4}_{-15.7} \ {\rm pb} \quad (m_t = 172.5 \ {\rm GeV})$$

What we got is $\cdots\cdots$ Next sheet

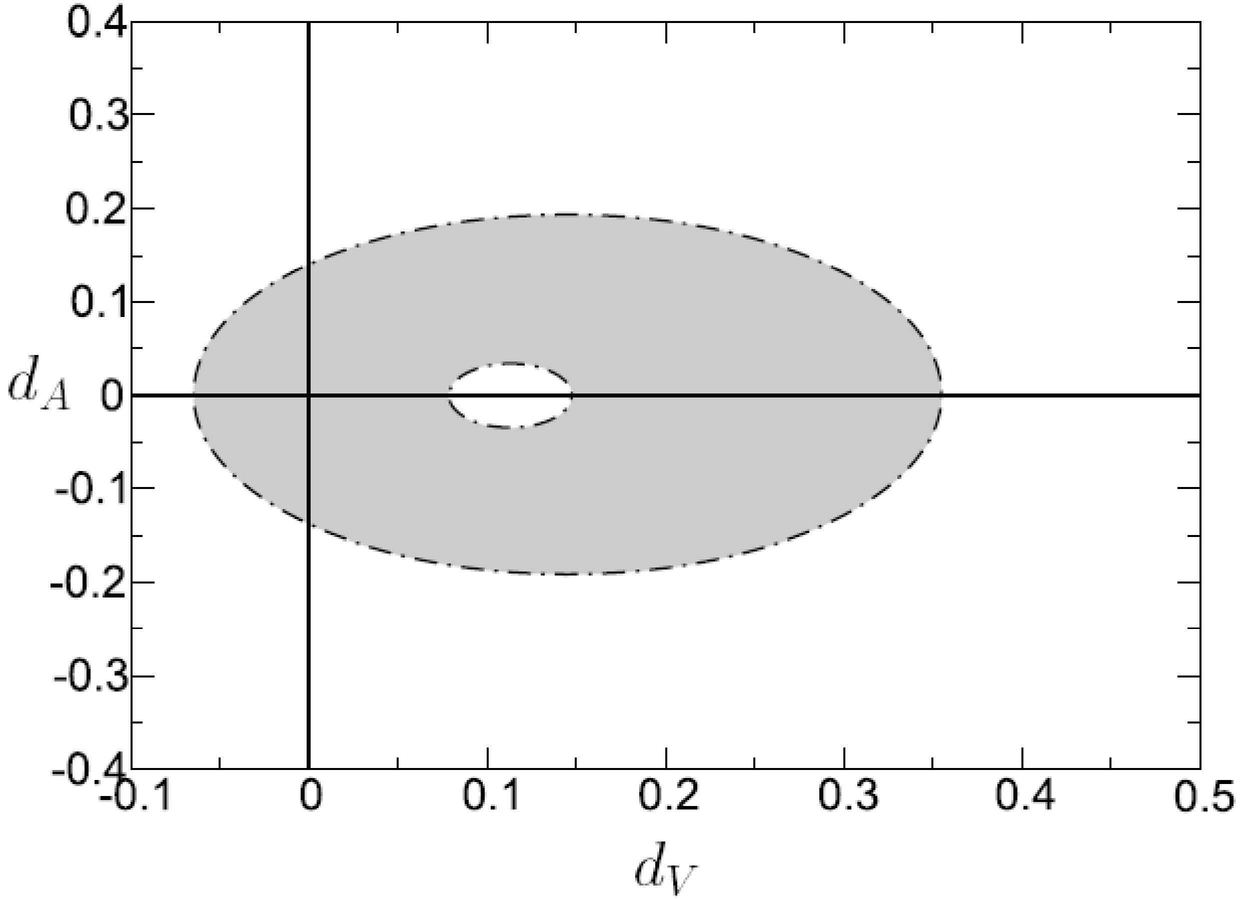

Figure 7: Constraint from the CMS data

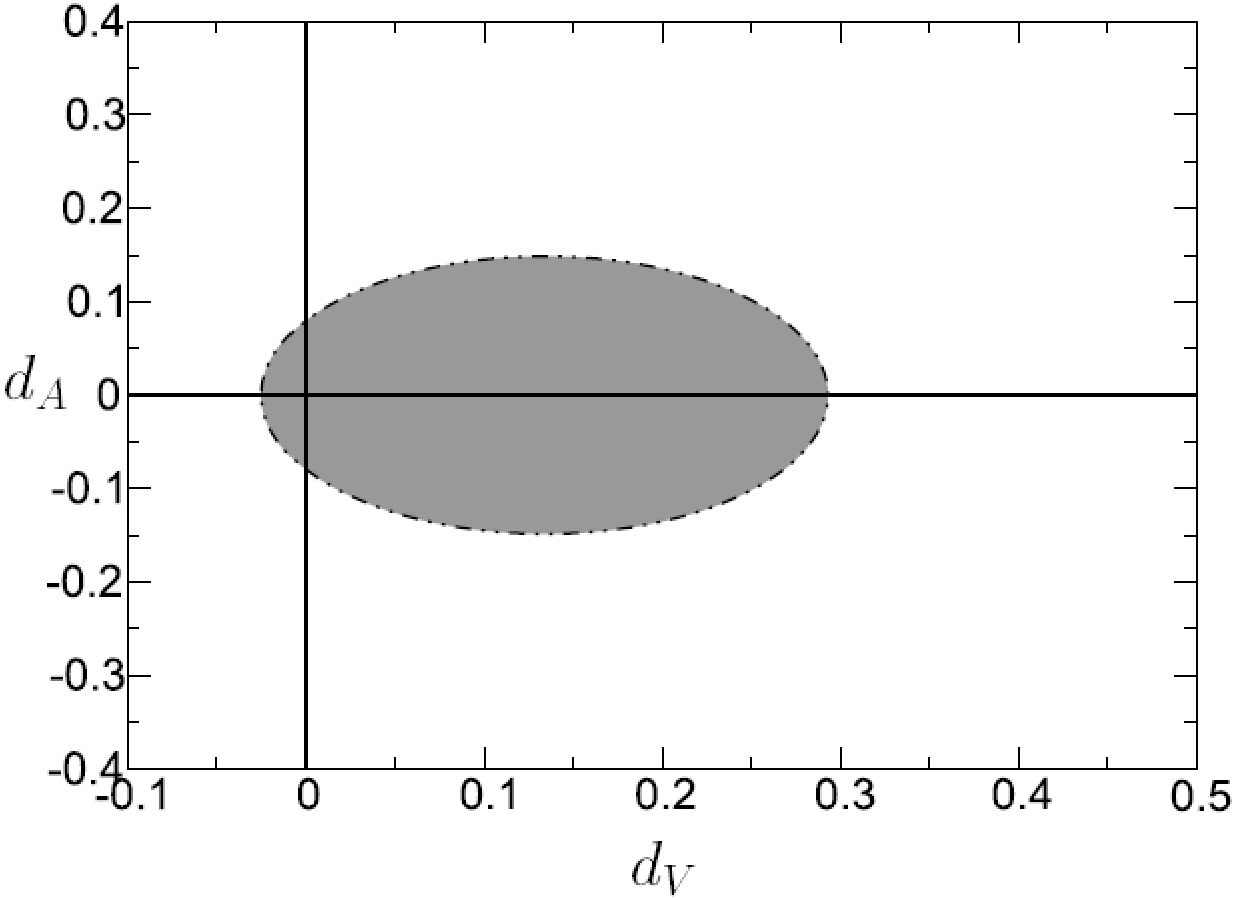

Figure 8: Constraint from the ATLAS data

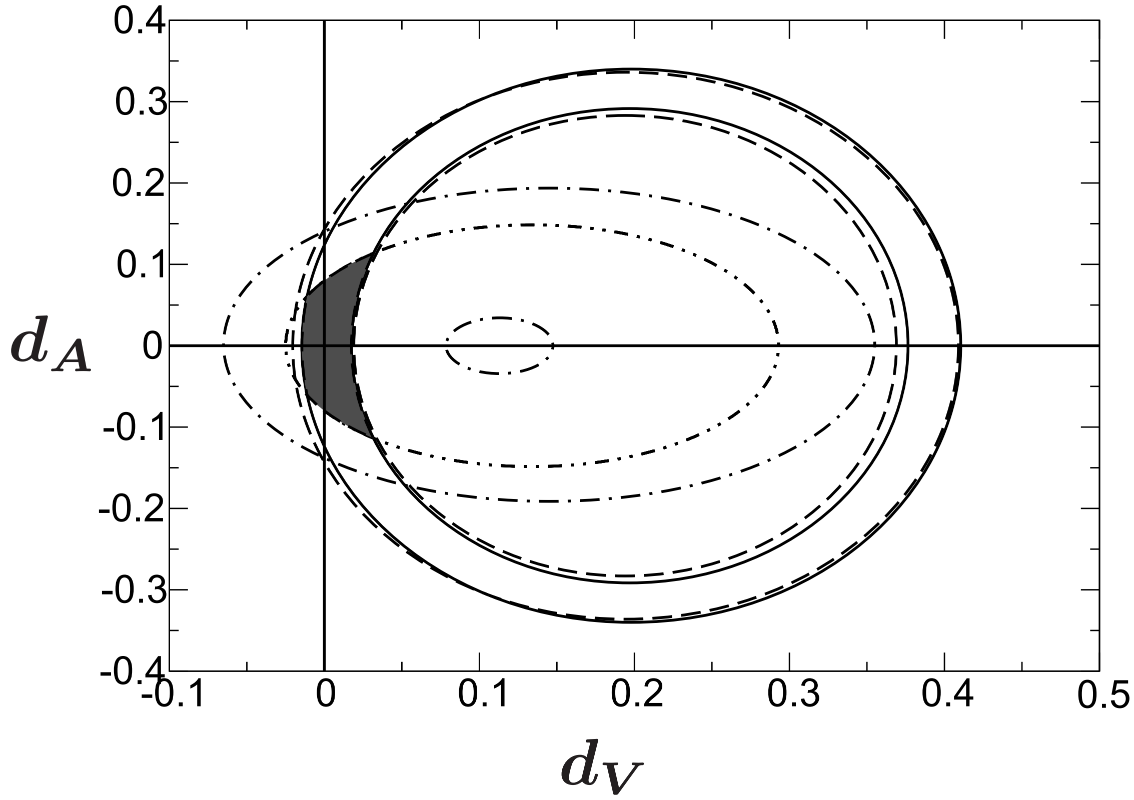

Figure 9: The $d_{V,A}$ region allowed by Tevatron and LHC data altogether (the shaded part). The solid curves, the dashed curves and the dash-dotted curves are respectively from CDF, D0 and CMS data, and the dash-dot-dotted curve is from ATLAS data.

5. Summary

We have studied anomalous top-gluon coupling effects
in the total cross section of $t\bar{t}$ productions at Tevatron/LHC
in the framework of dimension-6 effective operators.

We first obtained an experimentally allowed region
for the chromoelectric and chromomagnetic moments from
Tevatron (CDF/D0) data on the total cross section of $p\bar{p} \to t\bar{t}X$,

then we found analyses combining the Tevatron and LHC data work
very effectively.

Indeed we have obtained a much stronger constraint on $d_{V,A}$.

You might take our results pesimistically and complain that we observed nothing new and the standard model is just great!,

but ...

You could conclude that LHC gives us new power as expected!

********** **********

Anyway ...

we focused here on the top quark itself in the final state,
and did not go into detailed analyses of its various decay processes,
since it would help to maximize the number of events necessary for our studies.

However, if we get any nonstandard signal,
we have to perform more systematic analyses including decay products,
i.e., leptons/b quarks.

Thank you!

P.S. We have not given any comments on $A_{\rm FB}$ at Tevatron, but $d_{V,A}$ terms do not produce any large FB asymmetry.

Therefore, if $A_{\rm FB}^{\rm exp} \neq A_{\rm FB}^{\rm SM}$ is confirmed at Tevatron, we have to go beyond our framework.

We would like to wait and see for the time being.