DOUBLE TOP (ANTITOP) PRODUCTION AT HADRONIC COLLIDERS

Sergej Slabospitsky
IHEP, Protvino, RUSSIA

We investigate the process of double top quarks production (see Y.Gouz and S.Slabospitsky, *hep-ph/9811330* for details)

$$\begin{aligned} p\,p \;&\rightarrow\; t\,t\,X \\ p\,p \;&\rightarrow\; \bar{t}\,\bar{t}\,X \end{aligned}$$

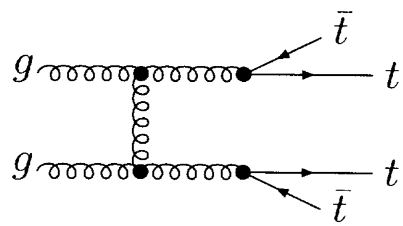
where both top quarks decay into charged lepton ($\mu^{\pm}$), neutrino and b-quark

$$t \rightarrow bW^{+} \rightarrow bl^{+}\nu$$

We also studied the contribution from related background processes.

Double top (antitop) may be produced in the following process:

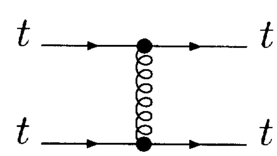
• SM QCD : $g\, g \;\rightarrow\; t\, \bar{t}\, t\, \bar{t}$



suppressed due to $\hat{\sigma} \propto \alpha_s^4$ and requirement that one $\overline{tt}$ (or tt) pair should produce in very forward (backward) direction

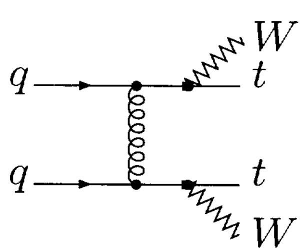
• SM QCD : $t\, t \;\rightarrow\; t\, t$, $(\bar{t}\, \bar{t} \;\rightarrow\; \bar{t}\, \bar{t})$

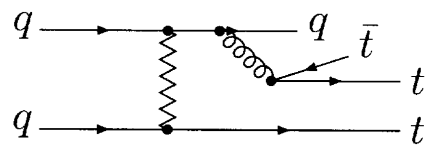
initial t-quarks are from a sea of colliding hadrons



• SM electro-weak processes

$qq \rightarrow ttWW$ $\qquad$ $qq \rightarrow\; tt\,\bar{t}q$

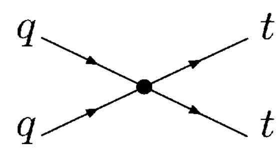




suppressed by $(\alpha_{QED})^n\, (\alpha_{QCD})^m$ + kinematics

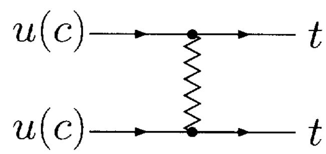
• beyond SM : four-fermion interaction

$$qq \to tt$$

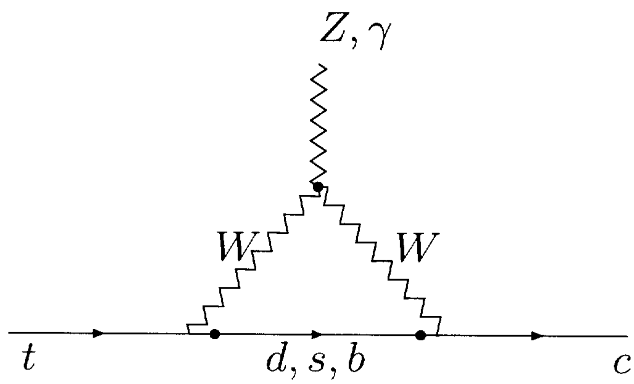


• beyond SM : Flavor Changing Neutral Current

$$qq \to tt$$



In Standard Model framework only loop contributions may generate FCNC t–quark decays



channel	Br_{sm}
$t \to g + c(u)$	$5 \cdot 10^{-11}$
$t \to \gamma + c(u)$	$5 \cdot 10^{-13}$
$t \to Z + c(u)$	$1.5 \cdot 10^{-13}$

Any experimental evidence for top-quark FCNC process would be an indication of a new physics beyond SM.

• two–Higgs–doublet model

$$\mathrm{Br}(t \to gc) \sim 10^{-6} \div 10^{-7}$$
$$\mathrm{Br}(t \to \gamma c) \sim 10^{-8}$$
$$\mathrm{Br}(t \to Zc) \sim 10^{-9}$$

• SUSY (without R–parity)

$$\mathrm{Br}(t \to gc) \sim 10^{-3}$$
$$\mathrm{Br}(t \to \gamma c) \sim 10^{-5}$$
$$\mathrm{Br}(t \to Zc) \sim 10^{-4}$$

Anomalous couplings lead to effective vertices of the FCNC transitions of $t \longrightarrow gc$, $t \longrightarrow \gamma c$, and $t \longrightarrow Zc$

$$tgc \;\Rightarrow\; g_s \frac{\kappa_g}{\Lambda} \bar{t} \sigma_{\mu\nu} [g_L (\frac{1-\gamma^5}{2}) + g_R (\frac{1+\gamma^5}{2})] t^a c \, G^{a\mu\nu}$$

$$t\gamma c \;\Rightarrow\; e \frac{\kappa_\gamma}{\Lambda} \bar{t} \sigma_{\mu\nu} [\gamma_L (\frac{1-\gamma^5}{2}) + \gamma_R (\frac{1+\gamma^5}{2})] c F^{\mu\nu}$$

$$tZc \;\Rightarrow\; \kappa_z \frac{e}{\sin 2\vartheta_W} \bar{t} \gamma_\mu [z_L (\frac{1-\gamma^5}{2}) + z_R (\frac{1+\gamma^5}{2})] c Z^\mu$$

where Λ is the new physics cutoff,

$$\Lambda = 1 \text{ TeV}$$

$$\Gamma(t \longrightarrow cg) = \Big(\frac{\kappa_g^2}{\Lambda^2}\Big) \frac{4}{3} \alpha_s m_t^3$$

$$\Gamma(t \longrightarrow c\gamma) = \Big(\frac{\kappa_\gamma^2}{\Lambda^2}\Big) \alpha m_t^3$$

$$\Gamma(t \longrightarrow cZ) = \kappa_z^2 \frac{\alpha}{8 M_Z^2 \sin^2 2\vartheta_W} m_t^3 \Big(1 - \frac{M_Z^2}{m_t^2}\Big)^2 \Big(1 + 2\frac{M_Z^2}{m_t^2}\Big)$$

• Indirect constraints (low energy)

The anomalous top interactions may generate the FCNC transitions in other quark sector (i.g. $b \to s\gamma$). From $K_L \to \mu^+\mu^-$, $K_L - K_S$ mass difference, $B^0 - \bar{B}^0$ mixing, $B \to l^+l^-X$, $b \to s\gamma$ one gets

$$|\kappa_z| < 0.29$$
$$|\kappa_\gamma| < 0.28$$

• Using CDF constraints on

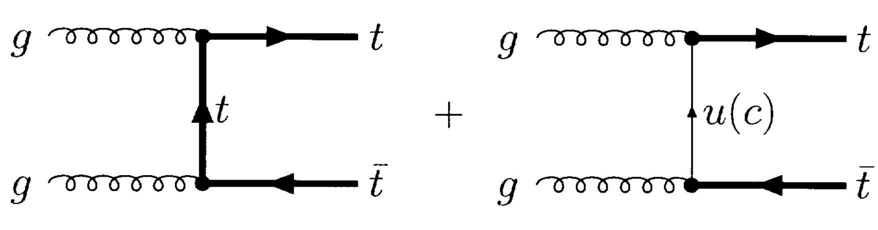
$$\mathrm{Br}(t \to c\gamma) + \mathrm{Br}(t \to u\gamma) < 3.2\% \quad (95\% \ \ \mathrm{CL})$$
$$\mathrm{Br}(t \to cZ) + \mathrm{Br}(t \to uZ) < 33\% \quad (95\% \ \ \mathrm{CL})$$

one finds

$$|\kappa_\gamma| \ < \ 0.77$$
$$|\kappa_z| \ < \ 0.74$$

• $t\bar{t}$ production via FCNC

The anomalous top interactions lead to appearance of the new diagrams having initial and final particles identical to the QCD case



require that $|\sigma_{QCD} - \sigma_{obs}| \leq \delta(\approx 2 \ \ \mathrm{pb})$ one finds

$$|\frac{\kappa_g}{\Lambda}| \leq 0.47 \ \mathrm{TeV}^{-1}$$

channel	W^+b	$(c+u)g$	$(c+u)\gamma$	$(c+u)Z$
κ/Λ		$8 \cdot 10^{-6}$	$3 \cdot 10^{-6}$	$\kappa_z \simeq 4 \cdot 10^{-7}$
Γ(GeV)	1.54	$7.7 \cdot 10^{-11}$	$7.7 \cdot 10^{-12}$	$2.2 \cdot 10^{-13}$
Br	1.	$5 \cdot 10^{-11}$	$5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$
κ/Λ		1	1	$\kappa_z = 1$
Γ(GeV)	1.54	1.4	0.084	1.4
Br	0.35	0.32	0.02(0.05)	0.32
κ/Λ		0.5	0.77	$\kappa_z = 0.74$
Γ(GeV)	1.54	0.35	0.05	0.77
Br	0.57	0.13	0.018	0.28
κ/Λ		0.5	0.28	$\kappa_z = 0.29$
Γ(GeV)	1.54	0.35	$6.6 \cdot 10^{-3}$	0.11
Br	0.77	0.17	0.003	0.056

where κ/Λ is in TeV^{-1}

Search for anomalous top couplings

- Rare decays

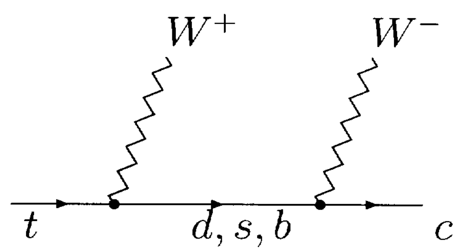
$$\sigma_{SM}(pp \to tX) \quad \times \quad \mathrm{Br}_{FCNC}(t \to ...)$$

- Direct production

$$\sigma_{FCNC}(pp \to tX) \quad \times \quad \mathrm{Br}_{SM}(t \to ...)$$

Rare decays (FCNC)

- $t \to cg$
- $t \to c\gamma$
- $t \to cZ$
- $t \to W^+W^-c$



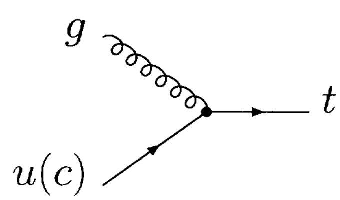
$$A \propto \Sigma_i V_{ti} V_{ci}^* = 0 \quad \text{for} \;\; m_d = m_s = m_b$$

Due to evident GIM suppression the corresponding branching ratio is very small

$$\mathrm{Br}(t \to W^+W^-c) \;\sim\; 10^{-12}$$

Top quark production via FCNC

• The largest cross-section has the process of "charm–gluon" fusion



The cross section depends on κ_g^2. For $\kappa_g/\Lambda = 1$ TeV^{-1} one gets

$$\begin{aligned} \sqrt{s} = 14 \text{ TeV} \quad \sigma(ug \to t) &\simeq 2 \cdot 10^4 \text{ pb} \\ \sigma(\bar{u}g \to t) &\simeq 5 \cdot 10^3 \text{ pb} \\ \sigma(cg \to t) &\simeq 3 \cdot 10^3 \text{ pb} \end{aligned}$$

however, the background processes ($Wjets$ and $t\bar{b}$) are very large.

• $2 \longrightarrow 2$ processes

$$\begin{aligned} gu &\longrightarrow tg(\gamma, Z) \\ q\bar{q} &\longrightarrow t\bar{c}, \quad gg \longrightarrow t\bar{c} \\ &\dots \end{aligned}$$

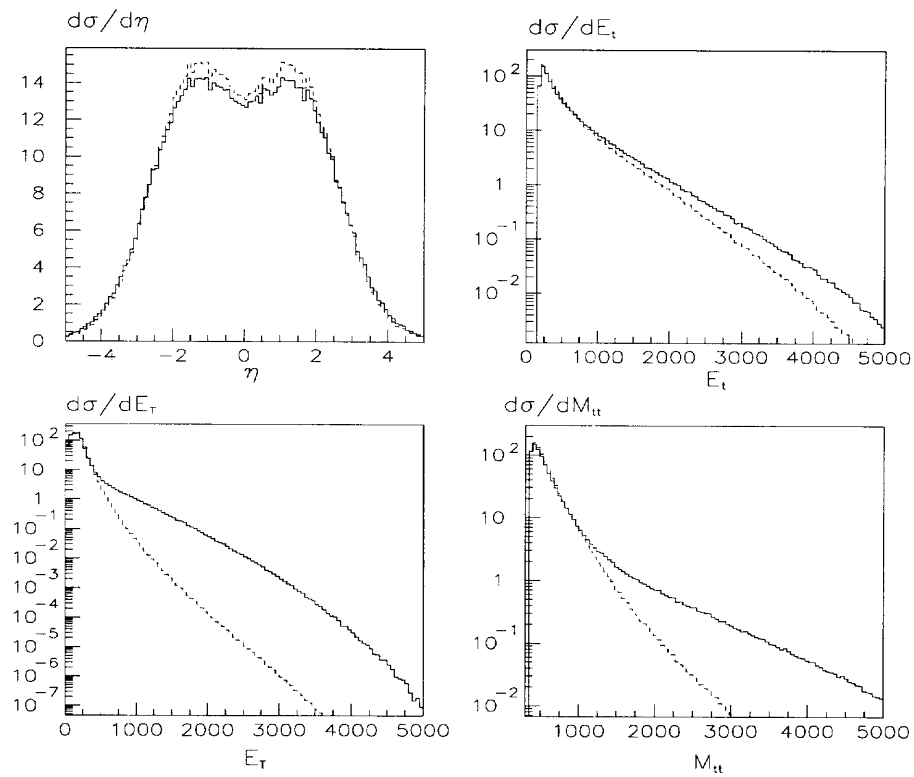
For example,

$$q\bar{q}' \to t\bar{c}, \quad \Rightarrow \sigma(14 \text{ TeV}) \simeq 20 \text{ pb}$$

These processes have large cross sections, however the background processes are also very large.

• FCNC contribution to $t\bar{t}$ production.

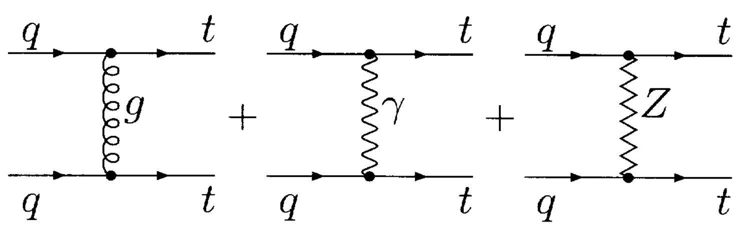
Can be seen at relatively large values of anomalous couplings ($\kappa \sim 0.1$)



Double top production

$$
\begin{aligned}
pp &\rightarrow ttX \\
pp &\rightarrow \overline{t}\overline{t}X \\
t &\rightarrow bW^+ \rightarrow bl^\pm\nu
\end{aligned}
$$

Three anomalous couplings contribute to this process

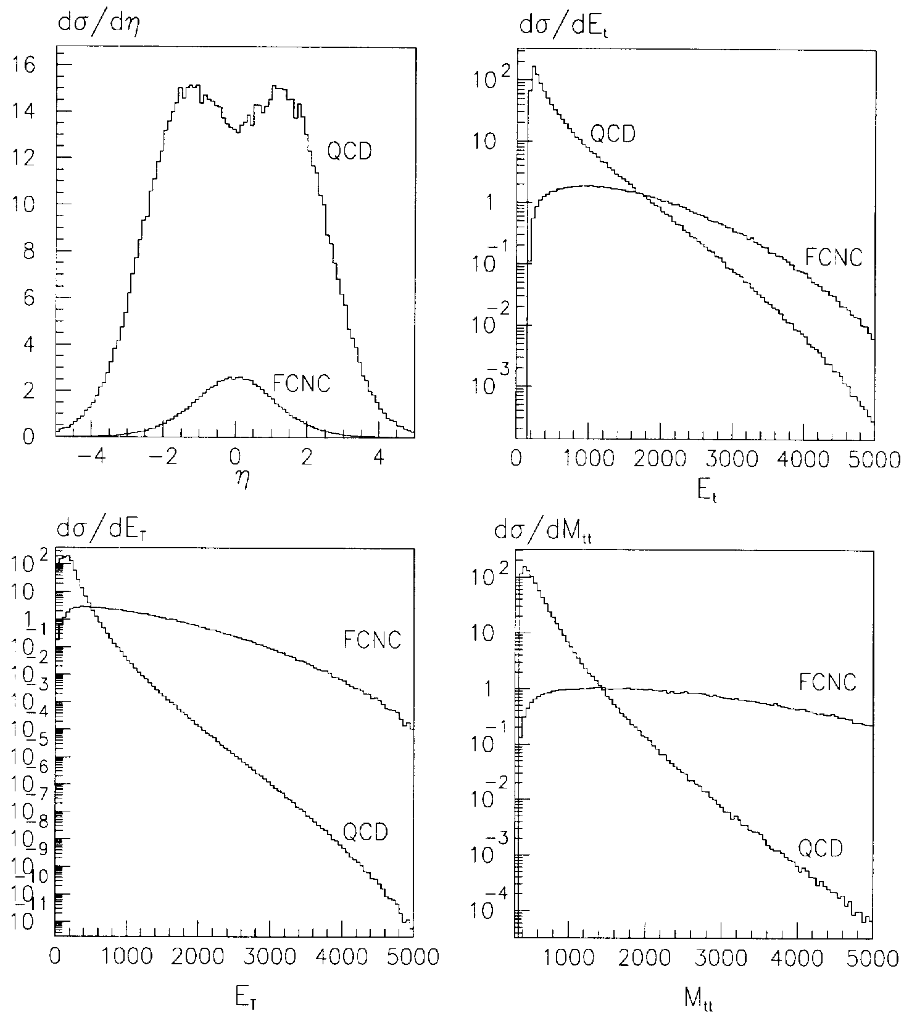


similar to $t\bar{t}$ production, however $\sigma(tt) \propto (\kappa_g)^4$
has no background from $t\bar{t}$ (for l^+l^+2jets final states) or from single-top production
For $\sqrt{s} = 14$ TeV and $\kappa_g = \kappa_\gamma = \kappa_z = 1$ one has

$$
\begin{aligned}
\sigma(tt) &\simeq 480 \text{ pb} \quad (70\%\ g,\ 5\%\ \gamma,\ 25\%\ Z) \\
\sigma(\overline{t}\overline{t}) &\simeq 16 \text{ pb}
\end{aligned}
$$

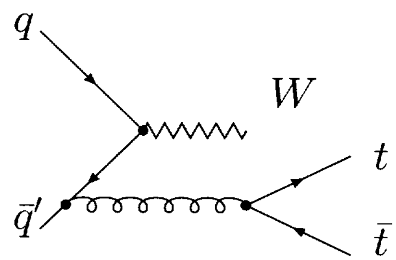
For $\mathcal{L} = 100$ fb^{-1} one may expect to achieve the upper limits

$$\frac{\kappa_g}{\Lambda} \sim 5 \cdot 10^{-2} \text{ TeV}^{-1}, \quad \text{Br}(t \rightarrow gc) \sim 2 \cdot 10^{-3}$$

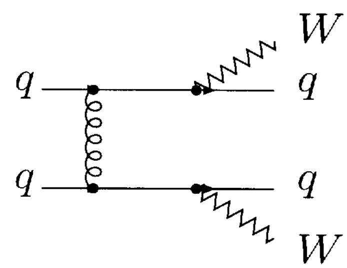

dσ/dη
QCD
FCNC
η
dσ/dE_t
QCD
FCNC
E_t
dσ/dE_T
FCNC
QCD
E_T
dσ/dM_tt
FCNC
QCD
M_tt

We study two background processes:

$$q\bar{q} \to W t\bar{t}$$



$$qq \to WWqq$$



The cross sections are equal to:

$$\begin{array}{lcl lcl} \sigma(tt) & = & 480 \text{ pb}, & \sigma(\bar{t}\bar{t}) & = & 16 \text{ pb}, \\ \sigma(W^+ t\bar{t}) & = & 0.5 \text{ pb}, & \sigma(W^- t\bar{t}) & = & 0.24 \text{ pb}, \\ \sigma(W^+ W^+ qq) & = & 0.5 \text{ pb}, & \sigma(W^- W^- qq) & = & 0.23 \text{ pb}. \end{array}$$

The contributions from $WWqq$ processes are very small (in pb):

$$\begin{array}{l} qq\mu^+\mu^+ = 6.6 \cdot 10^{-3}, \;\; cq\mu^+\mu^+ = 1.4 \cdot 10^{-4}, \;\; bq\mu^+\mu^+ = 2.1 \cdot 10^{-6}, \\ qq\mu^-\mu^- = 2.9 \cdot 10^{-3}, \;\; cq\mu^-\mu^- = 1.0 \cdot 10^{-4}, \;\; bq\mu^-\mu^- = 7.6 \cdot 10^{-7} \end{array}$$

for luminosity of $L = 10^5$ pb^{-1} one may expect before any cuts

$$\begin{array}{lclcrlclcr} WWqq & \Rightarrow & N(\mu^+\mu^+ bX) & \simeq & 19 & \text{and} & N(\mu^-\mu^- bX) & \simeq & 11 \\ Wt\bar{t} & \Rightarrow & N(\mu^+\mu^+ bX) & \simeq & 200 & \text{and} & N(\mu^-\mu^- bX) & \simeq & 100 \end{array}$$

We have included all these process in

PYTHIA 5.7 + JETSET 7.4

ATLFAST 2.0 + ATLFAST-B

We apply the following cuts:

$p_T^\mu > 15$ GeV, $|\eta| < 2.5$

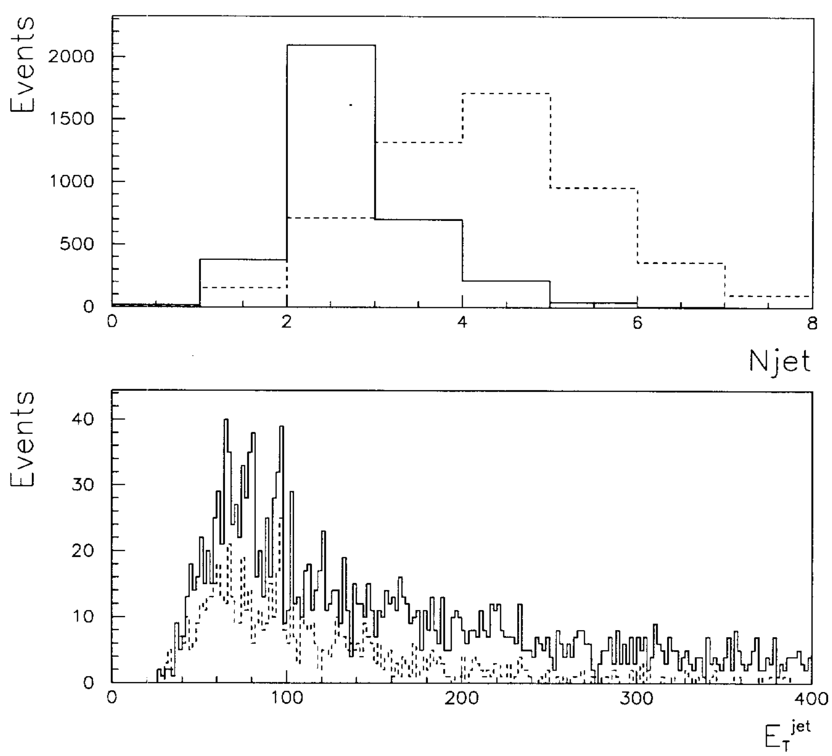
two isolated like-sign charged lepton ($\mu\mu$, μe or ee)

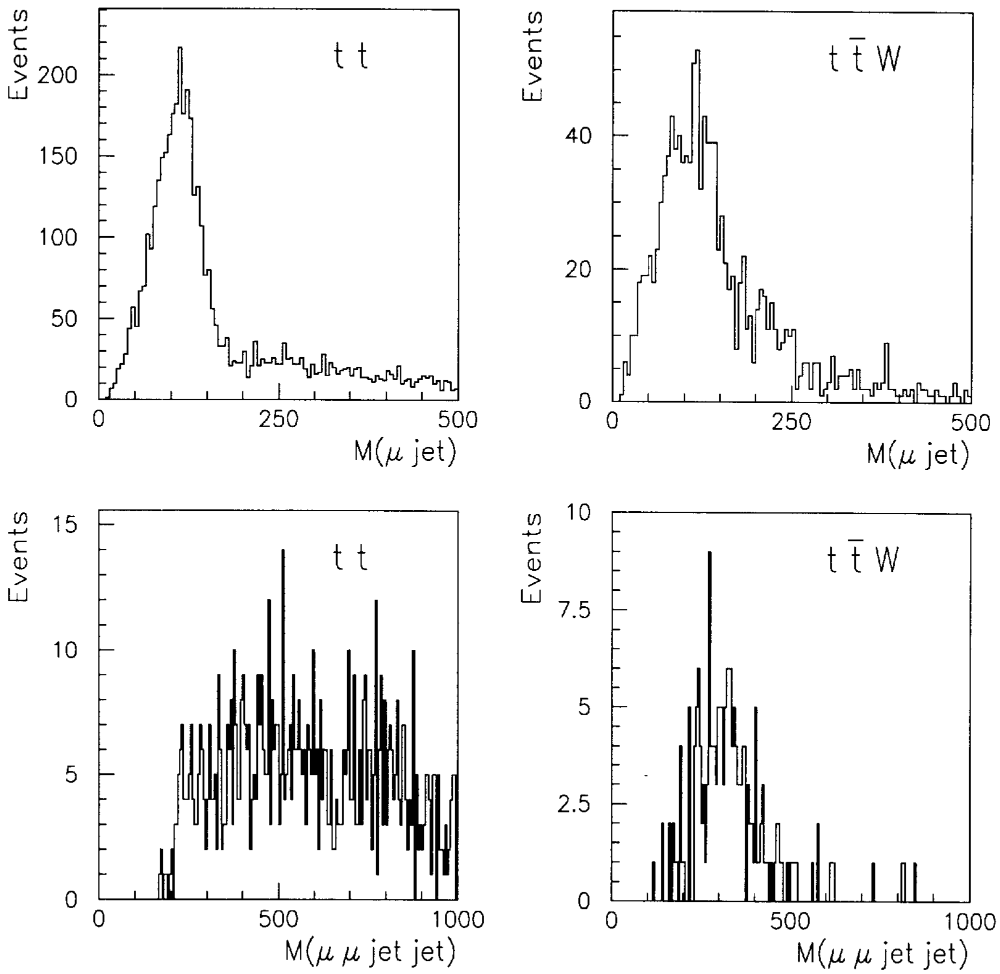
$R_{l-jet} > 0.4$

$E_T^{jet} > 20$ GeV, $|\eta_{jet}| < 5$, $|\eta_{b-jet}| < 2.5$

We use a standard b-tagging (NSET=5) with the efficiencies as follows:

$$\epsilon_b = 36\%, \quad \epsilon_c = 10\%, \quad \epsilon_{u,d,s} = 1\%.$$





We apply four additional cuts

- only two jets with $E_T^{jet} > 20$ GeV
- $E_T^{jet} > 40$ GeV and one (or two) b-jet
- both invariant masses $M(l_1 j_1)$ and $M(l_2 j_2)$ should be less than 160 GeV
- invariant mass of two charged leptons and two jets should be greater than 500 GeV

cut	$N_{events}(tt)$	$N_{events}(Wt\bar{t})$
σ (for $\kappa = 1$)	0.72 pb	0.004 pb
no cut	10000	10000
two isolated like-sign muons $p_T^\mu > 15$ GeV, no third muon	3452	5354
only two jets with $E_T^{jet} > 20$ GeV	2095	712
two jets with $E_T^{jet} > 40$ GeV and one (or two) b-jet	1221	316
$M(lj) < 160$ GeV	1177	190
$M(lljj) > 500$ GeV	853	15
N_{events} for $L = 10^5$ pb^{-1}	6100	0.6

To estimate the upper limit on the anomalous coupling we require:

$$N_{signal} \geq N_{back}$$

as a preliminary result we find

$$\frac{\kappa_g}{\Lambda} \leq 0.069 \quad \text{and} \quad \mathrm{Br}(t \to g(c+u)) \leq 4.3 \cdot 10^{-3}$$