Study of FCNC processes with top quarks

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Outline

- why we like top quark ?
- top quark production mechanisms
- top quark decays
- FCNC in top quark physics
- search for FCNC at LHC
- search for FCNC at LC
- summary & conclusion

WHY WE LIKE TOP QUARK ?

almost all top quark decays and production rates can be evaluated by means of perturbation theory

- due to the huge top mass, $m_t \approx 175$ GeV,

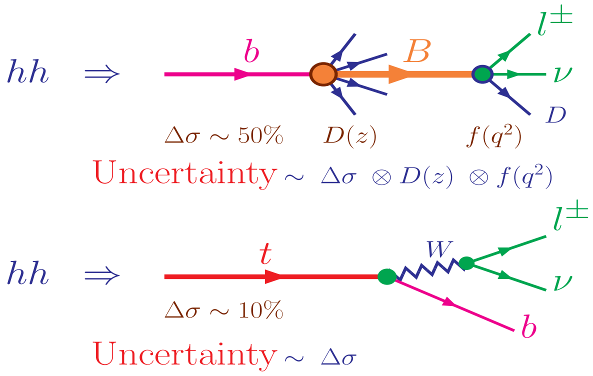
the t-quark properties are very unusual as compared to the light quarks (u, d, s, c, b)

- there are no top hadrons, $M(t\bar{q})$, $\Lambda(tqq)$, $T(t\bar{t})$

indeed, the life-time of top quark is much smaller then the typical "hadronisation time" ($q \rightarrow$ hadron)

$$\tau_{life}(t) = \frac{1}{\Gamma_{tot}(\approx 1.5\ \mathrm{GeV})} \ll \tau_h \sim \frac{1}{\Lambda_{QCD}(\approx 0.2\ \mathrm{GeV})}$$

therefore, top-quark should decay before hadronisation

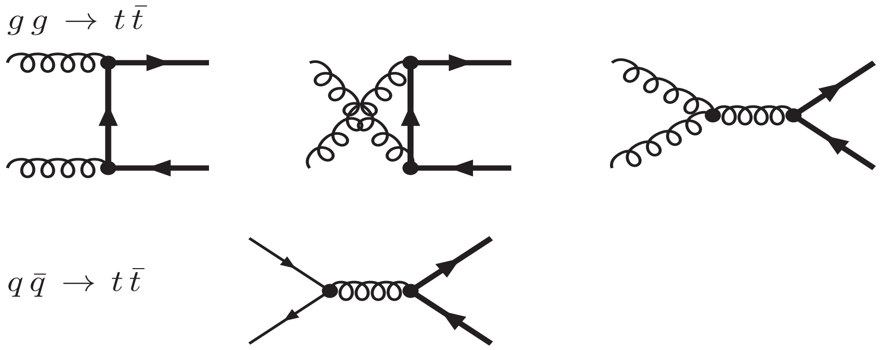


- there is only one observable decay channel, $t \rightarrow bW^+$,

all other decay channels within SM have very small probabilities

top quark is unique and powerful 'instrument' for study of SM physics as well as for search for manifestation of New Physics

$t\,\bar{t}$ PAIR PRODUCTION



$t\bar{t}$ pair productions cross section and inclusive distributions are calculated at $\mathcal{O}(\alpha_s^3)$ and resummation of enhanced leading logarithms has been also performed

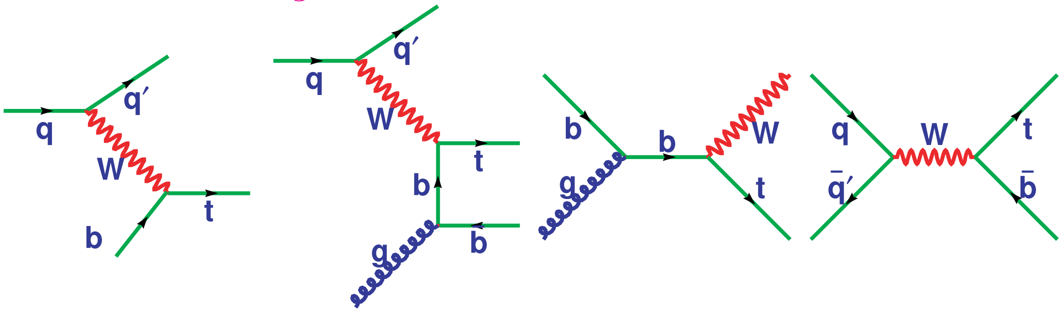
scale uncertainty ($\mu_R = m_t/2, m_t, 2m_t$) gives $\Delta\sigma_{t\bar{t}}(\mu_R) \approx 6\%$
PDF dependence of $\sigma_{t\bar{t}}$ is also studied, $\Delta\sigma(PDF) \approx 10\%$

$$\frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} = 12\%, \quad \Rightarrow \quad \sigma_{t\bar{t}}(\mathrm{LHC}) = 830 \pm 99 \ \ \mathrm{pb}$$

EW PRODUCTION OF TOP QUARK

- single top at LHC can be produced via three subprocesses

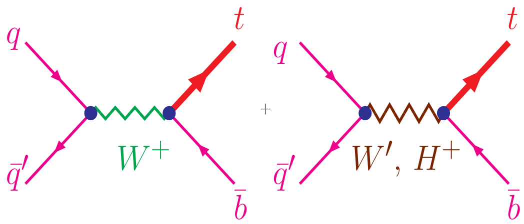
Wg fusion $\qquad\qquad Wt \qquad\qquad W^*$



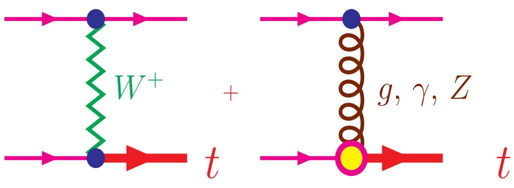
$$\sigma_{EW}(t) \propto |V_{tb}|^2$$

- $\sqrt{s} = 14$ TeV, $m_{top} = 175$ GeV
$\sigma(t\bar{t}) = 830$ pb, $\sigma(\text{single top}) \simeq 280$ pb

- new bosons (W', H^+) may increase $t\bar{b}$ (W^*) cross section

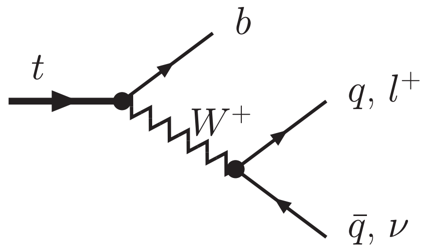


- Wg channel is sensitive to top couplings with other SM particles (FCNC, etc)



TOP QUARK DECAYS

perturbation theory can be used for description of top decays



3 generations $\Rightarrow V_{tb} \approx 1,\ |V_{ts}|, |V_{td}| \ll 1$

$$\Gamma_{tot}(m_t = 175 \text{ GeV}) \approx \Gamma(t \to bW)_{LO} \simeq 1.53 \text{ GeV}$$

within the SM the decay $t \to bW$ is by far the dominant one, while other qW decay widths are very small ($\sim |V_{tq}|^2$)

$$\begin{aligned} \mathrm{BR}(t \to s\, W) &= (1.23 \div 1.76) \times 10^{-3} \\ \mathrm{BR}(t \to d\, W) &= (0.16 \div 1.71) \times 10^{-4} \end{aligned}$$

top-quark decays into beauty hadrons are determined b-quark fragmentation

$\mathrm{BR}(\mathrm{t} \to \mathrm{B}^- \mathrm{X}) \simeq \mathrm{BR}(\mathrm{t} \to \mathrm{B}^0 \mathrm{X}) \simeq 40\%,\ \mathrm{BR}(\mathrm{t} \to \mathrm{B_s X}) \simeq \mathrm{BR}(\mathrm{t} \to \Lambda_\mathrm{b} \mathrm{X}) \simeq 10\%$

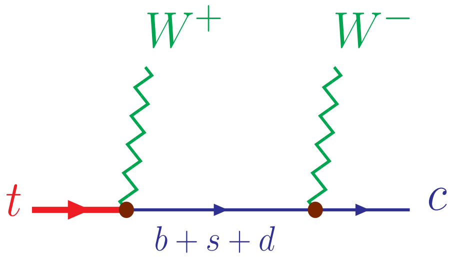
- $t \to b\,W\,H$ is almost closed ($m_H > 113$ GeV)

- $t \to b\,W\,Z$ is very sensitive to m_t, $m_t \approx m_b + m_W + m_Z$

$$\mathrm{BR}(t \to bWZ) = \begin{pmatrix} 10. \\ 5.4 \\ 3.4 \end{pmatrix} \times 10^{-7} \quad \text{for} \quad m_t = \begin{cases} 179 \\ 174 \ \ \mathrm{GeV} \\ 169 \end{cases}$$

- $t \to c\,W^+W^-$ is suppressed due to GIM mechanism

$$\sum_{j=d,s,b} V_{tj} V^*_{cj} = 0$$

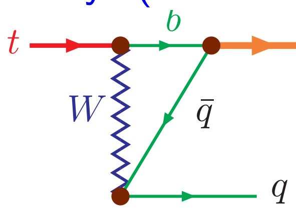


$$\mathrm{BR}(t \to cW^+W^-) \approx 10^{-13}$$

$\diamond$ new 4[th] generation may provide a significant contribution to W^+W^-q decay mode, for new b'-quark with $m_{b'} = 100\ (300)$ GeV

$$\mathrm{BR}(t \to W^+ b'(\to W^- c)) \sim 10^{-3} (10^{-7})$$

- $t \to B\, q$ "exclusive" decays (on-shell W), $B = B_d, B_s, \Upsilon, \chi_b$



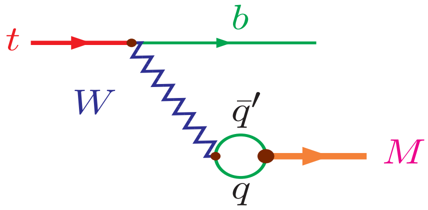
$$M \sim \frac{\Psi(0)\ V_{qq'}}{p_w^2 - M_W^2 \ + \ i\Gamma_W M_W}$$

$$\Gamma(t \to B\, q) \approx \frac{G_F^2\, m_t^3}{144\pi} f_B^2 \frac{|V_{qq'}|^2}{\left(1 - \left(1 - \frac{m_b}{m_B}\right) \frac{m_t^2}{M_w^2}\right)^2 + \frac{\Gamma_W^2}{M_W^2}}$$

is very sensitive to $f_B(\sim \Psi(0))$ and to m_b/m_B ratio

$$\mathrm{BR}(t \to \Upsilon q,\ \chi_b q) \quad \sim 10^{-9}$$
$$\mathrm{BR}(t \to B^0 q,\ B_s q) \ \sim 10^{-6}$$

- $t \to bM$ "exclusive" decays (off-shell W), $M = \pi^+, K^+, D^+$, ...



$$M \sim \frac{\Psi(0)\ V_{qq'}}{M_W^2}, \quad \Gamma(t \to b\, M) \approx \frac{G_F^2\, m_t^3}{144\pi} f_M^2 |V_{qq'}|^2$$

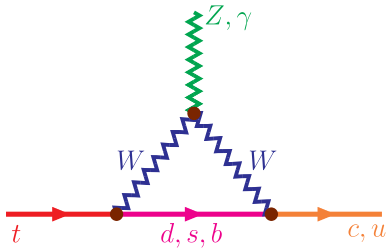
$$\mathrm{BR}(t \to b\pi) \quad \sim 10^{-8}$$
$$\mathrm{BR}(t \to bD_s) \ \sim 10^{-7}$$

FCNC IN TOP QUARK PHYSICS

◇ New Physics (beyond SM) can manifest itself by different ways

- anomalous $Wt\bar{b}$ and $gt\bar{t}$ couplings
- Flavour Changing Neutral Coupling (FCNC)
- new bosons ($H^{\pm}$, W', W_R, Z', η_T, ρ_T, ...)
- extra dimensions, ...

different interactions can affect on the same observable quantities
• in the SM only loop contributions may generate FCNC interactions of the top quark



	SM	two-Higgs	SUSY	exotic q
BR$(t \to cg)$	5×10^{-11}	10^{-6}	10^{-3}	5×10^{-4}
BR$(t \to c\gamma)$	5×10^{-13}	10^{-6}	10^{-5}	$\sim 10^{-5}$
BR$(t \to cZ)$	$\sim 10^{-13}$	10^{-9}	10^{-4}	$\sim 10^{-2}$

any experimental evidence for top quark FCNC process would be an indication of a New Physics beyond SM

effective Lagrangian for FCNC interactions

$$
\begin{aligned}
\mathcal{L}_{tgc} &= -g_s \frac{\kappa_g}{\Lambda} \bar{t} \sigma_{\mu\nu} (f_g + i h_g) t^a c \, G^{a\mu\nu} \\
\mathcal{L}_{t\gamma c} &= -e \frac{\kappa_\gamma}{\Lambda} \bar{t} \sigma_{\mu\nu} (f_\gamma + i h_\gamma) c F^{\mu\nu} \\
\mathcal{L}_{tZc} &= -\frac{e}{\sin 2\vartheta_W} \bar{t} \gamma_\mu (\alpha_z - \beta_z \gamma^5) c Z^\mu \\
&- \frac{e}{\sin 2\vartheta_W} \frac{\kappa_z}{\Lambda} \bar{t} \sigma_{\mu\nu} (f_z + i h_z) c Z^\mu
\end{aligned}
$$

Λ is the new physics cutoff, $\Lambda = 1$ TeV, $|f|^2 + |h|^2 = 1$

$$
\begin{aligned}
\Gamma(t \to cg) &= \left(\frac{\kappa_g^2}{\Lambda^2}\right) \frac{8}{3} \alpha_s m_t^3, \quad \Gamma(t \to c\gamma) = \left(\frac{\kappa_\gamma^2}{\Lambda^2}\right) 2\, \alpha m_t^3 \\
\Gamma(t \to cZ)_\gamma &= \frac{\sqrt{|\alpha_z|^2 + |\beta_z|^2}\, \alpha\, m_t^3}{4 M_Z^2 \sin^2 2\vartheta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_Z^2}{m_t^2}\right) \\
\Gamma(t \to cZ)_\sigma &= \left(\frac{\kappa_z^2}{\Lambda^2}\right) \frac{\alpha\, m_t^3}{\sin^2 2\vartheta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(2 + \frac{M_Z^2}{m_t^2}\right)
\end{aligned}
$$

$$m_t = 175 \text{ GeV}, \quad \Lambda = 1 \text{ TeV}, \; \alpha = \frac{1}{128}, \; \alpha_s = 0.1$$

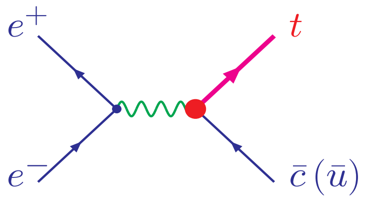
channel	W^+b	$(c+u)g$	$(c+u)\gamma$	$(c+u)Z_{(\gamma)}$	$(c+u)Z_{(\sigma)}$
$\kappa/\Lambda, \;\; \kappa_z$		5.6×10^{-6}	2.1×10^{-6}	2.8×10^{-7}	
$\Gamma(\mathrm{GeV})$	1.56	8×10^{-11}	8×10^{-12}	2.2×10^{-13}	
BR	1.	5×10^{-11}	5×10^{-13}	1.5×10^{-13}	
κ		1	1	1	1
$\Gamma(\mathrm{GeV})$	1.56	2.86	0.17	2.91	0.14
BR	0.20	0.37	0.022	0.38	0.018

- current constraints on FCNC

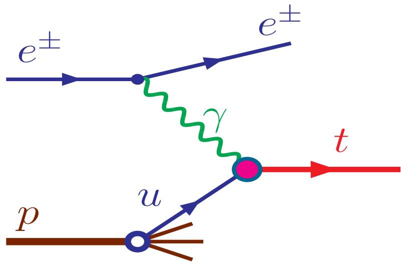
◇ Tevatron (CDF): $t\bar{t}$ pair production

$$\bar{p}p \to t\bar{t}X, \quad t(\bar{t}) \to qZ, \to q\gamma, \quad \bar{t}(t) \to bW$$

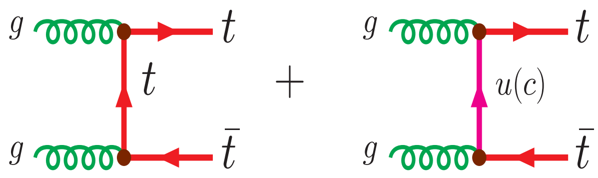
◇ LEP-2 ($\sqrt{s} \geq m_t + m_u$): single top production with $t \to bW$



◇ HERA: $e\,p$-collider, FCNC top production with $t \to bW$



◇ Tevatron (CDF + DØ): $t\bar{t}$ production via FCNC



◇ summary

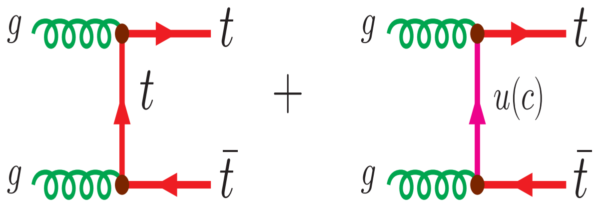
$$\begin{array}{lll} \mathrm{BR}(t \to \gamma\, q) & \leq 3.2\%\ (\mathrm{CDF}) & \leq 0.66\%\ (\mathrm{HERA}) \\ \mathrm{BR}(t \to Z\, q) & \leq 32\%\ (\mathrm{CDF}) & \leq 7\%\ (\mathrm{LEP\text{-}2}) \\ \mathrm{BR}(t \to g\, q) & \leq 29\%\ (\mathrm{Tevatron}) & \end{array}$$

top quark production via FCNC

$$\sigma_{\rm FCNC}(pp \to tX) \quad \times \quad {\rm BR}_{\rm SM}(t \to bW)$$

- ◇ deviation from SM expectations ($t\bar{t}$ production)
- ◇ single top ('direct top', tq, tg)
- ◇ tV $(tZ + t\gamma)$ production
- ◇ like top (tt or $\bar{t}\,\bar{t}$) pair production

- FCNC contribution to $t\bar{t}$ production



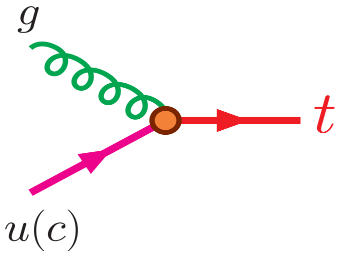
$$\sigma({\rm FCNC}) \propto \kappa^4$$

can be seen at $\kappa > 0.1$ as a deviation from SM expectations at large E_T and $M_{t\bar{t}}$

$$|\frac{\kappa_g}{\Lambda}|_{LHC} \simeq |\frac{\kappa_g}{\Lambda}|_{FNAL} \simeq 0.5$$

• single top production via FCNC

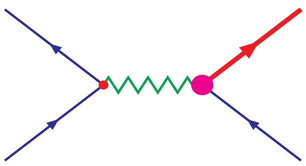
largest cross-section has the process of “charm–gluon” fusion



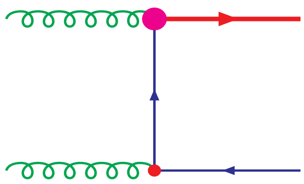
$$\frac{\kappa_g}{\Lambda} = 1\ \mathrm{TeV}^{-1} \quad \begin{array}{lcl} \sigma(ug \to t) & \simeq & 4 \times 10^4\ \mathrm{pb} \\ \sigma(\bar{u}g \to t) & \simeq & 1 \times 10^4\ \mathrm{pb} \\ \sigma(cg \to t) & \simeq & 6 \times 10^3\ \mathrm{pb} \end{array} \quad \sigma_{SM}(t\bar{t}) = 830\ \ \mathrm{pb}$$

• $2 \to 2$ processes of single top production

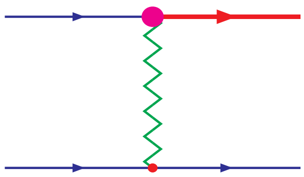
$q\bar{q} \to t\bar{c}$, $gg \to t\bar{c}$, $cq \to tq$, $qg \to tg$



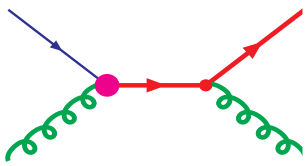
$q\bar{q} \to t\bar{c}$



$gg \to t\bar{c}$

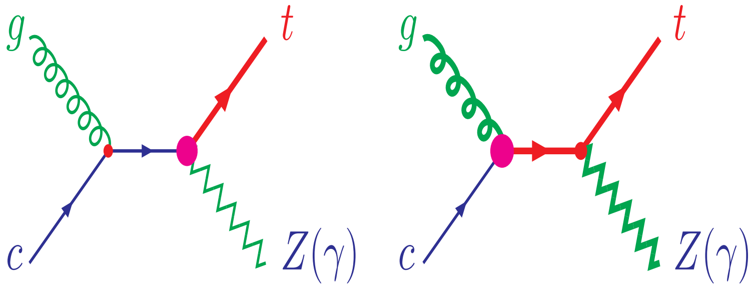


$c\bar{q} \to tq$



$cg \to tg$

- $t\,V$ **production** $\quad c\,g \to t\,Z(\gamma)$

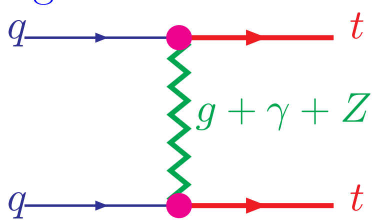


$$\begin{aligned}
\mathrm{BR}(t \to u(c)g) &\geq 1.7(7.3) \times 10^{-4}, \\
\mathrm{BR}(t \to u(c)Z)_\gamma &\geq 0.48(1.9) \times 10^{-4} \\
\mathrm{BR}(t \to u(c)\gamma) &\geq 0.18(1.5) \times 10^{-4} \\
\mathrm{BR}(t \to u(c)Z)_\sigma &\geq 0.25(1.5) \times 10^{-3}
\end{aligned}$$

- like top (tt or $\bar{t}\,\bar{t}$) pair production

$$pp \to t\,t\,X \quad p\,p \to \bar{t}\,\bar{t}\,X$$

three anomalous couplings contribute to this process



$$\mathrm{BR}(t \to gu) \approx 6.8 \times 10^{-3}$$

search for FCNC in top decays

- $t\bar{t}$ pair production

$$pp \to t\bar{t}X, \quad t(\bar{t}) \to q\gamma(qg, qZ), \; \bar{t}(t) \to bW(W \to \ell\nu)$$

$\sqrt{s} = 14$ TeV, $\int \mathcal{L}dt = 100$ fb^{-1}

- 'reachable' BR($t \to qV$) is evaluated by using the criterion

$$\frac{S}{\sqrt{S+B} + \sqrt{B}} \geq \frac{3\sigma}{2}, \quad (\mathrm{CL} = 99\%)$$

- TopRex 3.25 generator is used for event simulation
- PYTHIA 6.158 is used for hadronisation
- all events passed through CMSJET 4.703 for detector simulation

- background process ($\sqrt{s} = 14$ TeV)

◇ $t\bar{t}$ (600 pb); single top (240 pb)
◇ $W(\to e, \mu) + jets$ (~ 7500 pb for $\hat{k}_T > 20$ GeV)
◇ $WW + WZ + ZZ$ (110 pb)
◇ $W\gamma$ (17.3 pb)

- B-tagging:
  (B-tag) $\approx 60\%$, mistagging: $C \approx 10\%$ and $q, g \approx (1 \div 2)\ \%$

$$t \to q\gamma \implies t\bar{t} \to \gamma + \ell^{\pm} + \geq 2\text{jets}$$
$$t \to qg \implies t\bar{t} \to \ell^{\pm} + \geq 3\text{jets}$$
$$t \to qZ \implies t\bar{t} \to 3\ell^{\pm} + \geq 2\text{jets}$$

typical cuts on isolated photons, isolated leptons and jets

photons: $E_{\rm T} \geq 50$ GeV, $|\eta_\gamma| \leq 2.5$
leptons: $P_{\rm T} \geq 20$ GeV, $|\eta_L| \leq 2.5$
jets: $E_{\rm T} \geq 30$ GeV, $|\eta_j| \leq 4.5$

$|M(j_1 j_2) - M_W| \leq 20$ GeV $|M(ee,\mu\mu) - M_Z| \leq 20$ GeV
$|M(j\,W) - m_t| \leq 25$ GeV $|m_t - M(j\,\gamma)| \leq 15$ GeV
$|m_t - M(j_1 j_2, JZ)| \leq 25$ GeV

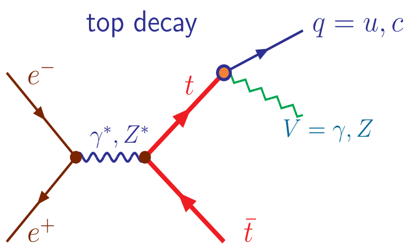
• to compare with top quark production processes we assume that only one flavour ('up' or 'charm') contributes to FCN interaction

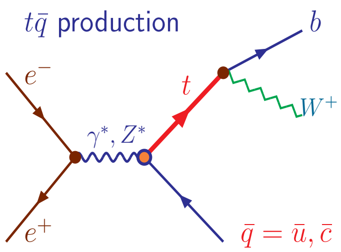
	decay	production
$t \to ug$	1.6×10^{-3}	$(0.3 \div 5.) \times 10^{-5}$
$t \to cg$	1.6×10^{-3}	$(2.1 \div 22.) \times 10^{-5}$
$t \to u\gamma$	2.5×10^{-5}	0.4×10^{-5}
$t \to c\gamma$	2.5×10^{-5}	3.5×10^{-5}
$t \to uZ$	1.6×10^{-4}	1.1×10^{-4}
$t \to cZ$	1.6×10^{-4}	4.8×10^{-4}

FCNC at Linear Collider

$\sqrt{S_{e^+e^-}} > 2m_t \quad \sqrt{S} = 500$ and 800 GeV
$\mathcal{L}_{int} = 300$ and 500 fb^{-1}

two ways are considered:
SM production $e^+e^- \to t\bar{t}$ with FCNC decays $t \to q\gamma\,(Z)$
FCNC production $e^+e^- \to tu(\bar{c})$ with SM decay $t \to bW^+$





• detector response is simulated by smearing of momenta of leptons, photons and jets(quarks and gluons),
then the simple kinematic cuts are applied

- top decays ($t \to qV$) versus top production ($t\bar{q}$)

top decay signal is cleaner than ($t\bar{q}$) production, on the other hand, the cross sections for $t\bar{q}$-processes is large than for $t\bar{t}$-production

◇ however, top decays (from $t\bar{t}$) could help to determine the nature of the couplings involved ($t\gamma q$ or tZq)

- beam polarisation

is very useful to improve the limits from $t\bar{q}$ production due to a substantial background decrease

- $\sqrt{S_{e^+e^-}}$ variation

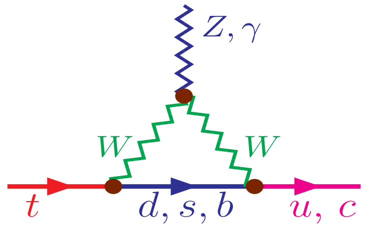
could help to improve the limits resulted from ($t\bar{q}$) production via $\sigma^{\mu\nu}$ couplings

however, the increase of $\sqrt{S}$ leads to worse results for γ^{μ}-couplings and top decays

	limits on BR($t \to qV$) $\times 10^5$					
	no Pol.		Pol. e^-		Pol. e^+e^-	
$\sqrt{S}$, GeV	500.	800.	500.	800.	500.	800.
$\mathcal{L}_{tot}$, 1/fb	300.	500.	300.	500.	300.	500.
qZ, "γ^{μ}" production	61.	59.	39.	43.	22.	23.
decay	120.	150.	170.	110.	140.	84.
qZ, "$\sigma^{\mu\nu}$" production	4.8	1.7	3.1	1.3	1.7	0.7
decay	120.	160.	180.	120.	140.	91.
$q\gamma$ production	3.0	1.0	1.7	0.7	0.9	0.36
decay	13.	15.	16.	18.	8.3	9.4

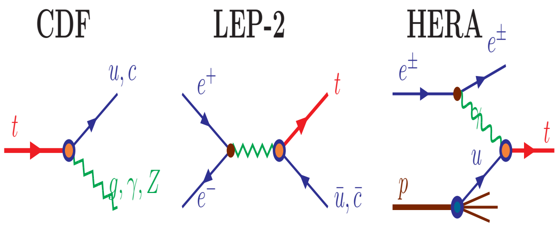
Summary for FCNC in top sector

◇ theoretical predictions for $\mathrm{BR_{FCNC}}(t \to qV)$, V = gluon, γ, Z



$t \to$	SM	two-Higgs	SUSY
$g\,q$	5×10^{-11}	10^{-6}	10^{-3}
$\gamma\,q$	5×10^{-13}	10^{-6}	10^{-5}
$Z\,q$	$\sim 10^{-13}$	10^{-9}	10^{-4}

◇ present experimental limits on BR



$t \to$	CDF	LEP-2	HERA
$g\,q$	$\le 29\%$		
$\gamma\,q$	$\le 3.2\%$		$\le 0.7\%$
$Z\,q$	$\le 32\%$	$\le 7.0\%$	

◇ future: Run II + LHC(CMS) + LC expectations

	Tevatron	LHC (100 fb^{-1})		LC
$t \to$	Run II	decay	production	
$g\,q$	0.06%	1.6×10^{-3}	1×10^{-5}	–
$\gamma\,q$	0.28%	2.5×10^{-5}	3×10^{-6}	4×10^{-6}
$Z\,q$	1.3%	1.6×10^{-4}	1×10^{-4}	2×10^{-4}

CONCLUSION

- perturbation theory can be used for calculation of top quark production and decays with a quite well accuracy
- SM probability of top quark decay into any channel (except $t \to bW$) is very small for detection in the experiment
- any experimental evidence for top quark FCNC process would be an indication of a New Physics beyond SM
- LHC sensitivity to top anomalous couplings are comparable with predictions of several extensions of the SM
- LHC and LC ($sqrtS \geq 500$ GeV) could achieve the comparable limits on FCN couplings

- **study for rare processes of top quark production and decays is a nice place for search of New Physics**