

# Probing Anomalous Top-Gluon Couplings at Colliders

LCWS10  
26th-30th March, 2010  
Beijing

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$$\text{SM} \quad : \quad g_s \bar{t} \gamma^\mu T_a t G_\mu^a$$

Higher Dimensional Operators:

$$g_s \frac{1}{\Lambda} \bar{t} \sigma_{\mu\nu} T_a t F_a^{\mu\nu}$$

← dimension-5

$$i g_s \frac{1}{\Lambda} \bar{t} \sigma_{\mu\nu} \gamma_5 T_a t F_a^{\mu\nu}$$

$$i g_s \frac{1}{\Lambda^2} \bar{t} T_a \gamma_\mu D_\nu t F_a^{\mu\nu}$$

← dimension-6

$$g_s \frac{1}{\Lambda^2} \bar{t}_L \sigma_{\mu\nu} T_a t_R \phi^C F_a^{\mu\nu}$$

Buchmuller and Wyler (1986)

Aguilar-Saavedra (2009)

$$\text{SM} : g_s \bar{t} \gamma^\mu T_a t G_\mu^a$$

$$g_s \frac{1}{\Lambda} \bar{t} \sigma_{\mu\nu} T_a t F_a^{\mu\nu}$$



Chromomagnetic Dipole Moment

$$ig_s \frac{1}{\Lambda} \bar{t} \sigma_{\mu\nu} \gamma_5 T_a t F_a^{\mu\nu}$$



Chromoelectric Dipole Moment

$$\mathcal{L}_{int} \ni \frac{g_s}{\Lambda} \bar{t} \sigma_{\mu\nu} (\rho + i\rho' \gamma_5) T_a t F_a^{\mu\nu}$$

# Testing Grounds

$$p\bar{p} \longrightarrow t\bar{t}$$

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

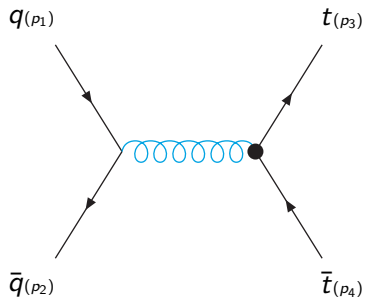
$$pp \longrightarrow t\bar{t}$$

LHC ( $\sqrt{s} = 7, 10, 14$  TeV)

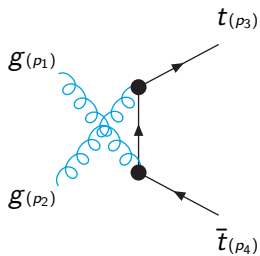
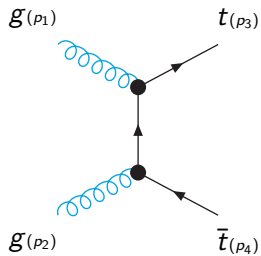
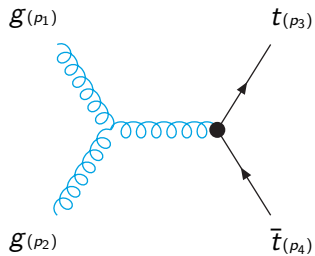
$$e^+e^- \longrightarrow t\bar{t}g$$

ILC ( $\sqrt{s} = 500$  GeV, 1 TeV)

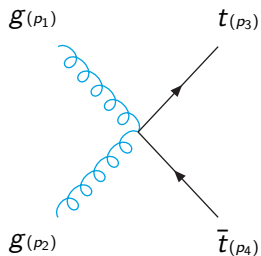
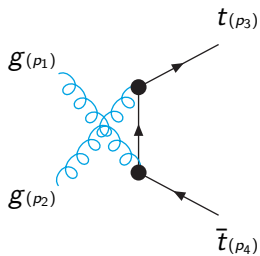
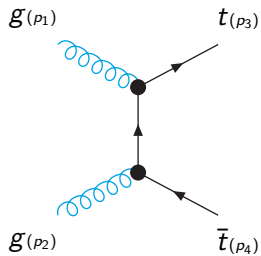
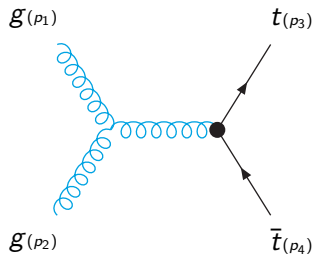
$$q\bar{q} \longrightarrow t\bar{t}$$



$$gg \longrightarrow t\bar{t}$$



$gg \longrightarrow t\bar{t}$



$$\sigma_{total} = \sigma_{q\bar{q}} + \sigma_{gg}$$



PDF : CTEQ6L1

$$Q = m_{top}$$

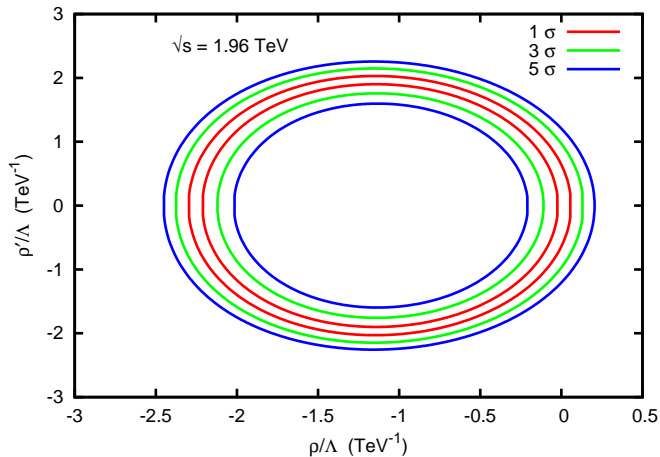
NLO K-Factor : Cacciari et. al. (2008)



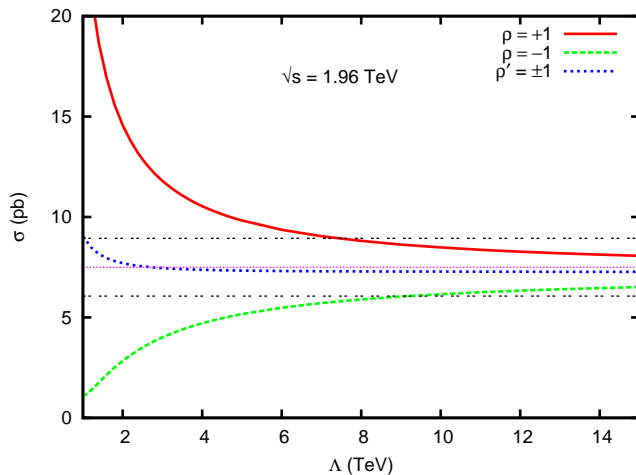
# Tevatron Limits : Allowed Parameter Range

$$\sigma_{t\bar{t}} (m_t = 172.5 \text{ GeV}) = 7.50 \pm 0.48 \text{ pb}$$

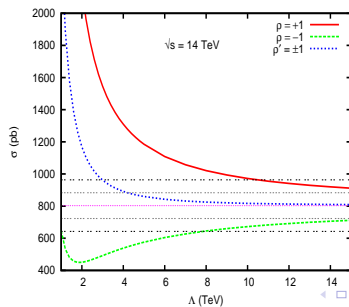
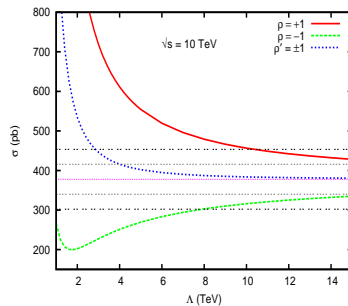
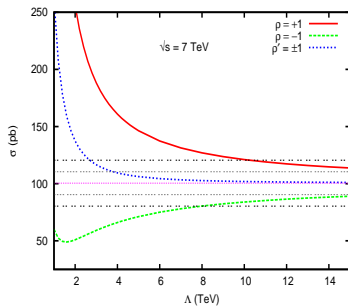
CDF 2009 ( $4.6 \text{ fb}^{-1}$ )



# Tevatron Limits : Total Cross-Section

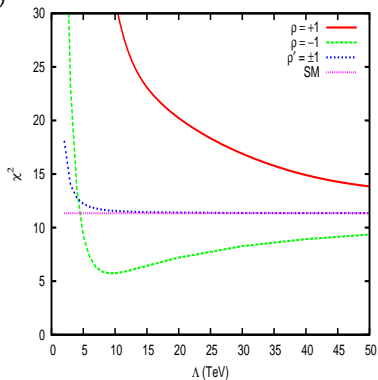
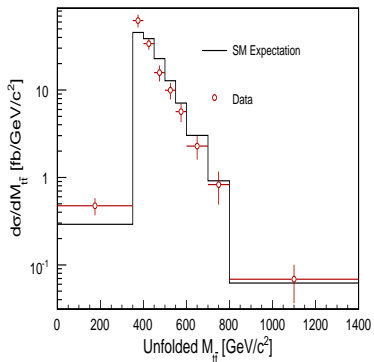


# LHC Projections : Total Cross-Sections

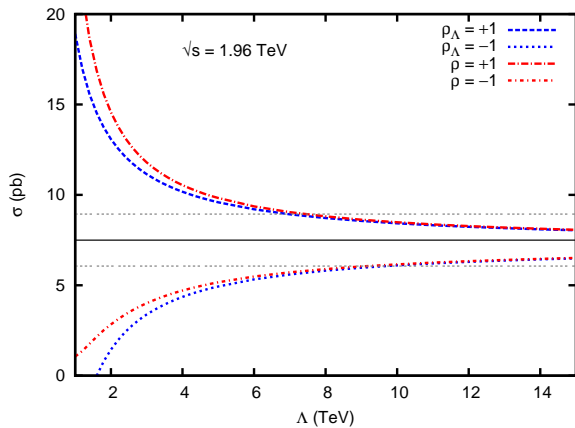


# Tevatron Limits : Invariant Mass Distribution

CDF 2009 ( $m_{top} = 175 \text{ GeV}$ ,  $2.7 \text{ fb}^{-1}$ )



$\mathcal{O}(1/\Lambda)$



# Summary of Limits from Hadron Colliders

Rephrasing the results in terms of commonly used notation :

$$\frac{1}{\Lambda}(\rho + i\rho') \longleftrightarrow \frac{1}{2m_t}(\kappa + i\tilde{\kappa})$$

$$\rho = +1 : \Lambda \geq 10 \text{ TeV}$$

$$\Rightarrow -0.038 \leq \kappa \leq 0.034$$

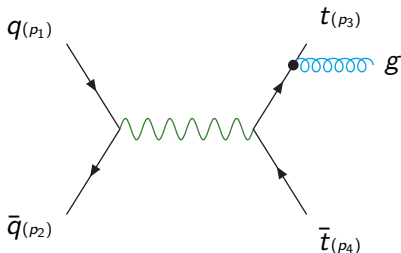
$$\rho = -1 : \Lambda \geq 9 \text{ TeV}$$

$$\rho' = \pm 1 : \Lambda \geq 3 \text{ TeV}$$

$$\Rightarrow |\tilde{\kappa}| \leq 0.12$$

# Linear Collider Prospects

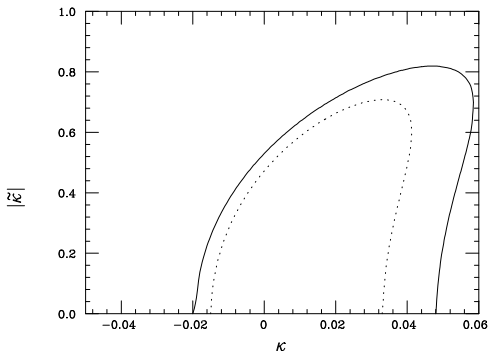
$$e^+ e^- \longrightarrow t \bar{t} g$$



T.G. Rizzo, Phys. Rev. D **50**, 4478 (1994); arXiv:hep-ph/9605361

Limits obtained by fitting the energy spectrum of the gluon assuming no excess in the total cross-section.

$\sqrt{s} = 500 \text{ GeV}$  ;  $\mathcal{L} = 50 \text{ fb}^{-1}$  (solid),  $100 \text{ fb}^{-1}$  (dotted) ;  $E_g^{min} = 25 \text{ GeV}$



95% CL allowed region

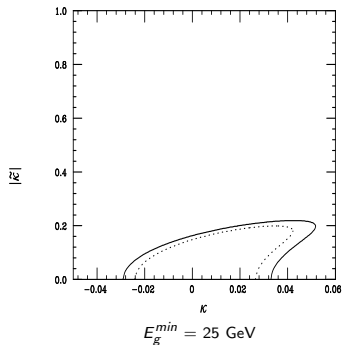
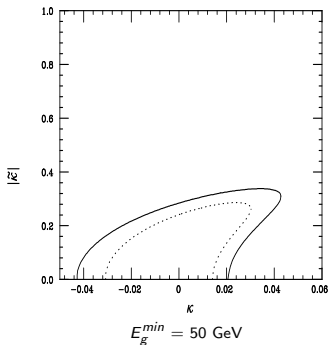
Considering only one of  $\kappa$  and  $\tilde{\kappa}$  to be non-zero at a time, from the dotted curve we have :

$$-0.015 \leq \kappa \leq 0.033$$

$$|\tilde{\kappa}| \leq 0.47$$



$\sqrt{s} = 1 \text{ TeV}$  ;  $\mathcal{L} = 100 \text{ fb}^{-1}$  (solid),  $200 \text{ fb}^{-1}$  (dotted)



95% CL allowed region

Considering only one of  $\kappa$  and  $\tilde{\kappa}$  to be non-zero at a time, from the dotted curve on the right panel we have :

$$-0.024 \leq \kappa \leq 0.026$$

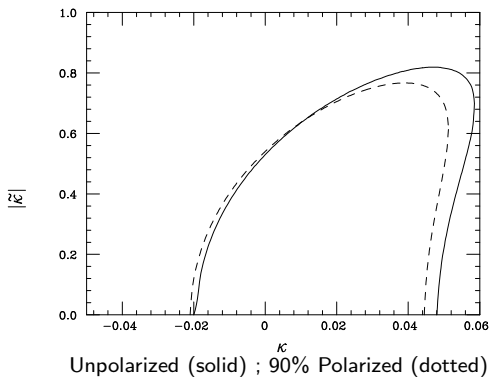
$$|\tilde{\kappa}| \leq 0.14$$

Better sensitivity to  $\kappa$  but not to  $\tilde{\kappa}$

# Using Polarized $e^-$ Beam

Rizzo (1996)

$$\sqrt{s} = 500 \text{ GeV} ; \mathcal{L} = 50 \text{ fb}^{-1} ; E_g^{\text{min}} = 25 \text{ GeV}$$



$$A(z) = \frac{N_L(z) - N_R(z)}{N_L(z) + N_R(z)}$$

# Summary

- ▶ Strong limits from hadron colliders.
- ▶ Limits on chromomagnetic moment can, in principle, be improved at the ILC even without polarized beams.

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<http://cdsweb.cern.ch/collection/CMS%20PHYSICS%20ANALYSIS%20SUMMARIES>

THE END

# EXTRA SLIDES

$$\begin{aligned}
\left(\frac{2\hat{s}}{\pi\alpha_s^2\beta}\right) \frac{d\hat{\sigma}_{q\bar{q}}}{d\cos\theta} &= \frac{2}{9}\Theta_+ + \frac{8}{9}\frac{m_t^2}{\hat{s}} \\
&+ \frac{32\rho m_t}{9\Lambda} + \frac{8\rho^2}{9\Lambda^2}(\hat{s}\Theta_- + 4m_t^2) + \frac{8\rho'^2}{9\Lambda^2}(\hat{s}\Theta_- - 4m_t^2) \\
\left(\frac{2\hat{s}}{\pi\alpha_s^2\beta}\right) \frac{d\hat{\sigma}_{gg}}{d\cos\theta} &= \frac{2}{3\Theta_-} \left(1 + \frac{4m_t^2}{\hat{s}} + \frac{m_t^4}{\hat{s}^2}\right) - \left(\frac{1}{3} + \frac{3}{16}\Theta_+ + \frac{3m_t^2}{2\hat{s}} + \frac{16m_t^4}{3\hat{s}^2} \frac{\Theta_+}{\Theta_-^2}\right) \\
&+ \frac{\rho m_t}{\Lambda} \left(-3 + \frac{16}{3\Theta_-}\right) + \frac{\rho^2}{\Lambda^2} \left[\frac{7}{3}\hat{s} + m_t^2 \left\{-6 + \frac{34}{3\Theta_-}\right\}\right] \\
&+ \frac{\rho'^2}{\Lambda^2} \left[\frac{7}{3}\hat{s} + \frac{2m_t^2}{3\Theta_-}\right] \\
&+ \frac{\rho}{\Lambda} \left(\frac{\rho^2}{\Lambda^2} + \frac{\rho'^2}{\Lambda^2}\right) m_t \left(\frac{28}{3}\hat{s} - \frac{20}{3\Theta_-}m_t^2\right) \\
&+ \frac{4}{3} \left(\frac{\rho^2}{\Lambda^2} + \frac{\rho'^2}{\Lambda^2}\right)^2 \left(\hat{s}^2\Theta_- - m_t^2\hat{s} + \frac{4}{\Theta_-}m_t^4\right)
\end{aligned}$$





# Combination of CDF top quark pair production cross section measurements with up to $4.6 \text{ fb}^{-1}$ :

CDF Public Note 9913

$$\sigma_{t\bar{t}} (m_t = 172.5 \text{ GeV}) = 7.50 \pm 0.48 \text{ pb}$$

CDF II Detector

Integrated Luminosity :  $4.6 \text{ fb}^{-1}$

Combination of :

- ▶ lepton+jets channel artificial neural network with a weight of 70%
- ▶ lepton+jets channel secondary vertex b-tagging with 18%
- ▶ dilepton channel with 18%
- ▶ all-hadronic channel with -6%

With :

- ▶ statistical uncertainty 0.31 pb
- ▶ experimental systematic uncertainty 0.33 pb
- ▶ Z boson theoretical cross section uncertainty 0.13 pb
- ▶ luminosity uncertainty 0.06 pb

# Theoretical Predictions : Tevatron

## Using CTEQ6.5

$$\sigma_{t\bar{t}}^{\text{NLO+NLL}}(\text{Tev}, m_t = 171 \text{ GeV}, \text{CTEQ6.5}) = 7.61 \begin{matrix} +0.30(3.9\%) \\ -0.53(6.9\%) \end{matrix} (\text{scales}) \begin{matrix} +0.53(7\%) \\ -0.36(4.8\%) \end{matrix} (\text{PDFs}) \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{NLO}}(\text{Tev}, m_t = 171 \text{ GeV}, \text{CTEQ6.5}) = 7.35 \begin{matrix} +0.38(5.1\%) \\ -0.80(10.9\%) \end{matrix} (\text{scales}) \begin{matrix} +0.49(6.6\%) \\ -0.34(4.6\%) \end{matrix} (\text{PDFs}) \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{LO}}(\text{Tev}, m_t = 171 \text{ GeV}, \text{CTEQ6.5}) = 5.92 \begin{matrix} +2.34(39.5\%) \\ -1.54(26.1\%) \end{matrix} (\text{scales}) \begin{matrix} +0.32(5.5\%) \\ -0.24(4.1\%) \end{matrix} (\text{PDFs}) \text{ pb}$$

## Using MRST2006nnlo

$$\sigma_{t\bar{t}}^{\text{NLO+NLL}}(\text{Tev}, m_t = 171 \text{ GeV}, \text{MRST2006nnlo}) = 7.93 \begin{matrix} +0.34(4.3\%) \\ -0.56(7.1\%) \end{matrix} (\text{scales}) \begin{matrix} +0.24(3.1\%) \\ -0.20(2.5\%) \end{matrix} (\text{PDFs}) \text{ pb}.$$

$$\sigma_{t\bar{t}}^{\text{NLO}}(\text{Tev}, m_t = 171 \text{ GeV}, \text{MRST2006nnlo}) = 7.62 \begin{matrix} +0.45(5.9\%) \\ -0.88(11.6\%) \end{matrix} (\text{scales}) \begin{matrix} +0.23(3\%) \\ -0.18(2.4\%) \end{matrix} (\text{PDFs}) \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{LO}}(\text{Tev}, m_t = 171 \text{ GeV}, \text{MRST2006nnlo}) = 6.05 \begin{matrix} +2.47(40.8\%) \\ -1.61(26.6\%) \end{matrix} (\text{scales}) \begin{matrix} +0.16(2.6\%) \\ -0.13(2.1\%) \end{matrix} (\text{PDFs}) \text{ pb}.$$

# Theoretical Prediction : LHC

## Using CTEQ6.5

$$\sigma_{t\bar{t}}^{\text{NLO+NLL}}(\text{LHC}, m_t = 171 \text{ GeV}, \text{CTEQ6.5}) = 908 \begin{matrix} +82(9.0\%) \\ -85(9.3\%) \end{matrix} (\text{scales}) \begin{matrix} +30(3.3\%) \\ -29(3.2\%) \end{matrix} (\text{PDFs}) \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{NLO}}(\text{LHC}, m_t = 171 \text{ GeV}, \text{CTEQ6.5}) = 875 \begin{matrix} +102(11.6\%) \\ -100(11.5\%) \end{matrix} (\text{scales}) \begin{matrix} +30(3.4\%) \\ -29(3.3\%) \end{matrix} (\text{PDFs}) \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{LO}}(\text{LHC}, m_t = 171 \text{ GeV}, \text{CTEQ6.5}) = 583 \begin{matrix} +165(28.2\%) \\ -120(20.7\%) \end{matrix} (\text{scales}) \begin{matrix} +20(3.4\%) \\ -19(3.3\%) \end{matrix} (\text{PDFs}) \text{ pb}$$

## Using MRST2006nnlo

$$\sigma_{t\bar{t}}^{\text{NLO+NLL}}(\text{LHC}, m_t = 171 \text{ GeV}, \text{MRST2006nnlo}) = 961 \begin{matrix} +89(9.2\%) \\ -91(9.4\%) \end{matrix} (\text{scales}) \begin{matrix} +11(1.1\%) \\ -12(1.2\%) \end{matrix} (\text{PDFs}) \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{NLO}}(\text{LHC}, m_t = 171 \text{ GeV}, \text{MRST2006nnlo}) = 927 \begin{matrix} +109(11.7\%) \\ -107(11.5\%) \end{matrix} (\text{scales}) \begin{matrix} +11(1.2\%) \\ -12(1.3\%) \end{matrix} (\text{PDFs}) \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{LO}}(\text{LHC}, m_t = 171 \text{ GeV}, \text{MRST2006nnlo}) = 616 \begin{matrix} +172(27.9\%) \\ -126(20.5\%) \end{matrix} (\text{scales}) \begin{matrix} +7.3(1.2\%) \\ -7.8(1.3\%) \end{matrix} (\text{PDFs}) \text{ pb}$$

# K-Factors

Tevatron (1.96 TeV) : 1.13

LHC (14 TeV) : 1.42

LHC (10 TeV) : 1.48

LHC (7 TeV) : 1.0 (not available)

# Chi-Square Calculation

$$\chi^2 = \frac{\sigma^{MC} - \sigma^{CDF}}{\Delta\sigma^{CDF}}$$