Single Top Quarks at the LHC and LC

Edward Boos
Theory Division of the Institute of Nuclear Physics
of Moscow State University,
and DESY

Outline

- Introduction
- Single Top processes at the LHC
- Single Top processes at Linear Colliders
- Spin Correlations in Single Top
- Probing Anomalous Wtb Couplings via Single Top
- Concluding Remarks

Top quark has been found by the Fermilab CDF and D0 collaborations. RUN1 results:

- $M_t = 174.3 \pm 3.2(stat) \pm 4.0(syst)$
- $\sigma_{t\bar{t}}(CDF\ M_t = 175GeV) = 6.5^{+1.7}_{-1.4}pb$
  $\sigma_{t\bar{t}}(D0\ M_t = 172GeV) = 5.9 \pm 1.7pb$
- $\lambda_t(M_t) = 1.00 \pm 0.03$
- $|V_{tb}| > 0.78$ (90% CL)
- The 95% Confidence Level Limit on single top production cross section :

  13.5 pb by CDF

  39 pb (17 pb Neural Network) (s-channel) and 58 pb (22 pb Neural Network) (W-gluon fusion) by D0

  Extracted cross section of single top production by the likelihood fit (CDF):
  $\sigma = 5.2^{+4.9}_{-3.4}$ pb
  SM prediction: $\sigma_{SM} = 2.43 \pm 0.32$ pb

Top quark is the heaviest found so far elementary particle with the mass slightly less than the mass of the gold nucleus.

- Top decays much faster than a typical time-scale for a formation of the strong bound states. So, top provides, in principle, a very clean source for a fundamental information.
- Top is so heavy and point like (up to now) at the same time. So, one might expect a possible deviations from the SM predictions more likely in the top sector.
- Top Yukawa coupling $\lambda_t = 2^{3/4} G_F^{1/2} m_t$ is very close to unit. Studies of top may shed a light on an origin of the mechanism of the EW symmetry breaking.

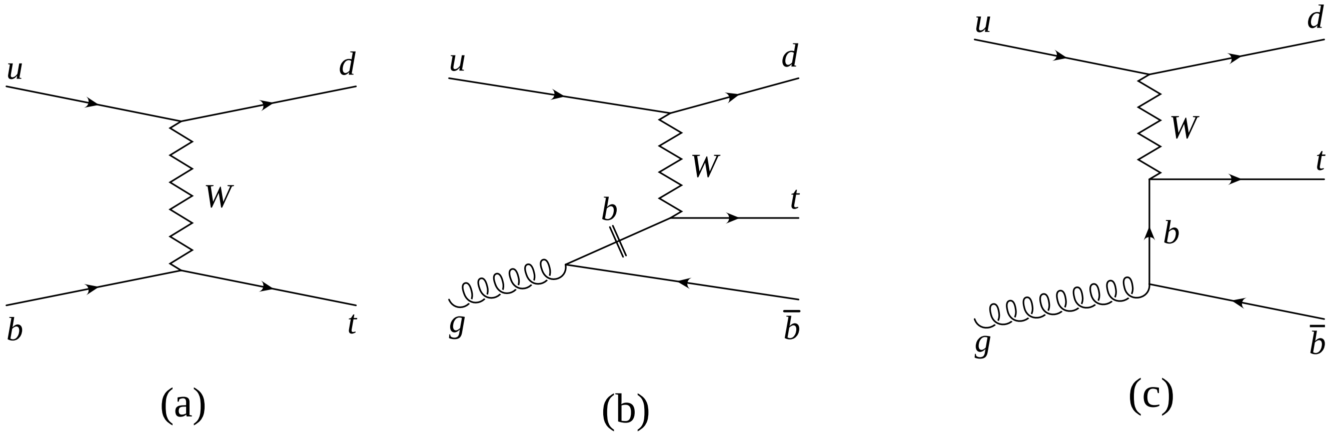
Top quark physics will be a very important part of research programs for all future hadron and lepton colliders. Processes with Single Top Quark production play a special role.

The main goals to search for single top:

- Independent channel of the top quark production
- Direct $|V_{tb}|$ CKM matrix element measurement
- Single Top is a significant background for the Higgs search and many other "new physics" processes
- Top polarisation and spin correlations
- Measurement of the top quark partial width
- "New physics"
  - W_{tb} anomalous couplings
  - FCNC
  - New strong dynamics
  - R-parity violating SUSY effects
  - CP-violation effects
  - effect of Kaluza-Klein excited W-boson and W'

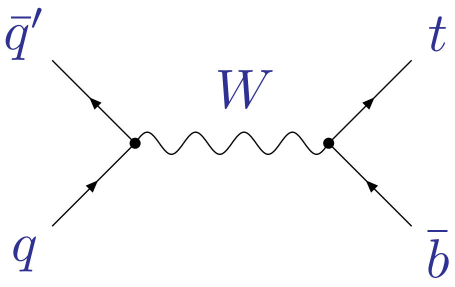
Representative Feynman diagrams for single top quark production at hadron colliders.

Production via Wg fusion:



t-channel $\sigma_{\rm NLO} \;=\; 245\; pb \;\pm\; 27$ (LHC) [a]

Diagram for s-channel single top production:



s-channel $\sigma_{\rm NLO} \;=\; 10.2\; pb \;\pm\; 0.7$ (LHC) [b]

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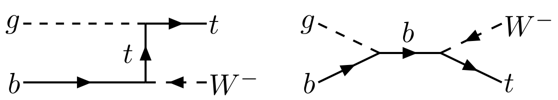
[a] S.Willenbrock *et al* Phys.Rev. **D56** (1997) 5919-5927

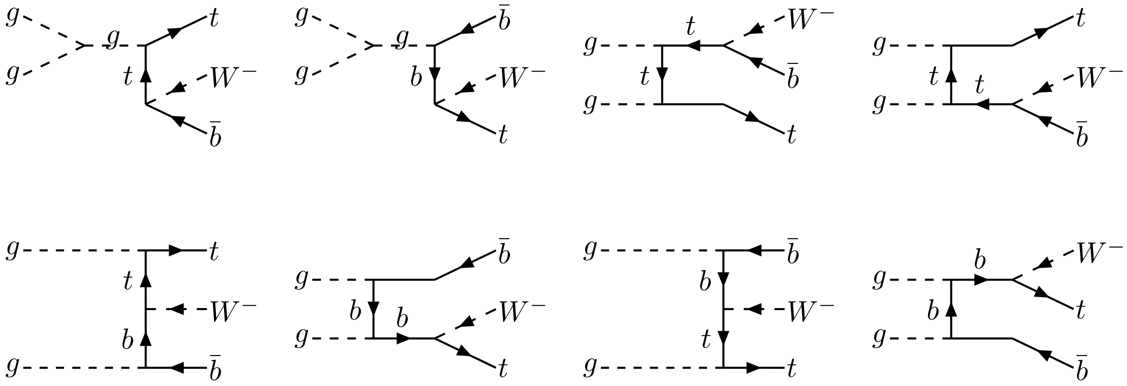
[b] M.Smith, S.Willenbrock Phys.Rev. **D54** (1996) 6696-6702

Diagrams for leading order $2 \to 2$ tW production (A) and $\mathcal{O}(1/log(m_t^2/m_b^2))$ $2 \to 3$ process (B), (C):

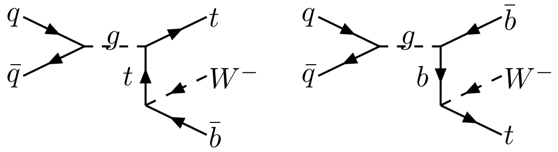
(A)



(B)



(C)



$\sigma(tW + X) = 62.0^{+16.6}_{-3.6}$ pb (LHC) [a]

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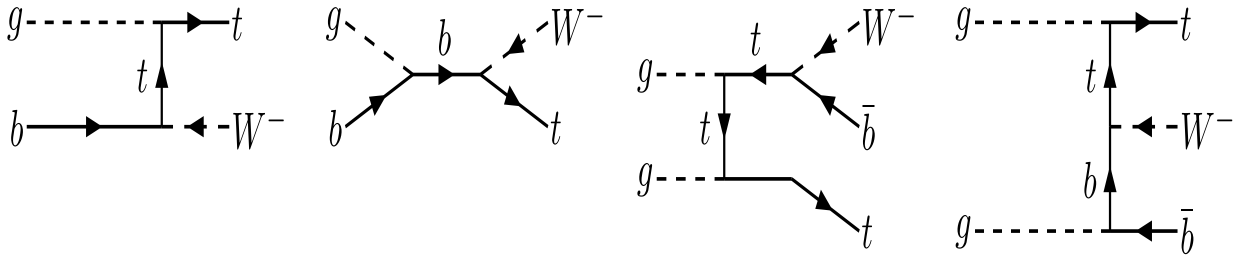
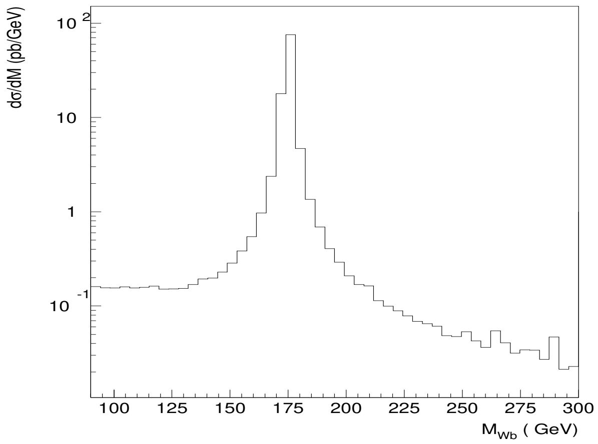
[a] A.Belyaev, E.Boos Phys.Rev. D63 (2001) 034012

Some details for $pp \to Wt + X$ process at the LHC



- one should remove the contribution from $t\bar{t}$ production giving the same tWb final state:

  1)the application of the cut on the invariant mass of Wb– pair is the straightforward way to simulate the proper kinematics; cut dependence is not arbitrary: $\simeq 25\ GeV\ Wb$ mass window cut completely removes $t\bar{t}$ contribution (same results from the Breit-Wiegner fit). It is also of the order of the experimental mass resolution.



2)narrow width approximation: T.Tait(PRD2000)

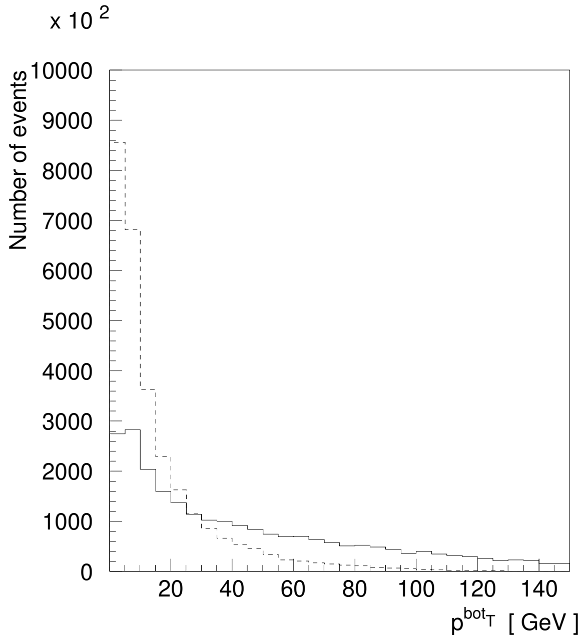
$$\sigma(gg \to tWb)_{total} - \sigma(gg \to t\bar{t}) * Br(t \to Wb)$$
$$- interf[t\bar{t} \otimes tWb]$$

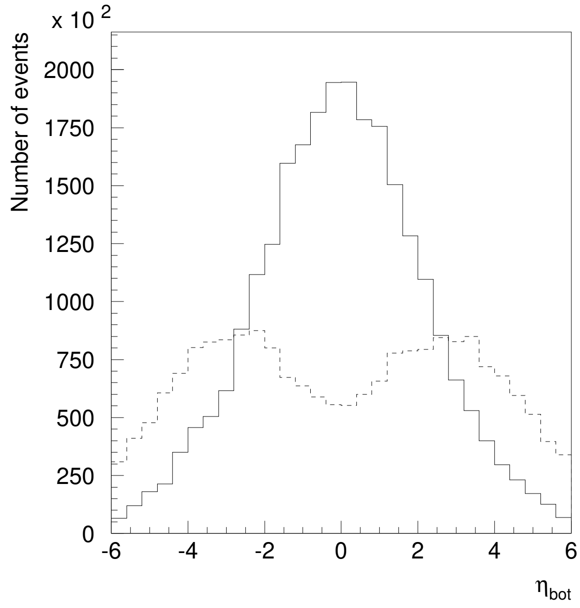
- one should avoid the double counting when one sim ply adds contribution from two processes: leading order $2 \to 2\, tW$ production and $\mathcal{O}(1/\log m_t^2/m_b^2)$ $2 \to 3$ process.

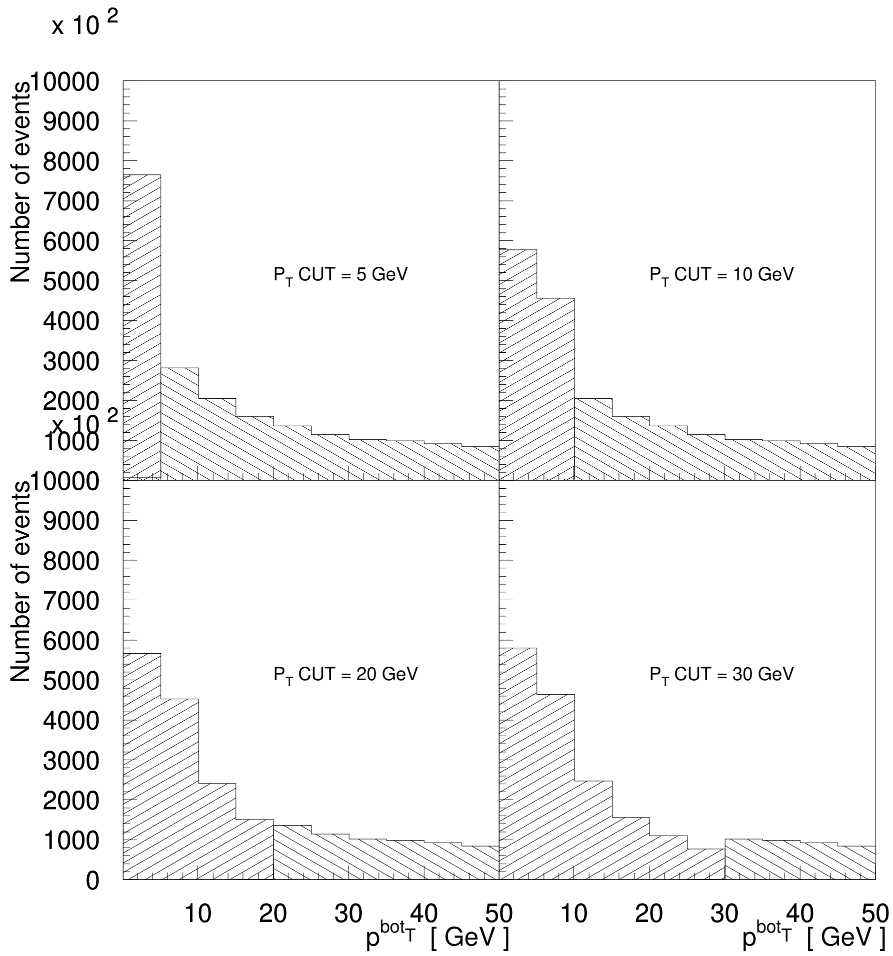
$$\sigma(gb \to tW) + \sigma(gg \to tW\bar{b}) - \sigma(g \to b\bar{b} \otimes gb \to tW)$$

Combining of the Wt+ISR and complete tWb processes: one needs to get the correct kinematics!

PROCESS	CS(pb), CTEQ4L			
	$\mu = m_W$	m_{top}	$m_{top} + m_W$	$\hat{s}$
$(gb + bg) \to W^- t$	29.4	29.1	28.6	27.8
$g \to b\bar{b} \otimes (gb + bg) \to tW^-$	25.3	23.9	22.9	21.8
$gg \to tW^- b\ (\pm 15\Gamma_{top})$	33.3	24.3	21.2	16.5
$q\bar{q} \to tW^- b\ (\pm 15\Gamma_{top})$	1.9	1.5	1.3	1.1
$W^- t\ +\ [W^- tb]_{I(\pm 15\Gamma)}\ -\ [subt]$	**39.3**	**31.0**	**28.2**	**23.6**
$W^- t\ +\ [W^- tb]_{II}\ -\ [subt]$	38.3	28.9	26.9	23.1


x 10 2
Number of events
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
20
40
60
80
100
120
140
p^bot_T [GeV]


x 10 2
Number of events
2000
1750
1500
1250
1000
750
500
250
0
-6
-4
-2
0
2
4
6
η_bot


x 10 2
Number of events
P_T CUT = 5 GeV
P_T CUT = 10 GeV
P_T CUT = 20 GeV
P_T CUT = 30 GeV
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
10
20
30
40
50
p^bot_T [GeV]

Signatures

t,s-channels production: $e^{\pm}(\mu^{\pm}) + \not{E}_T + b\bar{b}(jet)$

Backgrounds:

- $t\bar{t}$ pairs (≈ 800 pb)
- W+jets
  [A.Belyaev, E.Boos, L.Dudko Phys.Rev. D59 (1999)075001]
  $P_T^{jet} > 20$ GeV, $\Delta R(j,j') > 0.5$
  - Wjj (≈ 7500 pb)
  - $Wb\bar{b}$ (≈ 30 pb)
  - WW, WZ
- QCD multijets fake
  - $b\bar{b}j$ (≈ 511 nb)
  - $b\bar{b}jj$ (≈ 362 nb)

$tW(b)$ associated production:

Backgrounds:

- $t\bar{t}$
- W^+W^-b
- W^+W^-j

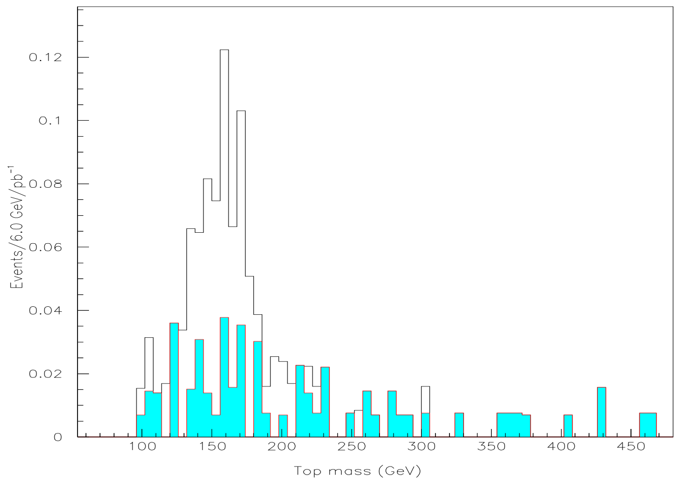
Search Strategies (1)

D.Green, K.Maeshima, R.Vidal, J.Womersley, W.Wu CMS NOTE 1999/048

Event selection criteria:

- exactly two jets with $E_T^{j1} > 20$ GeV, $|\eta^{j1}| < 2.5$, $E_T^{j2} > 50$ GeV, $2.5 < |\eta^{j2}| < 4$
- leading jet $E_T < 100$ GeV
- exactly one b-tagged jet
- $M_j j < 80$ GeV or $M_j j > 100$ GeV
- $P_T^l > 20$ GeV, $\not{E}_T > 20$ GeV
- $50 < M_T^{l,\nu} < 100$ GeV

Reconstructed top mass for the signal plus backgrounds (open histogram) and backgrounds only (shaded):



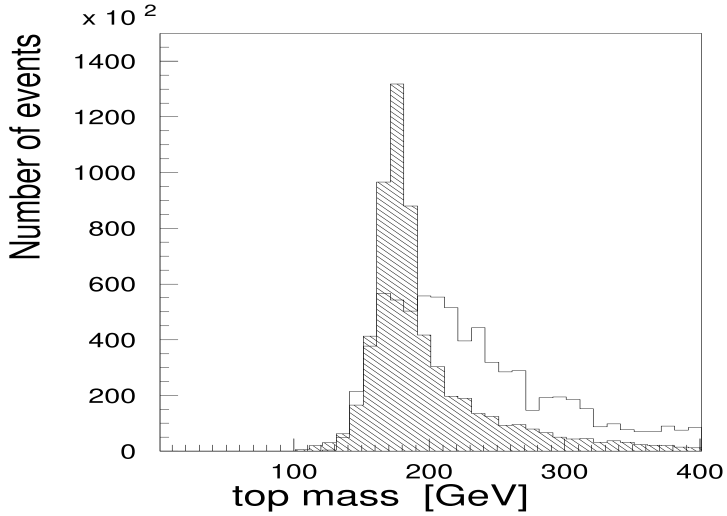
Search Strategies (2)

A.Belyaev, E.Boos, L.Dudko Phys.Rev. D59 (1999) 075001

Event selection criteria:

- $2 < N_{\text{jets}} < 3$
- leading jet $E_T > 45$ GeV
- $\sqrt{\hat{s}} > 180$ GeV
- $P_T^W > 30$ GeV
- $M_{jj} < 40$ GeV
- $100 < H_T < 260$ GeV
- $P_T^l > 20$ GeV, $\not{E}_T > 20$ GeV
- Top mass window cut ($m_t \pm 50$ GeV)

Reconstructed top mass for backgrounds (open histogram) and signal (shaded):



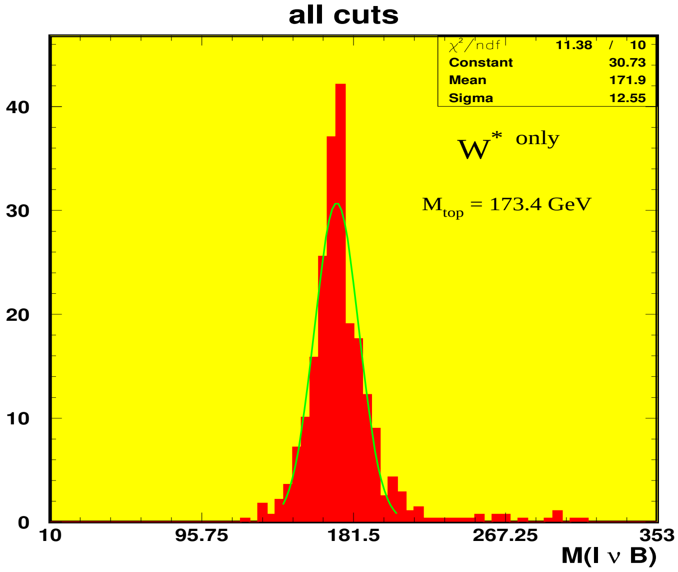
Search Strategies (3)

A. Kostritsky and S. Slabospitsky (TopRex 3.23)

Event selection criteria for W^*:

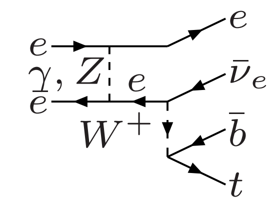
- $N_l = 1$ with $P_T^l > 10$ GeV
- missing $E_T > 20$ GeV
- Two b-jets with $p_T > 70$ GeV
- $P_T W b\bar{b} < 10$ GeV
- Top mass window cut ($m_t \pm 25$ GeV)

$\frac{\Delta V_{tb}}{V_{tb}} = 5\%$ Reconstructed top mass

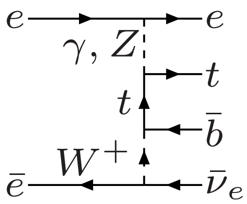


CC20 Diagrams in case of e^+e^- collisions

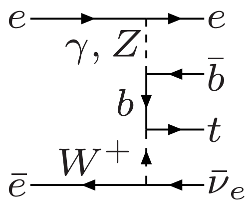
Gauge invariant t-channel subset of 10 diagrams



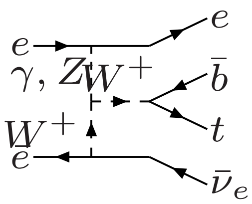
diagr.1,2



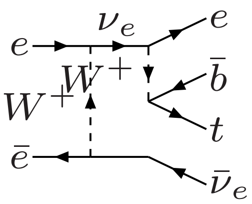
diagr.3,4



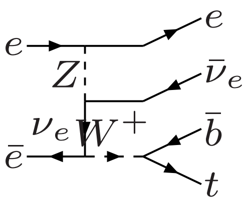
diagr.5,6



diagr.7,8

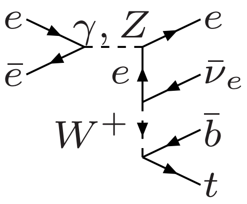


diagr.9

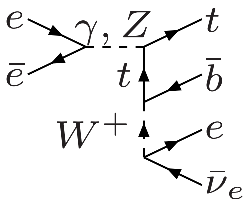


diagr.10

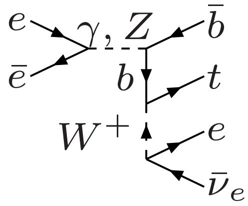
Gauge invariant s-channel subset of 10 diagrams



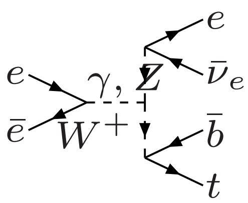
diagr.1,2



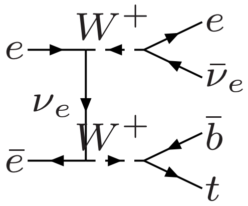
diagr.3,4



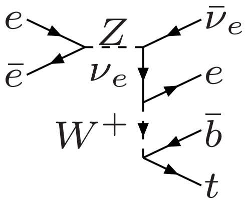
diagr.5,6



diagr.7,8

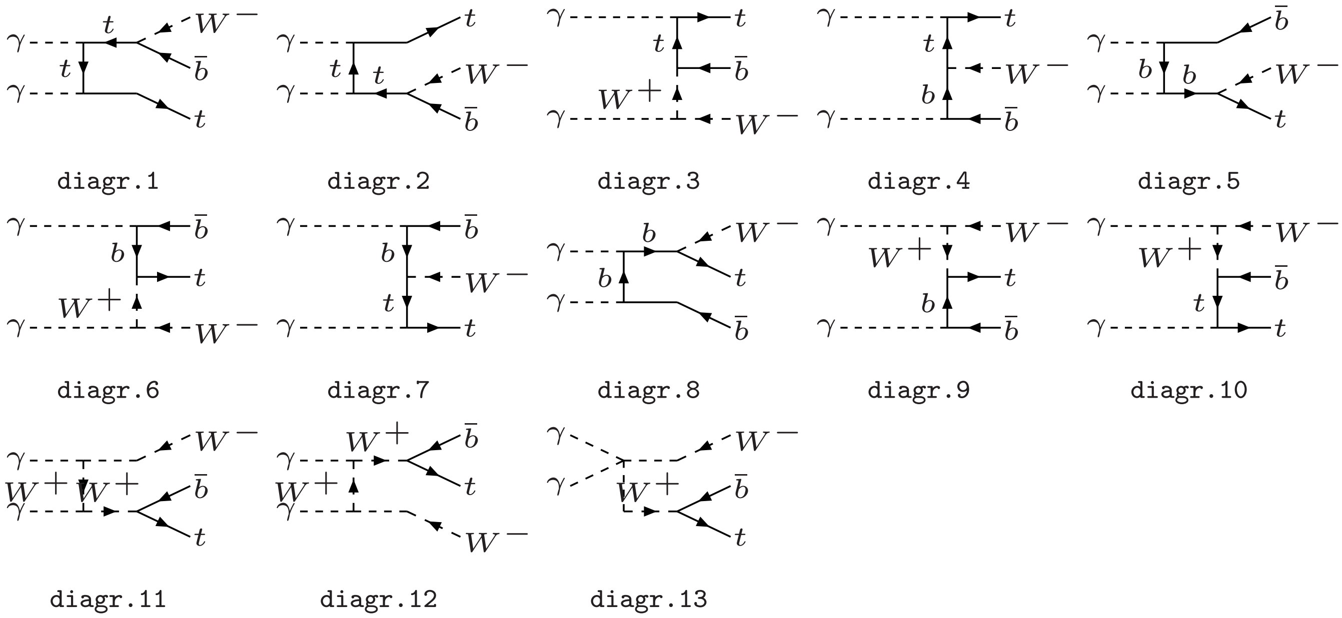


diagr.9



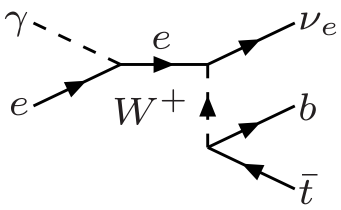
diagr.10

In case of $\gamma\gamma$ collisions there are no nontrivial gauge invariant subsets. A situation is similar to single top at the LHC in Wt mode.

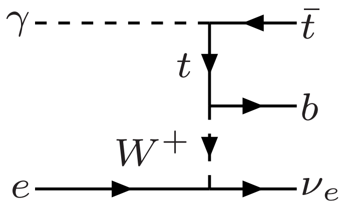


The top pair rate has to be removed in order to get the correct single top rate.

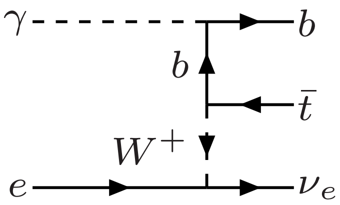
Single Top Diagrams in γe Collisions



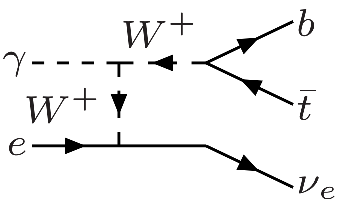
diagr.1



diagr.2



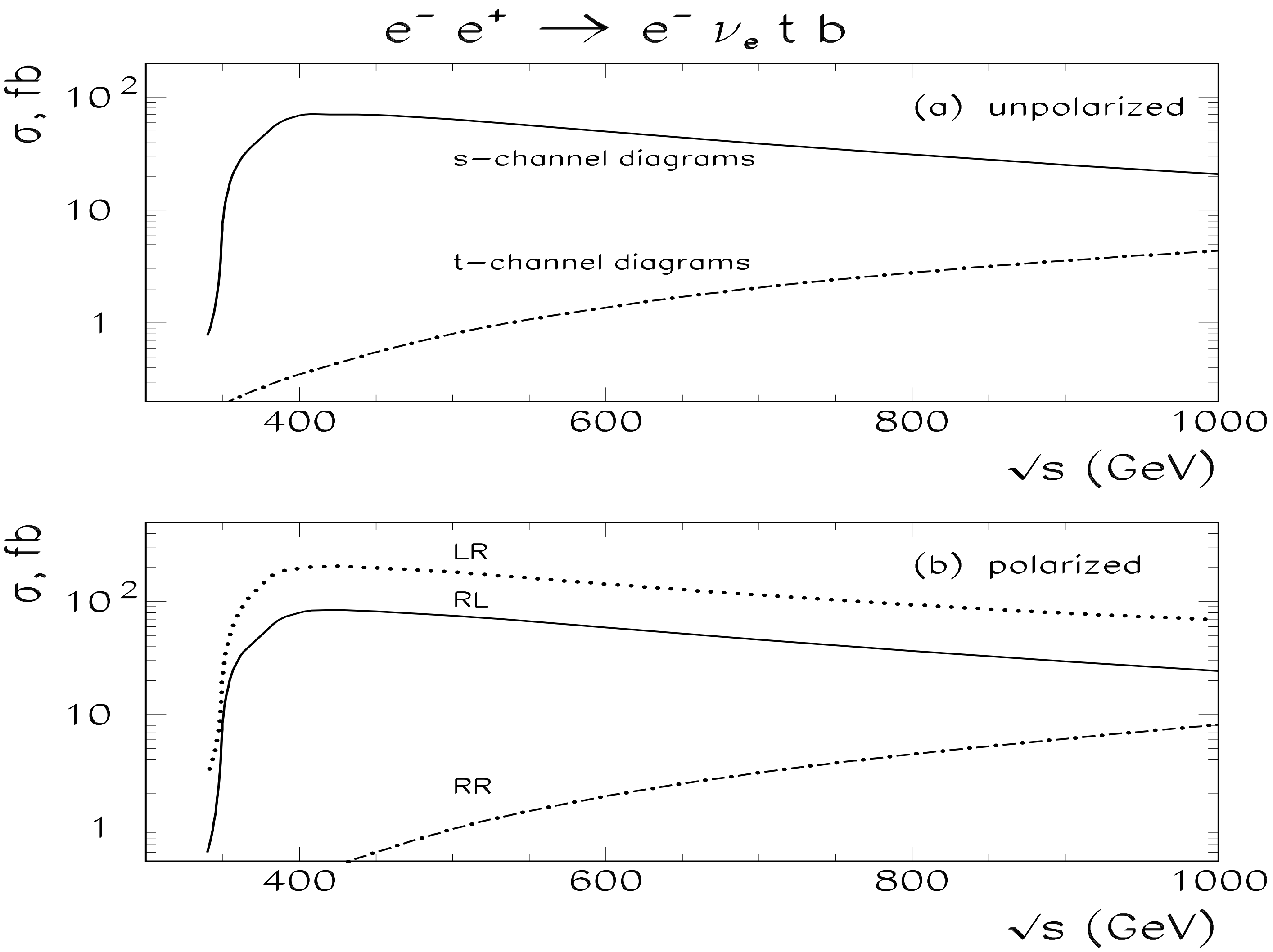
diagr.3



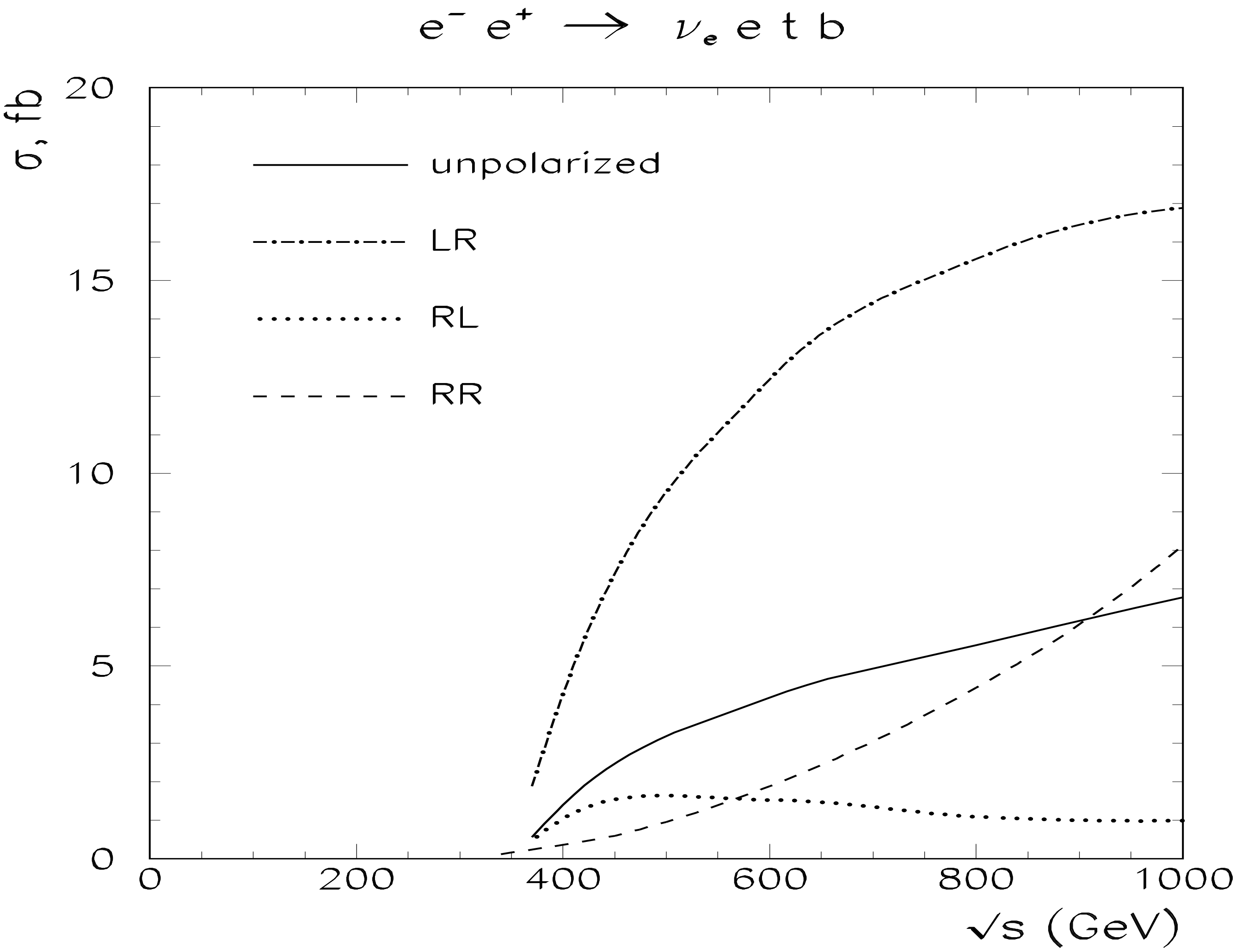
diagr.4

Energy dependence of the cross sections for s- and t-channel gauge invariant subsets in case of unpolarized collisions and total cross section for polarized cases. (Energy range below 1 TeV)

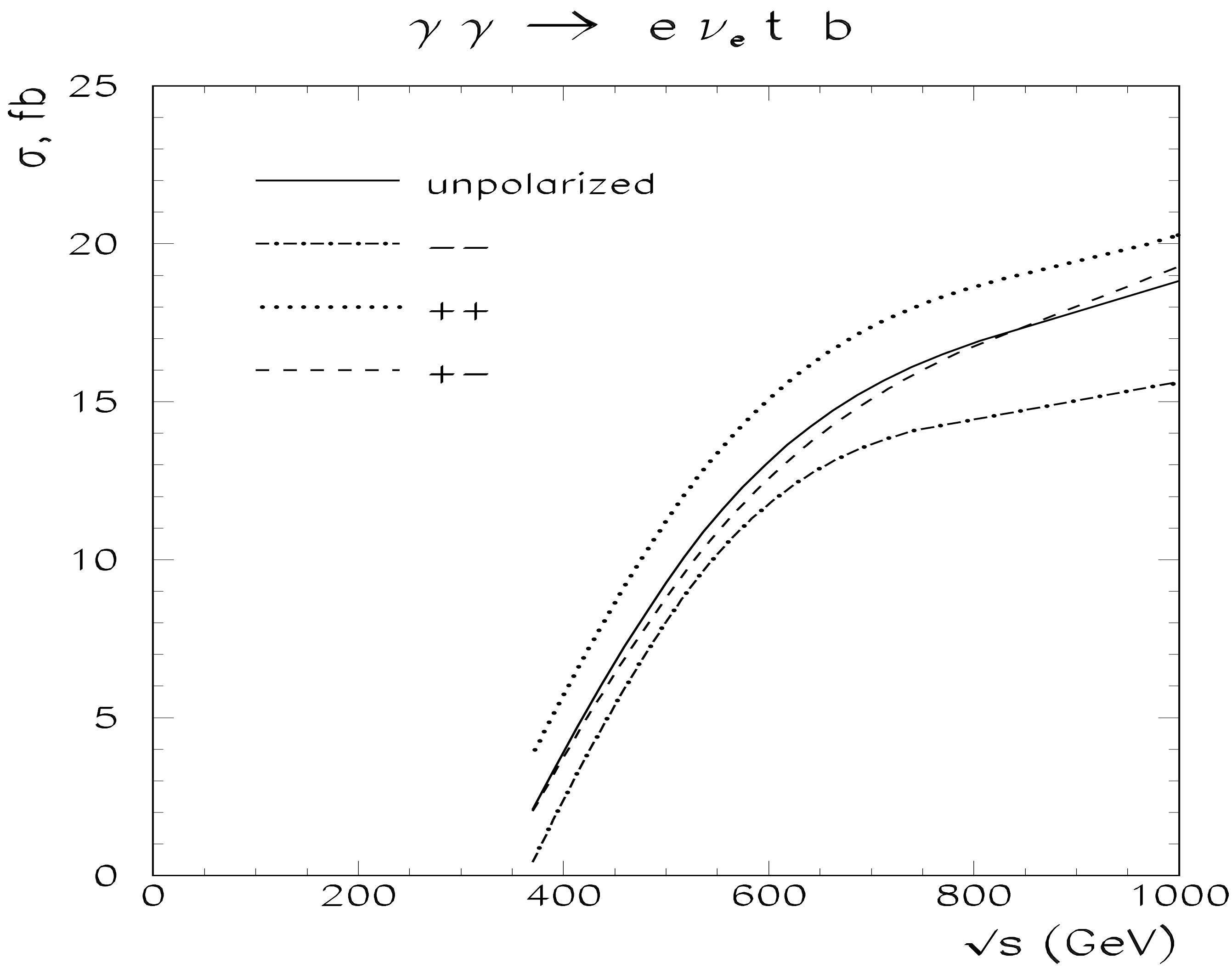
(E.B., M. Dubinin, A.Pukhov, M. Sachwitz, and H.J. Schreiber)



Single Top quark production cross section in the energy range below 1 TeV



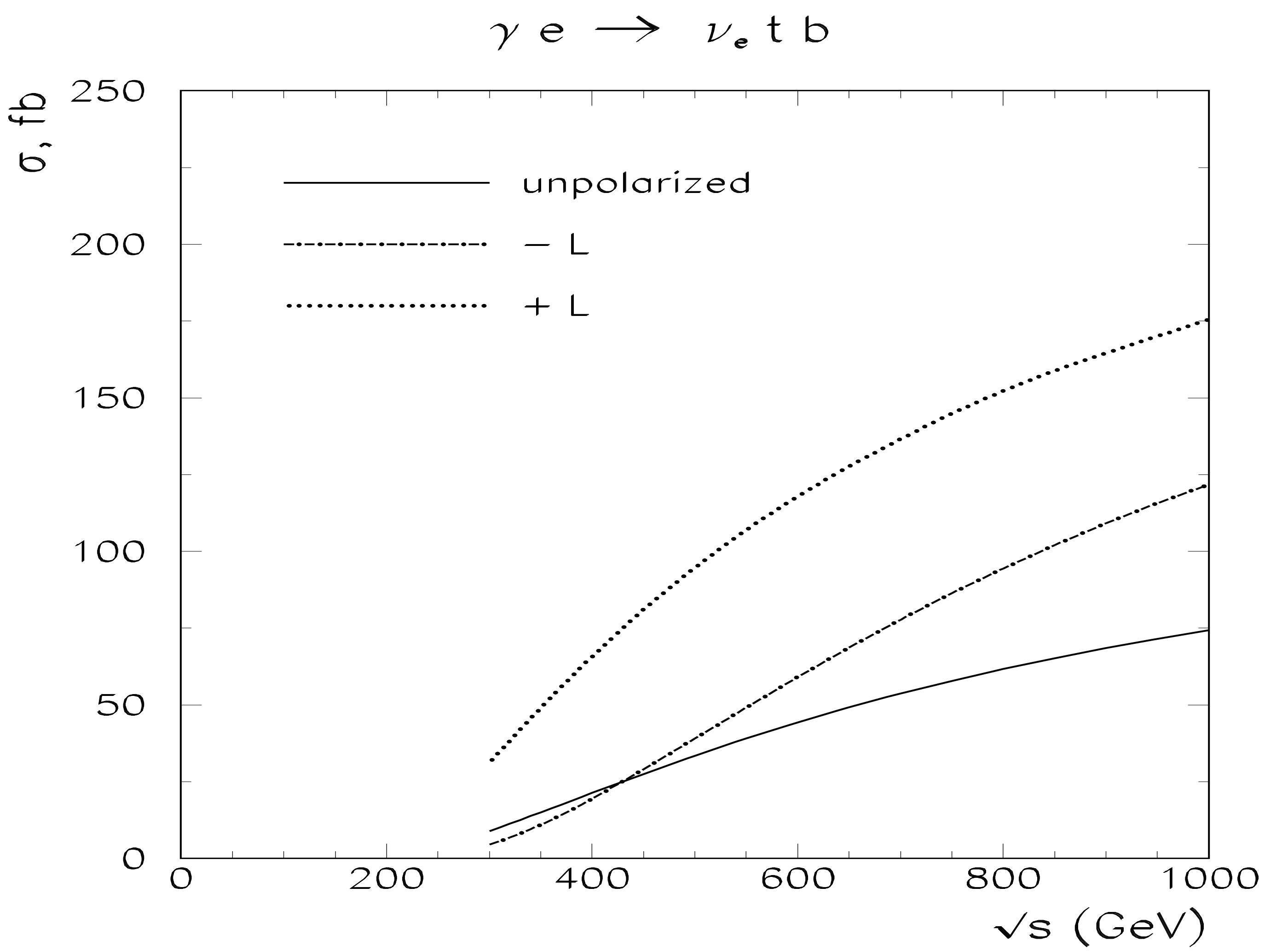
Single Top quark production cross section in $\gamma\gamma$ collisions (Energy range below 1 TeV)



In the region below 1 TeV for both cases of e^+e^- and $\gamma\gamma$ collisions the single top rate is extracted from much larger total rate which dominates by the top pair production. It leads to additional uncertainties (about 10 %)

Single Top quark production cross section in γe collisions (Energy range below 1 TeV)

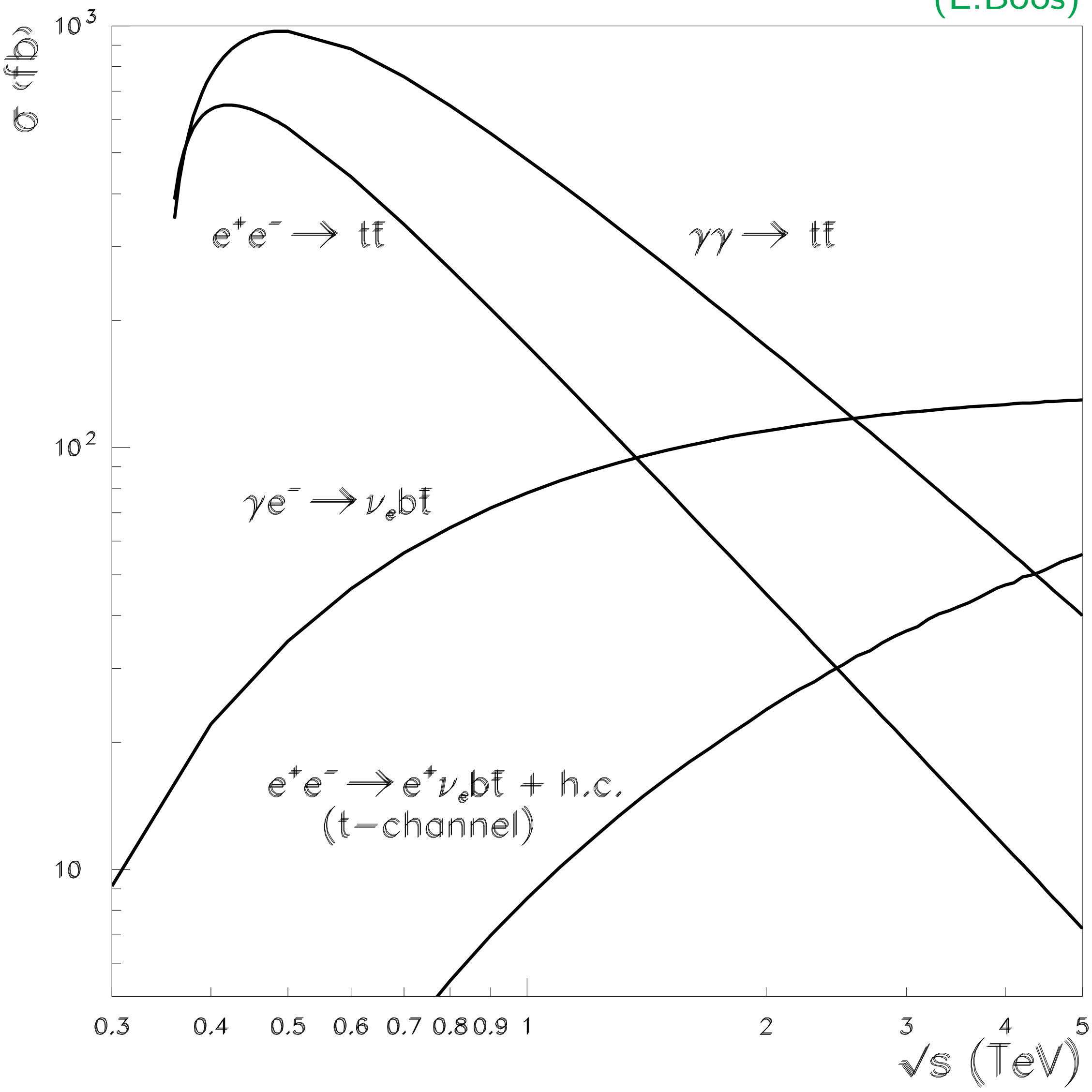
(E.B., M. Dubinin, A.Pukhov, M. Sachwitz, and H.J. Schreiber)



There is no top pair bakground

Cross sections of basic Top production processes in the energy range up to 5 TeV

(E.Boos)



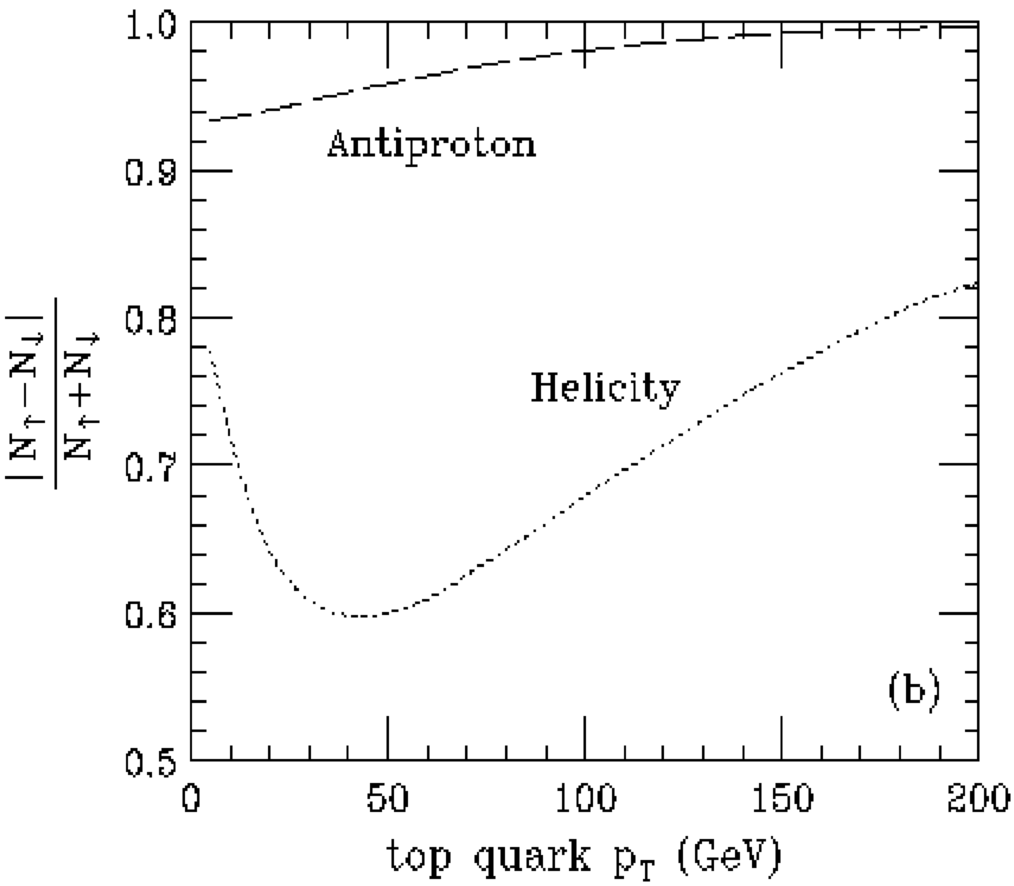
The top quark spin points along the direction of the d or $\bar{d}$ quarks in the events, in the top quark rest frame.
(G. Mahlon and S. Parke)

For the W-g fusion this is the direction of the final state light quark jet $(ub \rightarrow dt)$ or the beam direction $(\bar{d}b \rightarrow \bar{u}t)$

In the W^* channel, this is the beam direction $(u\bar{d} \rightarrow t\bar{b})$

The absolute value of the spin asymmetry for the W^* channel at the Tevatron (antiproton basis and helicity basis)

G.Mahlon and S.Parke



The results on strong correlations between the t-quark spin and d-quark momentum can to be obtained and explained in a very simple way based on properties of polarized top decay. (E.B. and A.Sherstnev hep-ph/0201271)

The diagram for the LO t-quark decay is topologically equivalent to the W^*-process and to the $2 \to 2$ part ($ub \to td$) of the W-gluon fusion.

The two single top production processes can be considered as a corresponding decay back in time. Analogue of d-quark in top decay $t \to e^+ \nu b$ is the positron or charged lepton since in the SM both d-quark and charged lepton are the down components of the electroweak doublets.

The angular distribution of the positron from the decay of the t-quark polarized along some axis $\bar{n}$ in the t-quark rest frame is

$$\frac{1}{\Gamma} \frac{d\Gamma(s_t \uparrow\uparrow \bar{n})}{d\cos\theta} = \frac{1+\cos\theta}{2} \quad ,$$

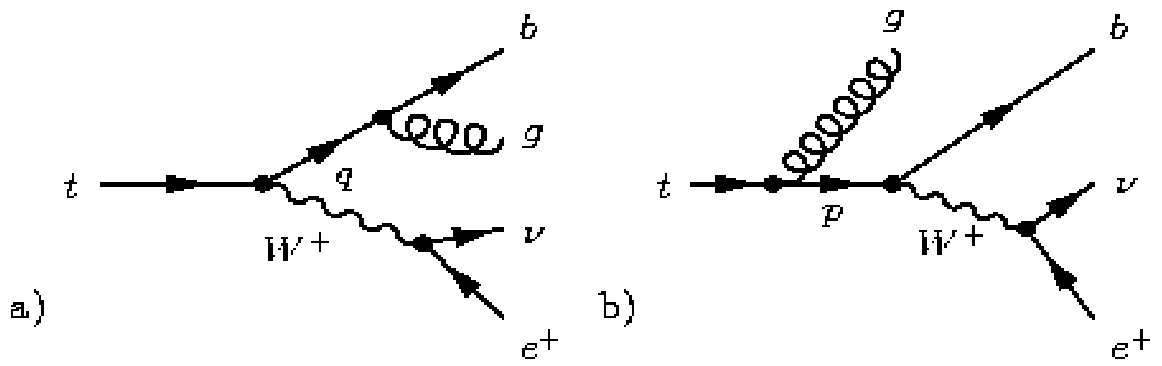
where θ – an angle between spin direction $\bar{n}$ and a momentum of the positron.

So, the psitron is the best probe of the top quark polarization. (J.H. Kühn, M. Jeżabek and J.H. Kühn)

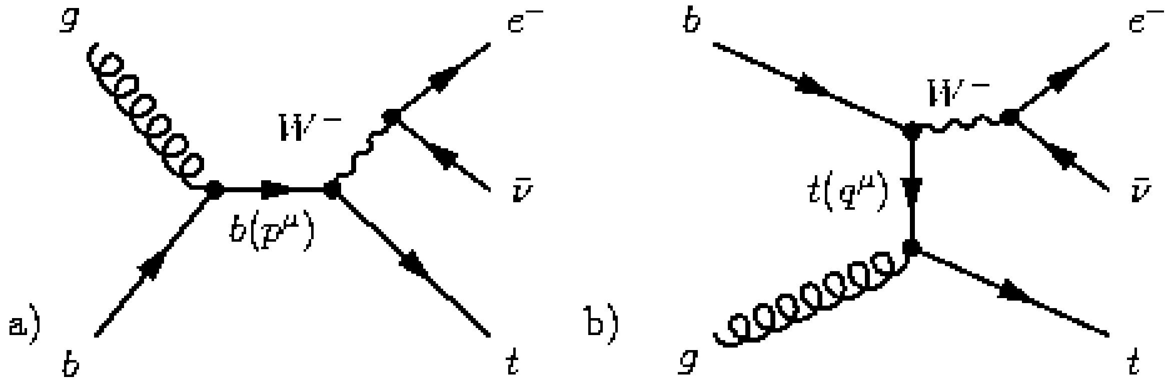
Therefore the overall production cross section including top decay has the form:

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta^*_{e+,d}} = \frac{1+\cos\theta^*_{e+,d}}{2}$$

Diagrams for the radiative decay



Diagrams for the Wt-production with W decay



The diagrams of the tW-process with the W-boson decay are topologically equivalent to the decay $t \to be^+\nu + g$ which is very simple to be analized.

In contrast to W-gluon fusion there are 2 diagrams with b-quark in the initial state

Spin decompose axis is taken to be the direction of the positron produced in the W-boson decay n^*_{e+}

The contribution from the Wtb-diagram to the top spin down configuration
$|M_{Wtb}(-, t \to be^+\nu + g)|^2$ and
the Wtb-gtt diagram interference
$|M_{Wtb*gtt}(-, t \to be^+\nu + g)|$
are equal to 0 exactly in the same manner as it was for the W^* process.

However the contribution of the gtt-diagram does not vanish and large, and it does not give a definite polarization.

But it has the following structure

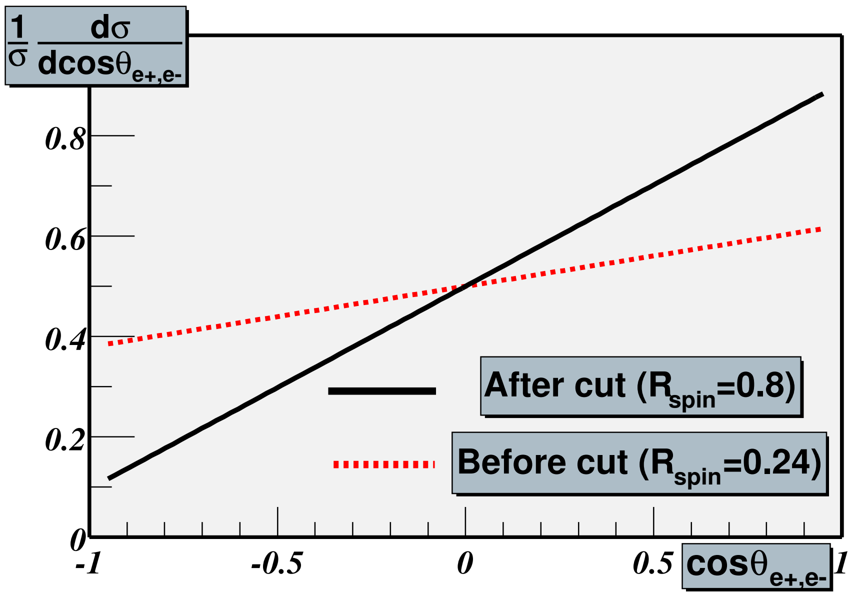
$$|M_{gtt}(-, t \to be^+\nu + g)|^2 = \frac{2\, g_s^2\, g_W^2 |V_{tb}|^2}{(w^2 - m_W^2)^2 + (m_W \Gamma_W)^2} \frac{1}{(t \cdot g)^2} (b \cdot \nu) \left[m_t E^*_e E^{*2}_g (1 - \bar{n}^*_e \bar{n}^*_g)^2 \right] ,$$

where E^*_e, E^*_g, $\bar{n}^*_g$ and $\bar{n}^*_g$ are the energies of positron and gluon and the directions of their 3-momenta in the top rest frame respectively.

The recommendation is to cut the angle between the electron from W decay and the gluon in the top rest frame. Also a cut on the gluon energy helps.

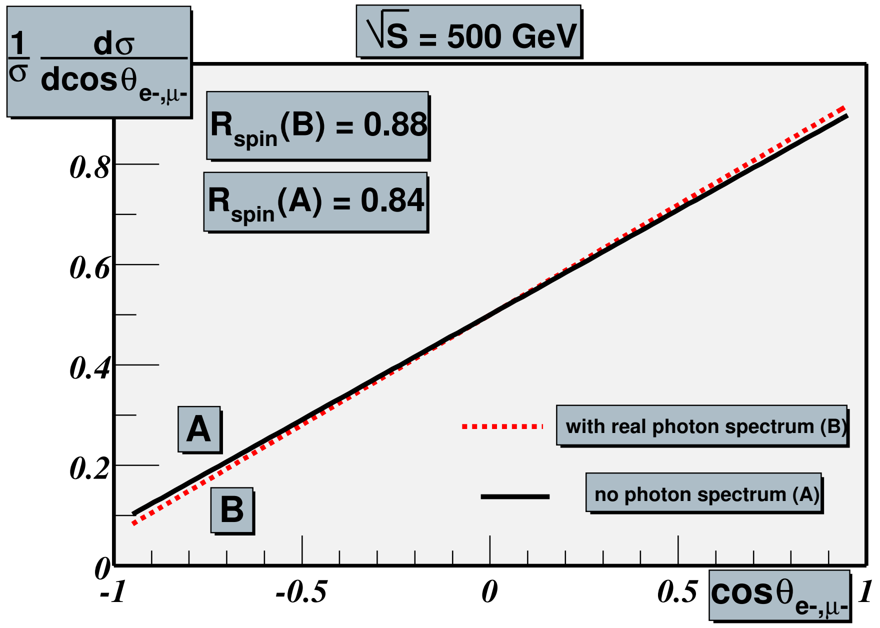
After a proper cut top in Wt-process is polarized along the direction of the electron from W^- decay.

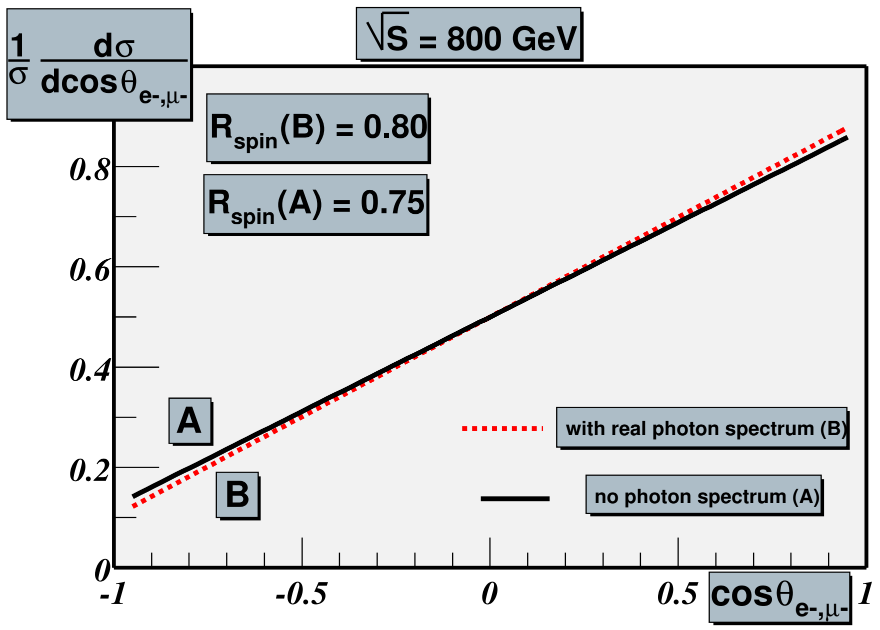
The best correlation variable is the angle between the electron from W^- decay and from the positron or (d-quark) from the subsequent top decay in the top rest frame.



Spin correlations and spin assymetry for single Top production processes in $\gamma - e$ collisions

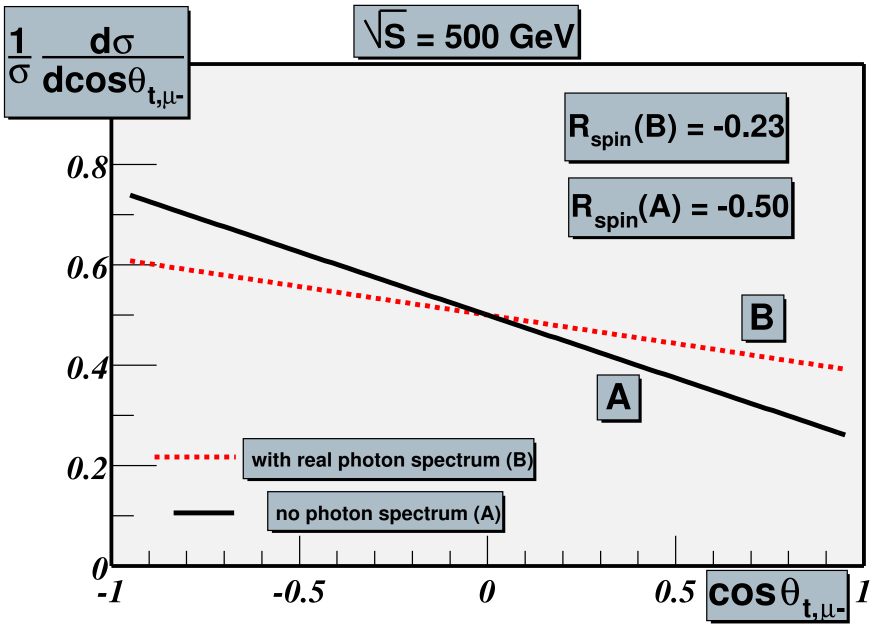
"electron beam basis"

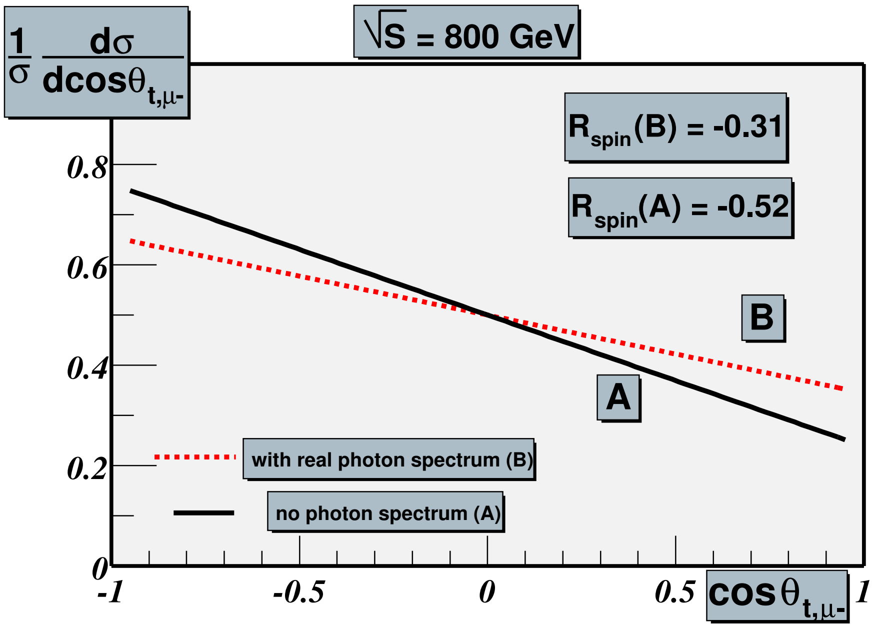




Spin correlations and spin assymetry for single Top production processes in $\gamma - e$ collisions

"helicity basis"





Anomalous Wtb Couplings

- Lagrangian

$$\mathcal{L} = \frac{g}{\sqrt{2}} \left[W_\nu^- \bar{b} \gamma_\mu P_- t - \frac{1}{2M_W} W_{\mu\nu}^- \bar{b} \sigma^{\mu\nu} (F_2^L P_- + F_2^R P_+$$

with $W_{\mu\nu}^\pm = D_\mu W_\nu^\pm - D_\nu W_\mu^\pm$, $D_\mu = \partial_\mu - ieA_\mu$, $\sigma^{\mu\nu} = i/2[\gamma_\mu, \gamma_\nu]$ and $P_\pm = (1 \pm \gamma_5)/2$. The couplings F_2^L and F_2^R are proportional to the coefficients $C_{tW\Phi}$ and $C_{bW\Phi}$ of the effective Lagrangian $F_2^{L(R)} = \frac{C_{t(b)W\Phi}}{\Lambda^2} \frac{\sqrt{2} v M_W}{g}$

- A possible $V + A$ form factor is severely constrained by the CLEO $b \to s\gamma$ data

Systematics	F_2^L	F_2^R
$\pm$ 10%	$-0.18 \quad \ldots \quad +0.55$	$-0.24 \quad \ldots \quad +0.25$

Table 1: Uncorrelated limits on anomalous couplings from Tevatron measurements with and without systematic uncertainties.

(E.Boos,L.Dudko,T.Ohl,EPJ99)

Systematics	F_2^L			F_2^R		
$\pm$ 10%	-0.094	$\ldots$	$+0.34$	-0.17	$\ldots$	$+0.18$
$\pm$ 5%	-0.052	$\ldots$	$+0.097$	-0.12	$\ldots$	$+0.13$
$\pm$ 1%	-0.013	$\ldots$	$+0.014$	-0.05	$\ldots$	$+0.06$
$\pm$ 0%	-0.003	$\ldots$	$+0.003$	-0.022	$\ldots$	$+0.03$

Uncorrelated limits on anomalous couplings from LHC measurements with for several estimates of systematic uncertainties.

Systematics	F_2^L			F_2^R		
$\pm$ 10%	-0.094	$\ldots$	$+0.34$	-0.17	$\ldots$	$+0.18$
$\pm$ 5%	-0.052	$\ldots$	$+0.097$	-0.12	$\ldots$	$+0.13$
$\pm$ 1%	-0.013	$\ldots$	$+0.014$	-0.05	$\ldots$	$+0.06$
$\pm$ 0%	-0.003	$\ldots$	$+0.003$	-0.022	$\ldots$	$+0.03$

Uncorrelated limits on anomalous couplings from LHC measurements with for several estimates of systematic uncertainties.

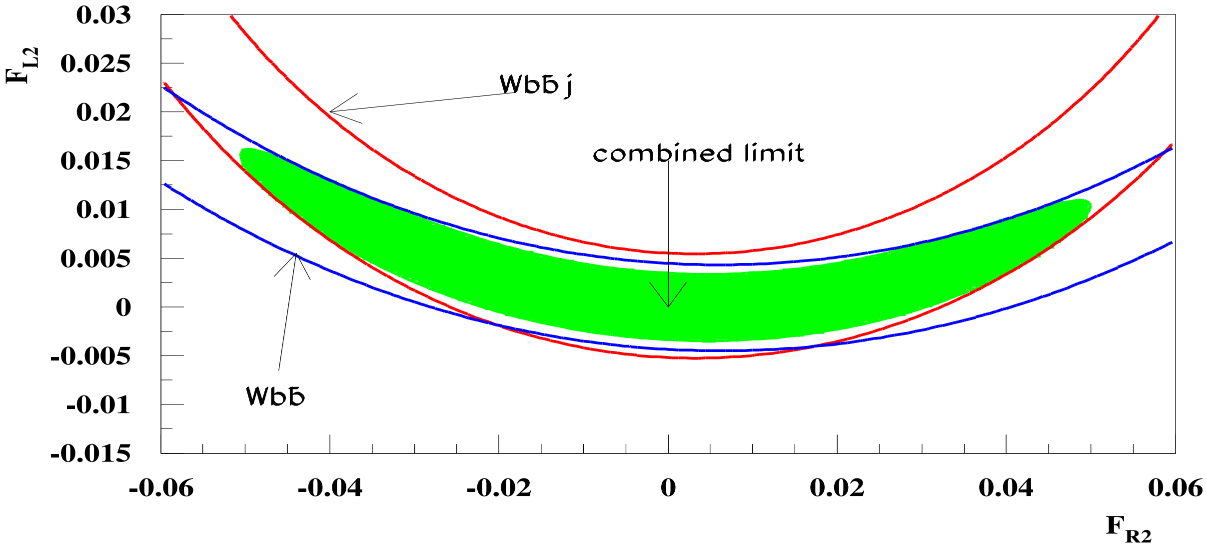
	F_2^L	F_2^R
Tevatron ($\Delta_{sys.} \approx 10\%$)	$-0.18 \div +0.55$	$-0.24 \div +0.25$
LHC ($\Delta_{sys.} \approx 5\%$)	$-0.052 \div +0.097$	$-0.12 \div +0.13$
γe ($\sqrt{s_{e^+e^-}} = 0.5$ TeV)	$-0.1 \div +0.1$	$-0.1 \div +0.1$
γe ($\sqrt{s_{e^+e^-}} = 2.0$ TeV)	$-0.008 \div +0.035$	$-0.016 \div +0.016$

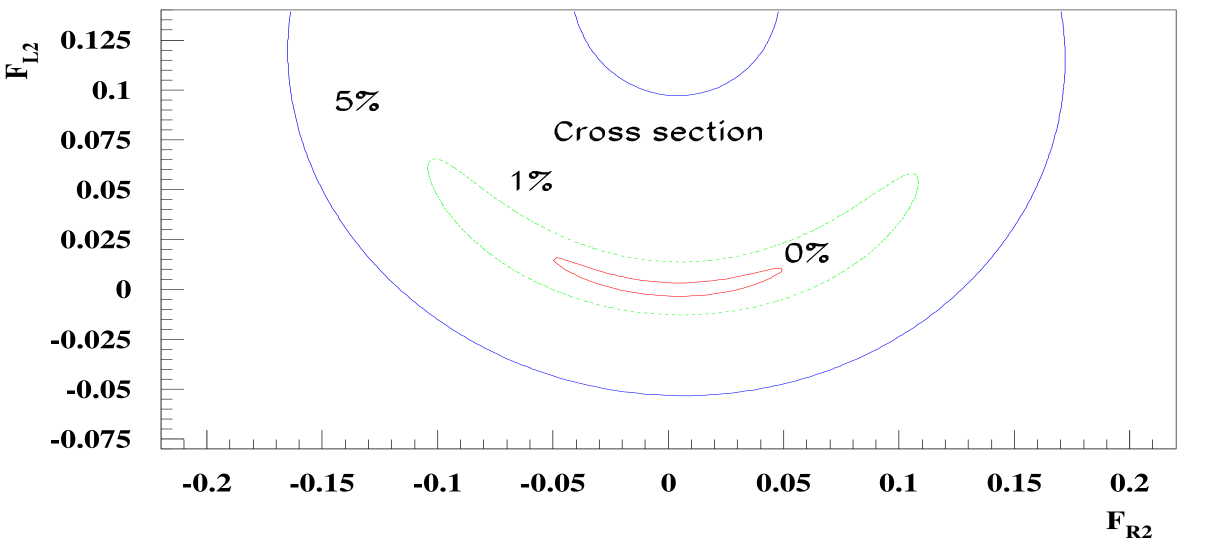
Uncorrelated limits on anomalous couplings from measurements at different machines.

Correlated limits on W_{tb} anomalous couplings:

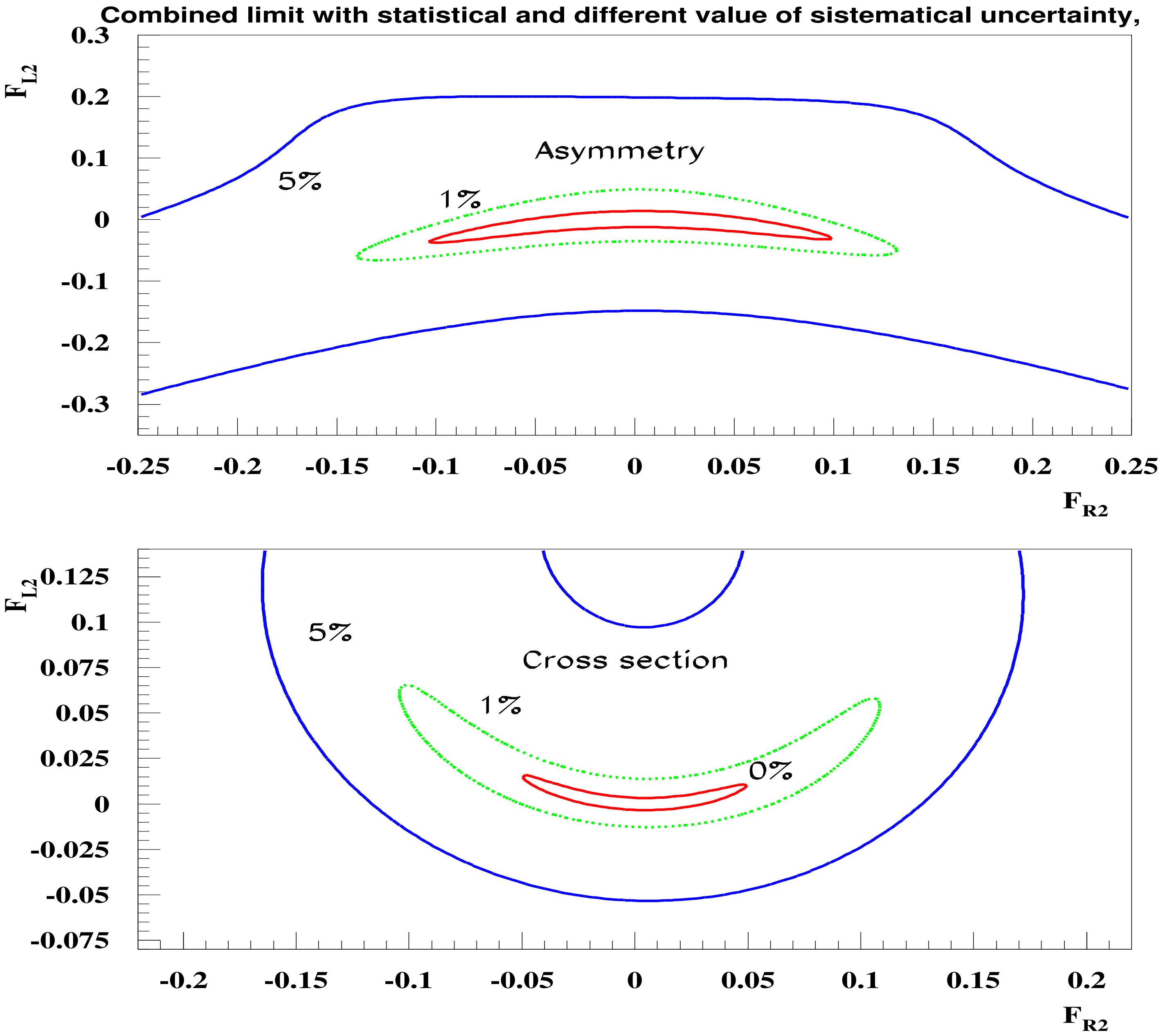
[E.Boos, L.Dudko, T.Ohl Eur.Phys.J. C (1999)]

$$\mathcal{L} = \frac{g}{\sqrt{2}}\left[W_\nu^- \bar{b}\gamma_\mu P_t - \frac{1}{2M_W} W_{\mu\nu}\bar{b}\sigma^{\mu\nu}(F_2^L P_- + F_2^R P_+)t \right]$$





Asymmetry of the top and antitop production provides an additional observable.
(Not available at the Tevatron)



Conclusions

- Studies of Single Top Quark production will be important for all future colliders as a signal process (measurements of top properties; searches for various new physics effects) and as a background to many other processes
- Single top production rate
  - at LHC energies is about 1/3 of the top pair rate
  - at TESLA energies is about $1/80$ for e^+e^- and $1/8$ for γe from of the top pair rate. A proper polarization leads to increase of the single top rate by a factor of 2
  - at CLIC energies in γe collision mode is the highest top rate among all possible top production processes
  - at CLIC in e^+e^- collision mode is larger than the total top pair rate
- Unique spin polarization properties because of $V-A$ SM coupling
- The best sensitivity to anomalous Wtb coupling in γe
- Many detail simulations remain to be done