Top Quark Physics

E. Boos

High Energy Theory Division
Skobeltsyn Institute of Nuclear Physics, Moscow State University

Outline

- Introduction. Discovery and Puzzles
- Basic production processes at colliders
- Decays and spin correlations
- Top mass, V_{tb}, Top Yuakawa coupling
- "New Physics" via top quark
- Conclusions

LHC/LC Study Group, "Physics interplay of the LHC and the ILC," arXiv:hep-ph/0410364
M. Beneke *et al.*, "Top quark physics," arXiv:hep-ph/0003033
S. Willenbrock, "The standard model and the top quark," arXiv:hep-ph/0211067
D.Chakraborty, J.Konigsberg, D.Rainwater, "Review of Top Quark Physics," arXiv:hep-ph/0303092
S.Dawson, "The Top Quark, QCD, and New Physics," arXiv:hep-ph/0303191
E. Boos, "Top quarks at photon colliders," arXiv:hep-ph/0009100

Top quark

- $Q^t_{em} = \frac{2}{3} \mid e \mid$
- Weak isospin partner of b quark: $T^t_3 = \frac{1}{2}$
- Color triplet
- spin-$\frac{1}{2}$

				$SU(3)$	$SU(2)$	$U(1)_Y$
$Q^i_L =$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	3	2	$\frac{1}{6}$
$u^i_R =$	u_R	c_R	t_R	3	1	$\frac{2}{3}$
$d^i_R =$	d_R	s_R	b_R	3	1	$-\frac{1}{3}$

In the Standard Model top quark couplings are uniquely fixed by the principle of gauge invariance, the structure of the quark generations, and a requirement of including the lowest dimension interaction Lagrangian.

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

- $M_t = 174.3 \pm 3.2(stat) \pm 4.0(syst)$
- $\sigma_{t\bar{t}}(CDF\ M_t = 175GeV) = 6.5^{+1.7}_{-1.4} pb$
  $\sigma_{t\bar{t}}(D0\ M_t = 172GeV) = 5.9 \pm 1.7 pb$
- $\lambda_t(M_t) = 1.00 \pm 0.03$
- $|V_{tb}| > 0.78$ (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 (22pb Neural Network) (W-gluon fusion) by D0

  SM prediction: $\sigma_{SM} = 2.43 \pm 0.32$ pb

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

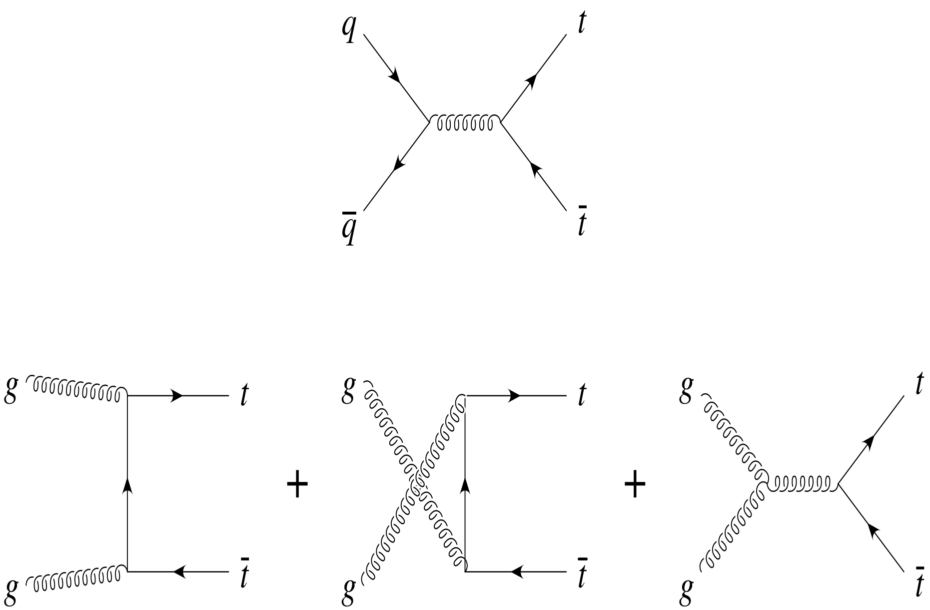
- Top decays ($\tau_t \sim 5 \times 10^{-25}\ sec$) much faster than a typical time-scale for a formation of the strong bound states ($\tau_{QCD} \sim 3 \times 10^{-24}\ sec$). So, top provides, in principle, a very clean source for a fundamental information.

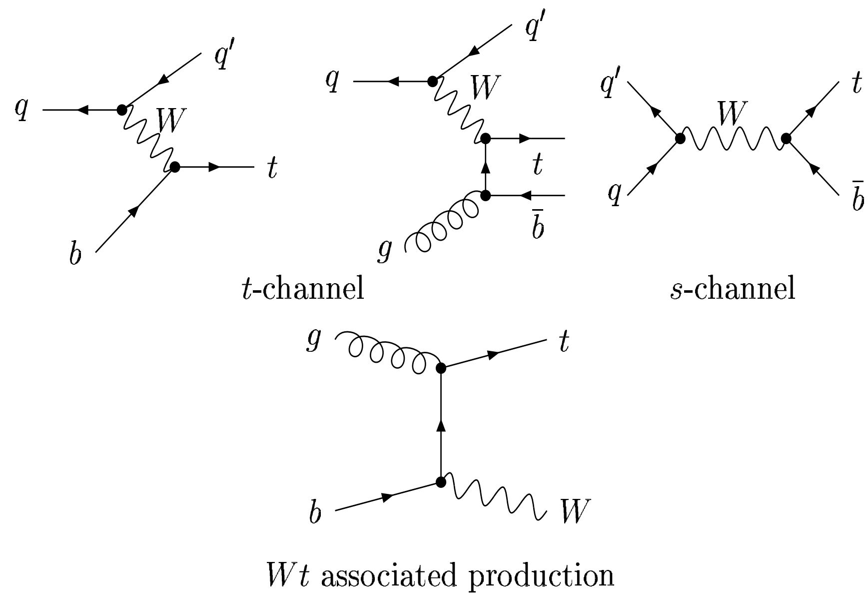
- Top is so heavy and point like at the same time. So, one might expect a possible deviations from the SM predictions more likely in the top sector.

- 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.

At hadron and lepton colliders, top quarks may be produced either in pairs or singly. At the Tevatron and LHC: Top pair (left), Single top (right)





Three mechanisms of the single top production:

t-channel ($Q^2_W < 0$)

s-channel ($Q^2_W > 0$)

associated tW ($Q^2_W = M^2_W$)

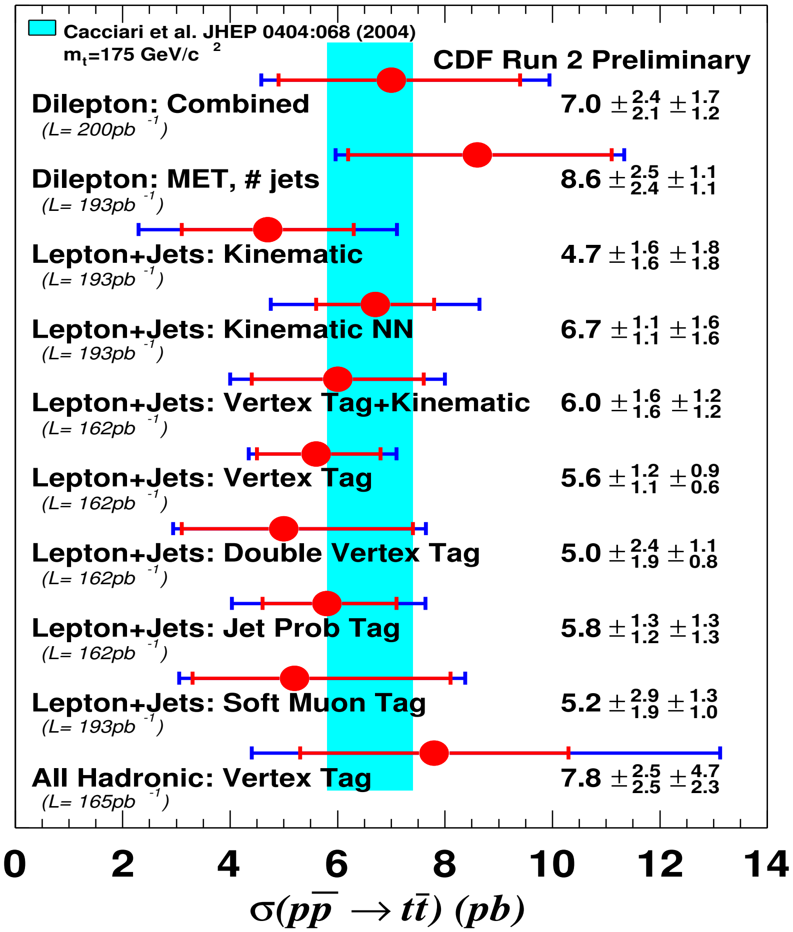
Q^2_W - W-boson virtuality

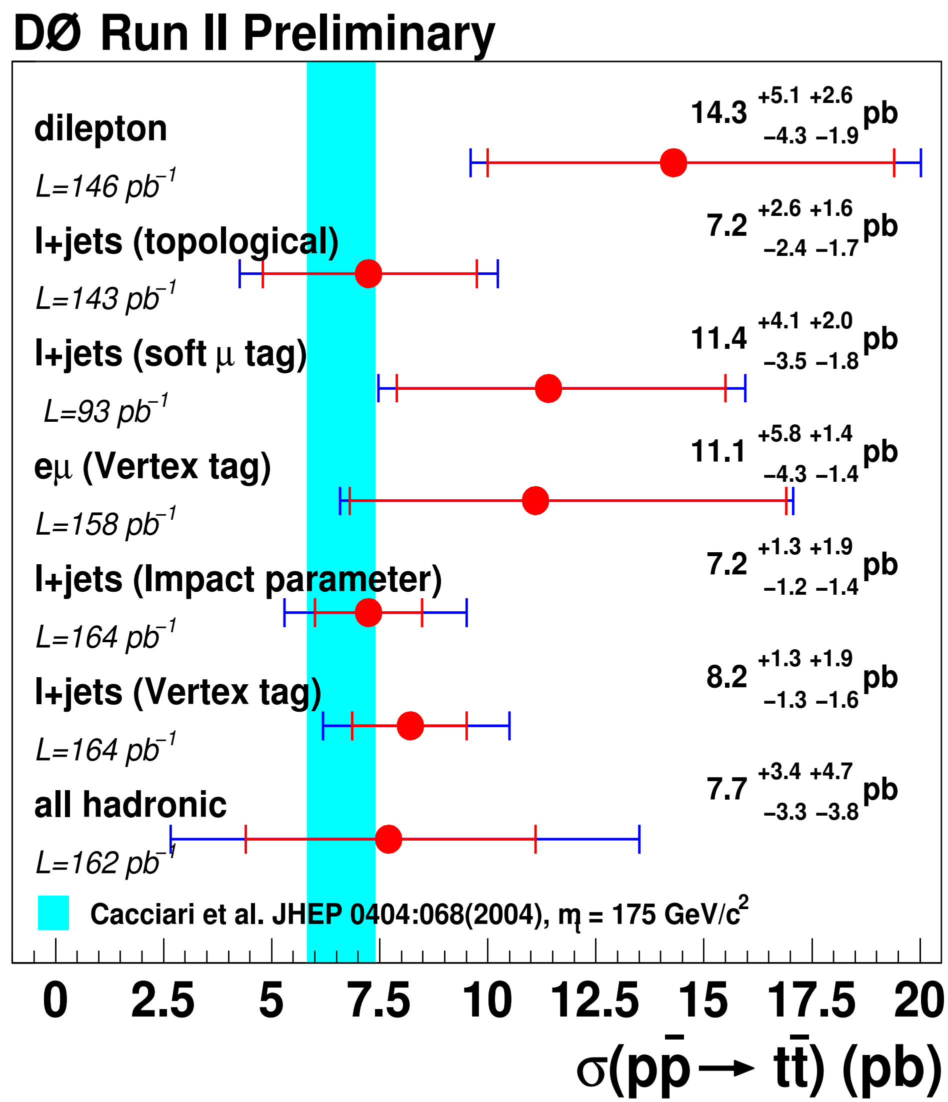
Basic production processes cross sections

	σ_{NLO} (pb)	$q\bar{q} \to t\bar{t}$	$gg \to t\bar{t}$
Tevatron ($\sqrt{s} = 1.8$ TeV $p\bar{p}$)	$4.87 \pm 10\%$	90%	10%
Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)	$6.70 \pm 10\%$	85%	15%
LHC ($\sqrt{s} = 14$ TeV pp)	$833 \pm 15\%$	10%	90%

	s channel	t channel	Wt
Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)	$0.90 \pm 5\%$	$2.1 \pm 5\%$	$0.1 \pm 10\%$
LHC ($\sqrt{s} = 14$ TeV pp)	$10.6 \pm 5\%$	$250 \pm 5\%$	$75 \pm 10\%$

LHC will the Top factory: about 10 mln top quarks per year (or 1 top per second) with 10 fb^{-1} luminosity hep-ex/0506005





The best 95% confidence level upper limits on single top production cross sections in RUN2 by D0 collaboration are

hep-ex/0505063

6.4 pb in the s-channel and
5.0 pb in the t-channel

The first Single Top observation is expected at the Tevatron RUN2 rather soon when accumulated integrated luminosity will be about 1-1.5 fb^{-1}

Main problem is large backgrounds $(W + jets, Wb\bar{b}, t\bar{t}$ etc.$)$ and complicated analysis to extract the signal

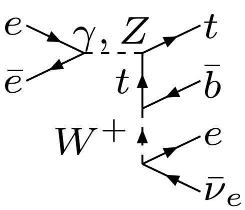
Top pair and single top in e^+e^- collisions (ILC)

$e^+e^- \to t\bar{t} \to WWb\bar{b}, \qquad W \to f\bar{f}',$

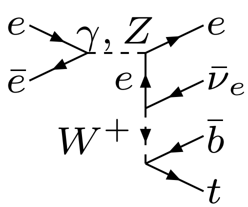
where e.g. for W^+

$f = u, c, \nu_e, \nu_\mu, \nu_\tau \nu_\mu;\ f' = d, s, e, \mu, \tau$

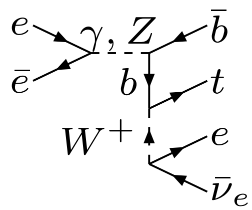
Gauge invariant s-channel subset of 10 diagrams



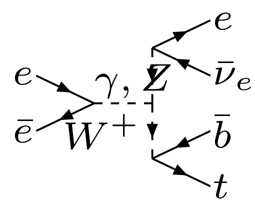
diagr.1,2



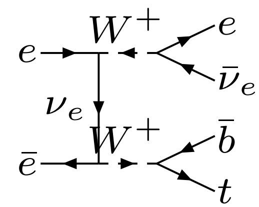
diagr.3,4



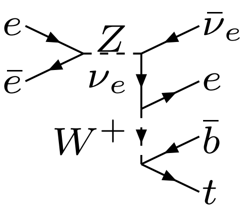
diagr.5,6



diagr.7,8



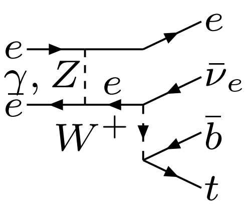
diagr.9



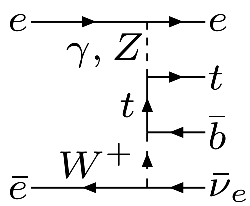
diagr.10

One should split top pair and single top contributions in the s-channel subset

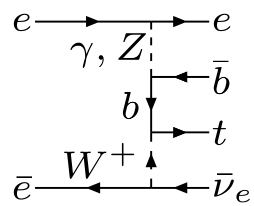
Gauge invariant t-channel subset of 10 diagrams



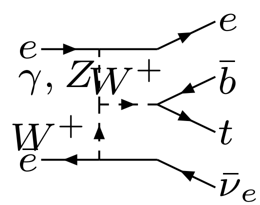
diagr.1,2



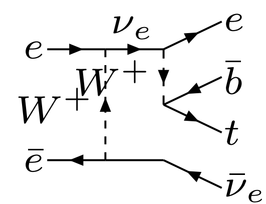
diagr.3,4



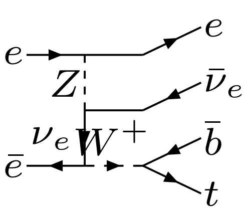
diagr.5,6



diagr.7,8



diagr.9

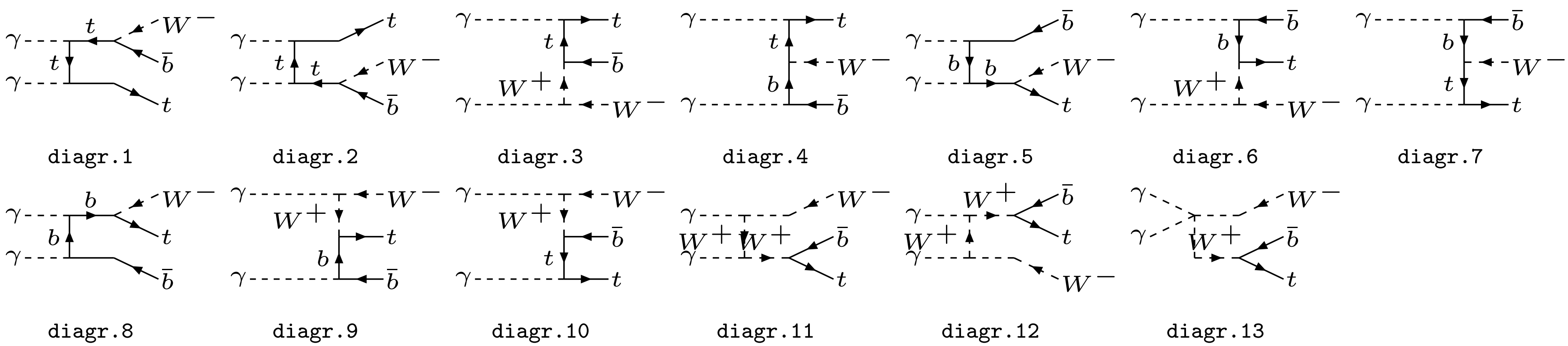


diagr.10

All the diagrams contribute to Single Top

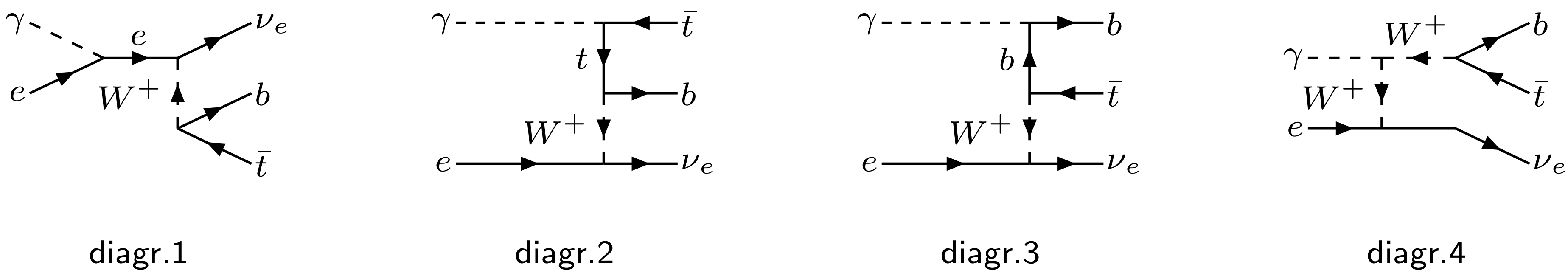
(at LEP2 the rate is too small, about 10^{-5} pb)

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.



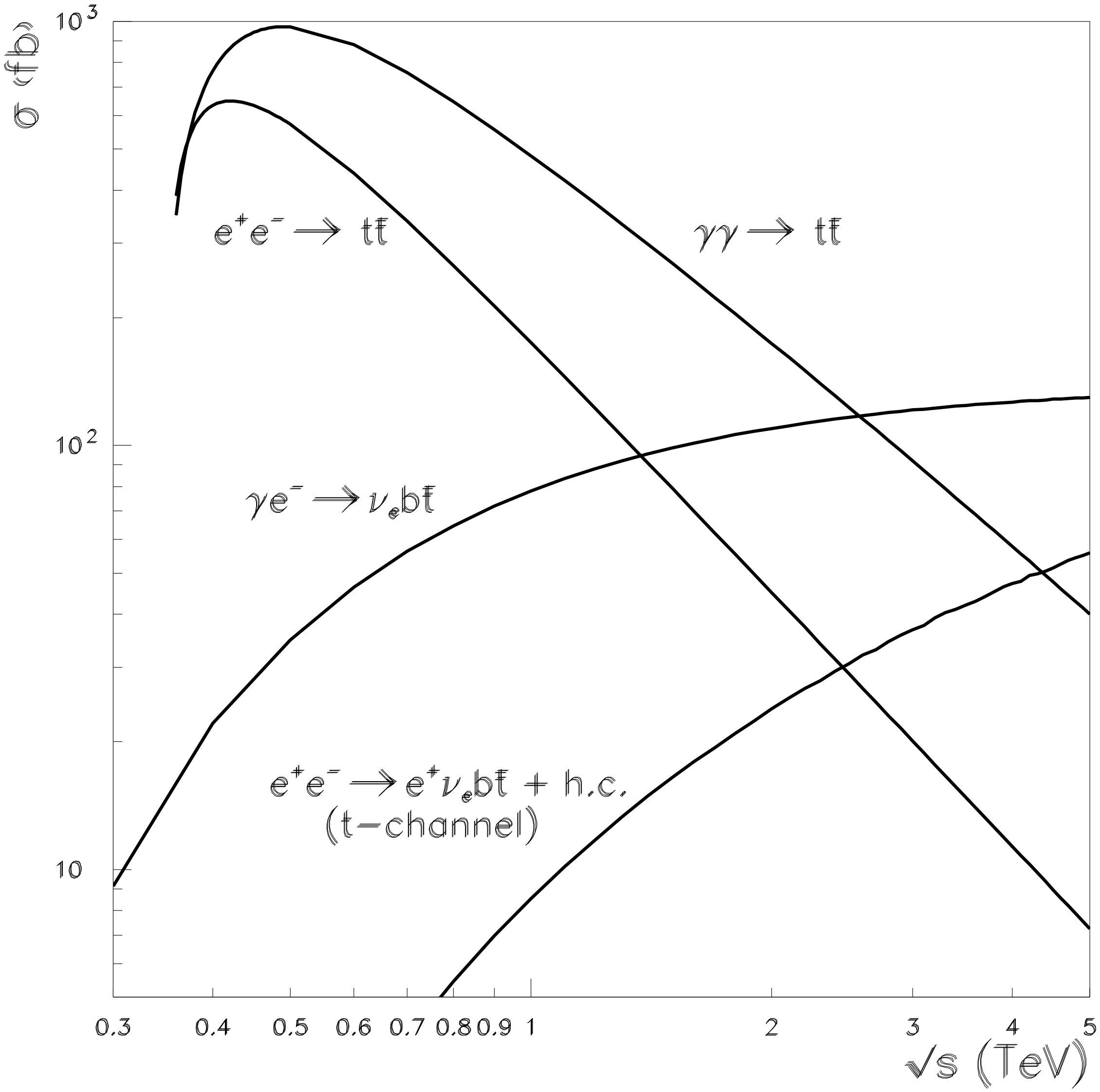
The top pair rate has to be removed in order to get the correct single top rate.

Single Top Diagrams in γe Collisions

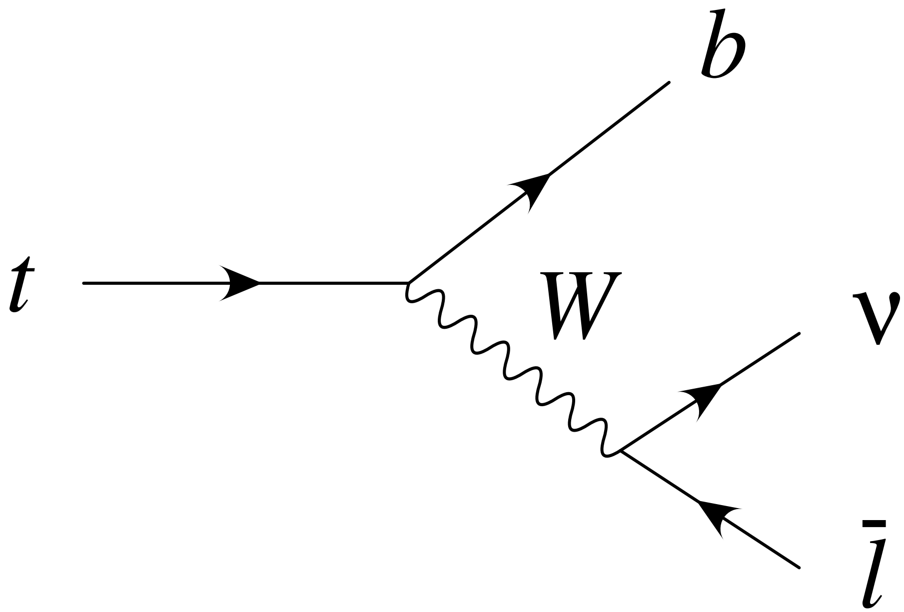


This is one of so called "gold plated" processes in γe collision mode of ILC

Cross sections of Top production processes at LC



In SM top decays to W-boson and b-quark practically with 100% probability



$d\Gamma \sim |\mathcal{M}|^2 \sim (t + ms) \cdot \ell b \cdot \nu$, where in the top-quark rest frame, the spin four-vector is $s = (0, \hat{s})$, and $\hat{s}$ is a unit vector that defines the spin quantization axis of the top quark

In the top quark rest frame:
$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \cos\theta_\ell)$
Hence the charged lepton tends to point along the direction of top spin.

Mahlon,Parke; E.B.,Sherstnev

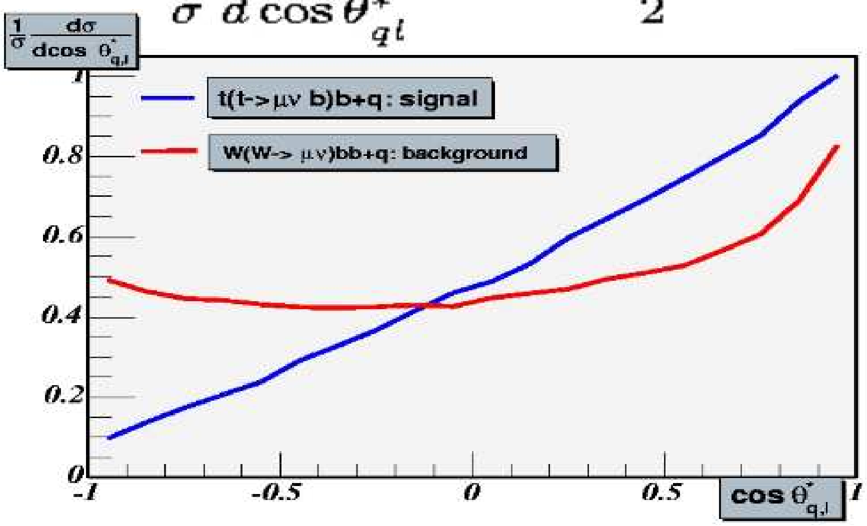
Spin_correlations:_theoretical_view

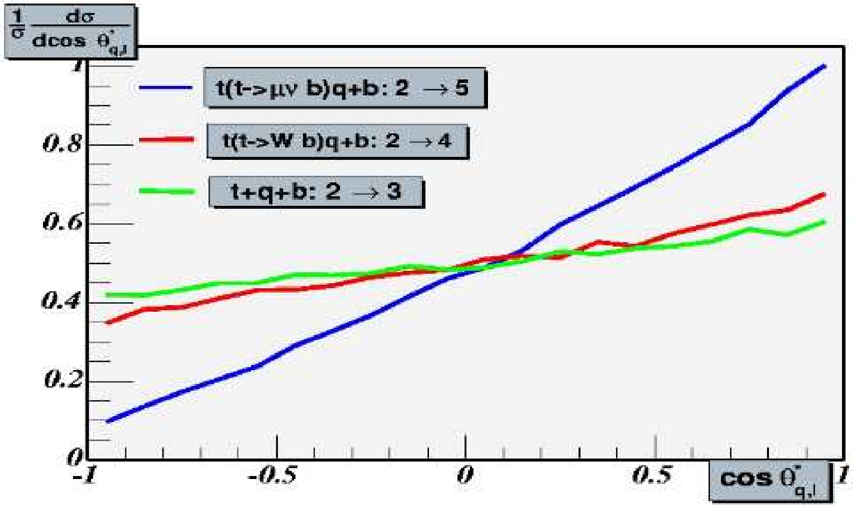
Single top quark is produced highly polarized via the Wtb vertex. Since top quarks do not have a time to form strong bound state, we can investigate a top polarization. There is a unique top spin decomposition axis in the top rest frame: momentum of lepton in top the rest frame from top decay: $t \rightarrow b\, l\, \nu_l$

For t-channel the best variable θ^*_{ql} - angle between lepton and quark momenta in the top rest frame

The top polarization can be defined as parameter P in a distribution

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



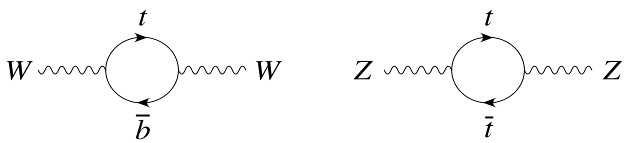


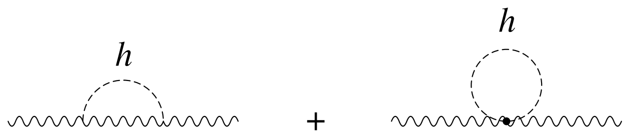
In ideal theoretical situation we have for t-channel:

$$P_{top} \approx 90\%$$

Top quark mass.

In SM W-boson, Top quark and H boson masses are connected to each other via loop contributions to W and Z propagators





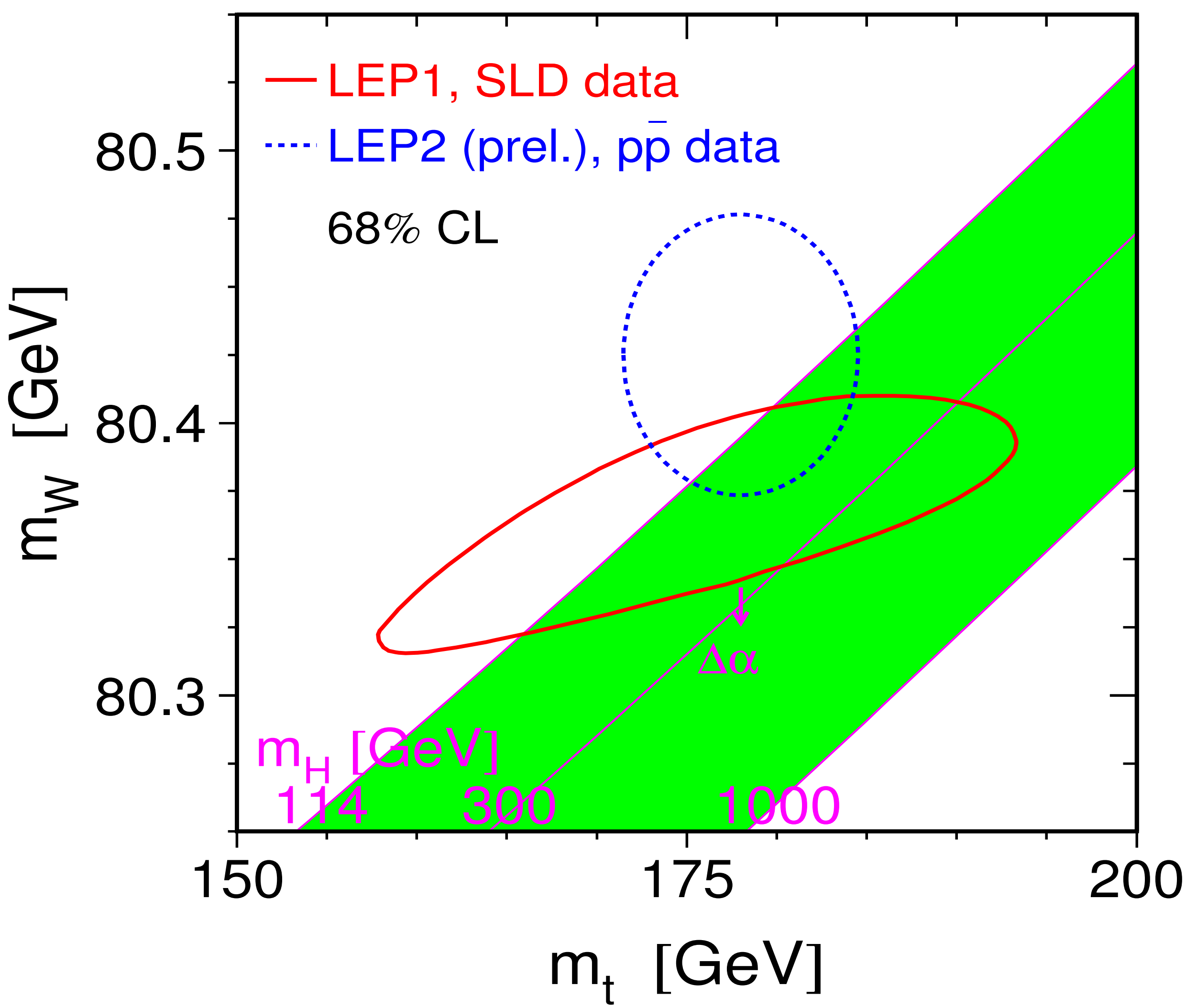
$M_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{s_W^2(1-\Delta r)}$ where Δr contains the one-loop corrections.

$(\Delta r)_{\rm top} \approx -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\frac{1}{t_W^2}$ where $t_W^2 \equiv \tan^2\theta_W$.

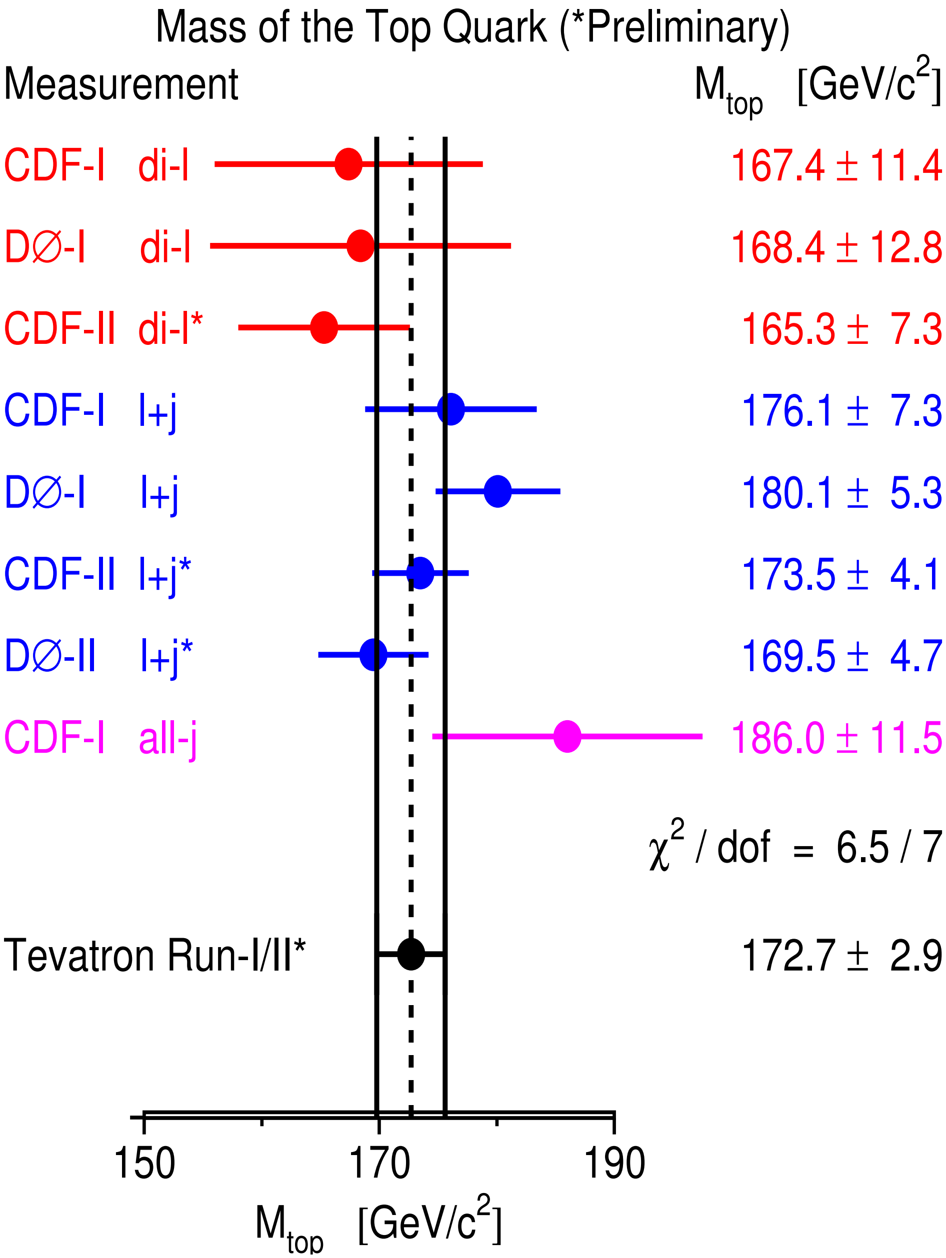
This one-loop correction depends quadratically on the top-quark mass.

$(\Delta r)_{\rm Higgs} \approx \frac{11 G_F M_Z^2 c_W^2}{24\sqrt{2}\pi^2}\ln\frac{m_h^2}{M_Z^2}$

This one-loop correction depends only logarithmically on the Higgs-boson mass, so Δr is not as sensitive to m_h as it is to m_t.



LEP1, SLD data
LEP2 (prel.), pp̄ data
68% CL
Δα
m_H [GeV]
114
300
1000
80.5
80.4
80.3
m_W [GeV]
150
175
200
m_t [GeV]



hep-ex/0507091 CDF and D0 combined

At the Tevatron Run II with $2fb^{-1}$ one expects:

$$\begin{aligned} \delta M_W &\sim 27\ MeV \\ \delta M_t &\sim 3\ GeV \end{aligned}$$

yielding a prediction for the Higgs mass with an uncertainty of

$$\frac{\delta M_h}{M_h} \sim 40\%$$

At the LHC with $10\ fb^{-1}$

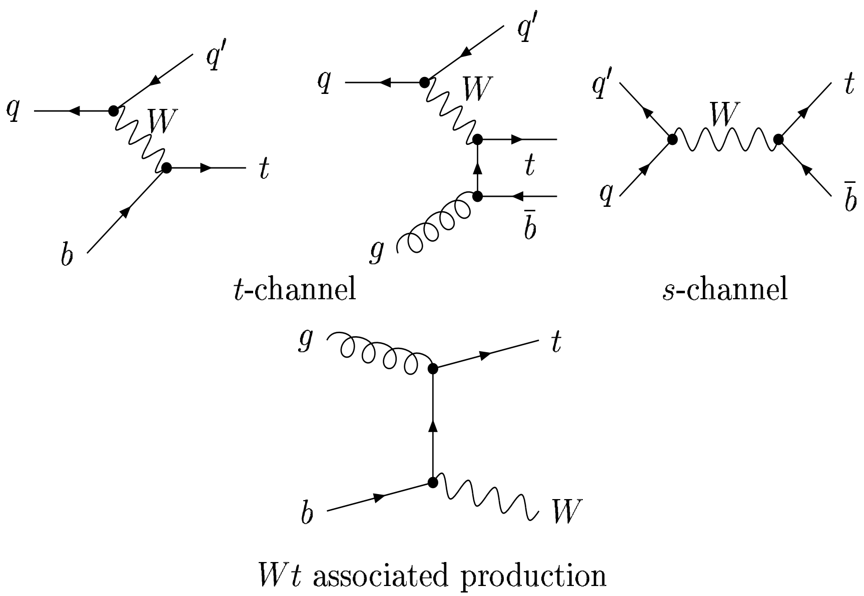
$$\delta M_t \sim 0.7\ GeV$$

At ILC with $500\ fb^{-1}$ from the top pair threshold scan one can get

$$\delta M_t \sim 0.1\ GeV$$

$|V_{tb}|$ measurements

At LHC and Tevatron Run2 via single top



V_{tb}^2 could be measured with an accuracy of 10% dominated by systematics

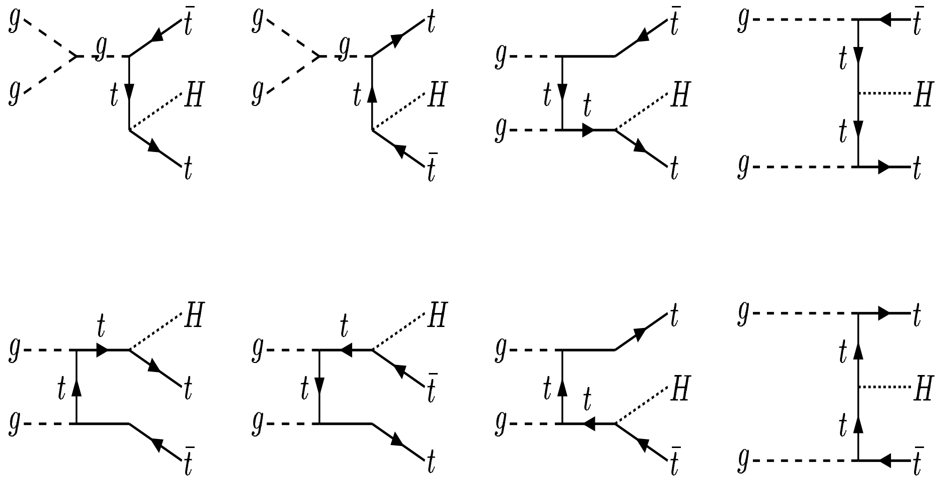
At ILC (1 TeV, 500 fb^{-1}) in $e\gamma$ collisions -
2-3 % accuracy dominated by statistics

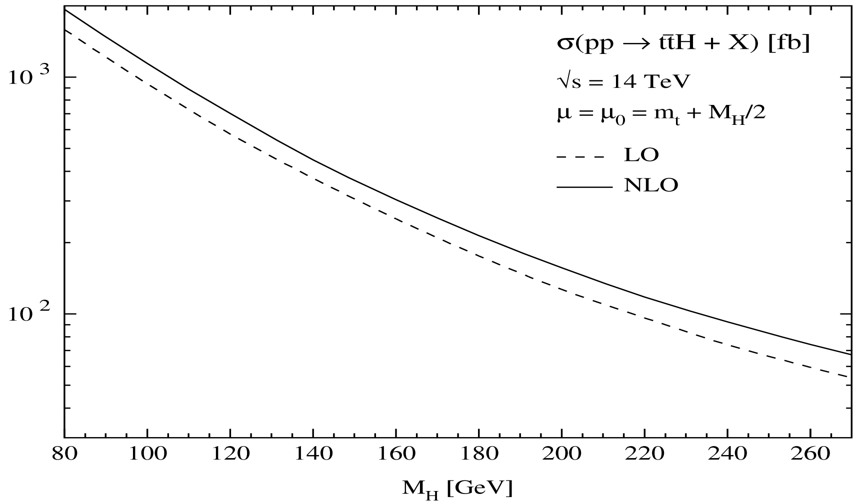
Top Yukawa coupling $t\bar{t}H$ measurements

For the LHC complete NLO computations have been performed

(LO diagrams are shown)

W. Beenakker et al. hep-ph/0211352; S.Dawson et al. hep-ph/0211438





Top Yukawa could be measured with an accuracy from 16% at low Lumi to 11% at high Lumi regime

New Physics via Top (examples):

- W_{tb} anomalous couplings
- FCNC
- Various SUSY effects without and with R-parity violation
- Charged Higgs in top decays
- New strong dynamics (W', Z', π_T, ρ_T, topgluon, $W_L W_L \to t\bar{t}$ ...)
- Kaluza-Klein graviton excitations and radion in ADD and RS scenarious
- ...

Maximal value of the CP even light Higgs in MSSM is about 135-140 GeV (not M_Z) due to large top quark mass

$$M_h^{\max} = \sqrt{M_Z^2 + \epsilon}$$

$$\epsilon = \frac{3 G_F \overline{m}_t^4}{\sqrt{2}\pi^2 \sin^2\beta}\left[f(t)\right], \qquad where \qquad t = \log\left(\frac{M_S^2}{m_t^2}\right)$$

Anomalous Top Couplings

The top quark interactions of dimension 4:

$$\begin{aligned}\mathcal{L}_4 &= -g_s \bar{t}\gamma^\mu T^a t G^a_\mu - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \bar{t}\gamma^\mu (v^W_{tq} - a^W_{tq}\gamma_5) q W^+_\mu \\ &\quad -\frac{2}{3} e \bar{t}\gamma^\mu t A_\mu - \frac{g}{2\cos\theta_W} \sum_{q=u,c,t} \bar{t}\gamma^\mu (v^Z_{tq} - a^Z_{tq}\gamma_5) q Z_\mu\end{aligned}$$

The dimension 5 couplings have the generic form:

$$\begin{aligned}\mathcal{L}_5 &= -g_s \sum_{q=u,c,t} \frac{\kappa^g_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f^g_{tq} + i h^g_{tq}\gamma_5) q G^a_{\mu\nu} - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \frac{\kappa^W_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^W_{tq} + i h^W_{tq}\gamma_5) q W^+_{\mu\nu} \\ &\quad -e \sum_{q=u,c,t} \frac{\kappa^\gamma_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^\gamma_{tq} + i h^\gamma_{tq}\gamma_5) q A_{\mu\nu} - \frac{g}{2\cos\theta_W} \sum_{q=u,c,t} \frac{\kappa^Z_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^Z_{tq} + i h^Z_{tq}\gamma_5) q Z_{\mu\nu}\end{aligned}$$

where $|f|^2 + |h|^2 = 1$.

Present constrains come from

- Low energy data via loop contributions
  $K_L \to \mu^+\mu^-$, $K_L - K_S$ mass difference, $b \to l^+l^-X$, $b \to s\gamma$
- LEP2
- Tevatron Run1
- HERA
- Unitarity violation bounds

Anomalous Wtb Couplings

- Lagrangian

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

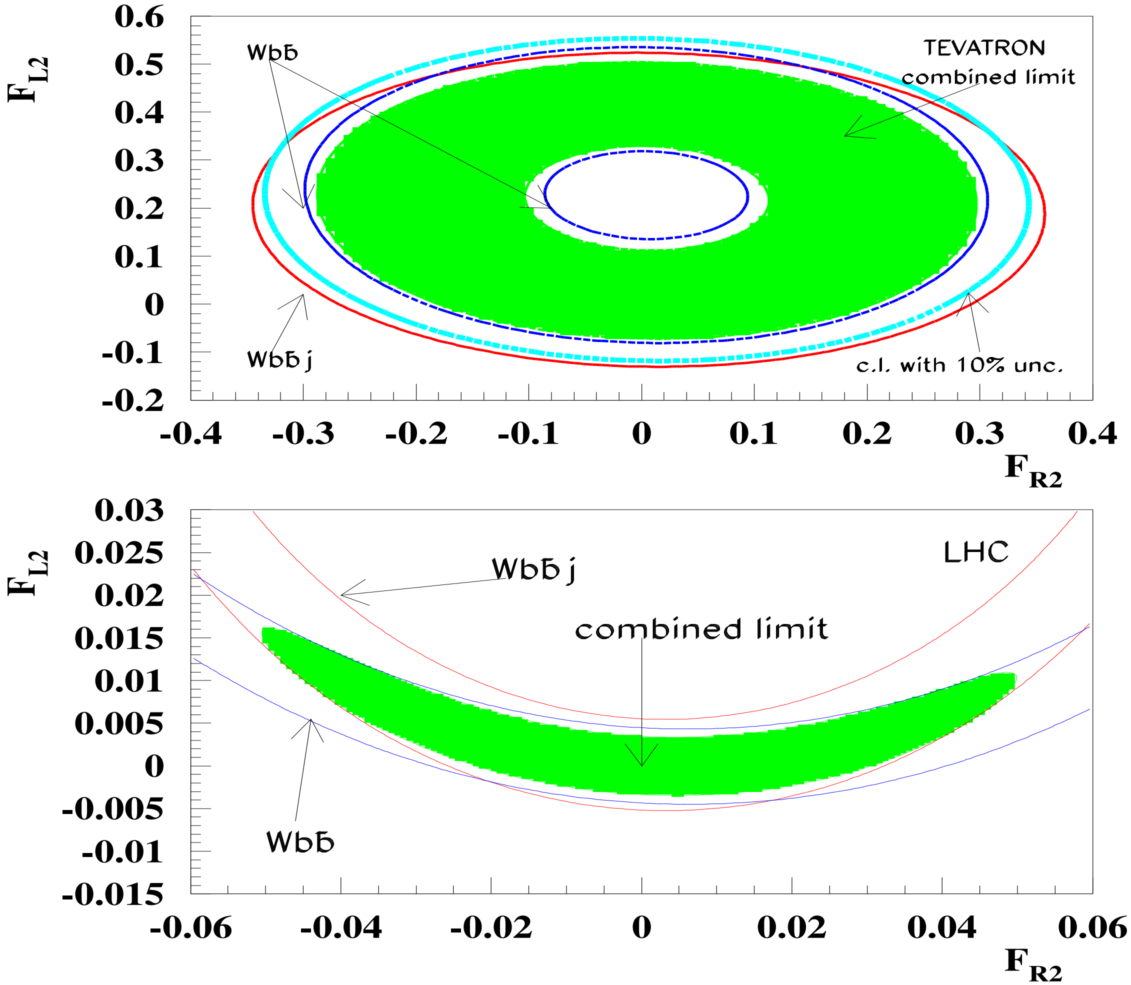
with $W_{\mu\nu}^{\pm} = D_\mu W_\nu^{\pm} - D_\nu W_\mu^{\pm}$, $D_\mu = \partial_\mu - ieA_\mu$,
$\sigma^{\mu\nu} = i/2[\gamma_\mu, \gamma_\nu]$ and $P_{\pm} = (1 \pm \gamma_5)/2$. The couplings F_2^L and F_2^R are proportional to the coefficients of the effective Lagrangian
$F_{L2} = \frac{2M_W}{\Lambda} \kappa_{tb}^W (-f_{tb}^W - ih_{tb}^W)$,
$F_{R2} = \frac{2M_W}{\Lambda} \kappa_{tb}^W (-f_{tb}^W + ih_{tb}^W)$, $|F_{L2,R2}| < 0.6$ from unitary bounds

- $|V_{tb}|$ is very close to 1 in SM with 3 generations. ($|V_{tb}|$ is very weakly constrained in case of 4 generations, e.g.)

- A possible $V + A$ form factor is severely constrained by the CLEO $b \to s\gamma$ data to 3×10^{-3} level

Wtb anomalous couplings limit on TEVATRON and LHC:

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



Uncorrelated limits on anomalous couplings from measurements at different machines.

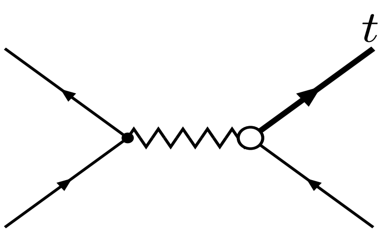
	F_2^L	F_2^R
Tevatron ($\Delta_{sys.} \approx 10\%$)	$-0.18 \div +0.55$	$-0.24 \div +0.25$
LHC ($\Delta_{sys.} \approx 5\%$)	$-0.052 \div +0.097$	$-0.12 \div +0.13$
γe ($\sqrt{s_{e^+e^-}} = 0.5$ TeV)	$-0.1 \div +0.1$	$-0.1 \div +0.1$
γe ($\sqrt{s_{e^+e^-}} = 2.0$ TeV)	$-0.008 \div +0.035$	$-0.016 \div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

FCNC couplings

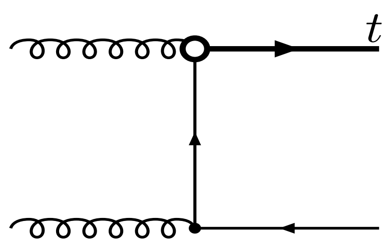
- Couplings: $tqg,\ tq\gamma,\ tqZ$, where $q = u, c$

$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda}\left[\kappa_{tq}^{\gamma,Z} e\bar{t}\sigma_{\mu\nu} q F^{\mu\nu}_{\gamma,Z} + \kappa_{tq}^{g} g_s \bar{t}\sigma_{\mu\nu}\frac{\lambda^i}{2} q G^{i\mu\nu}\right] + h.c.$$

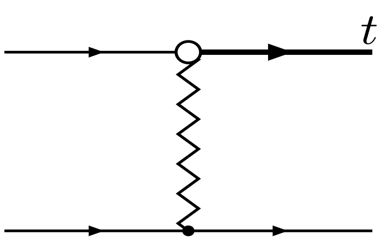
Information on FCNC couplings come from either top pair production with subsequent decays to rear modes $t \to q\,V$, where $V = \gamma, Z, g$
or from additional contributions to the single top production



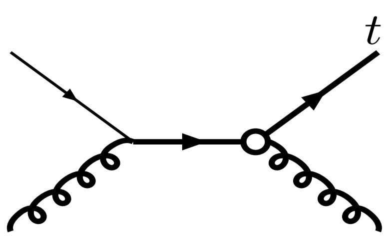
$q\bar{q} \to t\bar{c}$



$cg \to tg$



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



$gg \to t\bar{c}$

All present and expected limits are presented in terms of Br fractions:

$$\Gamma(t \to qg) = \left(\frac{\kappa^g_{tq}}{\Lambda}\right)^2 \frac{8}{3}\alpha_s m_t^3 \quad , \quad \Gamma(t \to q\gamma) = \left(\frac{\kappa^\gamma_{tq}}{\Lambda}\right)^2 2\alpha m_t^3,$$

$$\Gamma(t \to qZ)_\gamma = \left(|v^Z_{tq}|^2 + |a^Z_{tq}|^2\right) \alpha\, m_t^3 \frac{1}{4M_Z^2 \sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_Z^2}{m_t^2}\right),$$

$$\Gamma(t \to qZ)_\sigma = \left(\frac{\kappa^Z_{tq}}{\Lambda}\right)^2 \alpha\, m_t^3 \frac{1}{\sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(2 + \frac{M_Z^2}{m_t^2}\right)$$

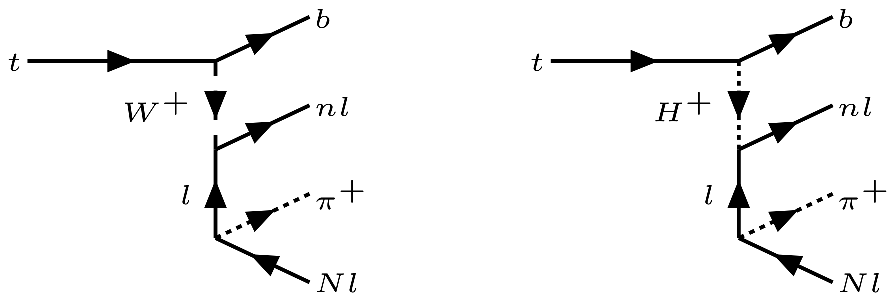
Current constraints

	CDF	LEP-2	HERA
BR($t \to gq$)	$\leq 29\%$	–	–
BR($t \to \gamma q$)	$\leq 3.2\%$	–	$\leq 0.7\%$
BR($t \to Zq$)	$\leq 32\%$	$\leq 7.0\%$	–

Future expectations

	Tevatron	LHC		e^+e^-
$t \longrightarrow$	Run II	decay	production	$\sqrt{s} > 500$ GeV
$g\,q$	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}

Charged Higgs in Top Decay (impact of tau polarization)



diagr.1 diagr.2

In the rest frame of top $t \to bR \to b\tau\nu_\tau \to b\nu_\tau\bar{\nu}_\tau\pi$

where a resonance R is W boson or charged H

$$\frac{1}{\Gamma}\frac{d\Gamma}{dy_\pi} = \frac{1}{x_{max}-x_{min}} \begin{cases} (1-P_\tau)log\frac{x_{max}}{x_{min}} + 2P_\tau y_\pi(\frac{1}{x_{min}} - \frac{1}{x_{max}}), & 0 < y_\pi < x_{min} \\ (1-P_\tau)log\frac{x_{max}}{y_\pi} + 2P_\tau(1 - \frac{y_\pi}{x_{max}}), & x_{min} < y_\pi \end{cases}$$

where $y_\pi = \frac{E_\pi^{top}}{M_{top}}, \quad x_{min} = \frac{E_\tau^{min}}{M_{top}}, \quad x_{max} = \frac{E_\tau^{max}}{M_{top}}, \quad E_\tau^{min} = \frac{M_R^2}{2M_{top}}, \quad E_\tau^{max} = \frac{M_{top}}{2}$

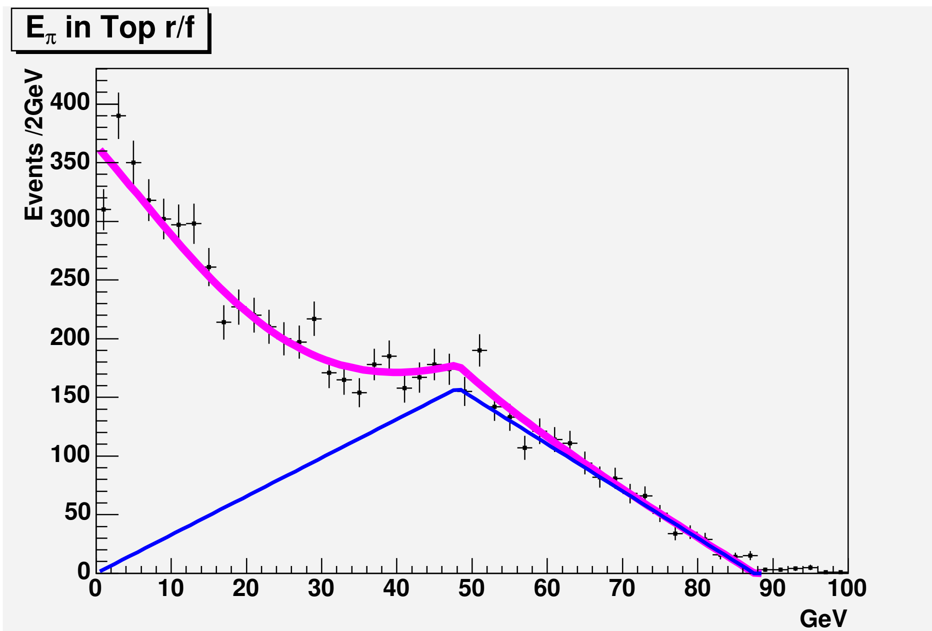
$P_\tau = -1$ for W boson and $P_\tau = 1$ for charged Higgs

$e^+e^- \to t\bar{t} \to \tau\nu_\tau b\bar{b} + 2jets$

Simulations are performed for e^+e^- collisions at 500 GeV cms
and for 500 fb^{-1} integrated luminosity

π-meson energy spectrum for the MSSM point
$\tan\beta = 50$, $\mu = 500$, $M_{H^\pm} = 130\ GeV$ with $Br(t \to H^+ b) = 9.1\%$

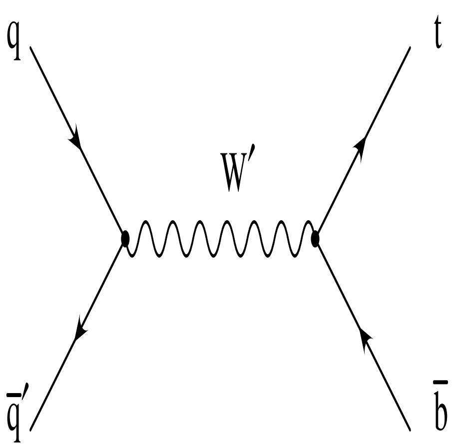
E.B., S.Bunichev, M.Carena, C.Wagner

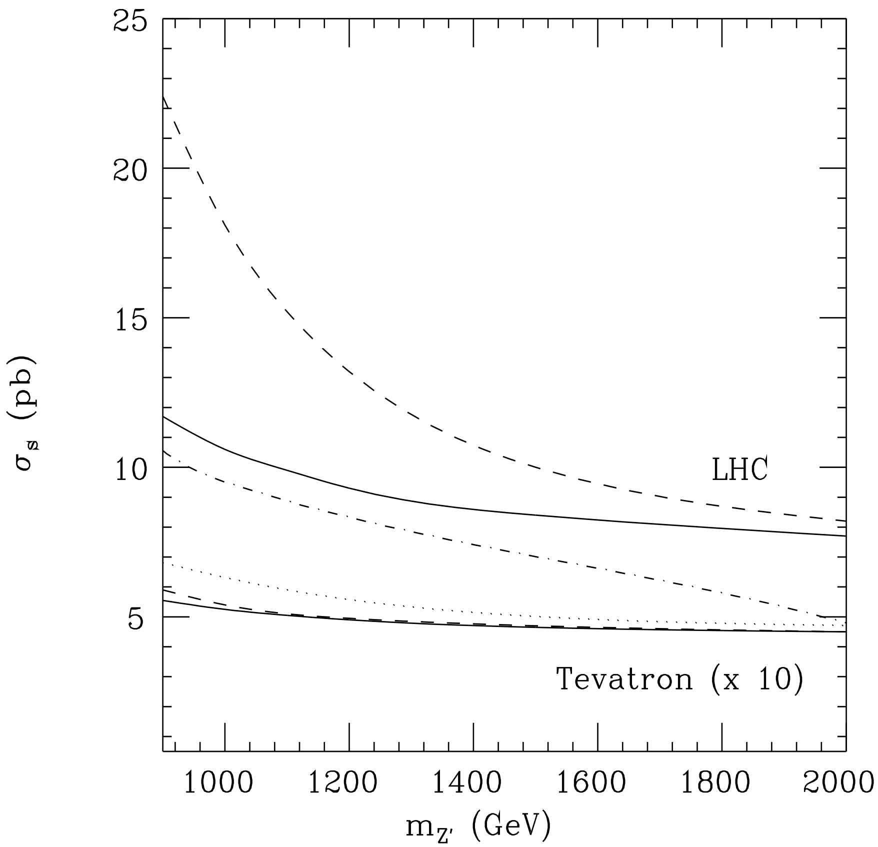


From the signal+backgr fit $M_{H^\pm}$ = 129.4 +/- 0.9 GeV

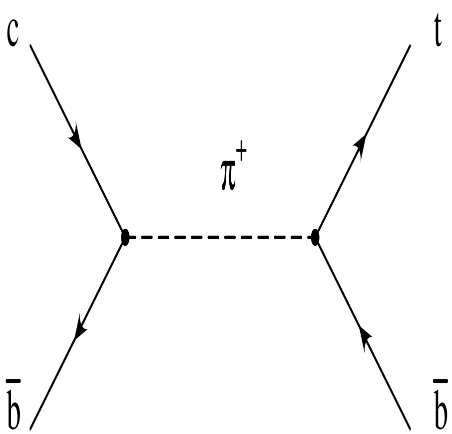
Extra Vector and Scalar Bosons

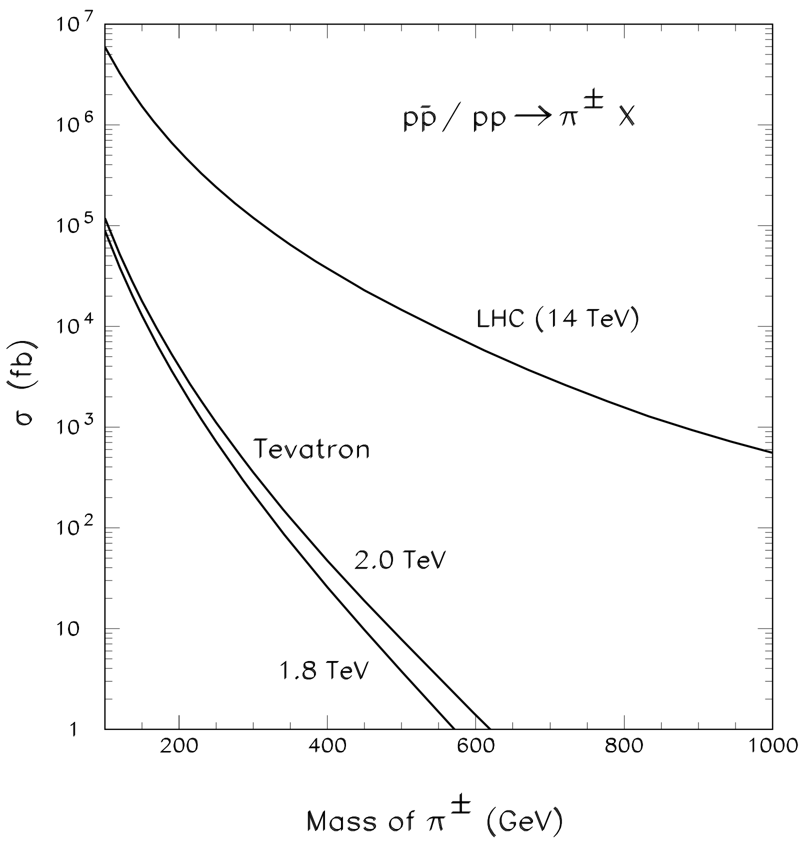
T.Tait, C.-P.Yuan hep-ph/0007298





The NLO rate of $q\,\bar{q}' \to W, W' \to t\,\bar{b}$ (σ_S) in pb at the Tevatron (lower curves) and LHC (upper curves) for various coupling parameters

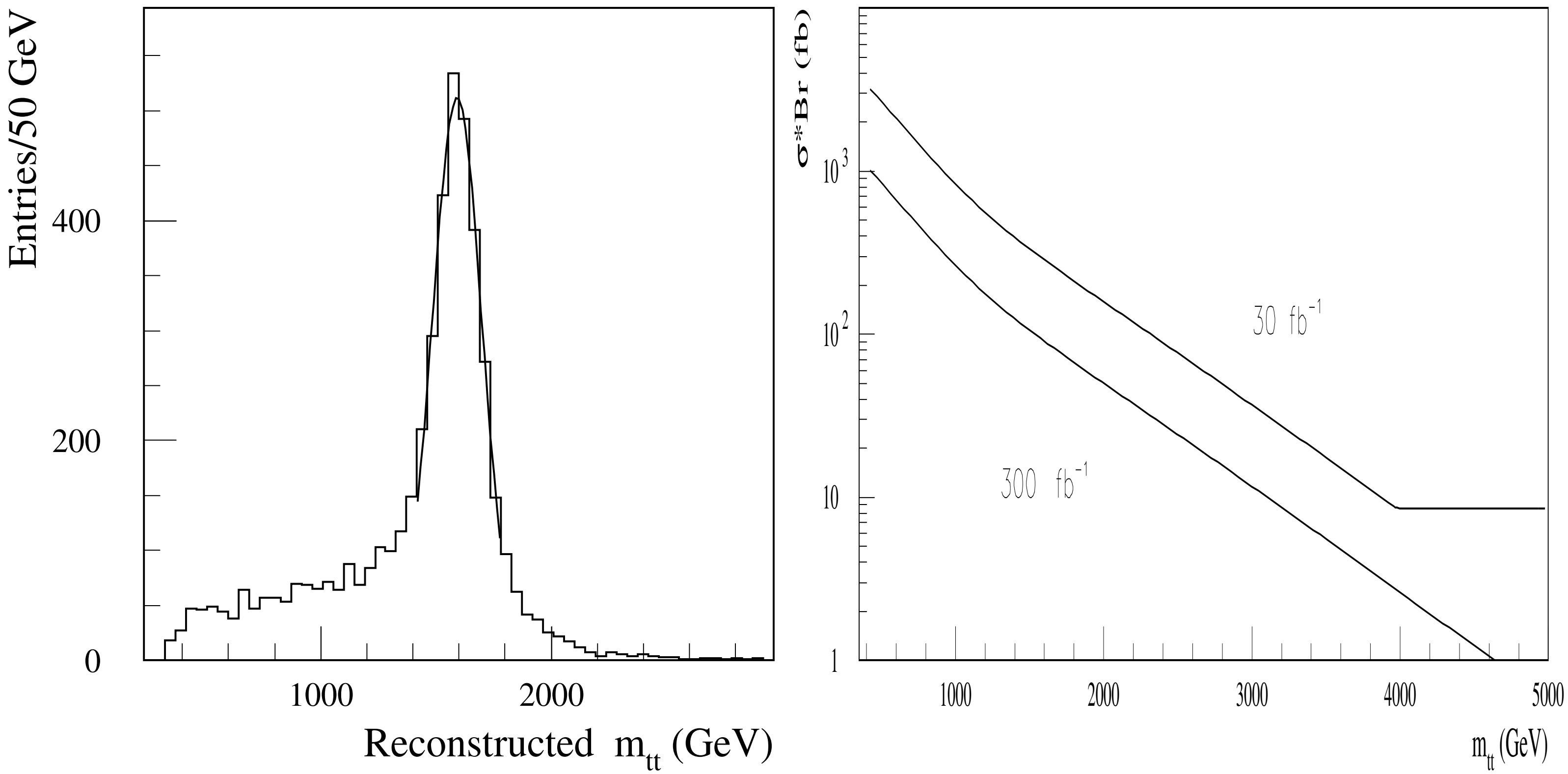




The LO rate of single top production through the reaction $c\,\bar{b} \to \pi^+ \to t\,\bar{b}$ as a function of $M_{\pi^\pm}$ in the top-color model.

Generic search for a resonance in top pair production at the LHC

(MSSM Higgses H/A, Z', topgluon, RS-graviton, KK excitations in UED etc.)

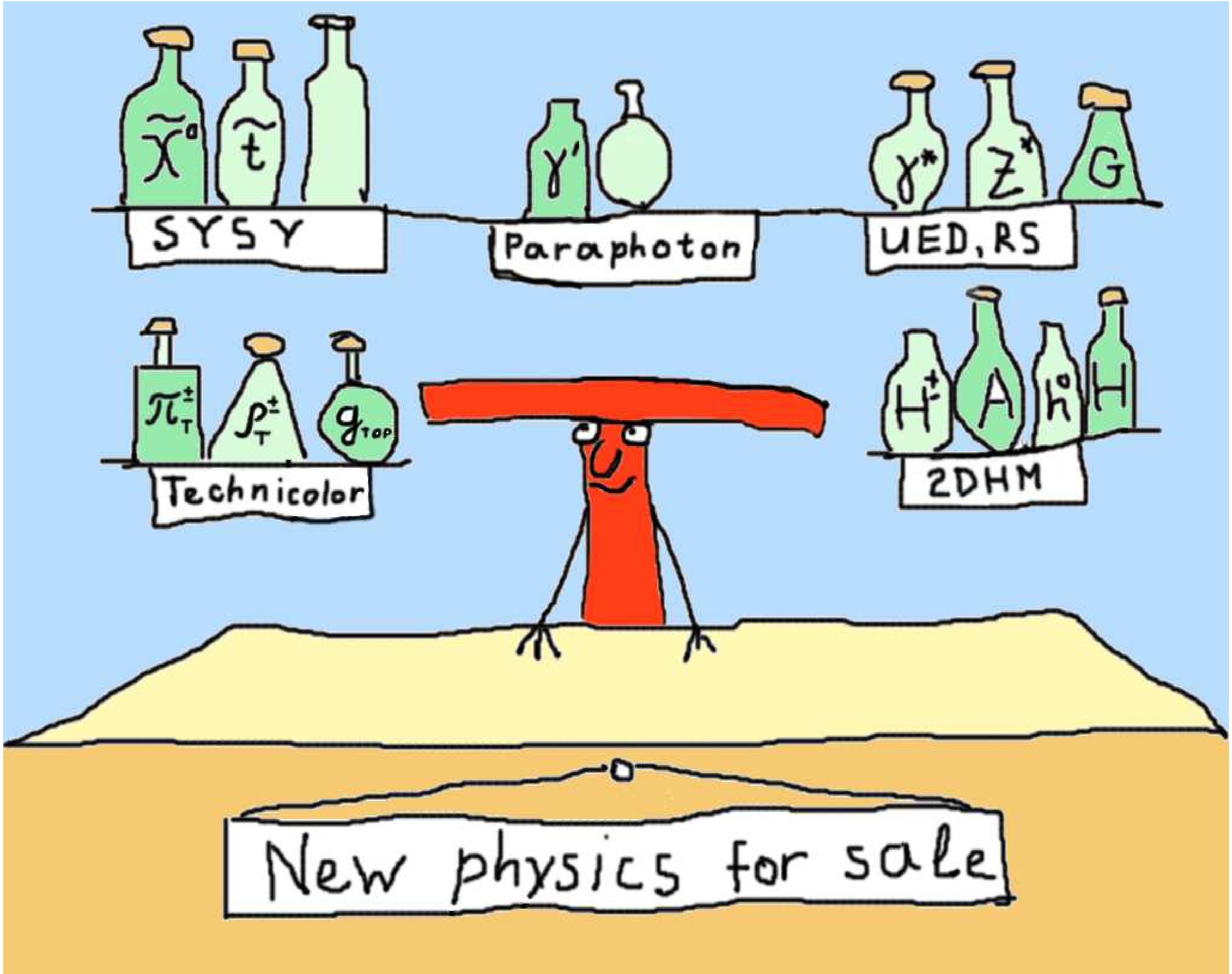


Measured $t\bar{t}$ invariant mass distribution for reconstruction of a narrow resonance of mass 1600 GeV decaying to $t\bar{t}$ and value of $\sigma\times$ BR required for a 5σ discovery potential.

Conclusions

Discovery of the top quark has opened up many new avenues to interesting physics

- Precision measurements of top quark characteristics such as mass, production cross sections, decay width and branching fractions, spin correlations are needed to test the SM
- Tests and understanding all possible deviations from the SM expectations to check if top is exotic in some way
- Precise calculations and simulations, and measurements of the top event kinematical characteristics to understand backgrounds to many other possible New physics processes
- Possible discovery and study of various New physics effects via top production and/or decay



$\tilde{\chi}^0$
$\tilde{t}$
SYSY
γ'
Paraphoton
γ^*
Z^*
G
UED, RS
$\pi_T^\pm$
$\rho_T^\pm$
g_{TOP}
Technicolor
$H^\pm$
A
h^0
H
2DHM
New physics for sale

V. Bunichev