Single Top Quarks at a Linear Collider

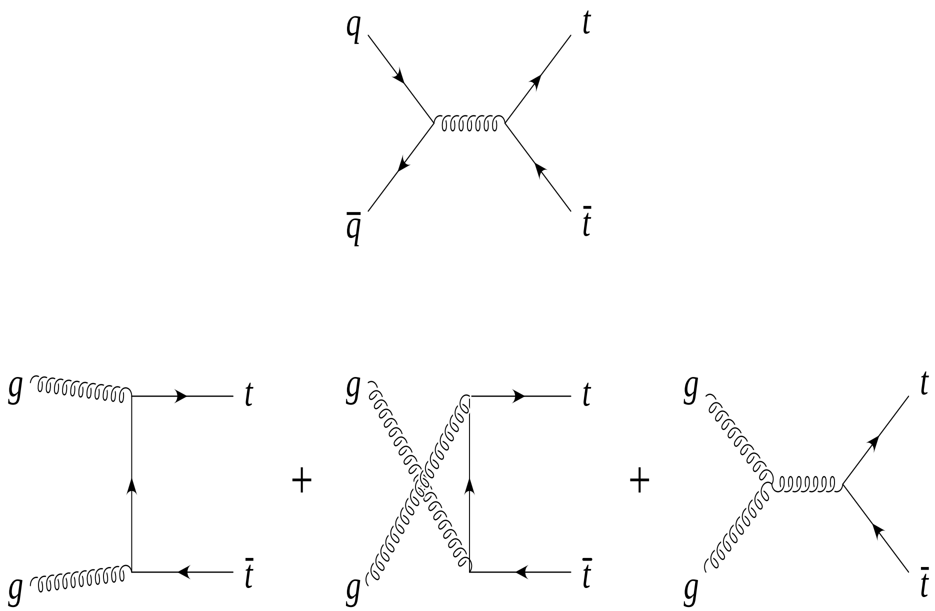
Edward Boos

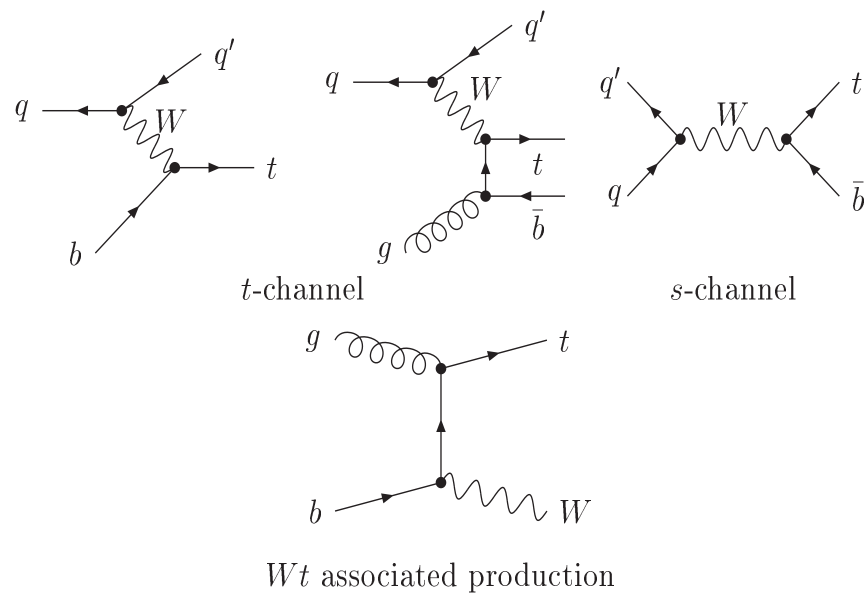
High Energy Theory Division
Skobeltsyn Institute of Nuclear Physics, Moscow State University

Outline

- Introduction. Single top at Tevatron and LHC
- Basic production processes at a linear collider
- Decays and spin correlations
- V_{tb}
- "New Physics" via single top (few examples)
- Conclusions

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 ($Q_W^2 < 0$)

s-channel ($Q_W^2 > 0$)

associated tW ($Q_W^2 = M_W^2$)

Q_W^2 - W-boson virtuality

First single top evidence by D0 at the Tevatron

- $\sigma(s+t) = 4.8 \pm 1.3$ pb, 3.5σ significance
- First $|V_{tb}|$ direct measurement, $|V_{tb}| > 0.68$ at 95% C.L.
- Good agreement of various independent multivariate analysis methods

The main goals to search for single top:

- Additional to top pair channel of the top quark production
- Direct $|V_{tb}|$ CKM matrix element measurement
- Unique spin correlations properties
- Searches for "New physics"
  - W_{tb} anomalous couplings
  - FCNC
  - Searches for new charged resonances: W' (f.e. Kaluza-Klein excitation of W-boson), charged Higgs etc
- Significant background to Higgs and many "new physics" (MSSM) processes
- New delicate analysis techniques to extract small signals

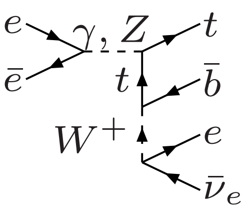
Top pair and single top in e^+e^- collisions (ILC) - both electroweak

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

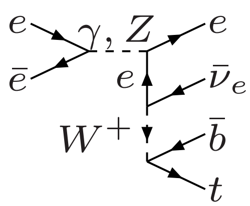
where e.g. for W^+

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

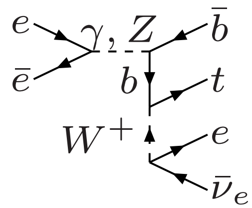
Gauge invariant s-channel subset of 10 diagrams



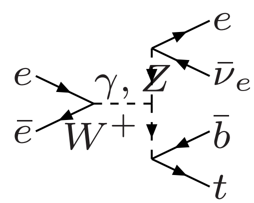
diagr.1,2



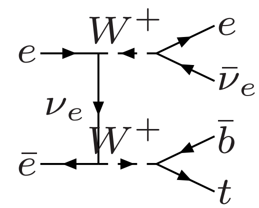
diagr.3,4



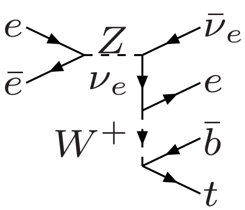
diagr.5,6



diagr.7,8



diagr.9



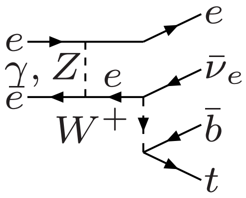
diagr.10

One should substract top pair from the total contribution in the s-channel subset

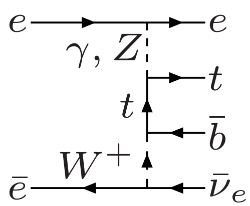
$$\sigma_{singletop} = \int dM_{e\nu b} \left(d\sigma^{CTL}/dM_{e\nu b} - d\sigma^{BW}/dM_{e\nu b} \right)$$

CTL - complete tree-level contribution; BW - Breit-Wigner contribution

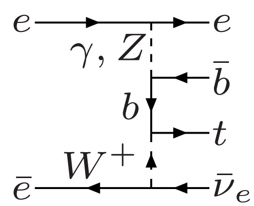
Gauge invariant t-channel subset of 10 diagrams



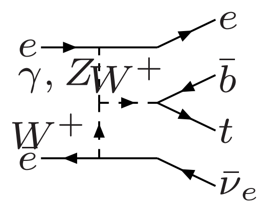
diagr.1,2



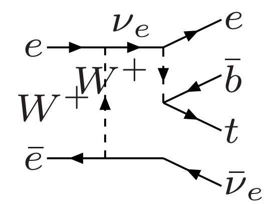
diagr.3,4



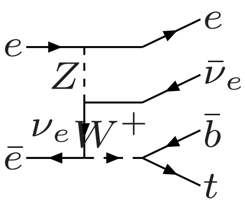
diagr.5,6



diagr.7,8



diagr.9

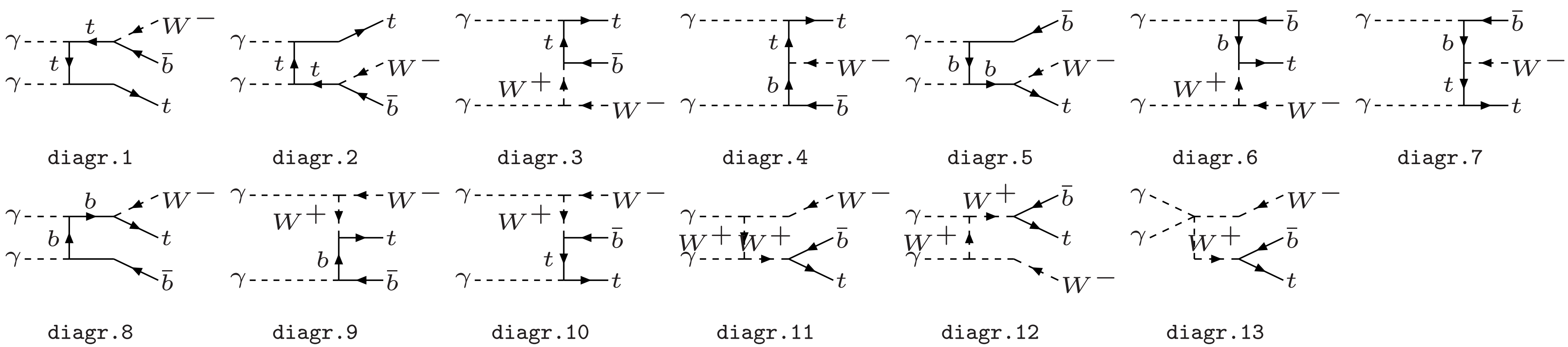


diagr.10

All the diagrams contribute to Single Top

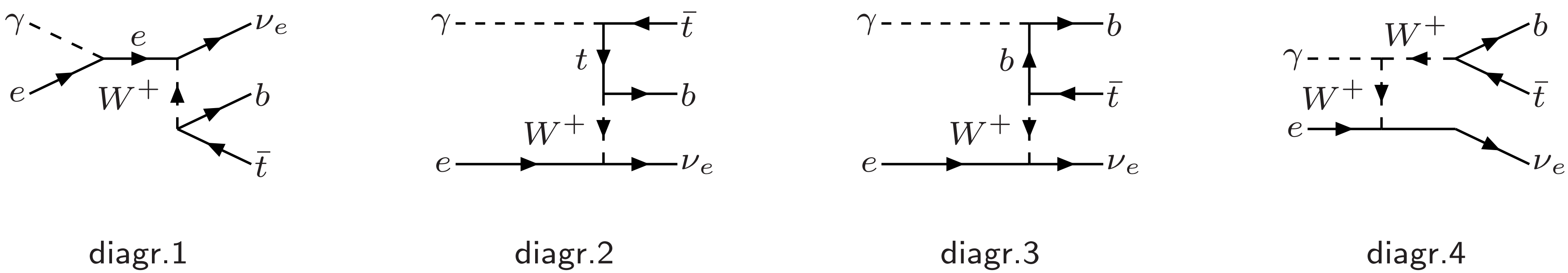
(at LEP2 the rate is too small, about 10^{-5} pb)

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.



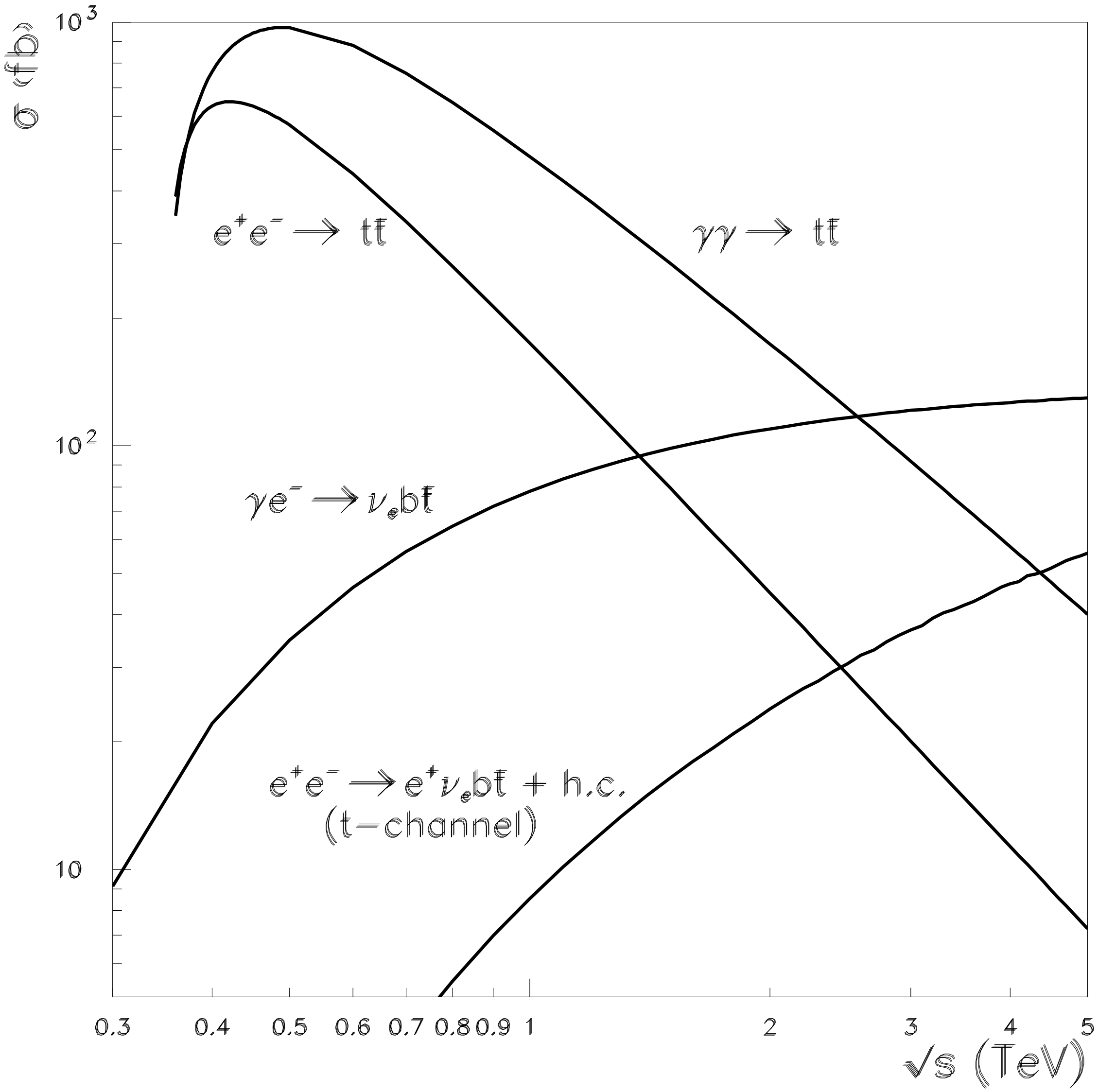
The top pair rate has to be removed in order to get the correct single top rate.

Single Top Diagrams in γe Collisions

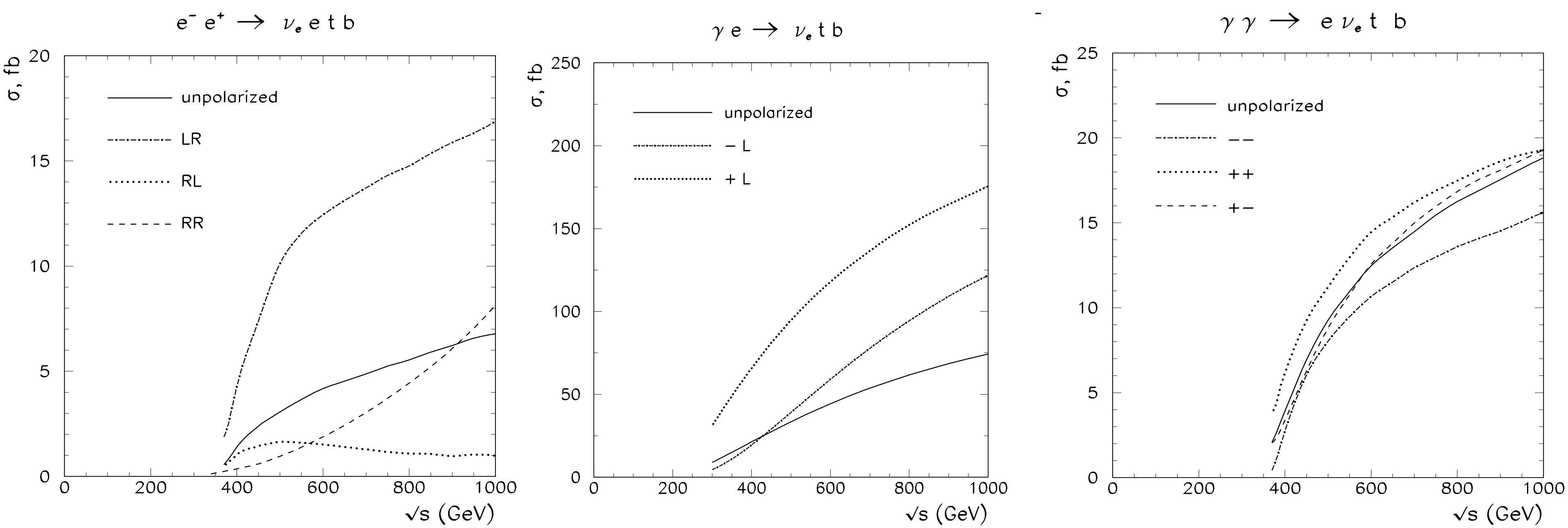


This is one of so called "gold plated" processes in γe collision mode of ILC

Cross sections of Top production processes at LC



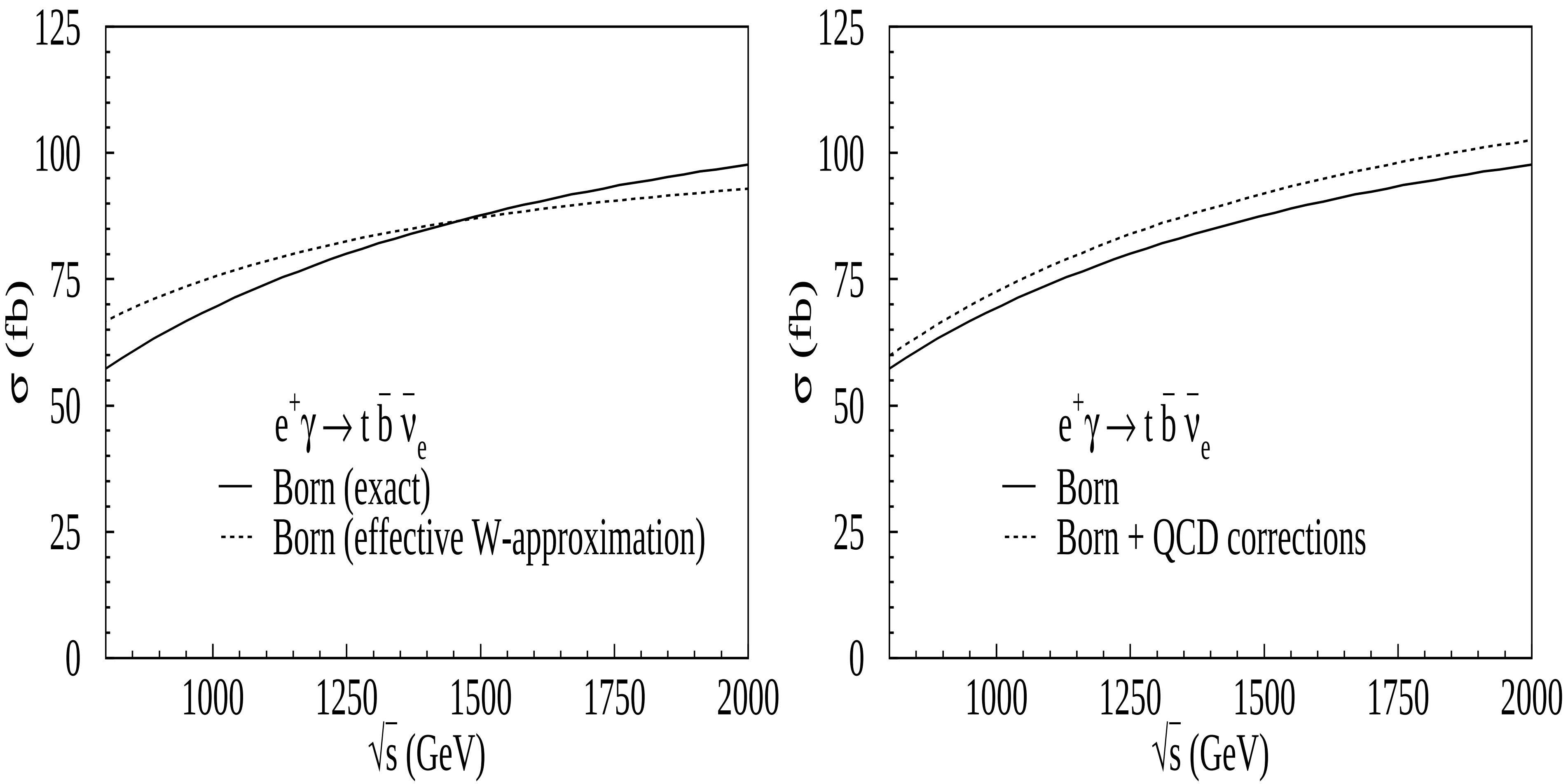
Cross sections of Single top production for polarized collisions



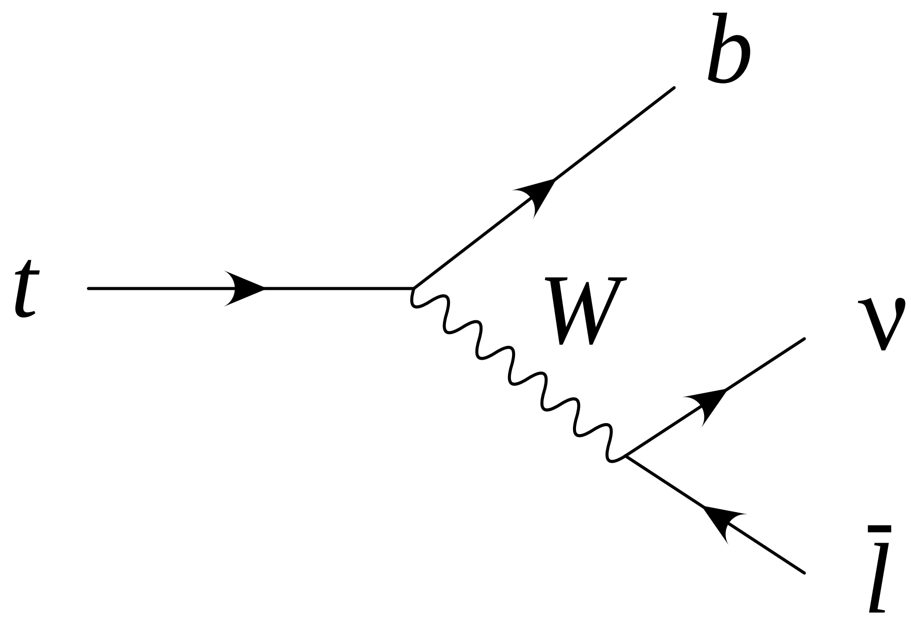
E.B., M. Dubinin, A. Pukhov, M. Sachwitz, H.J. Schreiber

NLO corrections in the effective W-approximation

J.H. Kuhn, C. Sturm, and P. Uwer



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

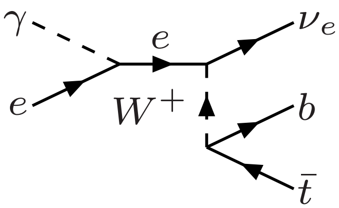
In the top quark rest frame:

$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \cos\theta_\ell)$

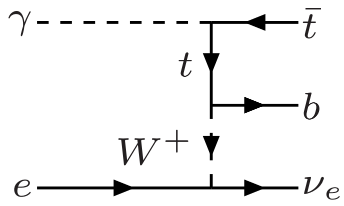
Hence the charged lepton tends to point along the direction of top spin.

Single Top production as a decay back in time

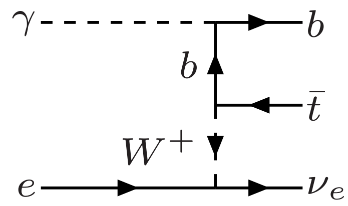
E.B., A.Sherstnev



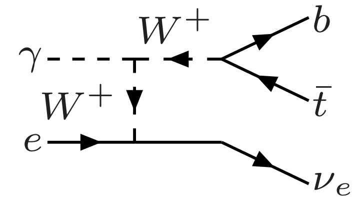
diagr.1



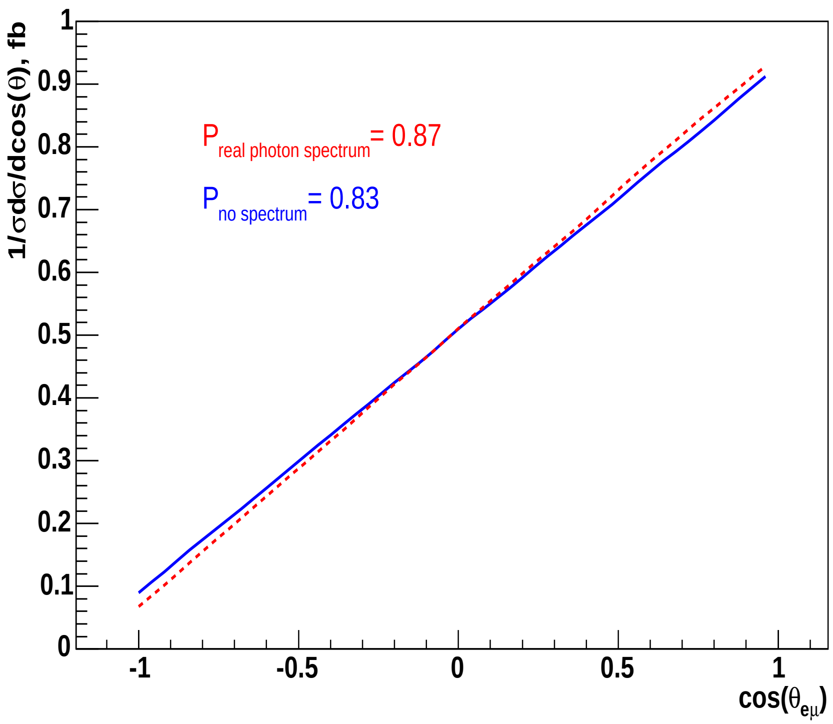
diagr.2



diagr.3



diagr.4



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

$|V_{tb}|$ measurements

If CKM unitarity and 3 generations are assumed

$|V_{tb}| = 0.9991^{+0.000034}_{-0.00004}$

Without the 3-generation unitarity constrain $|Vtb|$ is left practically unconstrained

$|Vtb| = 0.07 - 0.9993$

From top quark loop contributions to $\Gamma(Z \to b\bar{b})$

$|V_{tb}| = 0.77^{+0.18}_{-0.24}$

From measurements of $R = \frac{|V_{tb}|^2}{|V_{tb}|^2+|V_{ts}|^2+|V_{td}|^2}$ by D0 and CDF analysing top pair production

$R = 1.03^{+0.19}_{-0.17} => |V_{tb}| > 0.78$

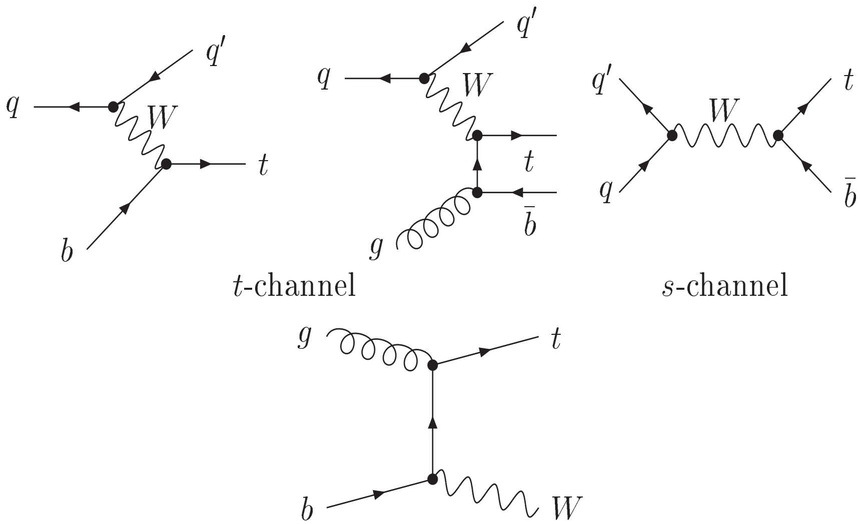
Measurements from the single top: Production*Decays $=> |V_{tb}|^2 \frac{|V_{tb}|^2}{|V_{tb}|^2+|V_{ts}|^2+|V_{td}|^2+(Exotics)}$

Assumptions (no 3-generation unitarity constrain):

* V-A interaction
* $|V_{tb}|^2 >> |V_{ts}|^2 + |V_{td}|^2 + (Exotics)$

$|V_{tb}|$ measurements

At LHC and Tevatron Run2 via single top



t-channel

s-channel

Wt associated production

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 -

1-2 % accuracy dominated by statistics

New Physics via Single Top at LC (examples):

- W_{tb} anomalous couplings
- Charged Higgs in top decays
- ...

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. Various assumptions

1. Magnetic type couplings E.B., L.Dudko, T.Ohl; E.B., M.Dubinin, A.Pukhov, M.Sahwitz, J.Schreiber

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

Expected sensitivity for Wtb anomalous couplings measurements at different machines.

The total integrated luminosity was assumed to be 500 fb^{-1} for e^+e^- collisions and 250 fb^{-1} and 500 fb^{-1} for γe collisions at 500 GeV and 2 TeV, respectively.

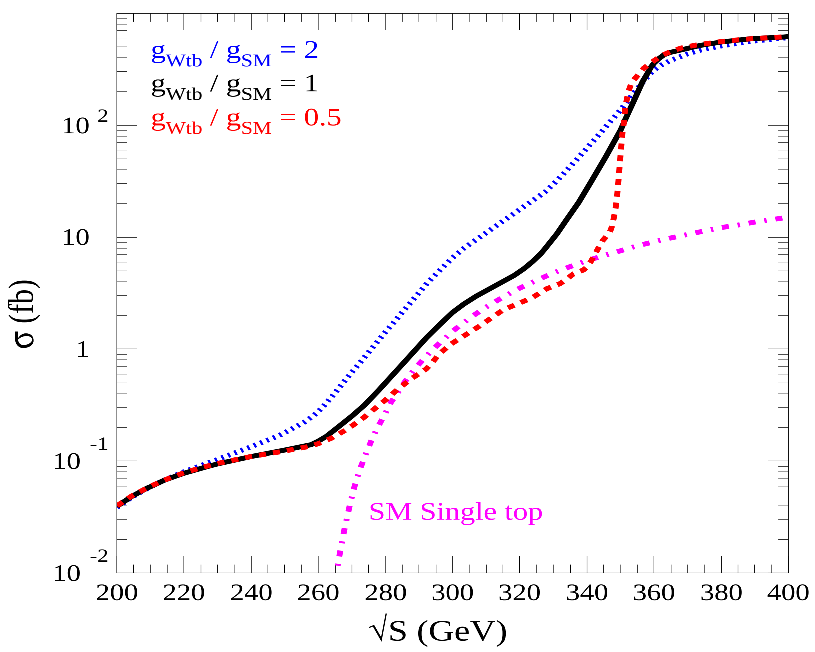
	f_2^L	f_2^R
Tevatron ($\Delta_{sys.} \approx 10\%$)	$-0.18 \div +0.55$	$-0.24 \div +0.25$
LHC ($\Delta_{sys.} \approx 5\%$)	$-0.052 \div +0.097$	$-0.12 \div +0.13$
e^+e^- ($\sqrt{s_{e^+e^-}} = 0.5$ TeV)	$-0.025 \div +0.025$	$-0.2 \div +0.2$
γe ($\sqrt{s_{e^+e^-}} = 0.5$ TeV)	$-0.045 \div +0.045$	$-0.045 \div +0.045$
γe ($\sqrt{s_{e^+e^-}} = 2.0$ TeV)	$-0.008 \div +0.035$	$-0.016 \div +0.016$

2. Left operator only P.Batra and T.Tait

$$g_{Wtb}\,\bar{t}\gamma^{\mu}W^{+}_{\mu}P_{L}b + h.c.$$

g_{Wtb} may be significantly different from SM values in various SM extensions with non-linear or linear of the EW symmetry breaking

Nice idea - to explore the region below $t\bar{t}$ pair threshold $e^{+}e^{-} \rightarrow W^{+}bW^{-}\bar{b}$

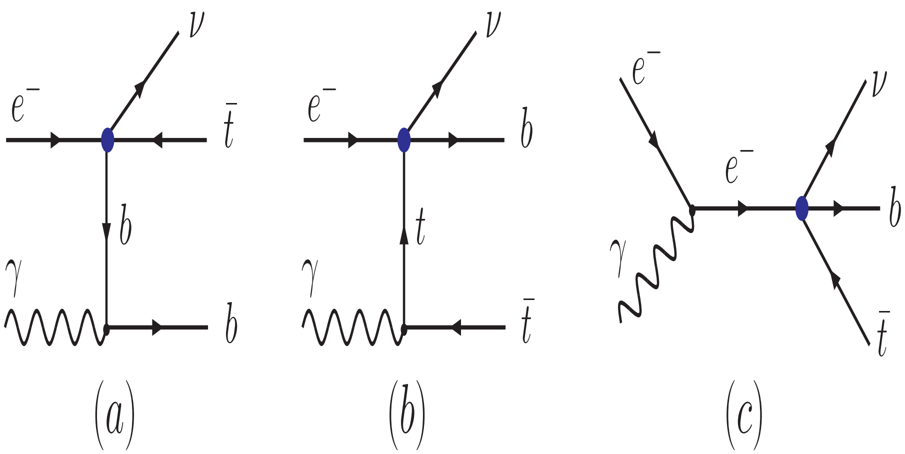


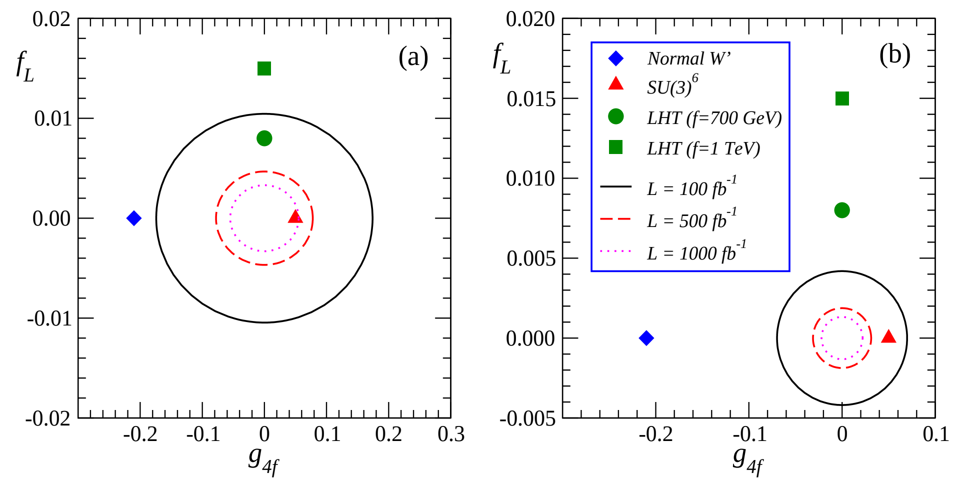
3. 4-fermion operator Q.-H.Cao, J.Wudka

$$L_{Wtb}^{dim6} = \frac{g}{\sqrt{2}} \left\{ \bar{t}\gamma^{\mu} \left(f_L P_L + \ f_R P_R \right) b W_{\mu}^{+} + \text{H.c.} \right\}$$

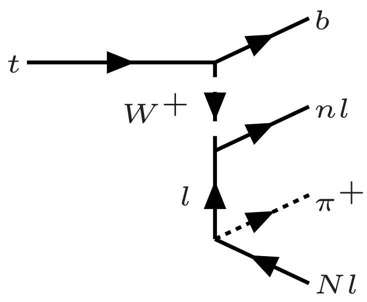
$$f_L = \frac{C_{\phi q}^{(3)} v^2}{\Lambda^2}, \qquad f_R = \frac{C_{\phi\phi} v^2}{2\Lambda^2}$$

$$L_{4f} = \frac{g_{4f}}{\Lambda^2} \left\{ \left(\bar{\nu}\gamma^{\mu} P_L e \right) \left(\bar{b}\gamma_{\mu} P_L t \right) + \text{H.c.} \right\}$$

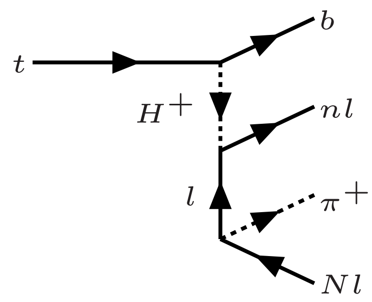




Charged Higgs in Top Decay (impact of tau polarization)



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

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

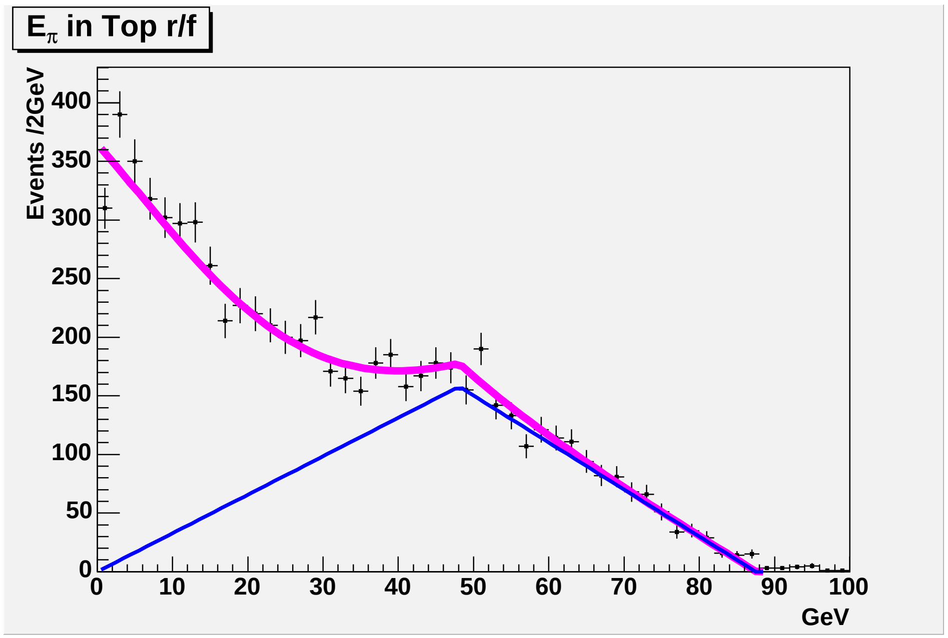
(M.Nojiri; E.B.,G.Moortgat-Pick, M.Sachwitz, A.Sherstnev, P.Zerwas;
E.B., S.Bunichev, M.Carena, C.Wagner)

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

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 $Br(t \rightarrow H^+ b) = 9.1\%$

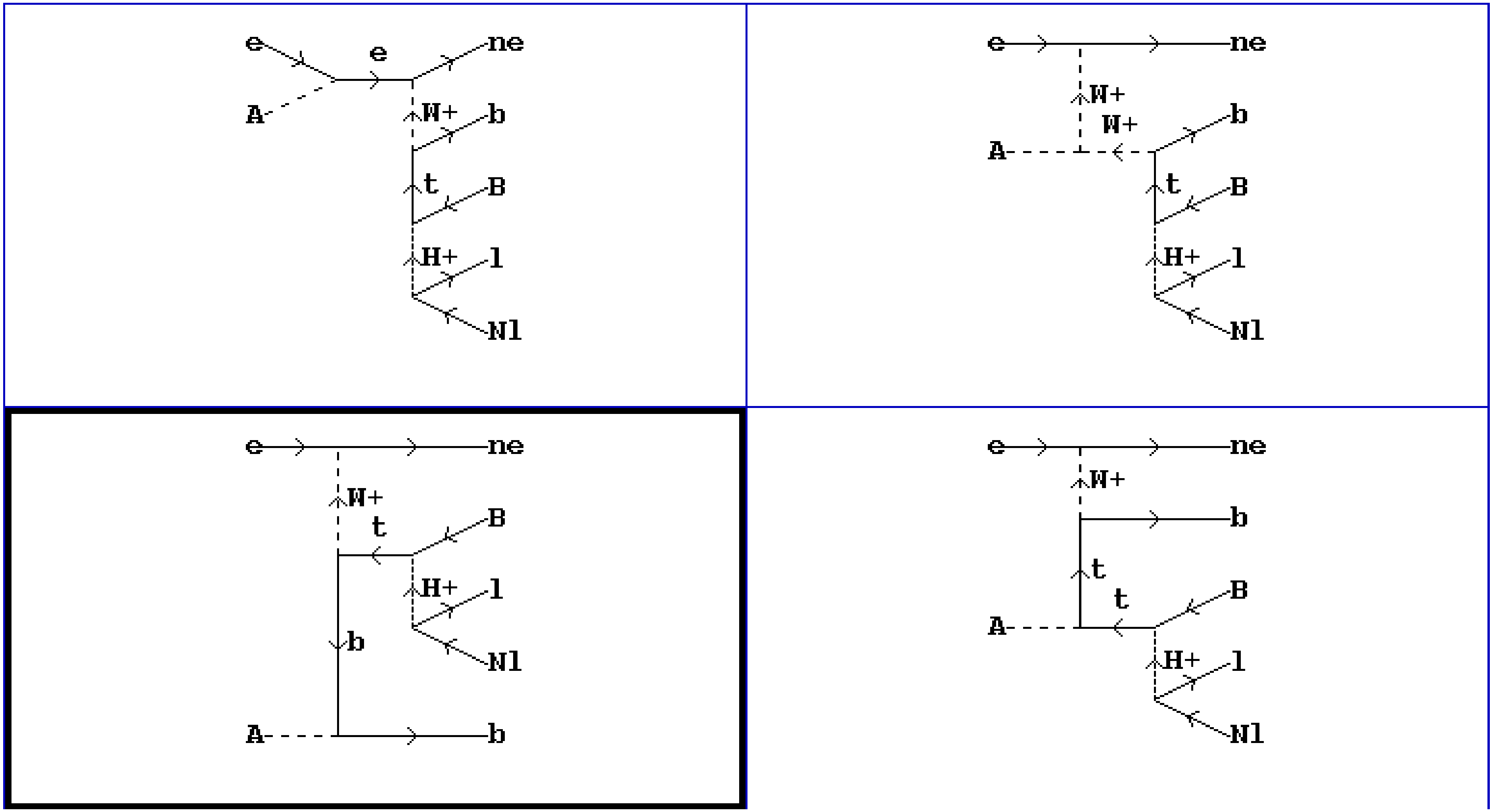
E.B., S.Bunichev, M.Carena, C.Wagner



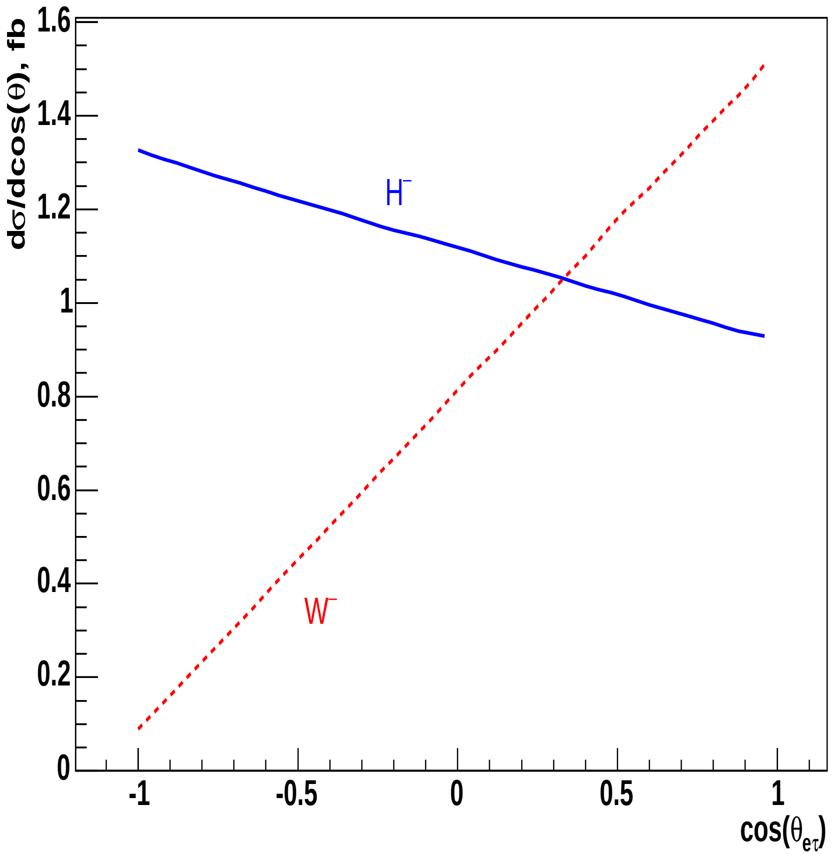
From the signal+backgr fit $M_{H^\pm}$ = 129.4 +/- 0.9 GeV

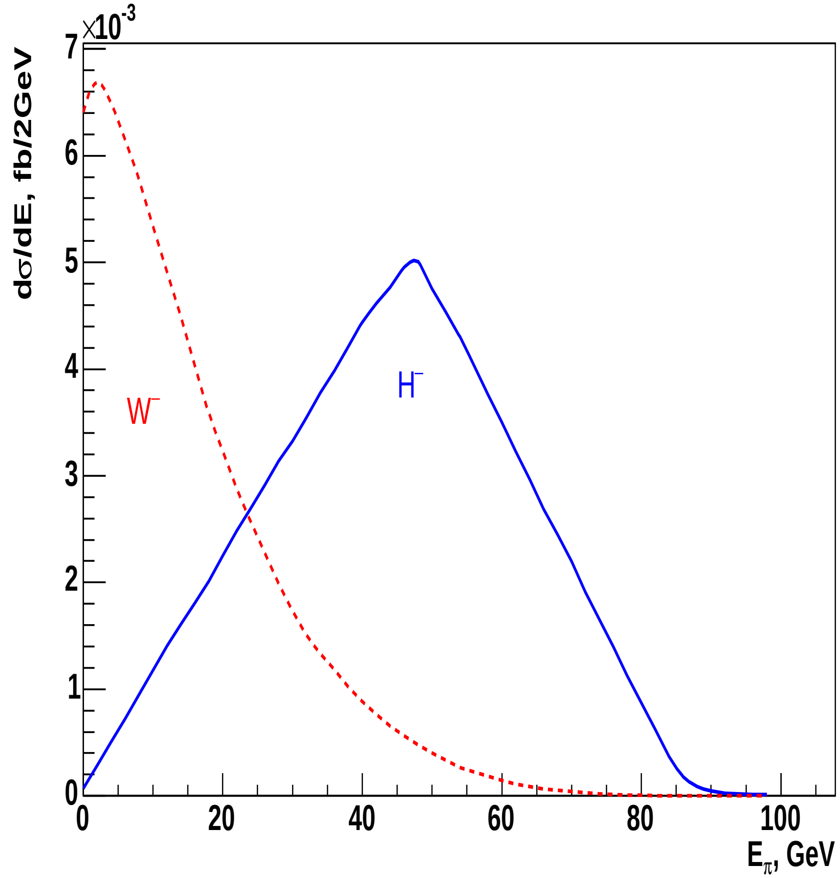
Charged Higgs in γe collisons

E.B., S.Bunichev



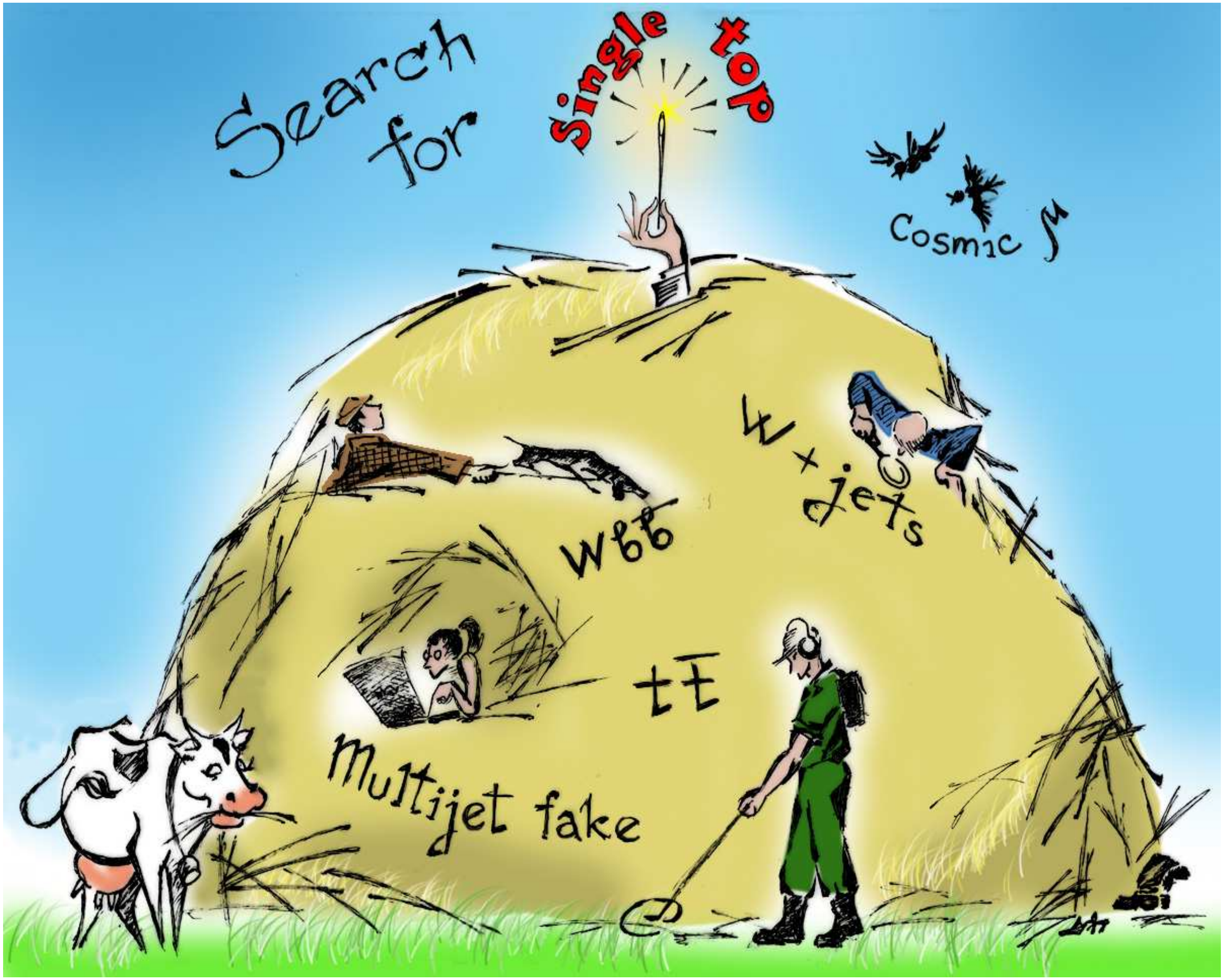
One can explore both differences it top polarization (left plot) and tau polarization (right plot)





Conclusions

- Single top is an interesting process to be studied at both hadron and lepton collider
- At lepton colliders: best accuracy for Vtb measurements and Wtb vertex structure studies. Unique spin correlation properties
- Polarized collisions help to increase rates in e^+e^- and γe collisions
- NLO computations and event generators are needed for precision measurements
- Detail simulations and analysis including a detector response are needed


Search for
single top
Cosmic μ
W + jets
Wbb
tt
Multijet fake