Single top at LC after the Tevatron/LHC

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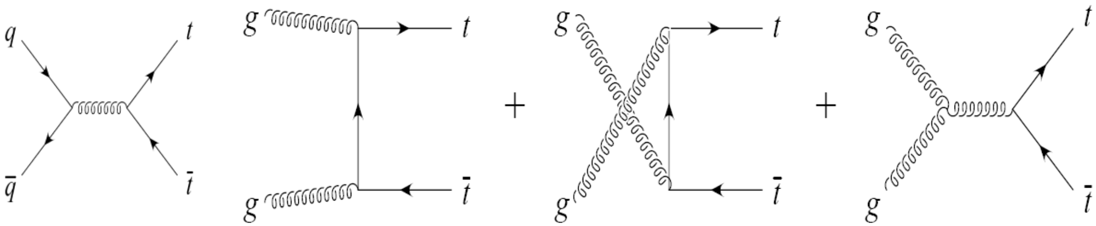
Outline

- Why single top is interesting?
- Single top production at the Tevatron and at the LHC
- Single top at LC
- Spin correlations in single top
- BSM in single top (few examples)
- Concluding remarks

At hadron colliders top quarks may be produced either in pairs or singly

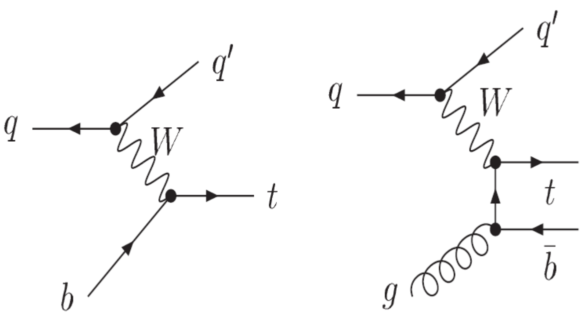
Two mechanisms of top pair production:



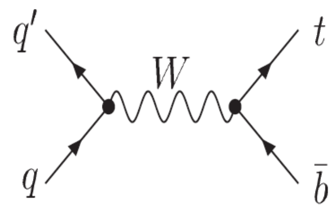
Top pair strong top–gloun coupling in production and top-W-b coupling in decay

Single top electroweak top-W-b coupling in production

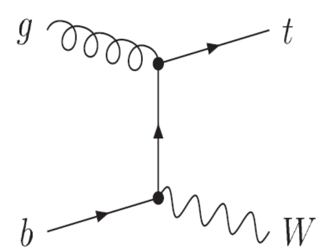
Three mechanisms of single top production:



t-channel



s-channel



Wt associated 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

Why Single top is interesting?

- Independent electroweak channel of the top quark production

- Direct |Vtb| CKM matrix element measurement

- Significant background to Higgs and many "new physics" (MSSM) processes

- Unique spin correlation properties

- Process of interest for "New physics"
  - Wtb anomalous couplings
  - FCNC
  - Searches for W' (e.g. Kaluza-Klein excitation of W-boson)
  - Searches for new strong dynamics (π_T, ρ_T,vector-like top parner)
  - …

Top quark pair production cross sections

NLO + NLL resummation

Tevatron, 1.96 TeV: σ= 7.1 ± 0.5 pb

Kidonakis

LHC, 7 TeV: σ= 163 ± 11 pb
14 TeV: σ= 920 ± 60 pb

Single top quark production cross sections

NLO + NLL resummation

Tevatron, 1.96 TeV: s-channel **σ= 0.88 ± 0.11 pb**
t-channel **σ= 1.98 ± 0.25 pb**

3 pb

Sullivan

LHC, 7 TeV: t-channel **σ= 64.3 ± 3.1 pb**
s-channel **σ= 4.6 ± 0.2 pb**
tW-channel **σ= 15.6 ± 1.1 pb**

89 pb

Kidonakis

LHC, 14 TeV: t-channel **σ= 243 ± 6 pb**
s-channel **σ= 11.9 ± 0.5 pb**
tW-channel **σ= 84 ± 6 pb**

339 pb

Single top rate is about ~40% of the top pair rate

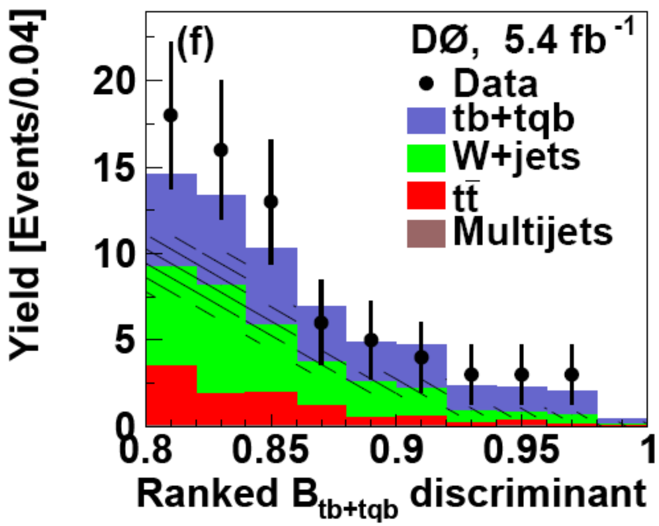
Computations and MC Tools: Dicus, Willenbrock, Smith, Yuan, Pittau, Cortese, Petronzio, Jikia, Slabospitsky, R-K Ellis, Parke, Mahlon, Kane, Ladinsky, , Heinson, Belyaev, Boos, Dudko, Ohl, Stelzer, Tait, Cao, Wudka, Berger, Sullivan, Weinzierl, Harris, Laenen, Phaf, Sherstnev, Bunichev, Schwienhorst, Frixione, Motylinski, Webber, Benitez, Brock, Beccaria, Macorini, Renard, Verzegnassi, Hollik, Campbell, Nason, Oleari, Alioli, Re.....

Single top was observed by the Tevatron collaborations at 5 sigma level using multivariate methods (boosted decision tree, NN…)

Combined Results

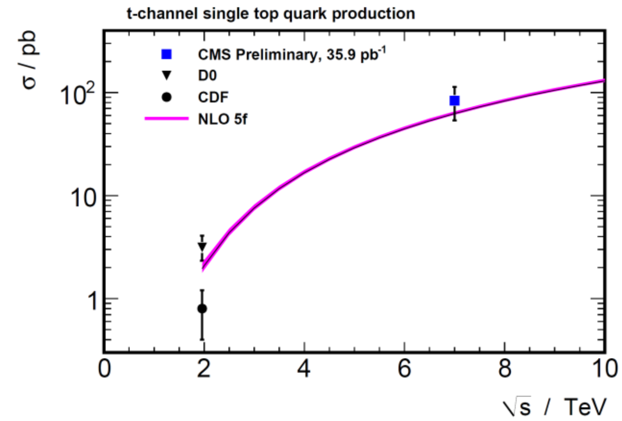
	$\mathcal{L}$ [fb^{-1}]	Significance Exp.	Significance Obs.	σ_{s+t} [pb]
	2.3	4.5σ	5.0σ	$3.9^{+0.9}_{-0.9}$
	3.2	5.9σ	5.0σ	$2.3^{+0.6}_{-0.5}$

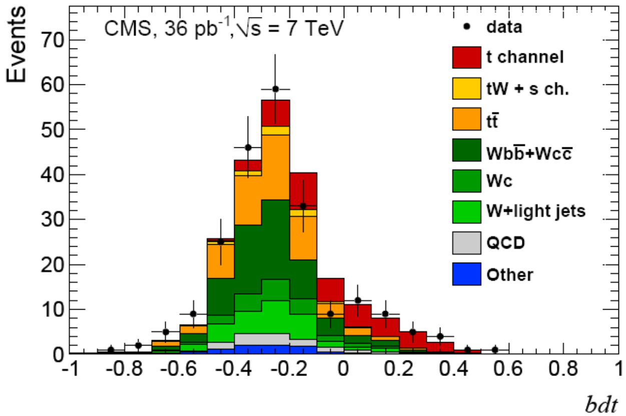
Theory (NLO) : σ = 2.9 ± 0.3 pb



Discriminant	Expected cross section	Observed cross section
tb	$1.12^{+0.45}_{-0.43}$ pb	$0.68^{+0.38}_{-0.35}$ pb
tqb	$2.43^{+0.67}_{-0.61}$ pb	$2.86^{+0.69}_{-0.63}$ pb
$tb + tqb$	$3.49^{+0.77}_{-0.71}$ pb	$3.43^{+0.73}_{-0.74}$ pb

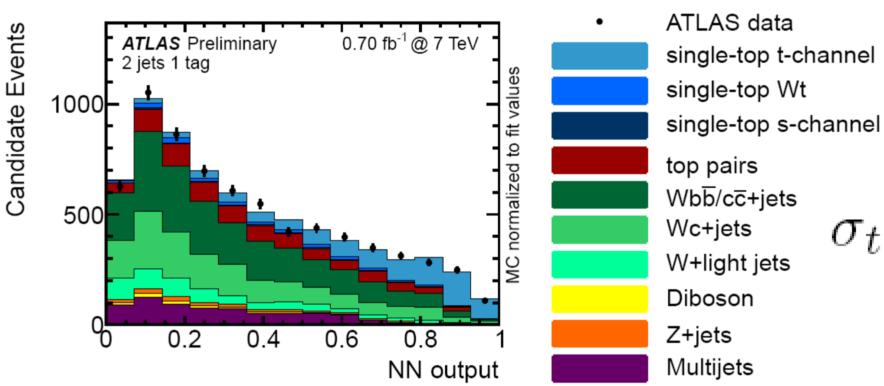
Single top has been observed at the LHC





$$\sigma = 83.6 \pm 29.8\ (\text{stat.} + \text{syst.}) \pm 3.3\ (\text{lumi.})\ \text{pb}$$

$$|V_{tb}| = \sqrt{\frac{\sigma^{exp}}{\sigma^{th}}} = 1.16 \pm 0.22(exp) \pm 0.02(th)$$



Theory (NLO) : σ = 64.3 ± 3.1 pb

$$\sigma_t = 90^{+9}_{-9}(\text{stat})\ ^{+31}_{-20}(\text{syst}) = 90^{+32}_{-22}\ \text{pb}$$

First results for Wt mode

ATLAS ($0.7\ \text{fb}^{-1}$)

$$\sigma(pp \to Wt + X) = 14.4^{+5.3}_{-5.1}(\text{stat})^{+9.7}_{-9.4}(\text{syst})\ \text{pb}$$

$$\sigma(pp \to Wt + X) < 39.1\ \text{pb}$$

CMS (**2.1 fb^{-1}**)

$$\sigma_{\text{tW}} = 22^{+9}_{-7}\text{pb}$$

Boos, Sachwitz, Schreiber, Shichanin

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

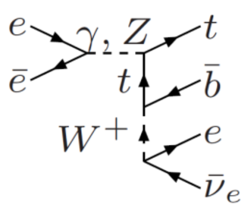
$e^+e^- \rightarrow t\bar{t} \rightarrow WWb\bar{b}, \qquad W \rightarrow f\bar{f}',$

where e.g. for W^+

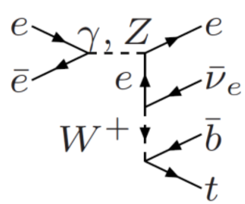
$f = u, c, \nu_e, \nu_\mu, \nu_\tau\nu_\mu;\ f' = d, s, e, \mu, \tau$

$$e^- e^+ \rightarrow \nu_e\, e\, t\, b$$

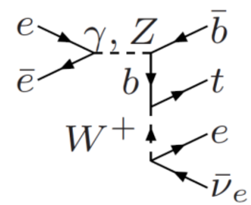
Gauge invariant s-channel subset of 10 diagrams



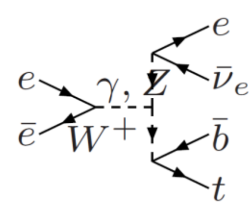
diagr.1,2



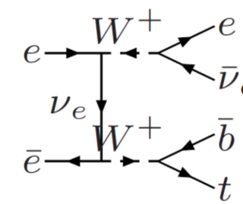
diagr.3,4



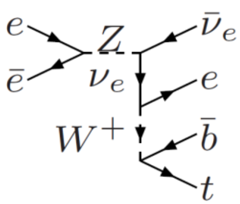
diagr.5,6



diagr.7,8



diagr.9



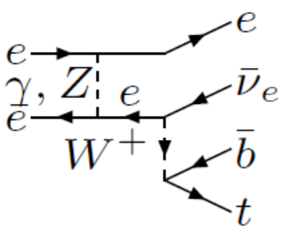
diagr.10

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

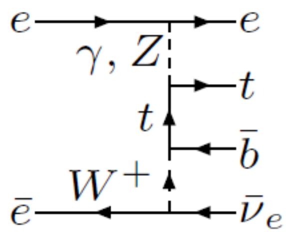
$$\sigma_{singletop} = \int dM_{e\nu b}\left(d\sigma^{CTL}/dM_{e\nu b} - d\sigma^{BW}/dM_{e\nu b}\right)$$

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

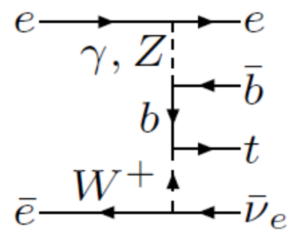
Gauge invariant t-channel subset of 10 diagrams



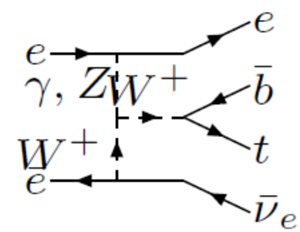
diagr.1,2



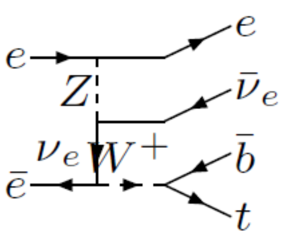
diagr.3,4



diagr.5,6



diagr.7,8



diagr.10

All the diagrams contribute to Single Top

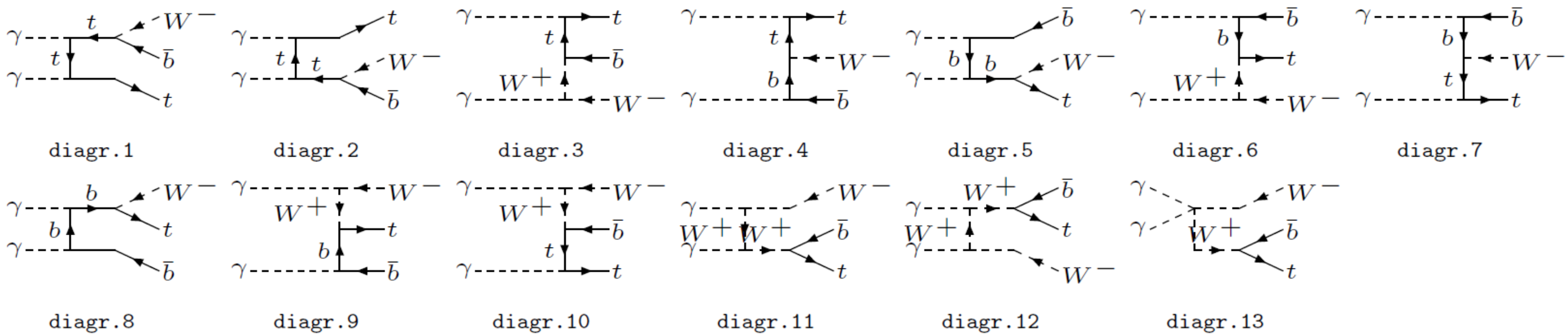
(at LEP2 the rate is too small, about 10^{-5} pb)

Hagiwara, Tanaka M, Stelzer;
Boos, Sachwitz, Schreiber, Shichanin,
Ilyin, Pukhov,
Ishikawa, Kaneko, Kawabata, Kurihara, Shimizu, Tanaka H

(SM single top cross section is less than 1 fb at HERA) Stelzer, Sullivan, Willenbrock

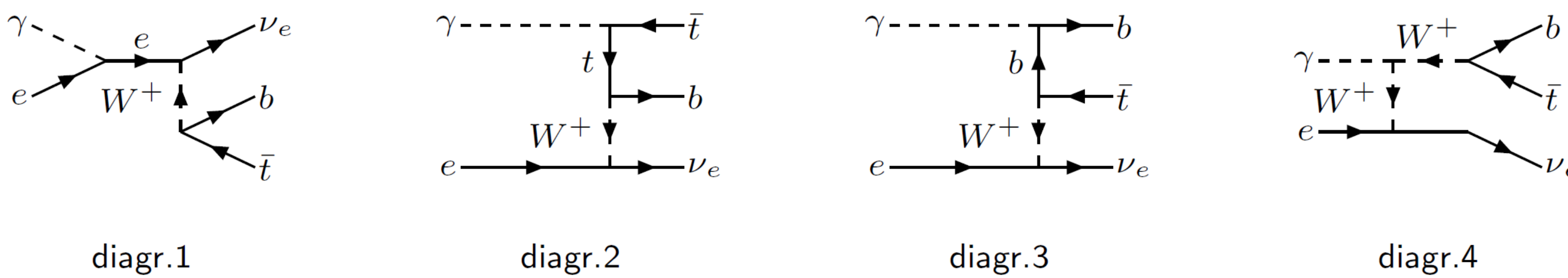
In case of $\gamma\gamma$ collisions there are no nontrivial gauge invariant subsets. A situation is similar to single top at the LHC in Wt mode.

Boos, Ohl



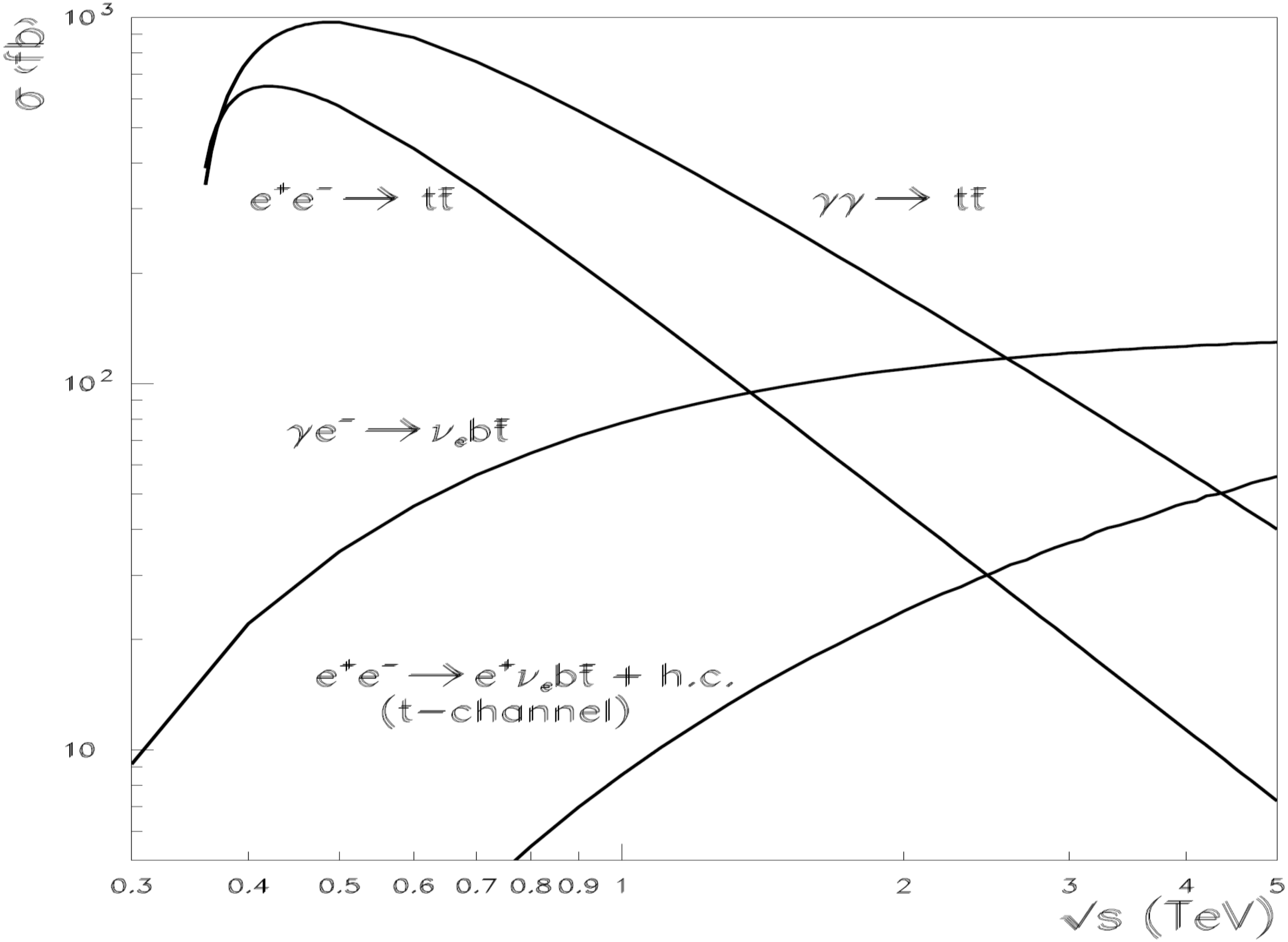
The top pair rate has to be removed in order to get the correct single top rate.

Single Top Diagrams in γe Collisions



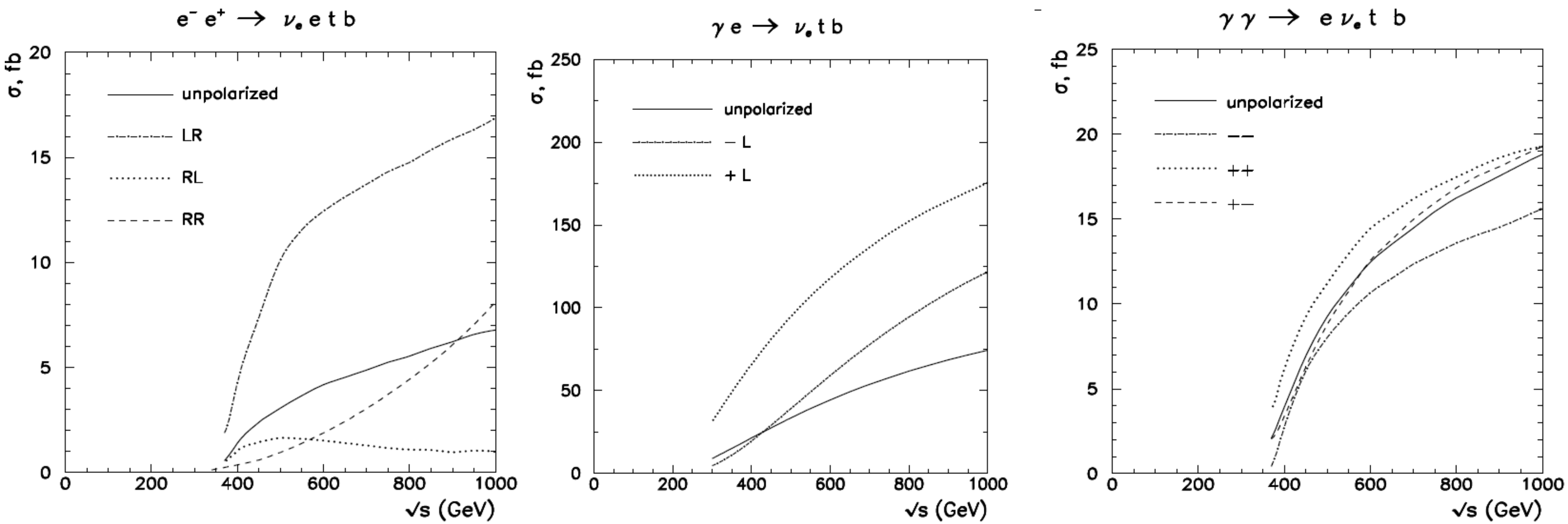
This is one of so called "gold plated" processes in γe collision mode of ILC

Cross sections of Top production processes at LC



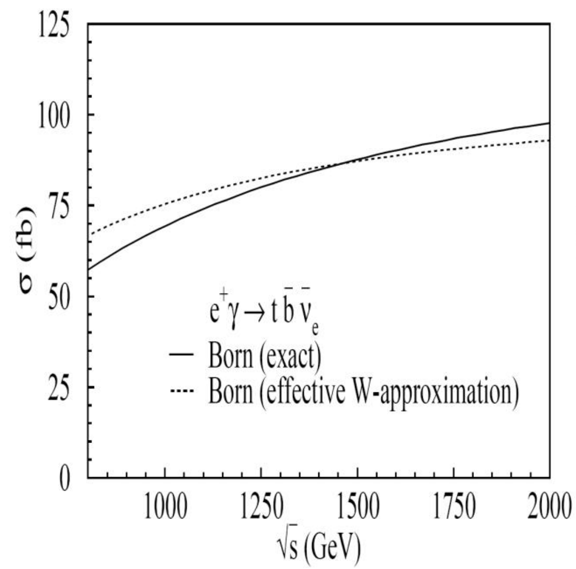
Boos, Dubinin, Pukhov, Sachwitz, Schreiber

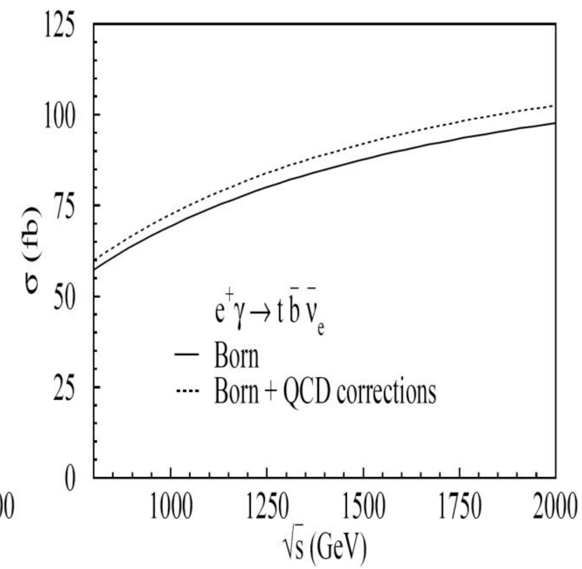
Cross sections of Single top production for polarized collisions



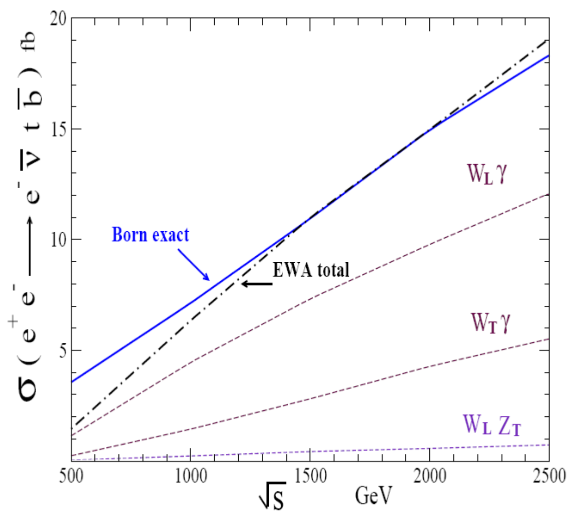
NLO corrections are available for γe and e+e-

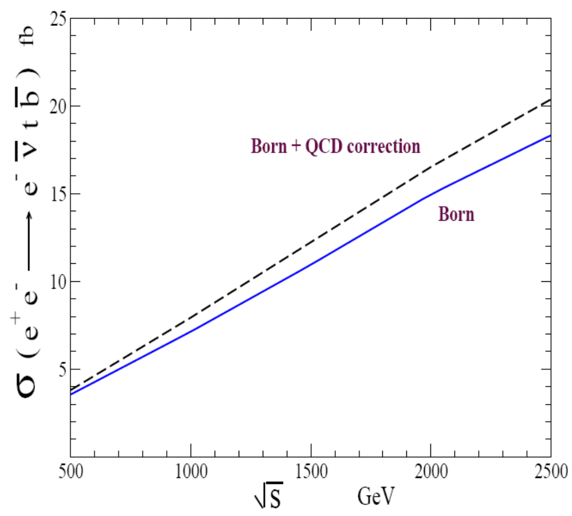
Kuhn, Sturm, Uwer





Penunuri , Larios, Antonio O. Bouzas





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

Direct measurements from single top

D0: $|V_{tb} f_{L1}| = 1.07 \pm 0.12$, $|V_{tb}| > 0.78$ at 95% CL

CDF: $|V_{tb}| = 0.91 \pm 0.11$, $|V_{tb}| > 0.71$ at 95% CL

CMS: $|V_{tb}| = \sqrt{\frac{\sigma^{exp}}{\sigma^{th}}} = 1.16 \pm 0.22(exp) \pm 0.02(th)$

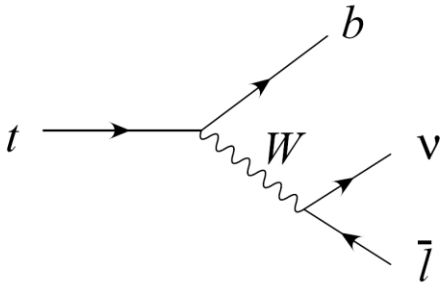
At LC in e-gamma mode

$\sqrt{s_{e^+e^-}}$, TeV	0.5	1.0	1.5	2.0
$\mathcal{L}$ fb^{-1}	50	200	300	500
$\delta\|V_{tb}\|$	8%	2%	1.5%	1%

Boos, Pukhov, Sachwitz, and Schreiber

Spin correlations in single top

V-A vertex structure in SM



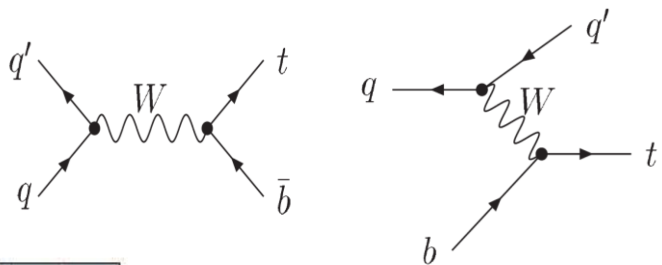
$$d\Gamma \sim |\mathcal{M}|^2 \sim (t + ms)\cdot \ell b \cdot \nu$$

where in the top-quark rest frame, the spin four-vector $s = (0, \hat{s})$ is a unity $\hat{s}$ vector that defines the spin quantization axis of the top quark. In the top quark rest frame: $$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{1}{2}(1+\cos\theta_\ell)$$

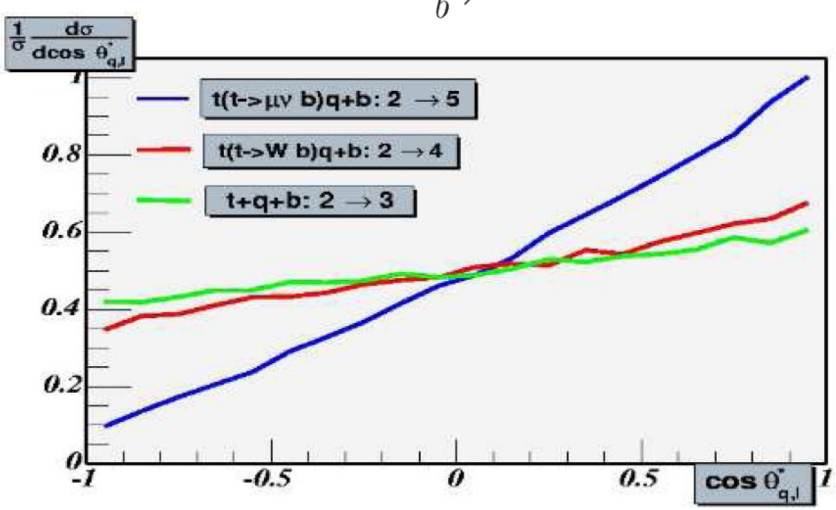
Hence the charged lepton tends to point along the direction of top spin

Single top production as top decay back in time

Mahlon, Parke;
Boos, Sherstnev



Down-type component of weak isospin doublet - d-quark In production plays a role of lepton In decay



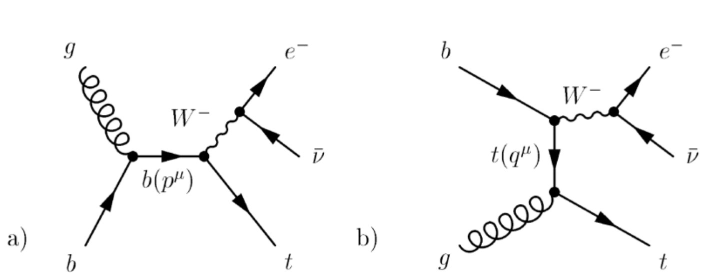
t-channel production

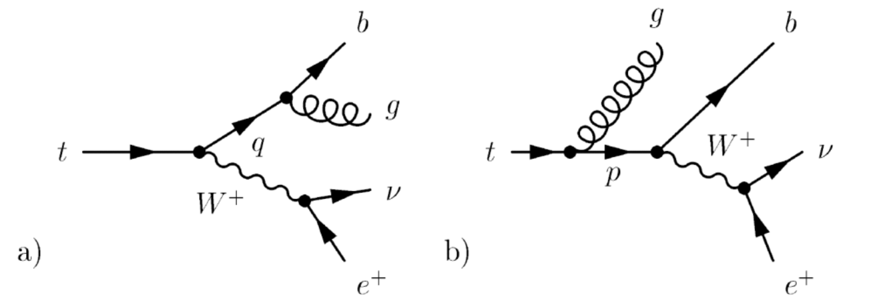
Best spin correlation variable - the angle between the lepton from W-decay and momentum of outgoing light jet in the top-quark rest frame. Polarization

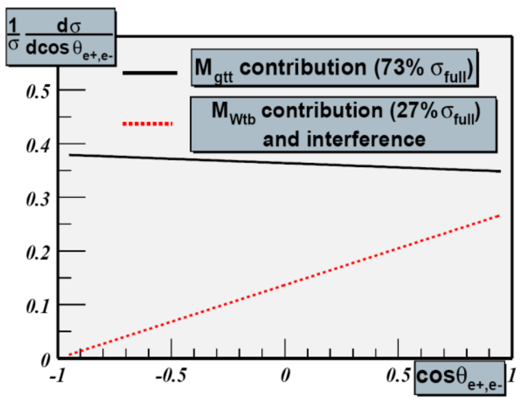
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_{ql}} = \frac{1+P\cos\theta^*_{ql}}{2} \qquad P_{top} \approx 90\,\%$$

Spin correlations in tW-mode

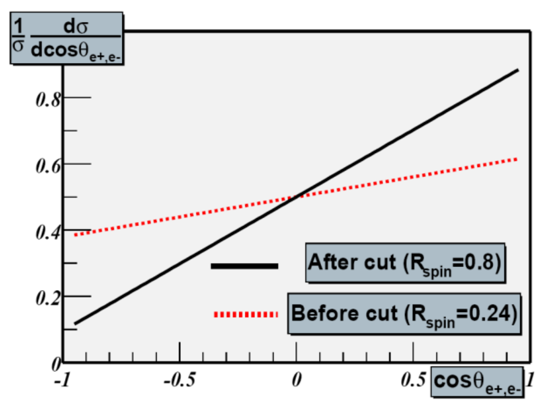
Boos, Sherstnev







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

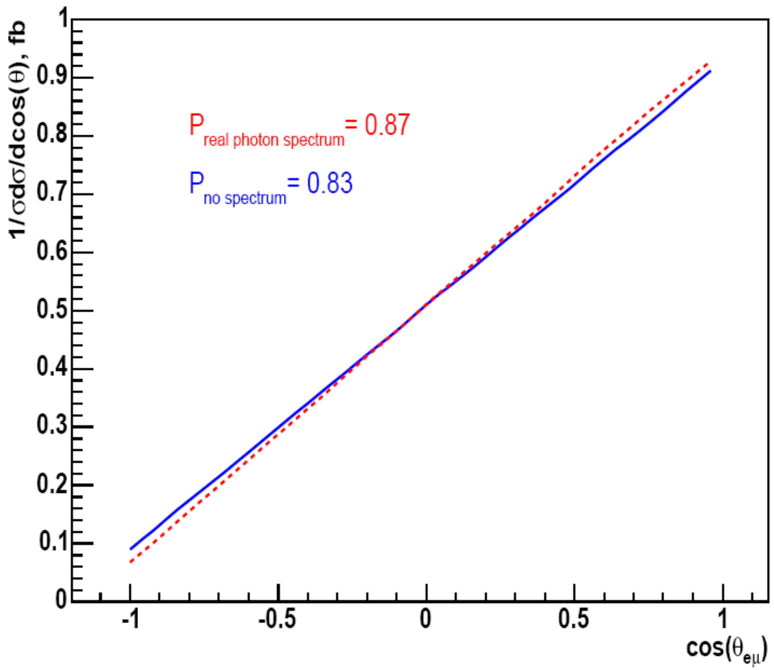


$$X_{g,e^-} = E_g^* (1 - \cos\theta_{e^-,g}^*)$$

$$X_{g,e^-} < 110 \text{ GeV}$$

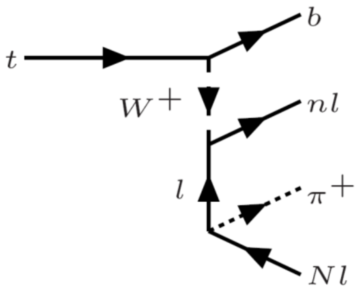
Spin correlations in e-gamma collisions

Boos, Sherstnev

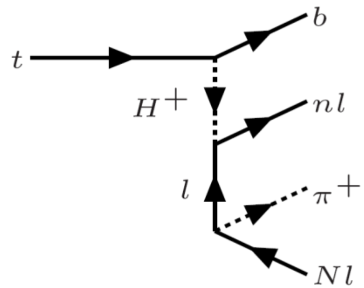


$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_{e,\mu}} = \frac{1+P\cos\theta^*_{e,\mu}}{2}$$

Charged Higgs in Top Decay (impact of tau polarization)

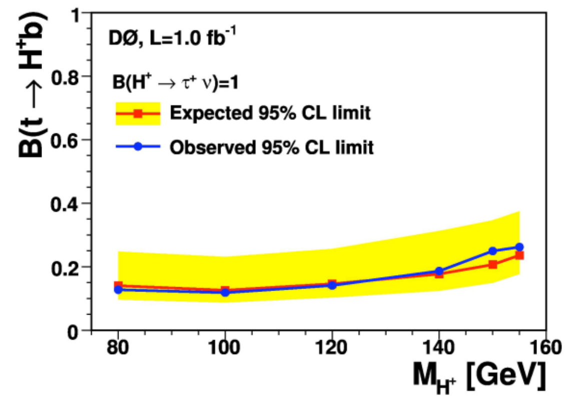


diagr.1



diagr.2

Curent limits from D0



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

$$\frac{1}{\Gamma}\frac{d\Gamma}{dy_\pi} = \frac{1}{x_{max} - x_{min}}$$

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

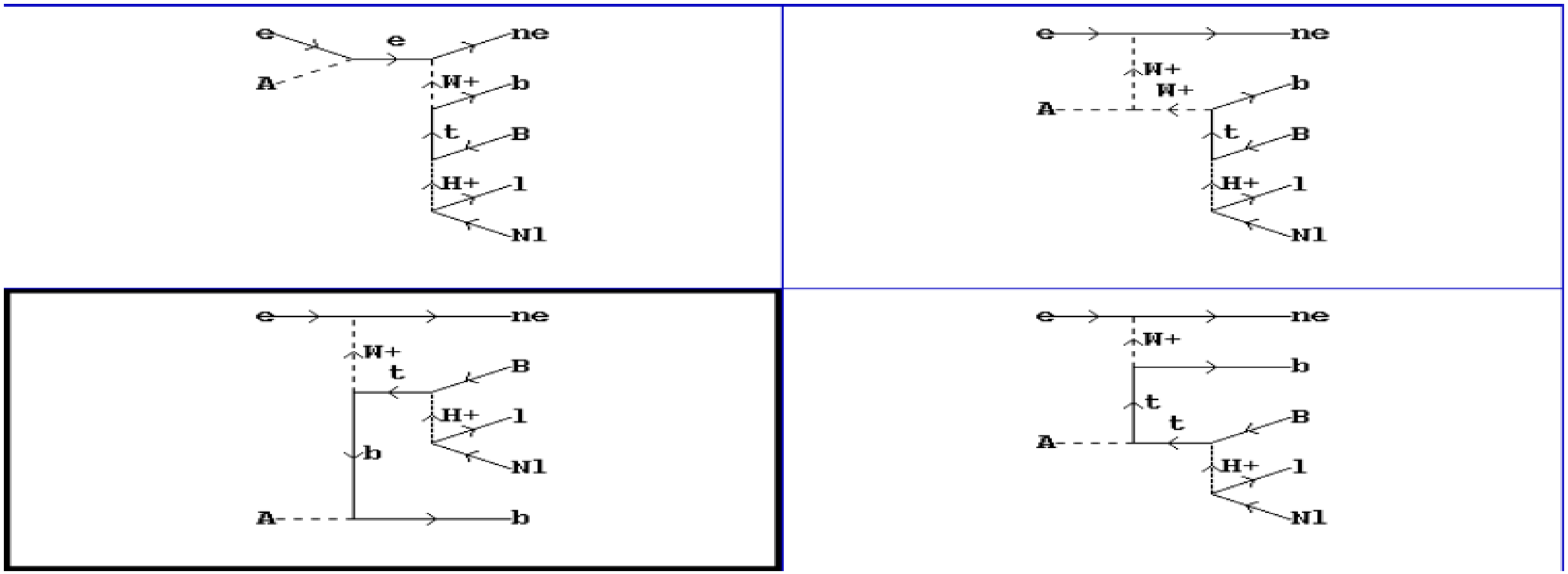
where $y_\pi = \frac{E_\pi^{top}}{M_{top}}, \quad x_{min} = \frac{E_\tau^{min}}{M_{top}}, \quad x_{max} = \frac{E_\tau^{max}}{M_{top}}, \quad E_\tau^{min} = \frac{M_R^2}{2M_{top}}, \quad E_\tau^{max} = \frac{M_{top}}{2}$

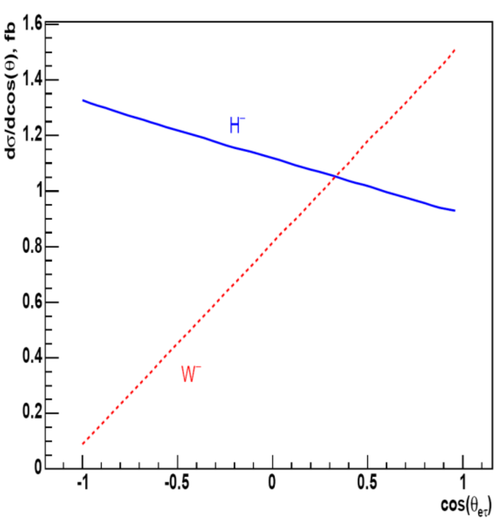
$P_\tau = -1$ for W boson and $P_\tau = 1$ for charged Higgs

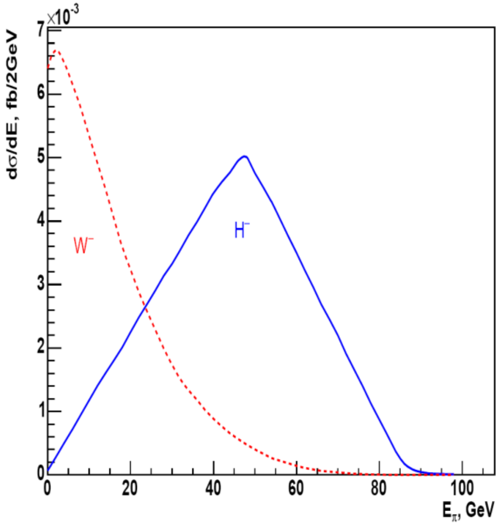
(M.Nojiri; E.B.,G.Moortgat-Pick, M.Sachwitz, A.Sherstnev, P.Zerwas;
E.B., S.Bunichev, M.Carena, C.Wagner)

One can explore both top and tau polarization informations

Boos, Bunichev







Two possibilities in general

Collision energy E < production thresholds

$\Rightarrow$New effective anomalous interactions of the top with other SM particles (modification of top decay and production properties)

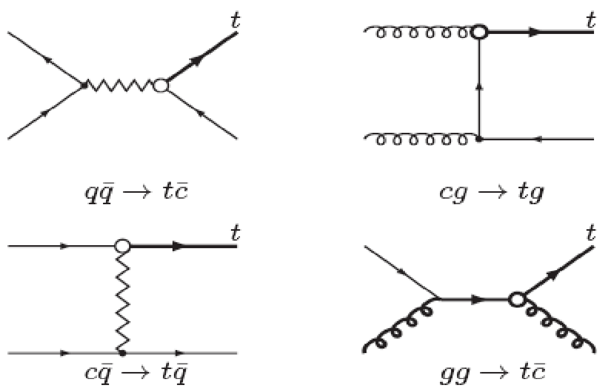
Collision energy E > production thresholds

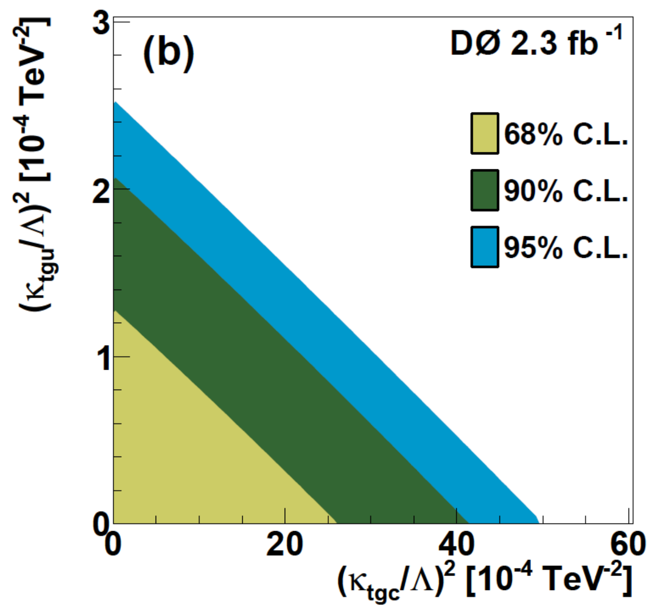
$\Rightarrow$New resonances decaying to tops
$\Rightarrow$New states produced in association with the top

FCNC couplings

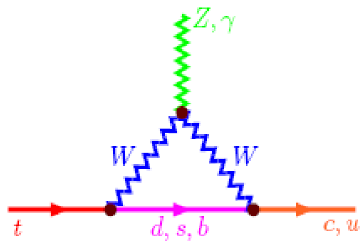
- Couplings: tqg, $tq\gamma$, tqZ, where $q = u, c$

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





W' boson and FCNC MC event samples from SingleTop (CompHEP) generator



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

FCNC decays are highly suppressed in SM $t \to qg$, $t \to q\gamma$, $t \to qZ$

To compare FCNC limits from top decays and top production one can express limits on FCNC couplings in term of Br fractions

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

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

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

D0:

	tgu	tgc
Cross section	0.20 pb	0.27 pb
κ_{tgf}/Λ	0.013 TeV^{-1}	0.057 TeV^{-1}
$\mathcal{B}(t \to qg)$	2.0×10^{-4}	3.9×10^{-3}

CDF:

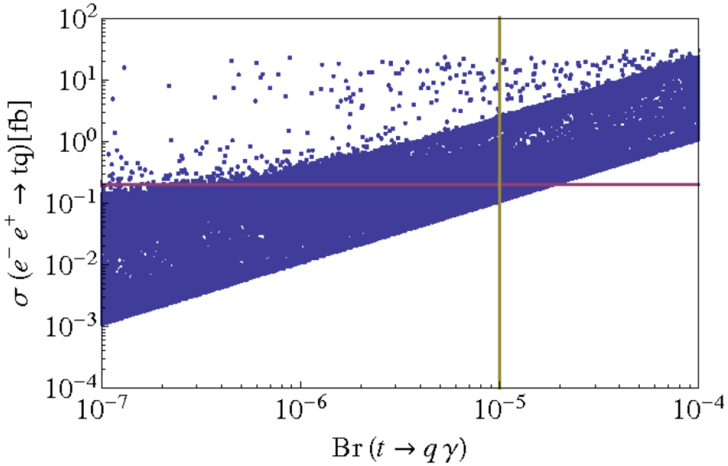
$$\mathcal{B}(t \to u + g) < 3.9 \cdot 10^{-4}$$

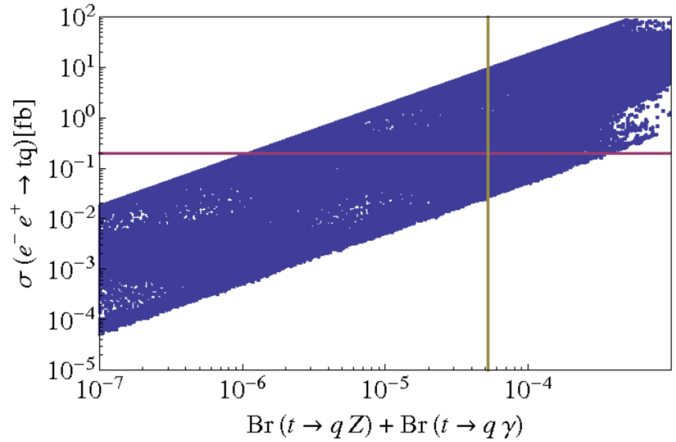
$$\mathcal{B}(t \to c + g) < 5.7 \cdot 10^{-3}$$

LHC: B(t->gq)< 1×10^{-5}

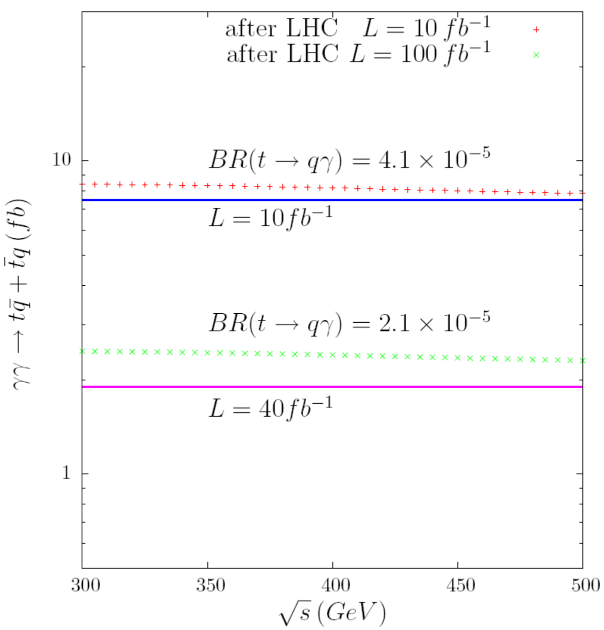
$$\sqrt{s} = 500\,GeV$$

Guedes, Santos, Won

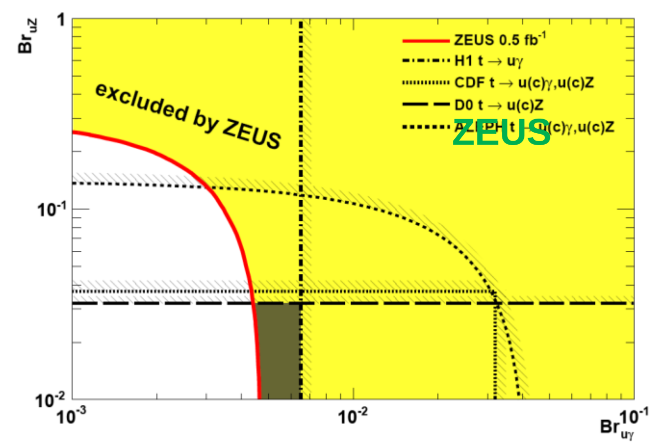




Difficult to improve the LHC bounds with 500 fb-1



Stronger than current HERA limit



A total luminosity of 40 fb-1 would be enough to overcame the LHC 100 fb-1 bound almost independently of the collider center of mass energy.

Structure of the Wtb vertex

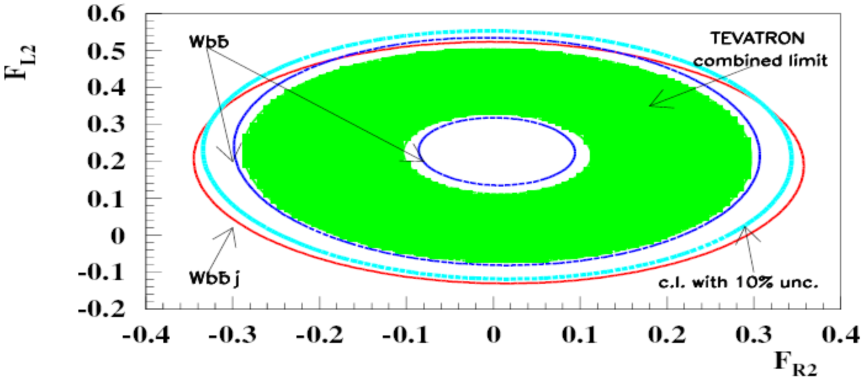
$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

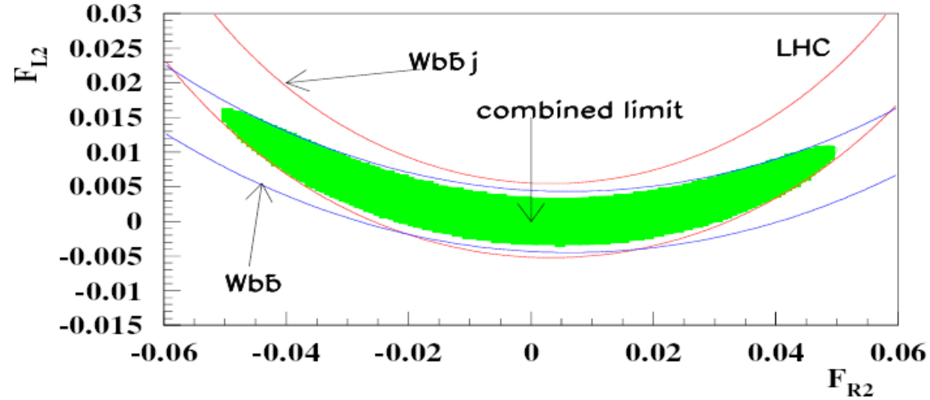
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix}$$

B CM: $f_1^L = 1$, $f_1^R = 0$, $f_2^{L,R} = 0$

Expectations for Wtb anomalous couplings for the Tevatron and LHC

Boos, Dudko, Ohl





D0 limits based on 900 pb^{-1} data

Scenario	Cross Section	Coupling
(L_1, L_2)	$4.4^{+2.3}_{-2.5}$ pb	$\lvert V_{tb} f_1^L \rvert^2 = 1.4^{+0.6}_{-0.5}$
		$\lvert V_{tb} f_2^L \rvert^2 < 0.5$ at 95% C.L.
(L_1, R_1)	$5.2^{+2.6}_{-3.5}$ pb	$\lvert V_{tb} f_1^L \rvert^2 = 1.8^{+1.0}_{-1.3}$
		$\lvert V_{tb} f_1^R \rvert^2 < 2.5$ at 95% C.L.
(L_1, R_2)	$4.5^{+2.2}_{-2.2}$ pb	$\lvert V_{tb} f_1^L \rvert^2 = 1.4^{+0.9}_{-0.8}$
		$\lvert V_{tb} f_2^R \rvert^2 < 0.3$ at 95% C.L.

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.

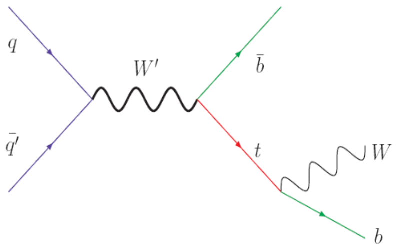
Boos, Pukhov, Sachwitz, Schreiber

	$\lvert V_{tb} \cdot f_{R_T} \rvert$	$\lvert V_{tb} \cdot f_{L_T} \rvert$
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)	$-0.008 \div +0.035$	$-0.016 \div +0.016$

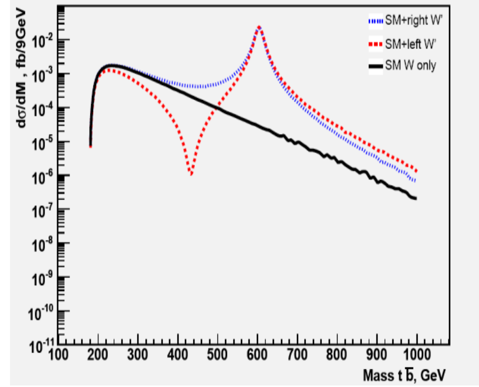
D0 bounds with $5.4\ \mathrm{fb}^{-1}$

Scenario	Cross section	Coupling
(L_V, L_T)	< 1.21 pb	$\lvert V_{tb} \cdot f_{L_T} \rvert^2 < 0.13$
(L_V, R_V)	< 2.81 pb	$\lvert V_{tb} \cdot f_{R_V} \rvert^2 < 0.93$
(L_V, R_T)	< 0.60 pb	$\lvert V_{tb} \cdot f_{R_T} \rvert^2 < 0.06$

Searches for W' resonance in single top

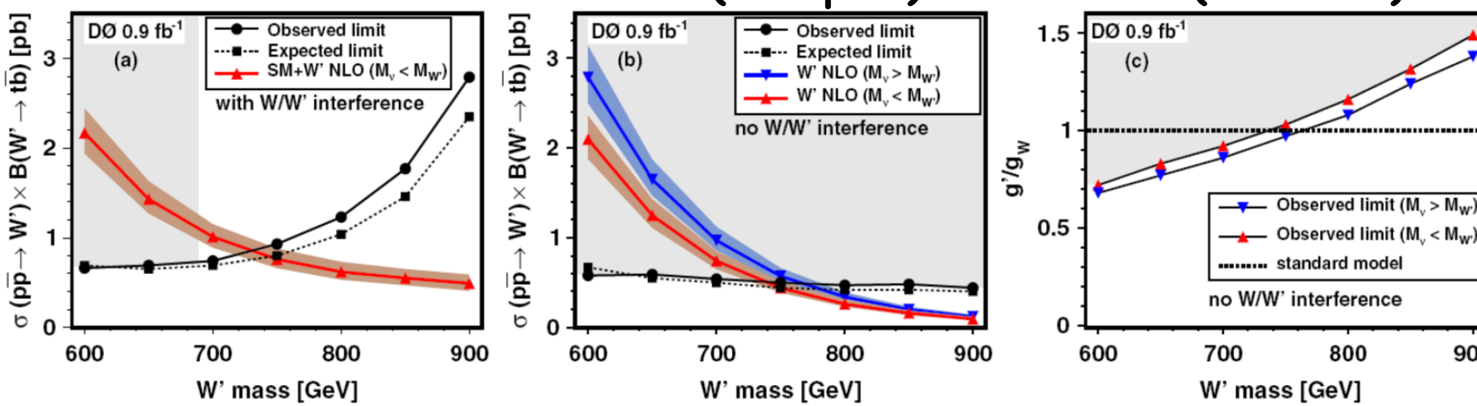


Boos, Bunichev, Dudko, Perfilov



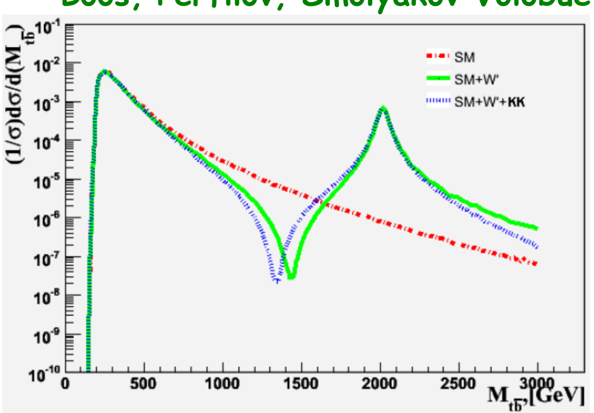
Negative interference

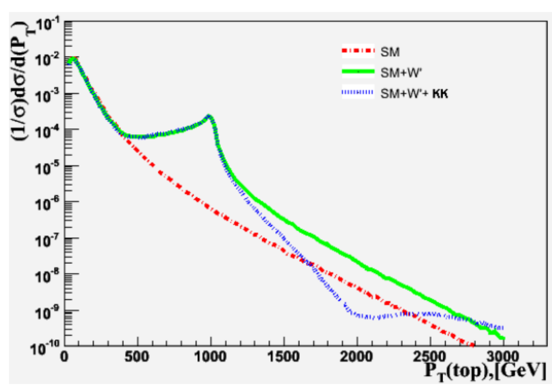
Tevatron Limits on W' boson mass (900 pb^{-1}): MW' > 710(730-770)GeV L(R)



Boos, Perfilov, Smolyakov Volobuev

KK W' at the LHC





Expected LHC limits:
2-3 TeV
(Detail CMS study
in progress)

In case of LC W' would lead to effetive 4-fermion operator

Qing-Hong Cao and Jose Wudka

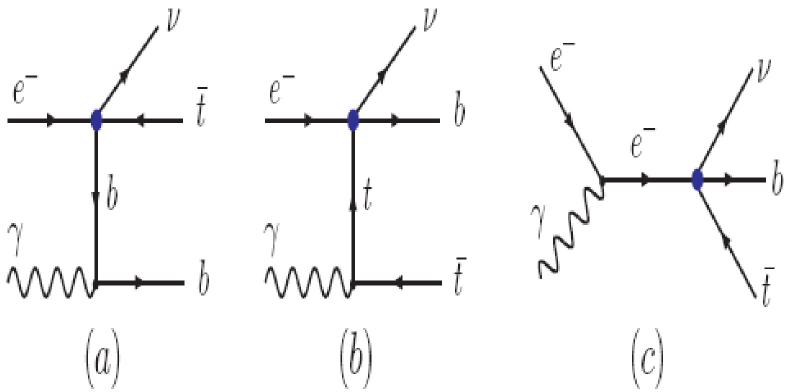
$$\mathcal{O}_{\ell q}^{(3)} = \frac{1}{2}\left(\bar{\ell}\gamma_\mu \tau^I \ell\right)\left(\bar{q}\gamma^\mu \tau^I q\right) \qquad \mathcal{G}_{4f} = C_{\ell q}^{(3)}/2$$

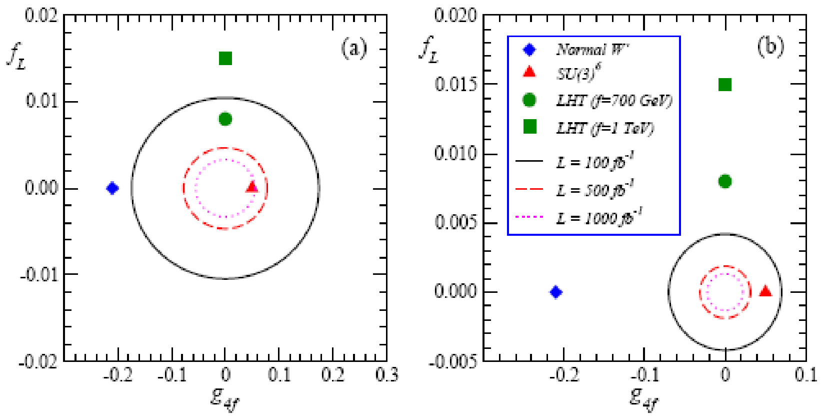
$$\mathcal{L}_{4f} = \frac{\mathcal{G}_{4f}}{\Lambda^2}\left\{\left(\bar{\nu}\gamma^\mu P_L e\right)\left(\bar{b}\gamma_\mu P_L t\right) + \left(\bar{e}\gamma^\mu P_L \nu\right)\left(\bar{t}\gamma_\mu P_L b\right)\right\}$$

$$\mathcal{O}_{\phi q}^{(3)} = i\left(\phi^\dagger \tau^I D_\mu \phi\right)\left(\bar{q}\gamma^\mu \tau^I q\right) + \text{H.c.}, \qquad \mathcal{L}_{Wtb}^{(\text{dim}-6)} = \frac{g}{\sqrt{2}}\left\{\bar{t}\gamma^\mu\left(\mathcal{F}_L P_L + \mathcal{F}_R P_R\right) b W_\mu^+ + \text{H.c.}\right\}$$

$$\mathcal{O}_{\phi\phi} = i\left(\phi^\dagger \epsilon D_\mu \phi\right)\left(\bar{t}\gamma^\mu b\right) + \text{H.c.},$$

$$\mathcal{F}_L = \frac{C_{\phi q}^{(3)} v^2}{\Lambda^2}, \qquad \mathcal{F}_R = \frac{C_{\phi\phi} v^2}{2\Lambda^2},$$





Concluding remarks

Single top quark production has been observed by the Tevatron and the LHC experiments (not yet in all expected production modes, tW at the Tevatron and s-channel at the LHC).

Several precision measurements (Wtb, FCNC tqg, W') have been made at the Tevatron and corresponding limits have been obtained. Stronger limits are expected from the LHC.

Single top at LC allows to improve an accuracy for direct measurements of Vtb CKM element, improve limits on anomalous Wtb and FCNC couplings…

Not all advantages of LC, especially polarization properties of colliding and produced particles, have been fully explored yet. More realistic simulations are needed for more accurate predictions…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