PROBING CHIRALITY OF TOP-HIGGS FCNC COUPLINGS AT LINEAR COLLIDERS

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FCNC IN THE TOP-HIGGS COUPLINGS

- search for the Flavor Changing Neutral Current (FCNC) processes has been one of the leading tools to test the Standard Model (SM), in an attempt of either discovering or putting stringent limits on the new physics scenarios
- we investigate rare **top-Higgs** flavor changing neutral current decays

$$t \to cH, t \to uH$$

$$BR(t \to cH)_{SM} \sim 10^{(-15)}$$

(many orders of magnitude smaller than the value to be measured at the LHC, at 14 TeV)

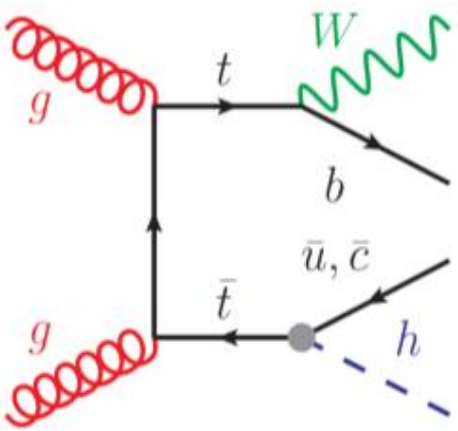
- An affirmative observation of the process t -> qH, well above the SM rate, will be a conclusive indication of a new physics beyond the SM
- tight constranints on $|Y_{qq'}|$ form the flavor oscillations

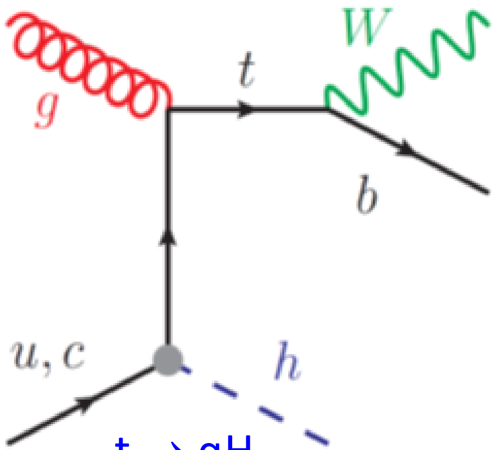
Technique	Coupling	Constraint
D^0 oscillations	$\|Y_{uc}\|^2, \|Y_{cu}\|^2$	$< 5.0 \times 10^{-9}$
	$\|Y_{uc}Y_{cu}\|$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations	$\|Y_{db}\|^2, \|Y_{bd}\|^2$	$< 2.3 \times 10^{-8}$
	$\|Y_{db}Y_{bd}\|$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations	$\|Y_{sb}\|^2, \|Y_{bs}\|^2$	$< 1.8 \times 10^{-6}$
	$\|Y_{sb}Y_{bs}\|$	$< 2.5 \times 10^{-7}$
K^0 oscillations	$\Re(Y_{ds}^2), \Re(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\Im(Y_{ds}^2), \Im(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\Re(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\Im(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$

LHC CONSTRAINTS

CMS $\mathrm{BR}(t \to cH) < 0.0056 \quad \leftrightarrow \quad \sqrt{|y_{tc}|^2 + |y_{ct}|^2} < 0.14$

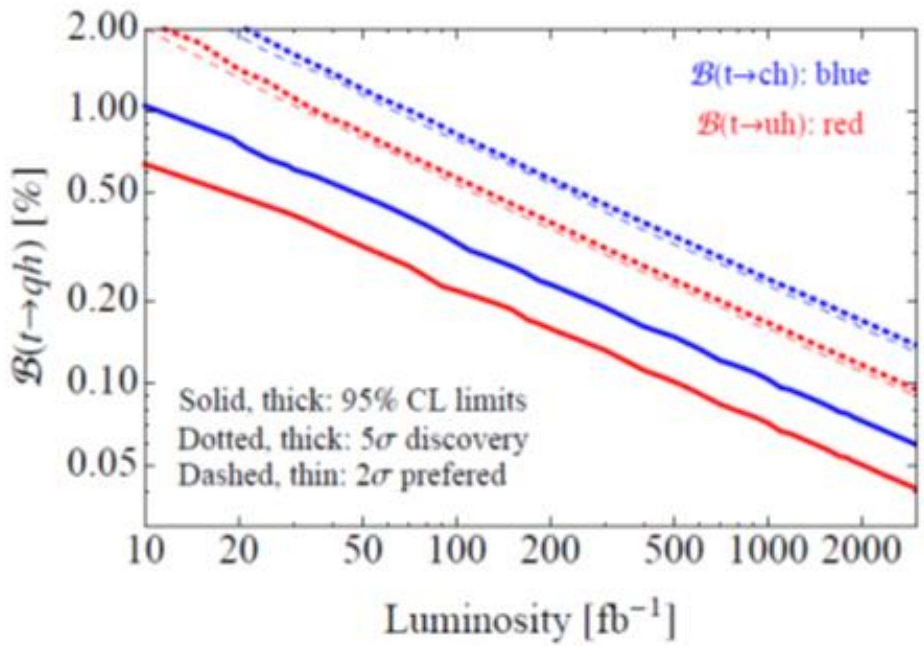
ATLAS $\mathrm{BR}(t \to cH) < 0.0079 \quad \leftrightarrow \quad \sqrt{|y_{tc}|^2 + |y_{ct}|^2} < 0.17$





$t \to qH$

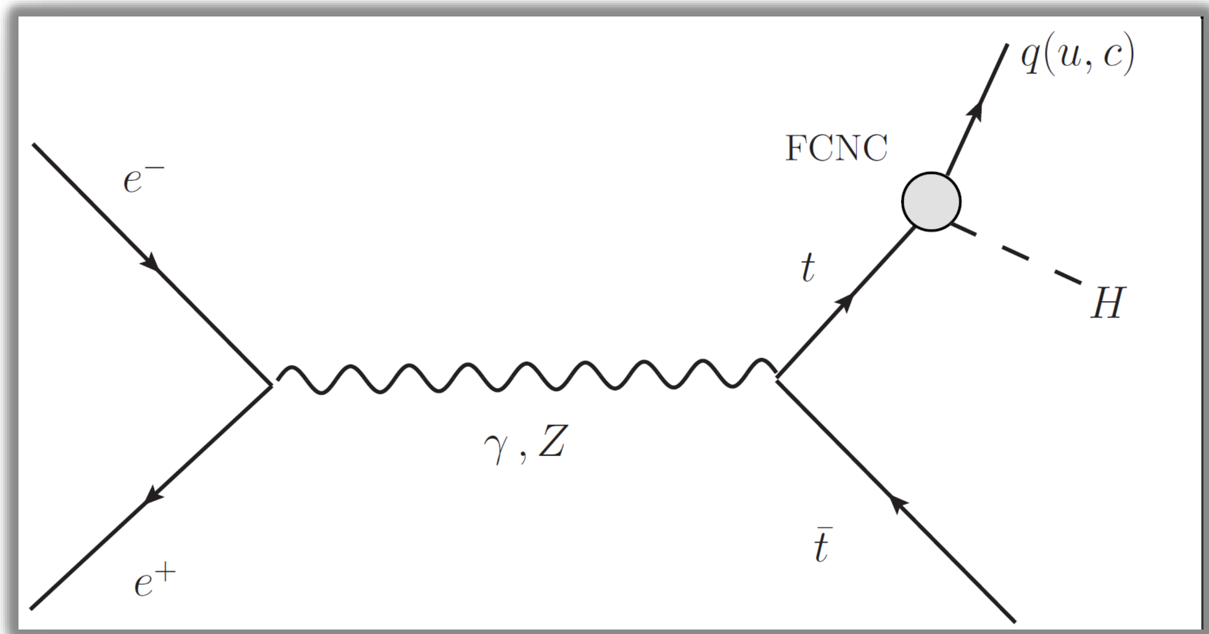
[Greljo, Kamenik, Kopp, 1404.1278]



Discrimination between tuH and tcH coupling at LHC:

(for 5 σ discovery, the discrimination is possible at 2 σ)

FCNC AT LINEAR COLLIDERS



ILC – International Linear Collider
CLIC – Compact Linear Collider

Operation at: $\sqrt{s}$ = 350, 500, 1000 GeV (up 3 TeV CLIC); our reference point $\sqrt{s}$ = 500 GeV

BEAM POLARIZATIONS can be tuned independently:

+/-80% for electrons, +/- 30% for positrons (both longitudinal and transversal)

Excellent opportunities for precision measurements of top-quark and Higgs properties

FCNC AT LINERAR COLLIDERS

The most general FCNC tqH Lagangian:

$$\boxed{\begin{aligned}\mathcal{L}^{tqH} &= g_{tu}\bar{t}_R u_L H + g_{ut}\bar{u}_R t_L H + g_{tc}\bar{t}_R c_L H + g_{ct}\bar{c}_R t_L H + h.c \\ &= \bar{t}(g_{tq}P_L + g^*_{qt}P_R)qH + \bar{q}(g_{qt}P_L + g^*_{tq}P_R)tH.\end{aligned}}$$

$t \to qH$ normalized to the standard tWb decay:

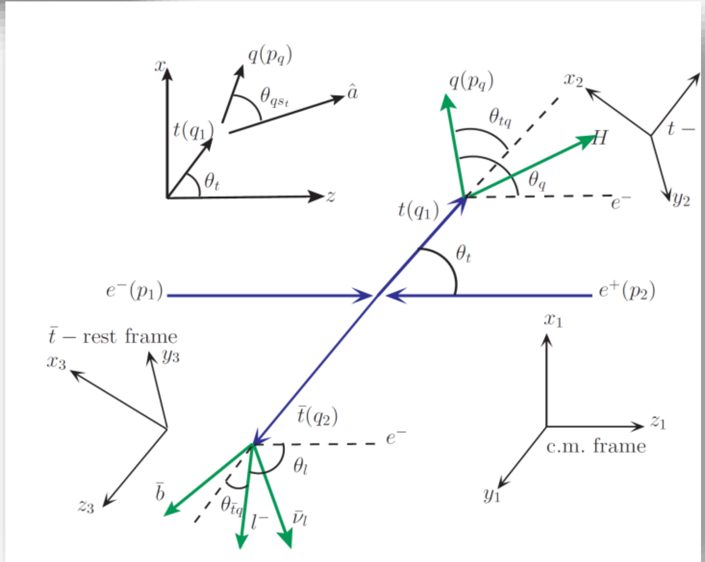
$$\mathrm{BR}(t \to qH) = \frac{1}{2\sqrt{2}G_F}\frac{(m_t^2 - m_H^2)^2}{(m_t^2 - m_W^2)^2(m_t^2 + 2m_W^2)}\boxed{(\mid g_{tq}\mid^2 + \mid g_{qt}\mid^2)}\alpha_{QCD}$$

$$\boxed{\Gamma_t = \Gamma_t^{SM} + \Gamma_{t\to qH} \approx \Gamma_t^{SM} + 0.155(\mid g_{tq}\mid^2 + \mid g_{qt}\mid^2)}$$

ANALYSIS

$$e^-(p_1) + e^+(p_2) \to t(q_1) + \bar{t}(q_2),$$
$$t(q_1) \to q(p_q) + H, \quad \left[\bar{t}(q_2) \to \bar{b}(p_b) + l^+(p_l) + \nu(p_\nu)\right]$$

$$d\sigma = \frac{1}{2s}\int \frac{ds_1}{2\pi}\frac{1}{((s_1-m_t^2)^2+\Gamma_t^2 m_t^2)} \times |\bar{\mathcal{M}}^2|$$
$$\times (2\pi)^4\delta^4(q_1+q_2-p_1-p_2)\frac{d^3q_1}{(2\pi^3)2E_1}\frac{d^3q_2}{(2\pi^3)2E_2} \qquad [\text{production of } t\bar{t}]$$
$$\times (2\pi)^4\delta^4(p_q+p_H-q_1)\frac{d^3p_q}{(2\pi^3)2E_q}\frac{d^3p_H}{(2\pi^3)2E_H} \qquad [\text{decay of t}],$$



Spin of the top λ_t will be considerd as well as the beam polarizations :

$$|\bar{\mathcal{M}}^2| = \sum_{L,R}\sum_{(\lambda_t\lambda'_t=\pm)} \mathcal{M}^{L,R}_{\lambda_t}\mathcal{M}^{*L,R}_{\lambda'_t}\rho^{D^t}_{\lambda_t\lambda'_t}$$

PRODUCTION HELICITY MATRIX for the top quark

DECAY HELICITY MATRIX for the top

(antitop helicities are summed over)

After boosting and integration over some angles like ϕ_q, θ_t

$$\frac{d\sigma}{ds\ d\cos\theta_q\ d\phi_t} = \frac{1}{4}\Big((1-P^L_{e^-})(1+P^L_{e^+})|T_{e^-_L e^+_R}|^2 + (1+P^L_{e^-})(1-P^L_{e^+})|T_{e^-_R e^+_L}|^2\Big)$$
$$-\frac{1}{2}P^T_{e^-}P^T_{e^+}\mathrm{Re}\ \mathrm{e}^{\mathrm{i}(\eta-2\phi_t)}\mathrm{T}^*_{\mathrm{e}^-_\mathrm{R}\mathrm{e}^+_\mathrm{L}}\mathrm{T}_{\mathrm{e}^-_\mathrm{L}\mathrm{e}^+_\mathrm{R}},$$

dependence on the initial beam polarizations $P_{L,T}$ (e-) = +/- 0.8 $P_{L,T}$(e+) = +/- 0.3

$$|T_{e^\mp_L e^\pm_R}|^2 = \boxed{(|g_{tq}|^2 + |g_{qt}|^2)}\Big(a_0 + a_1\cos\theta_q + a_2\cos^2\theta_q\Big)$$
$$+\boxed{(|g_{tq}|^2 - |g_{qt}|^2)}\Big(b_0 + b_1\cos\theta_q + b_2\cos^2\theta_q\Big)$$

The coefficients a_0, a_1, a_2 and b_0,b_1,b_2 differ from each other

– the couplings $|g_{qt}|^2$ have different angular dependences from $|g_{tq}|^2$

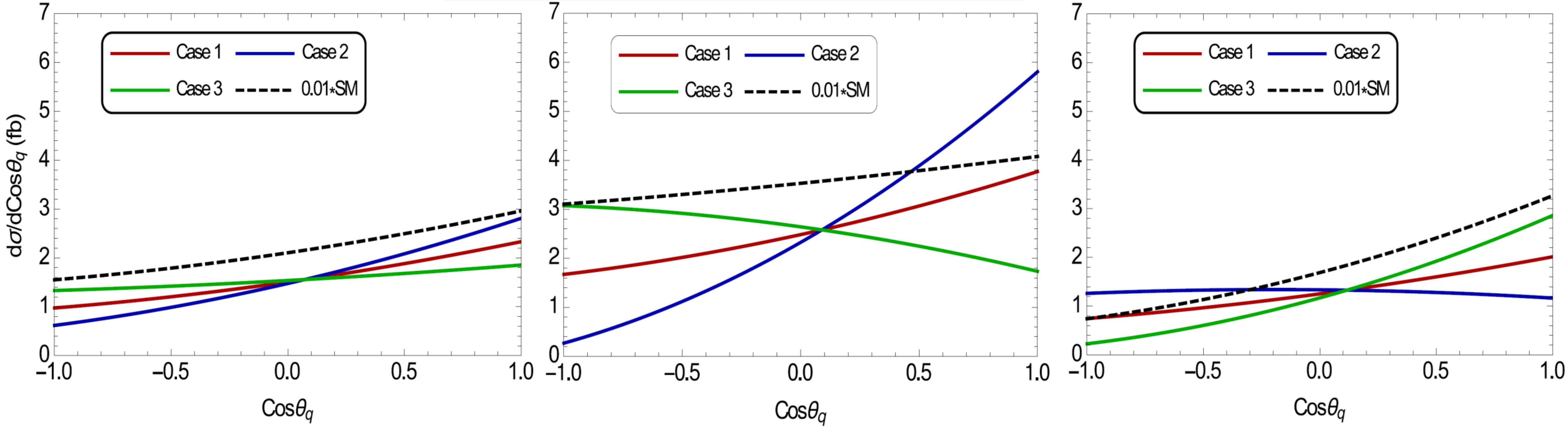
➡ **possibility to test chirality of the FCNC tqH couplings !**

POLAR ANGLE DISTRIBUTION

POLAR ANGLE DISTRIBUTION

- Case 1 : $\sqrt{|g_{tq}|^2 + |g_{qt}|^2} = 0.16$ present LHC bound
- Case 2 : $\sqrt{|g_{tq}|^2 + |g_{qt}|^2} = 0.16$, with $|g_{qt}|^2 = 0$
- Case 3 : $\sqrt{|g_{tq}|^2 + |g_{qt}|^2} = 0.16$, with $|g_{tq}|^2 = 0$

$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_q}$ vs $\cos\theta_q$



$P_L(e^-)= 0 \quad P_L(e^+)=0$

$P_L(e^-)=-0.8 \quad P_L(e^+)=+0.3$ LR

$P_L(e^-)=+0.8 \quad P_L(e^+)=-0.3$ RL

Clear dependence on the initial beam polarizations in differentiating among the chiral couplings !

FULL NUMERICAL ANALYSIS

$$e^-(p_1,\lambda_{e-}) + e+(p_2,\lambda_{e+}) \to t(q_1,s_t) + \bar{t}(q_2,s_{\bar{t}})$$

$$t(q_1,s_t) \to q(p_q) + H(\to b\bar{b})$$

$$\bar{t}(q_2,s_{\bar{t}}) \to b(p_b) + l(\mathrm{p}_l) + \nu(p_\nu)$$

- **background** for the processs is the ttbar –production, with one top decaying hadronically and the other to lepton, neutrino and a b-quark
- **applying cuts** in the search for
  – an isolated lepton; q-quark from the top decay; b-tagged jet; reconstructed Higgs decay from two b-jets

$$\frac{d\sigma}{d\cos\theta_f \, d\cos\theta_{\bar{f}}} = \frac{\sigma}{4}(1 + \kappa_f B_t \cos\theta_f + \kappa_{\bar{f}} B_{\bar{t}} \cos\theta_{\bar{f}} - \kappa_f \kappa_{\bar{f}} C \cos\theta_f \cos\theta_{\bar{f}})$$

κ_f top spin analysing power factors of the top decaying products f :

SM: $\kappa_{\bar{f}} = \kappa_l = 1$

$t \to qH$: $\kappa_f = \kappa_q = \dfrac{|g_{qt}|^2 - |g_{tq}|^2}{|g_{qt}|^2 + |g_{tq}|^2}$

for $|g_{qt}|^2 \simeq |g_{tq}|^2$ spin information is lost

TOP SPIN OBSERVBLES (TOP DECAY PRODUCTS OF CONTAIN INFO ABOUT THE TOP SPIN)

$$\frac{d\sigma}{d\cos\theta_f \, d\cos\theta_{\bar f}} = \frac{\sigma}{4}\left(1 + \kappa_f B_t \cos\theta_f + \kappa_{\bar f} B_{\bar t} \cos\theta_{\bar f} - \kappa_f \kappa_{\bar f} C \cos\theta_f \cos\theta_{\bar f}\right)$$

$$\boxed{\langle \mathcal{O}_2 \rangle = B_t} \qquad \boxed{\langle \mathcal{O}_3 \rangle = C}$$

$$O_1 = S_t \cdot S_{\bar t}$$

$$O_2 = S_t \cdot \hat a \,, \quad O_{\bar 2} = S_{\bar t} \cdot \hat b$$

$$O_3 = 4(S_t \cdot \hat a)(S_{\bar t} \cdot \hat b)$$

$$O_4 = 4((S_t \cdot \hat p)(S_{\bar t} \cdot \hat q_1) + (S_t \cdot \hat q_1)(S_{\bar t} \cdot \hat p))$$

OPENING ANGLE DISTRIBUTION

between directions of two spin analaysers

(final particles in the top decays):

$$\frac{d\sigma}{d\cos\phi_{f\bar f}} = \frac{\sigma}{2}\left(1 - \kappa_f D \cos\phi_{f\bar f}\right)$$

$$\boxed{\langle \mathcal{O}_1 \rangle = D}$$

QUANTIZATION AXES:

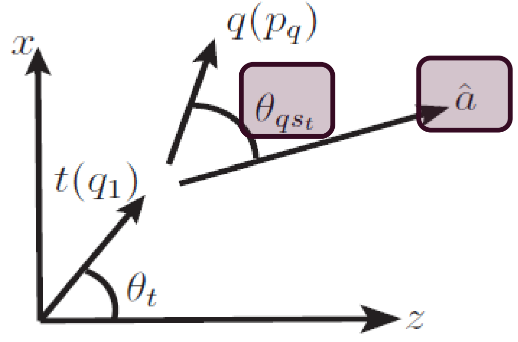
$\hat a = -\hat b = \hat q_1$	**helicity basis (top dir.)**
$\hat a = \hat b = \hat p$	**beamline basis**
$\hat a = \hat b = \hat d_X$	**max basis – OFF-DIAGONAL** (specific for each model X)
$\hat a = \hat b = \hat e_X$	**minimal basis** (specific for each model X)

OFF-DIAGONAL = max correlations – almost 100% at ILC/Tevatron

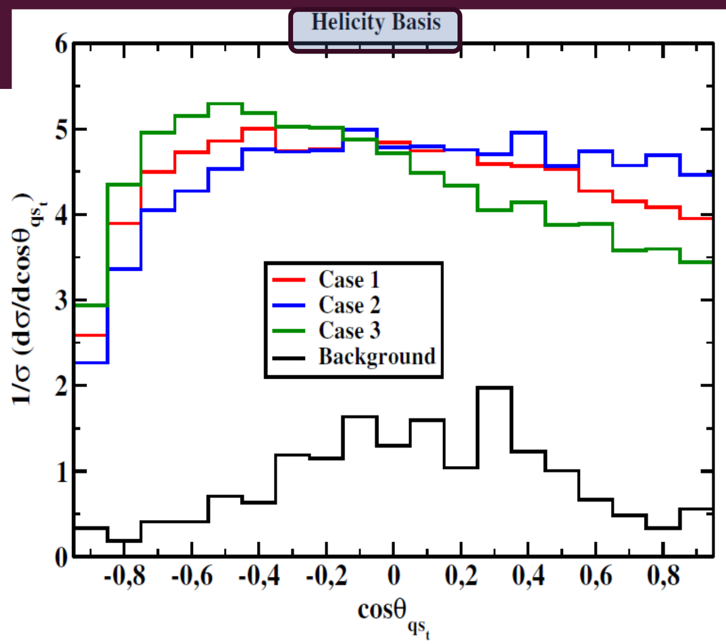
[Mahlon and Parke, hep-ph/9512264
Bernreuther et al., hep-ph/0403035]

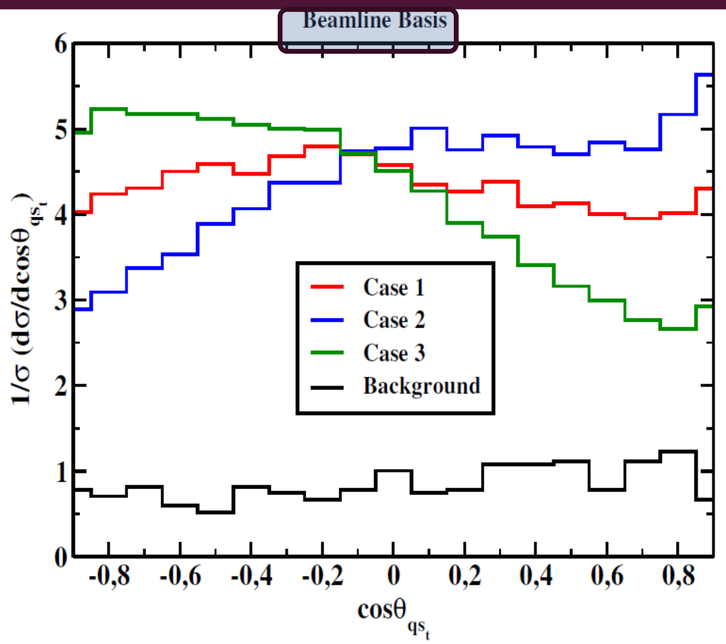
$$\hat{\mathbf{d}}_{SM} = \hat{\mathbf{d}}^{max}_{SM} = \frac{-\hat{\mathbf{p}} + (1-\gamma) z \, \hat{\mathbf{q}}_1}{\sqrt{1 - (1-\gamma^2) z^2}}$$

TOP SPIN

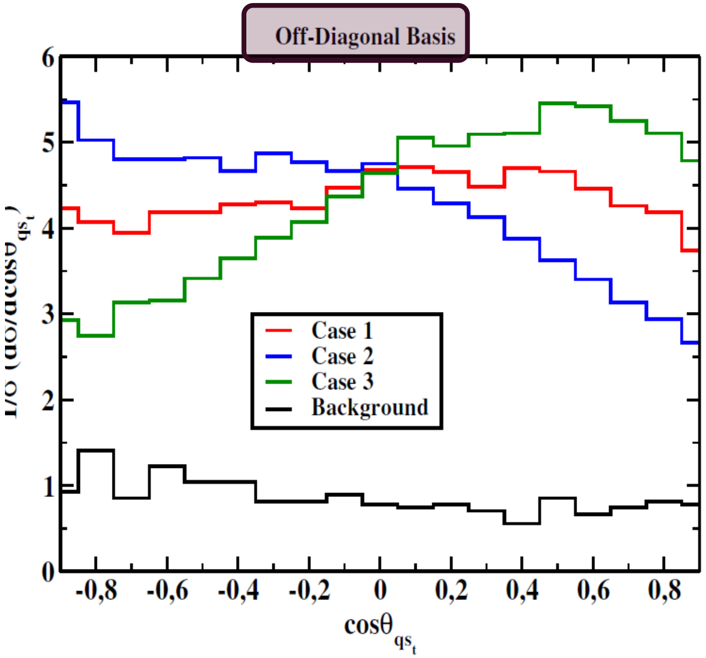


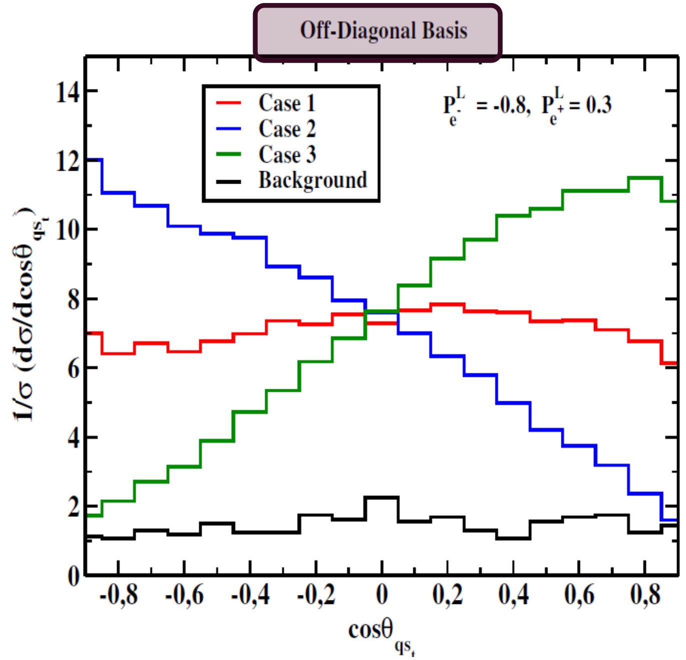
$B_t = \langle O_2 \rangle = \langle S_t \cdot \hat{a} \rangle$





- ❖ Clear distiction between chiral couplings
- ❖ Clear enhancment of the effect by using inital beam polarizations





– $\sqrt{|g_{qt}|^2 + |g_{tq}|^2} = 0.16$

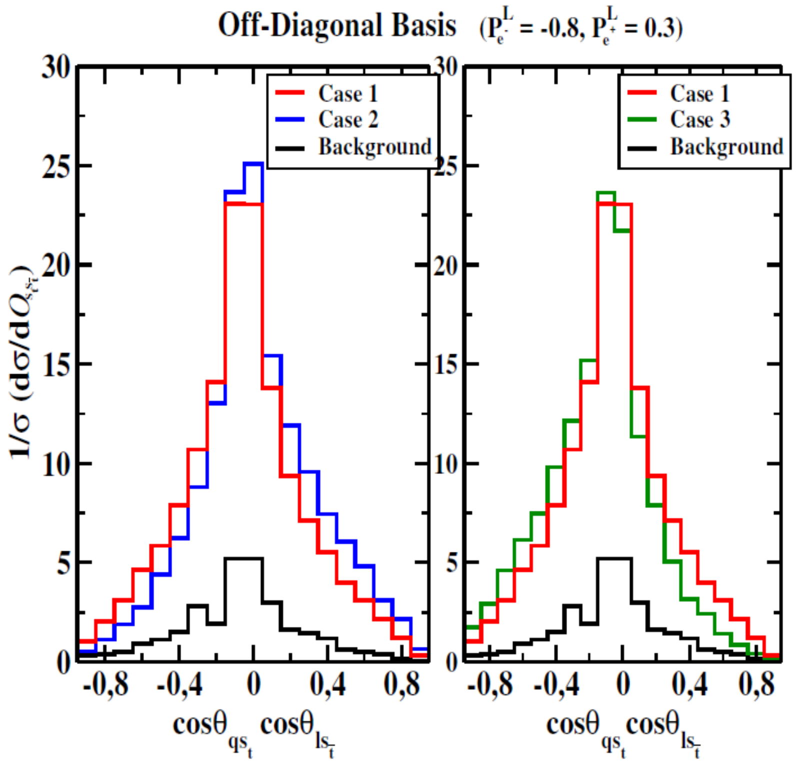
– $\sqrt{|g_{tq}|^2} = 0.16,\ \sqrt{|g_{qt}|^2} = 0$

– $\sqrt{|g_{tq}|^2} = 0,\ \sqrt{|g_{qt}|^2} = 0.16$

TOP-ANTITOP SPIN CORRELATIONS | OPENING ANGLE DISTIBUTION

$\mathcal{O}_{s_t,s_{\bar{t}}} = \cos\theta_f \cos\theta_{\bar{f}}$ distribution:

$\sim \langle O_3 \rangle = \langle 4(S_t \cdot \hat{a})(S_{\bar{t}} \cdot \hat{b}) \rangle$



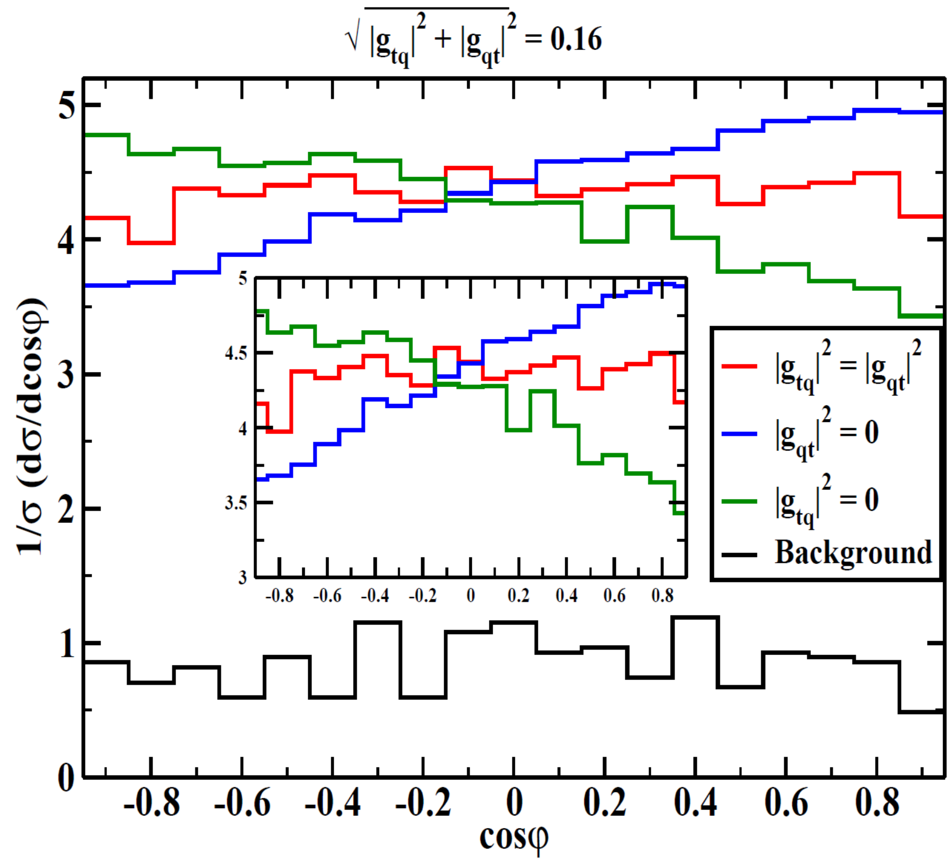
$$\frac{d\sigma}{d\cos\phi_{f\bar{f}}} = \frac{\sigma}{2}(1 - \kappa_f\, D \cos\phi_{f\bar{f}})$$

$D = \langle O_1 \rangle = \langle S_t \cdot S_{\bar{t}} \rangle$

– $\sqrt{|g_{qt}|^2 + |g_{tq}|^2} = 0.16$

– $\sqrt{|g_{tq}|^2} = 0.16,\ \sqrt{|g_{qt}|^2} = 0$

– $\sqrt{|g_{tq}|^2} = 0,\ \sqrt{|g_{qt}|^2} = 0.16$



One can see asymmetry when compared Case2 and Case3

- possibilty to distinquish chiral couplings

BR AND DISCOVERY AT LINEAR COLLIDERS

Most stringent upper bounds at 95 % C.L. $t\bar{t} \to Wb + qH \to \ell\nu b + \gamma\gamma q$

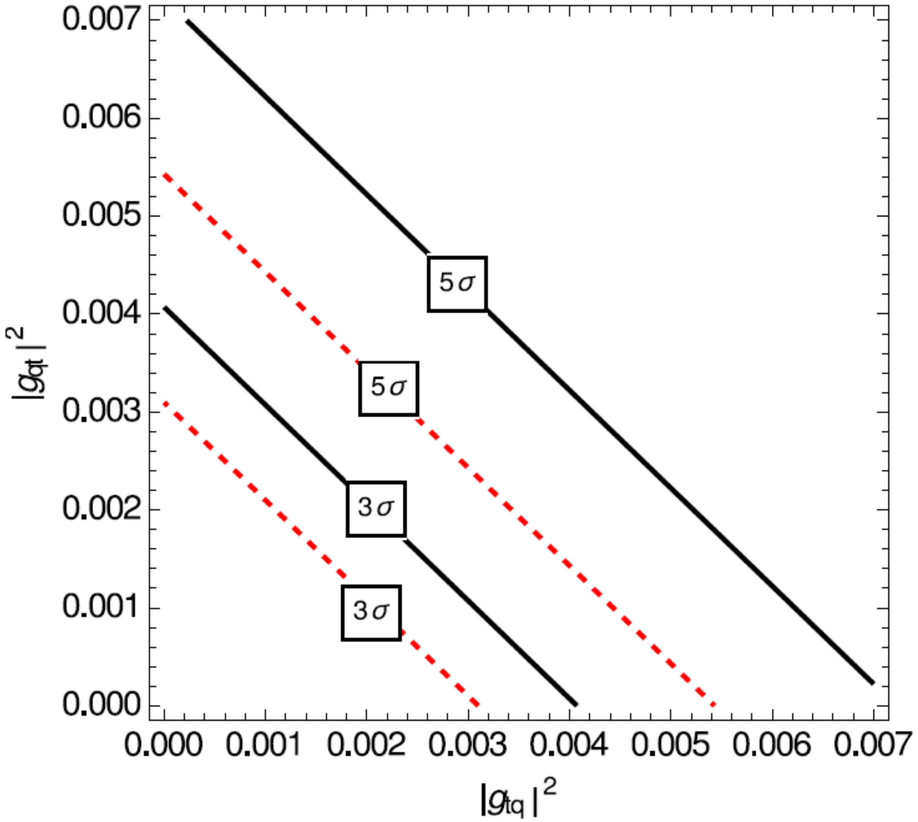
@ 7 TeV: $t \to qH < 0.79\%$ (ATLAS, JHEP 1406 (2014) 008)

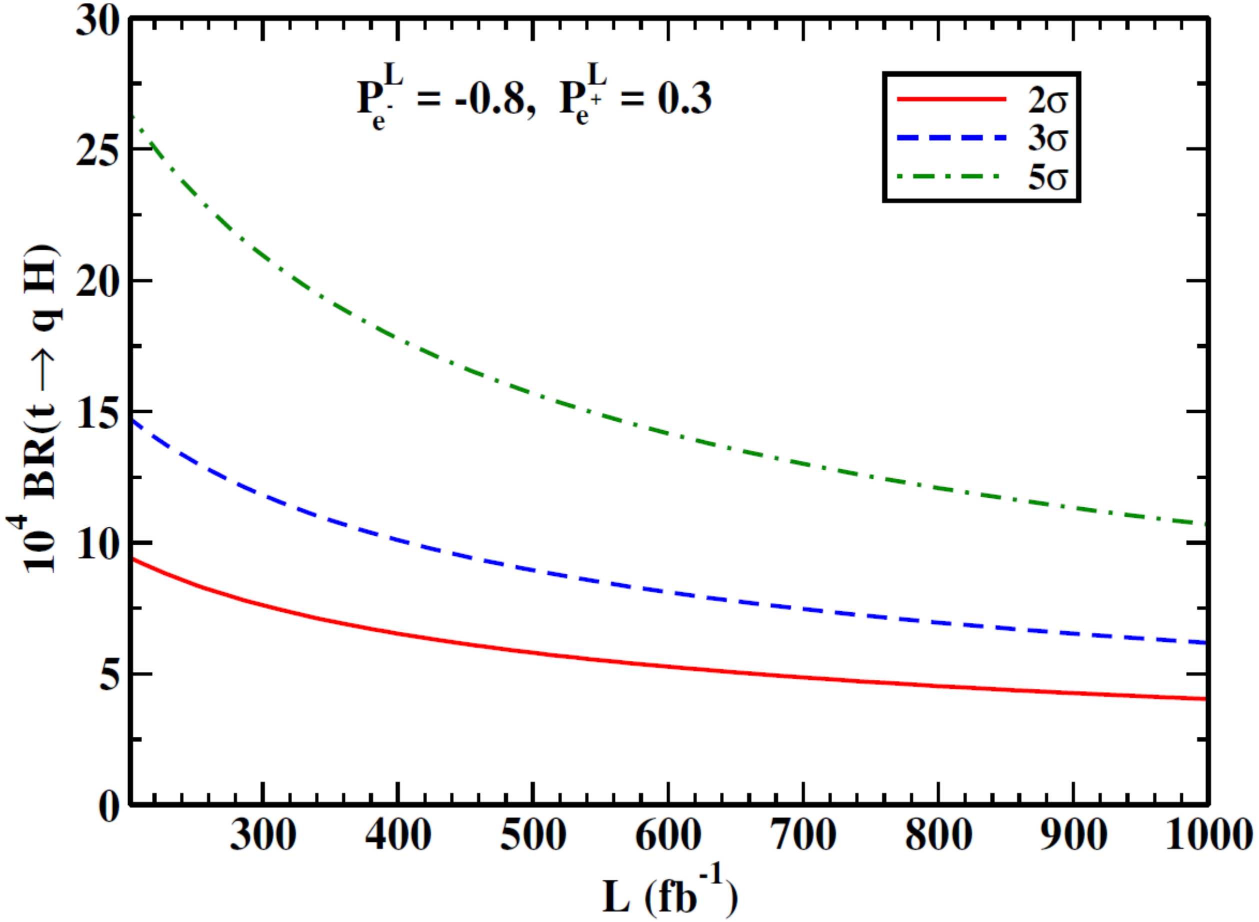
future @ 14 TeV: $t \to qH < 0.05\%$ at 3000 fb-1(ATL-PHYS-PUB-2013-012)

_____ unpolarized beams

------- polarized beams

P_L (e-) = - 0.8 P_L(e+) =+ 0.3





CONCLUSIONS

- Nature of the FCNC top-Higgs couplings can be probed by using complementary machines, the LHC and the linear colliders

- At LHC one can distiquish among $|g_{ct}|$ and $|g_{ut}|$ FCNC couplings

- At linear colliders one can distinquish among different chiral FCNC couplings $|g_{qt}|$ and $|g_{tq}|$ by use of
  - the initial beam polarizations (longitudinal (and possibly transversal))
  - the top-spin polarization observables

  and by exploring various angular asymmetries

- bound obtained at linear colliders could be about a factor of 2 better then the one obtained at LHC

$$\sqrt{|g_{qt}|^2 + |g_{tq}|^2} < 0.05 - 0.07$$