EXPLORING TOP-HIGGS FCNC COUPLINGS AT COLLIDERS

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- 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**

$$t \rightarrow cH, t \rightarrow uH$$

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

(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

- The analysis of the tqH couplings can be carried out in the context of the **LHC** (in single top and ttbar production) and the next generation **e+e− linear colliders** (in ttbar production).

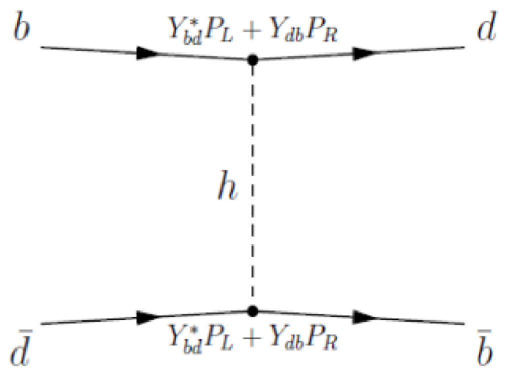
- The high energy e+e− colliders (ILC /CLIC) operating at √ s = 500GeV and a total luminosity of 500 fb^{-1}, using the initial beam polarizations, both longitudinal and transverse, will give us an excellent opportunity for precision measurements of top-quark and Higgs boson properties

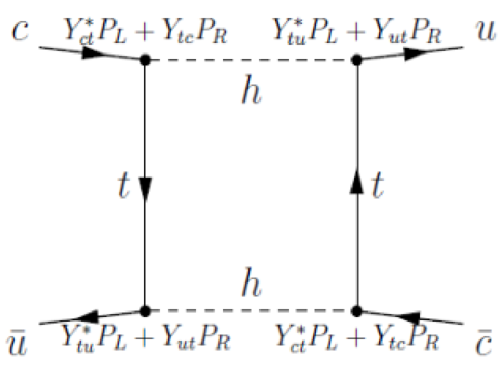
FCNC COUPLING TO QUARKS

FLAVOR PHYSICS:

- tight constranints to the **FCNC light-quark couplings** $|Y_{qq'}|$ form the flavor oscillations :

from Joachim Kopp's talk



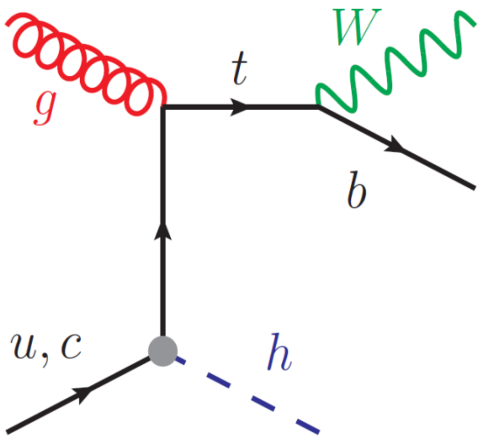


- Wilson coefficients constrained by UTfit (Bona et al.), arXiv:0707.0636

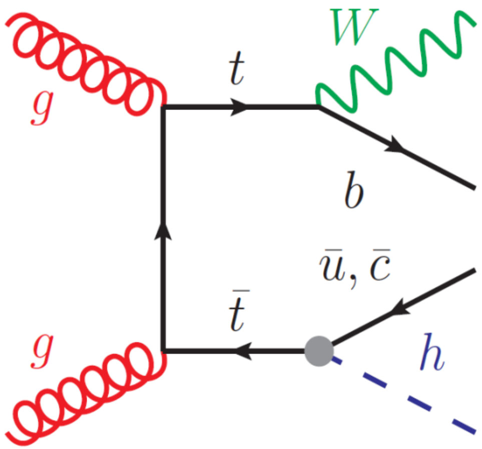
see also Blankenburg Ellis Isidori, arXiv:1202.5704

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

LHC PHYSICS on $t \to qH$:



single top + Higgs production



$t \to hq$ decay

[Greljo, Kamenik, Kopp, 1404.1278]

from J.Kopp's talk

- Only relevant for *tuh* couplings (PDF suppression for charm)
- $\ell + 2\gamma$ or up to 5ℓ
- not included in LHC searches

- Relevant for *tuh* and *tch* couplings (no PDF suppression)
- $\ell + 2\gamma$ or up to 5ℓ

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

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

Comparison of current and projected future limits

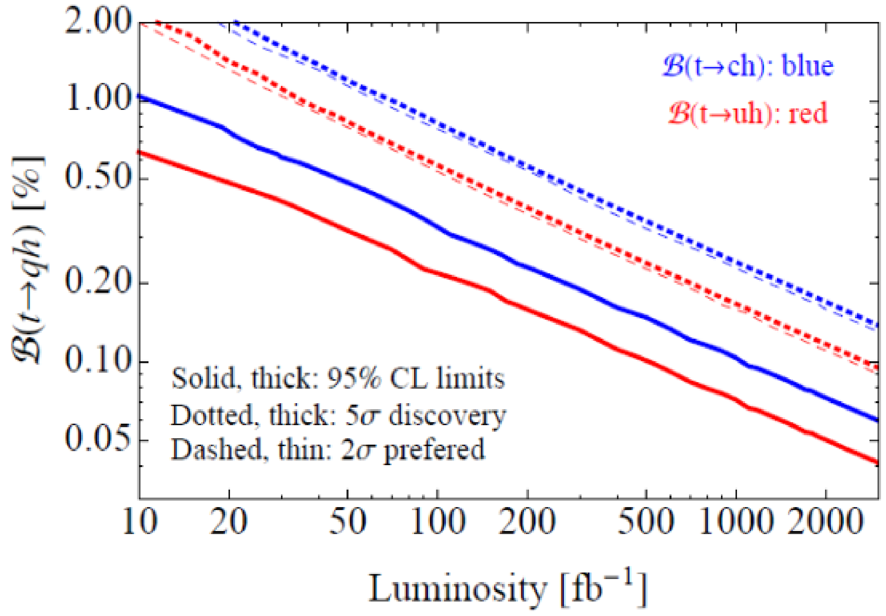
[Greljo, Kamenik, Kopp, 1404.1278]

from J.Kopp's talk

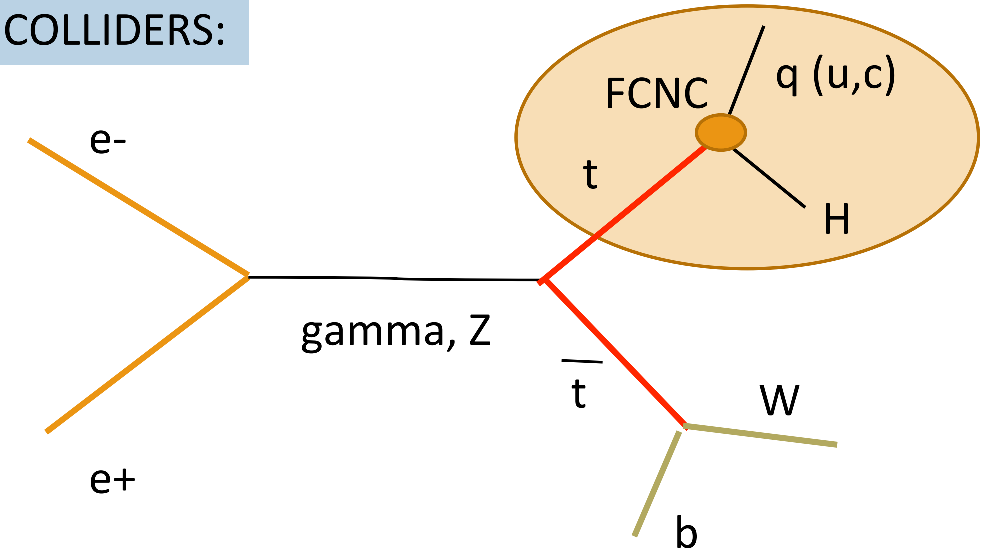
	$\sqrt{y_{ut}^2 + y_{tu}^2}$	BR($t \to hu$)	$\sqrt{y_{ct}^2 + y_{tc}^2}$	BR($t \to hc$)
New limits from existing data				
Multilepton	< 0.19	< 0.010	< 0.23	< 0.015
Diphoton plus lepton	< 0.12	< 0.0045	< 0.15	< 0.0066
Vector boson plus Higgs	< 0.16	< 0.0070	< 0.21	< 0.012
Projected future limits (13 TeV, 100 fb^{-1})				
Vector boson plus Higgs	< 0.076	< 0.0015	< 0.084	< 0.0019
Multilepton	< 0.087	< 0.0022	< 0.11	< 0.0033
Fully hadronic	< 0.12	< 0.0036	< 0.13	< 0.0048

Discriminating between *tuh* and *tch* couplings

For a 5σ discovery, discrimination between *tuh* and *tch* is possible at 2σ



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)

The most general FCNC tqH Lagangian:

$$\begin{aligned}\mathcal{L}^{tqH} &= g_{tu}\bar{t}_L u_R H + g_{ut}\bar{u}_L t_R H + g_{tc}\bar{t}_L c_R H + g_{ct}\bar{c}_L t_R H + h.c \\ &= \bar{t}(g_{tq}P_R + g_{qt}^* P_L)qH + \bar{q}(g_{qt}P_R + g_{tq}^* P_L)tH.\end{aligned}$$

Three level decays:

$$\Gamma_{t\to qH} = \frac{1}{32\pi m_t^3}\sqrt{m_t^2 - (m_q - m_H)^2}\sqrt{m_t^2 - (m_q + m_H)^2}\Big[(| g_{tq} |^2 + | g_{qt} |^2)(m_t^2 + m_q^2 - m_H^2) + 4 m_t m_q \left(g_{tq}^* g_{qt} + g_{qt}^* g_{tq}\right)\Big].$$

normalized to the standard tWb decay:

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

$$\Gamma_t = \Gamma_t^{SM} + \Gamma_{t\to qH} \approx \Gamma_t^{SM} + 0.397(| g_{tq} |^2 + | g_{qt} |^2)$$

Analysis of the tqH final state at e+e- colliders

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

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

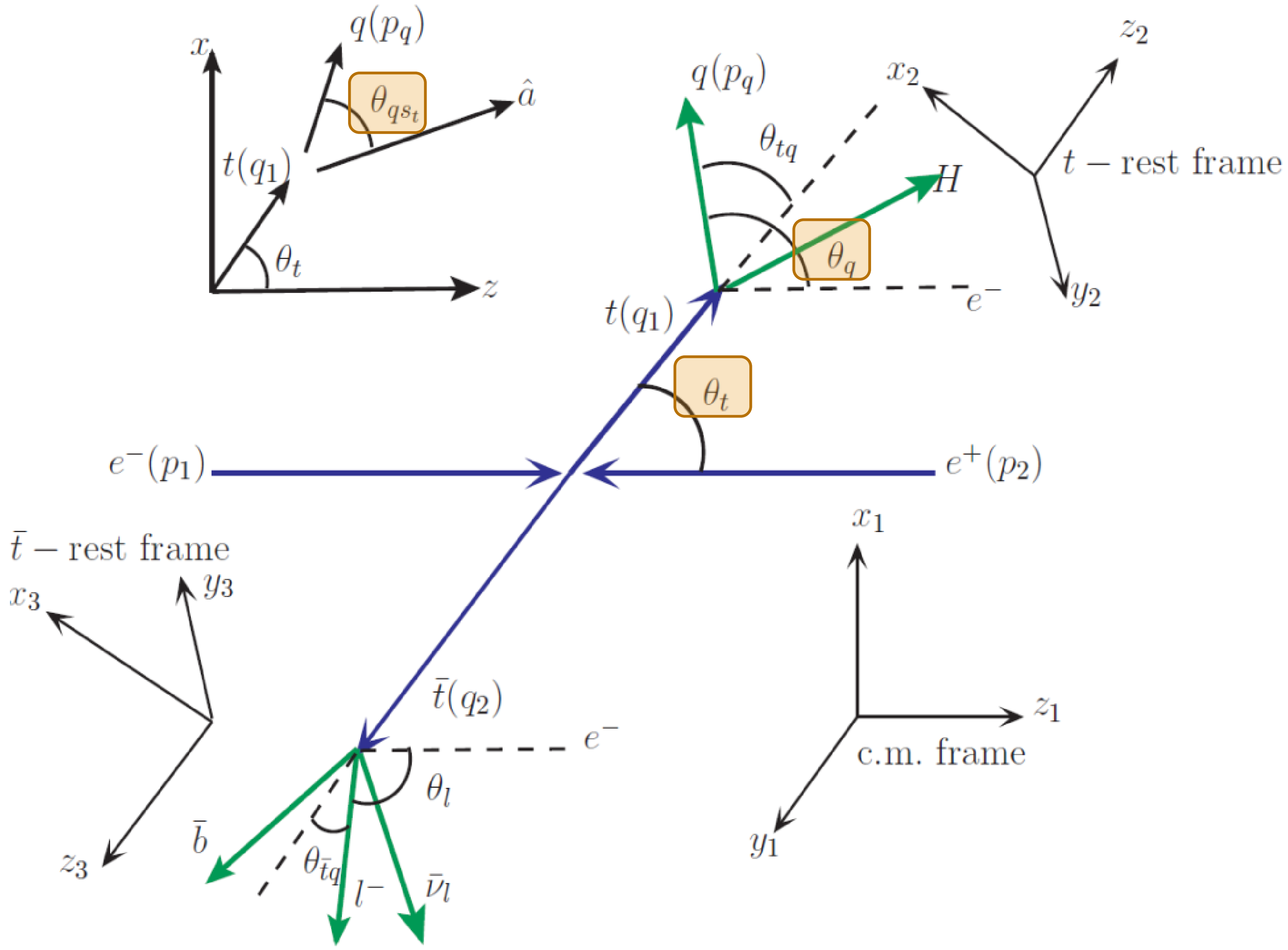
Spin of the top λ_t will be considerd as well as the beam polarizations :

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

Production helicity matrices for the top quark

Decay helicity matrix for the top

(antitop helicities are summed over)



All vectors in the t-rest frame need boosting and the rotation to the center of mass frame:

$$q_1 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_t & 0 & \sin\theta_t \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\theta_t & 0 & \cos\theta_t \end{pmatrix} \begin{pmatrix} \gamma & 0 & 0 & \gamma\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \gamma\beta & 0 & 0 & \gamma \end{pmatrix} q_1^{top}$$

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

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

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 !

Constraints on the chiral FCNC couplings by angular asymmetries

$e^+e^- \to t\bar{t}$ production +

signal $t \to qH$

background $t \to Wb$

$$\sigma_{Signal} = \frac{2\pi}{1-\beta^2}(m_t^2 - m_H^2)(|g_{tq}|^2 + |g_{qt}|^2)\Big((1-P_{e-}^L)(1+P_{e+}^L)\left(s\beta^2 B_L^2 + (2m_t^2+s)A_L^2\right) + (1+P_{e-}^L)(1-P_{e+}^L)\left(s\beta^2 B_R^2 + (2m_t^2+s)A_R^2\right)\Big).$$

$$\sigma_{Bkg} = \frac{4\pi g^2 m_t^2}{s(1-\beta^2)^2 m_W^2}(m_t^2 - m_W^2)(m_t^2 + 2m_W^2)\Big((1-P_{e-}^L)(1+P_{e+}^L)\left(s\beta^2 B_L^2 + (2m_t^2+s)A_L^2\right) + (1+P_{e-}^L)(1-P_{e+}^L)\left(s\beta^2 B_R^2 + (2m_t^2+s)A_R^2\right)\Big).$$

THREE CASES CONSIDERED:

- 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 $|g_{tq}|^2 = 0$

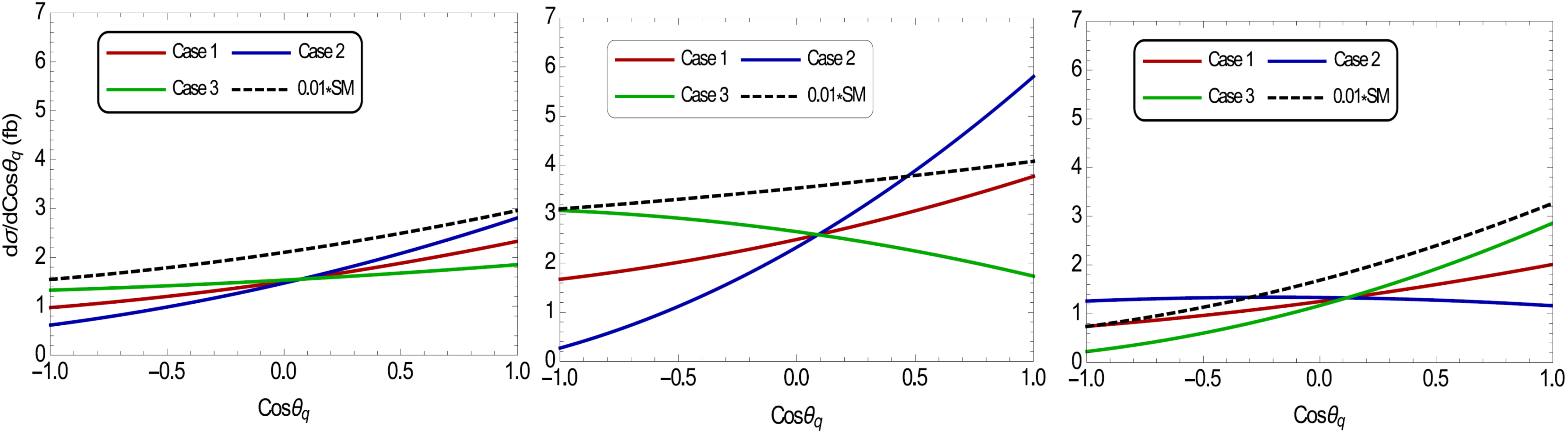
POLAR ANGLE DISTRIBUTION

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

– $\sqrt{|g_{qt}|^2+|g_{tq}|^2}=0.16$

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

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



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

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

CONSTRAINTS FROM ASYMMETRIES

- forward-backward:

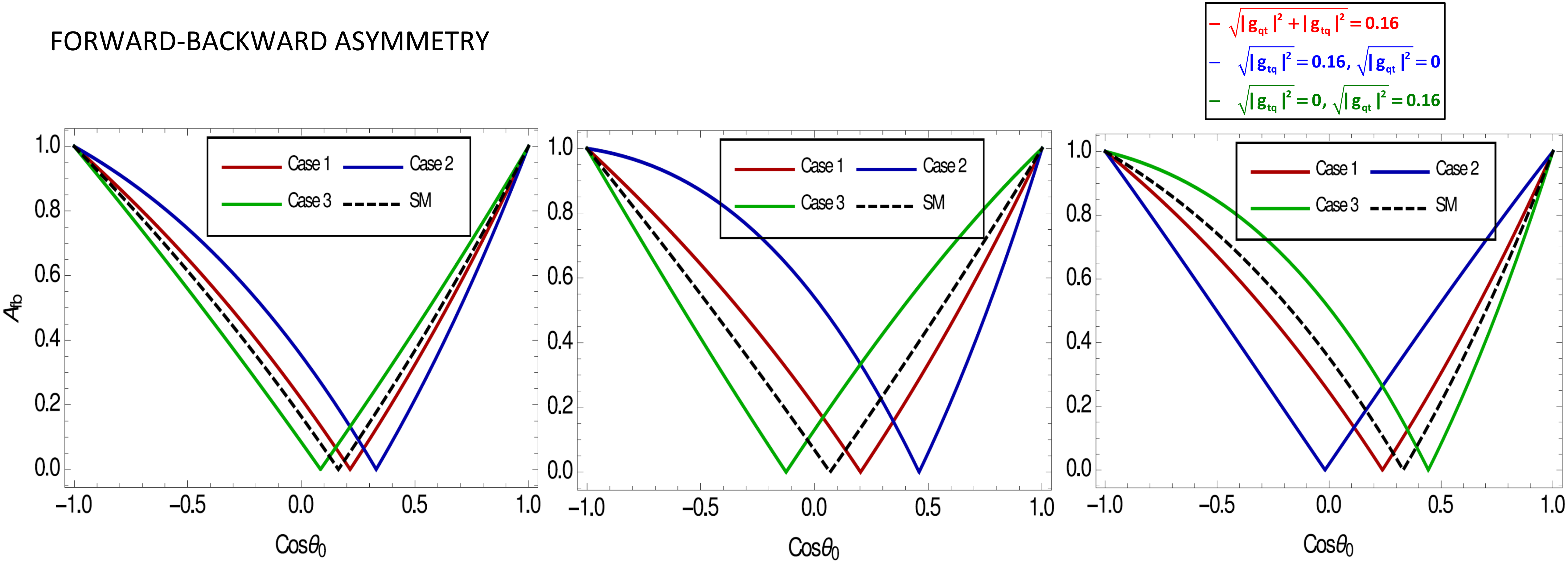
$$A_{fb}(\cos\theta_0) = \frac{1}{d\sigma/ds}\left(\int_{\cos\theta_0}^{1} \frac{d\sigma}{ds\ d\cos\theta_q} - \int_{-1}^{\cos\theta_0} \frac{d\sigma}{ds\ d\cos\theta_q}\right)$$

- asymutal:

$$A_{\phi}(\cos\theta_0) = \frac{1}{d\sigma/ds}\left(\int_{-\cos\theta_0}^{\cos\theta_0}\int_{0}^{2\pi} sgn(\cos(\eta - 2\phi_t))\frac{d\sigma}{ds\ d\cos\theta_q\ d\cos(\eta - 2\phi_t)}\right)$$

θ_0 is the experimental polar-angle cut

FORWARD-BACKWARD ASYMMETRY



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

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

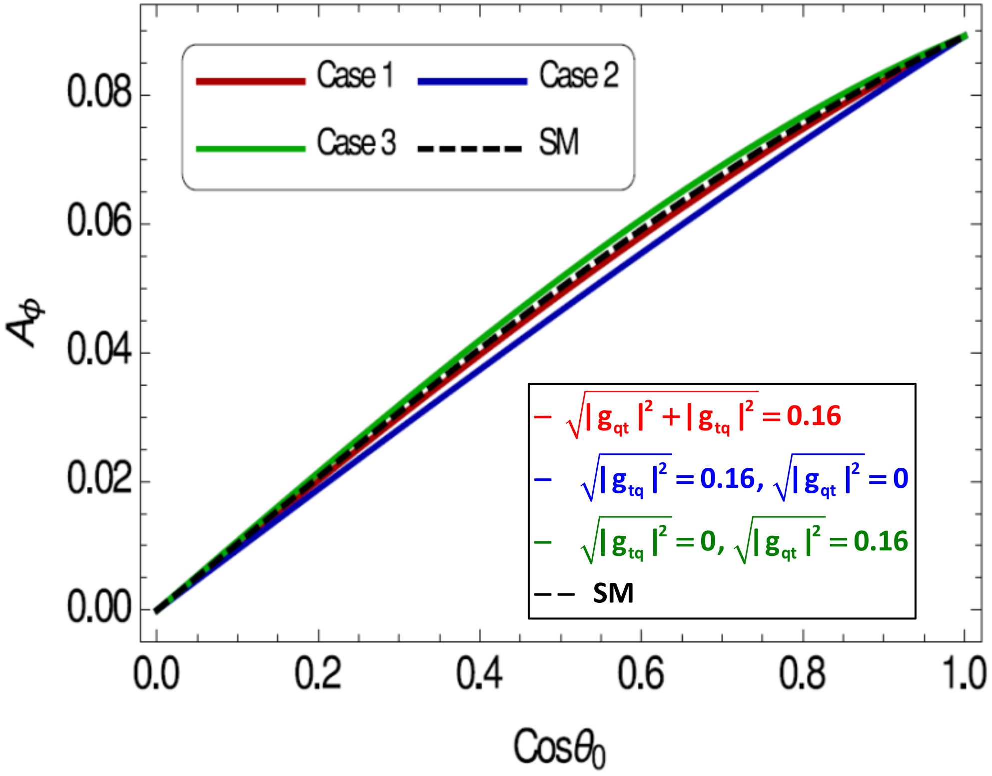
$P_L(e^-) = +0.8 \quad P_L(e^+) = -0.3$ RL

- the advantage of the bean polarization is clearly visible
  (one can also see that by changing the beam polarization Case2 becomes more prominent than Case3 and vice verse)

ASYMUTHAL ASYMMETRY

- It is coming from the transversally polarized beams

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

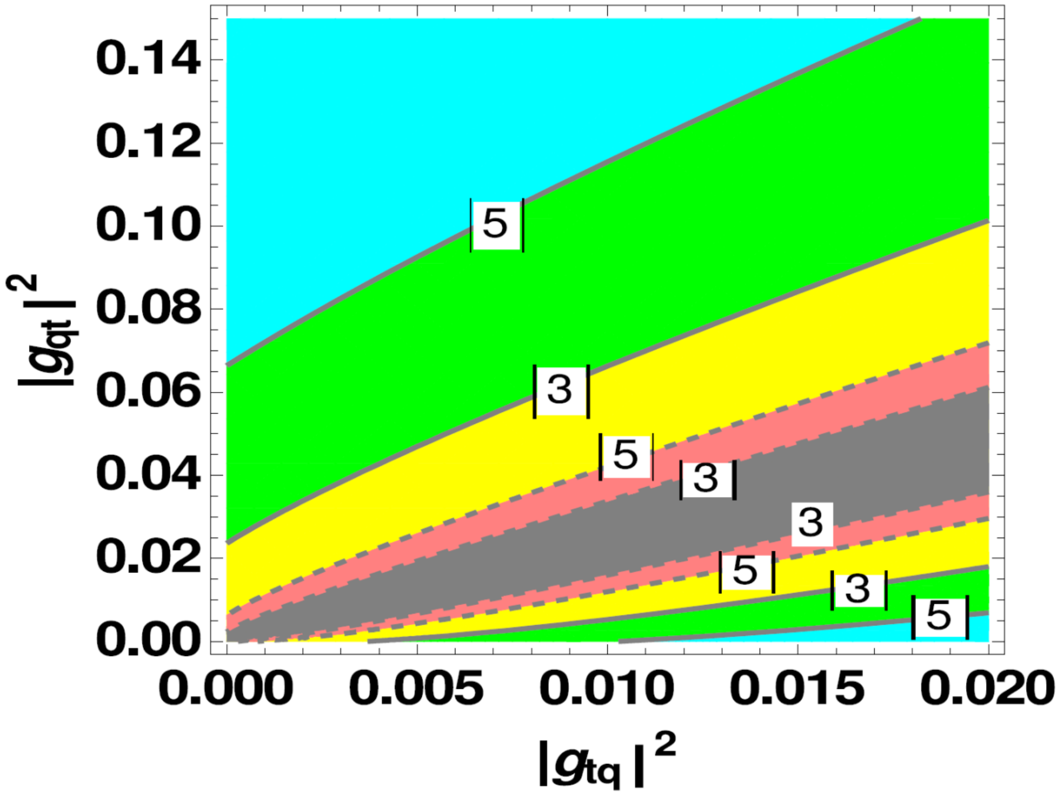


- the distribution is amost the same for the signal and the background
- it could be useful observable once FCNC couplings are discovered

LIMITS ON FCNC COUPLINGS FROM THE FORWARD-BACKWARD ASYMMETRY

- statistical significance:

$$s = \frac{|A_{sig} - A_{bkg}|}{\sqrt{\Delta A_{sig}^2 + \Delta A_{bkg}^2}}$$



$\theta_0 = 0$

$\sqrt{s} = 500$ GeV

luminosity of 500 fb^{-1}

solid lines – unpolarized case
dashed lines - P_L (e-) = - 0.8 P_L(e+) = - 0.3

The area which can be probed is above or below the curves.
The gray area cannot be probed at ILC
(much smaller region that cannot be probed when compared to LHC)

TOP SPIN OBSERVABLES

- top decays before hadronizing - decay products contain information about the top spin

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

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

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

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

QUANTIZATION AXES:

$\hat a = -\hat b = \hat q_1$ **helicity basis (top dir.)**

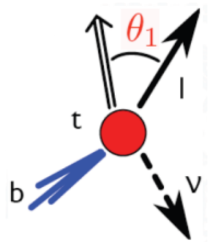
$\hat a = \hat b = \hat p$ **beamline basis**

$\hat a = \hat b = \hat d_X$ **off-diagonal – max basis** (specific for each model X)

$\hat a = \hat b = \hat e_X$ **minimal basis** (specific for each model X)

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

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



OPENING ANGLE DISTRIBUTION

between directions of two spin analysers:

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

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

max correlations – almost 100% at ILC/Tevatron
[Mahlon and Parke, hep-ph/9512264
Bernreuther et al., hep-ph/0403035]

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

d_X [Fajfer, Kamenik, Melic, hep-ph/1205.0264]

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

i	$l^+, \bar{d}, \bar{s}$	ν_l, u, c	b	W+	j<
κ	1	-0,31	-0,41	0,41	0,51

$$\kappa_f = \frac{\rho_{++}^{t\to f} - \rho_{--}^{t\to f}}{\rho_{++}^{t\to f} + \rho_{--}^{t\to f}}$$

Our case: $t \to qH$ -spin analyser is the q-quark

$$\kappa_q = \frac{|g_{qt}|^2 - |g_{tq}|^2}{|g_{qt}|^2 + |g_{tq}|^2}$$

for $|g_{qt}|^2 \simeq |g_{tq}|^2$ Information about the top spin will be lost

$\bar{t} \to bl\nu$ -spin analyser is the lepton

$$\kappa_l = 1$$

Observables	Basis	$P^L_{e^-} = 0, P^L_{e^+} = 0$	$P^L_{e^-} = 0.8, P^L_{e^+} = -0.3$	$P^L_{e^-} = -0.8, P^L_{e^+} = 0.3$
$\mathcal{O}_1$		$0.333\kappa_f$	$0.333\kappa_f$	$0.333\kappa_f$
$\mathcal{O}_2$	hel	$-0.076\kappa_f$	$0.247\kappa_f$	$-0.239\kappa_f$
	beam	$-0.174\kappa_f$	$0.344\kappa_f$	$-0.436\kappa_f$
	off	$0.176\kappa_f$	$-0.351\kappa_f$	$0.443\kappa_f$
	min	$0.04\kappa_f$	$-0.131\kappa_f$	$0.127\kappa_f$
$\mathcal{O}_3$	hel	$-0.654\kappa_f$	$-0.666\kappa_f$	$-0.648\kappa_f$
	beam	$0.881\kappa_f$	$0.852\ \kappa_f$	$0.897\kappa_f$
	off	$0.911\kappa_f$	$0.886\kappa_f$	$0.924\kappa_f$
	min	$0.224\kappa_f$	$0.229\ \kappa_f$	$0.222\kappa_f$
$\mathcal{O}_4$		$0.546\kappa_f$	$0.612\kappa_f$	$0.512\kappa_f$

From analytical fromulas

$$\kappa_f = \kappa_q$$

FULL NUMERICAL ANALYSIS FOR THE TOP-HIGGS FCNC COUPLINGS AT ILC

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

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

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

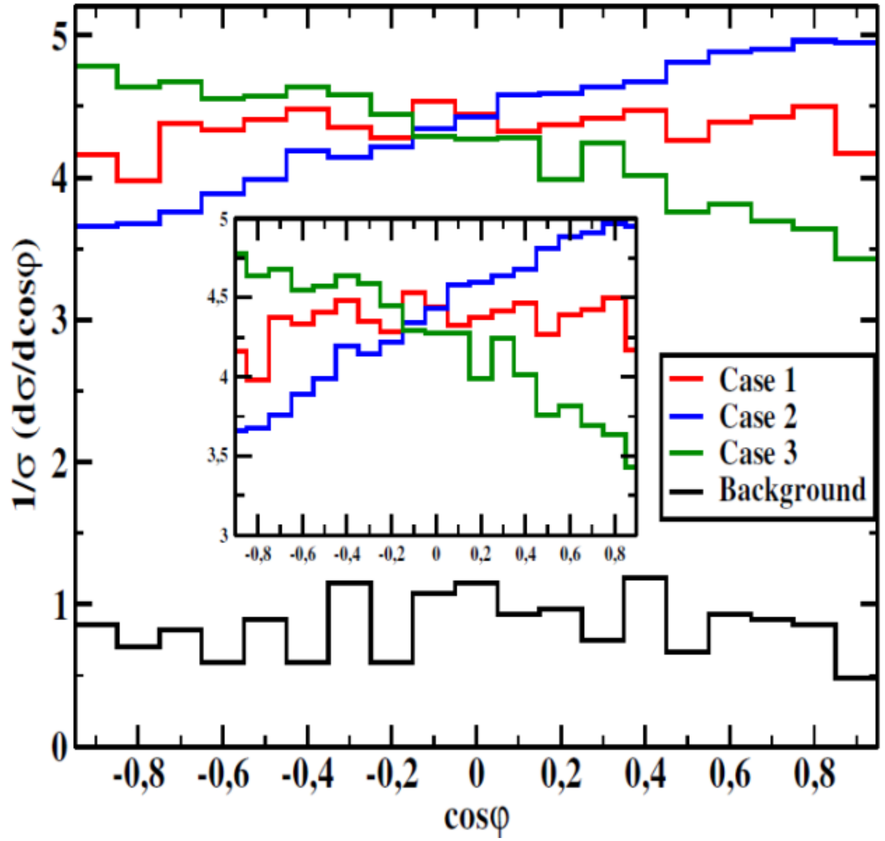
- **background** for the processs is the ttbar –production, with one top decaying hadronically and the other to lepton, neutrino and a b-quark
- **applying cuts** in the search for
  – an isolated lepton; q-quark from the top decay; b-tagged jet; reconstructed Higgs decay from two b-jets

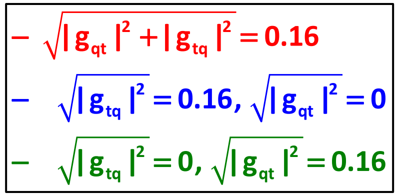
OBSERVABLES SENSITIVE TO THE CHIRAL NATURE OF FCNC INTERACTIONS (calculated in tt-ZMF)

- polar angular distribution of the q-quark from the top decay – shown before
- opening angle distribution :

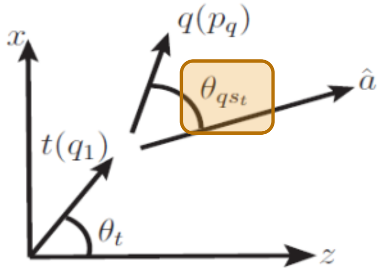
$$\frac{d\sigma}{d\cos\phi_{ql^-}} = \frac{\sigma}{2}(1 - \kappa_q D \cos\phi_{ql^-})$$

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

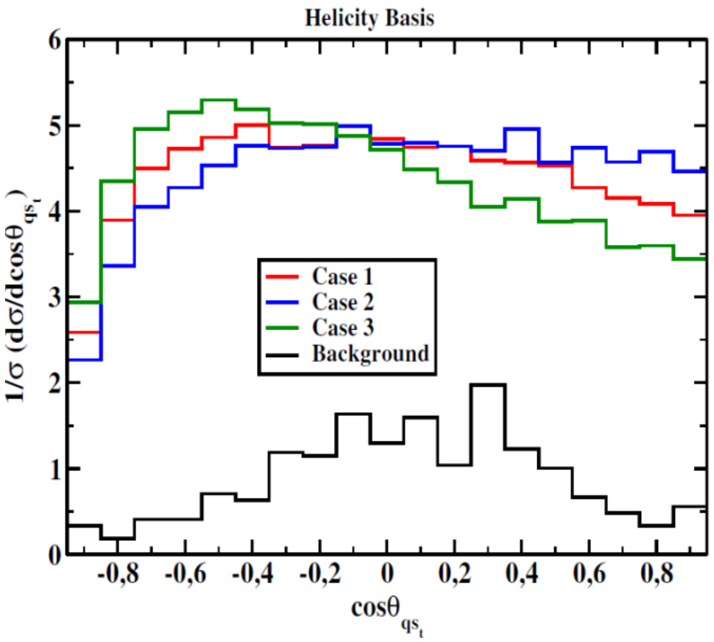


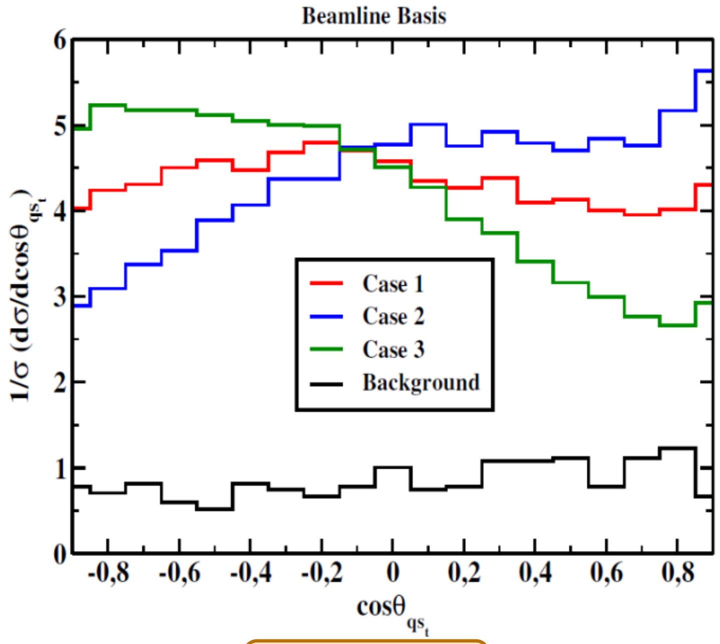


❖ TOP-SPIN

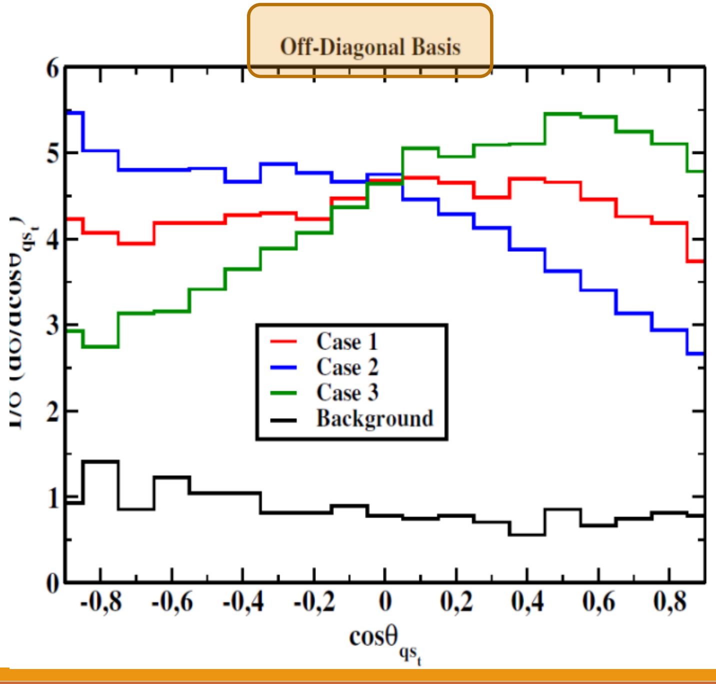


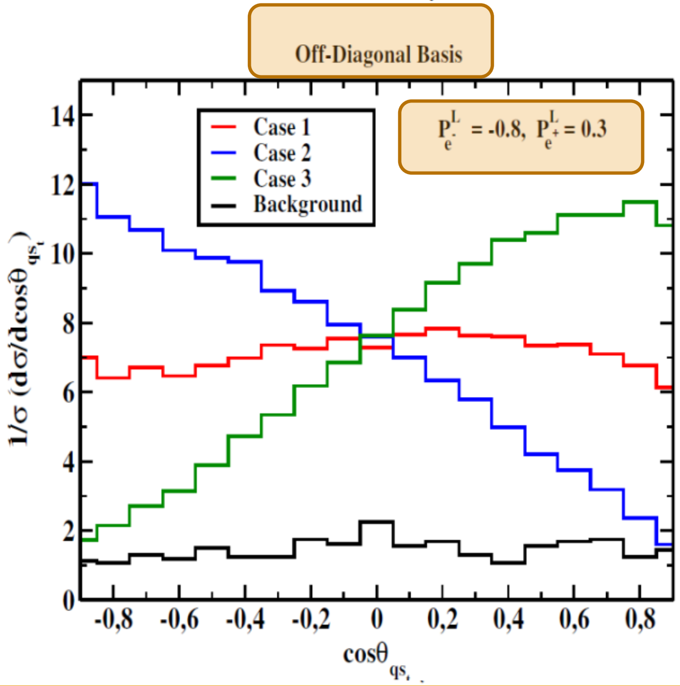
$B_t = \langle O_2 \rangle = \langle S_t \cdot \hat{a} \rangle$





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





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

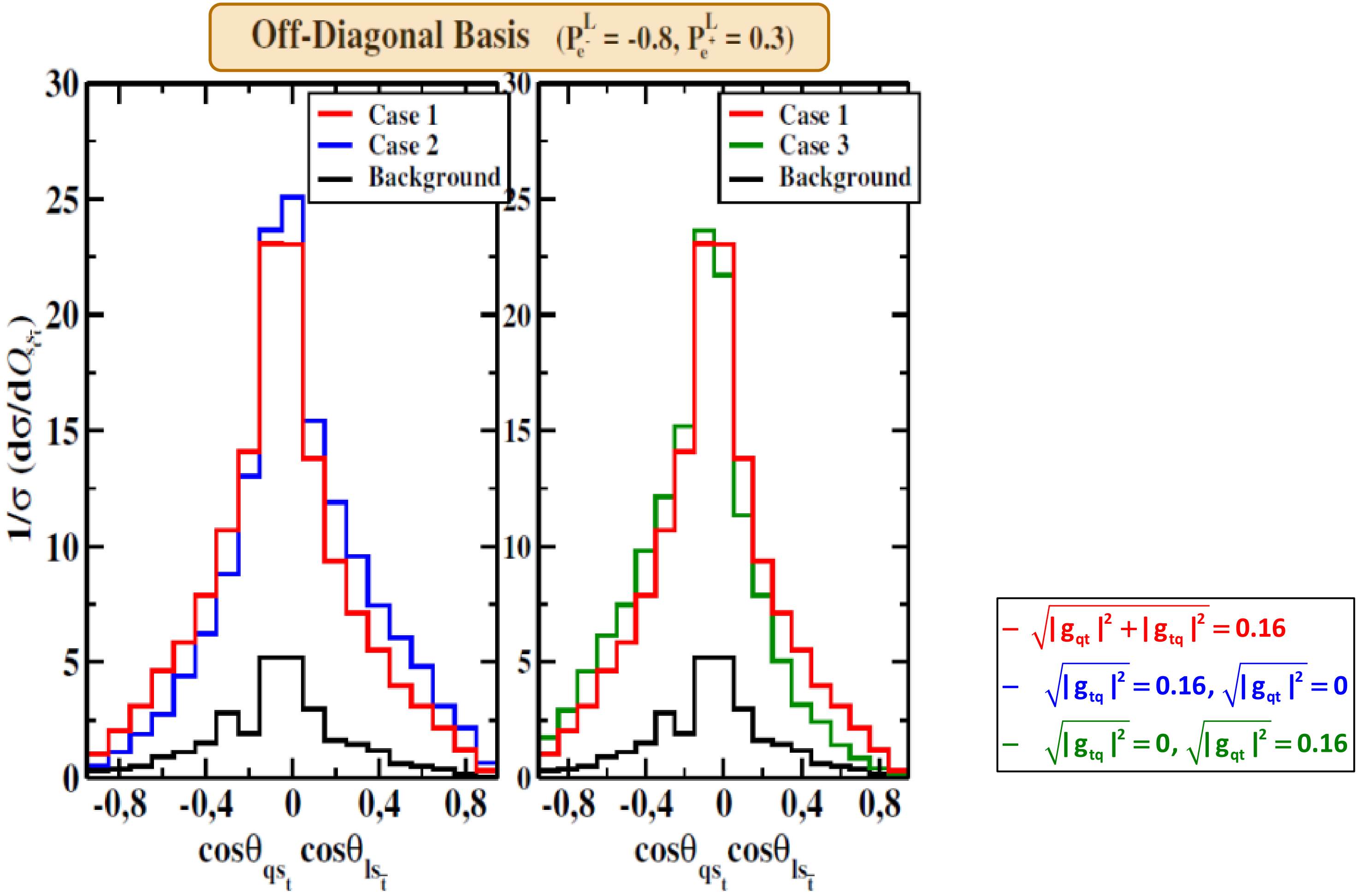
– $\sqrt{|g_{tq}|^2} = 0.16, \sqrt{|g_{qt}|^2} = 0$

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

- **SPIN-SPIN CORRELATIONS**

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

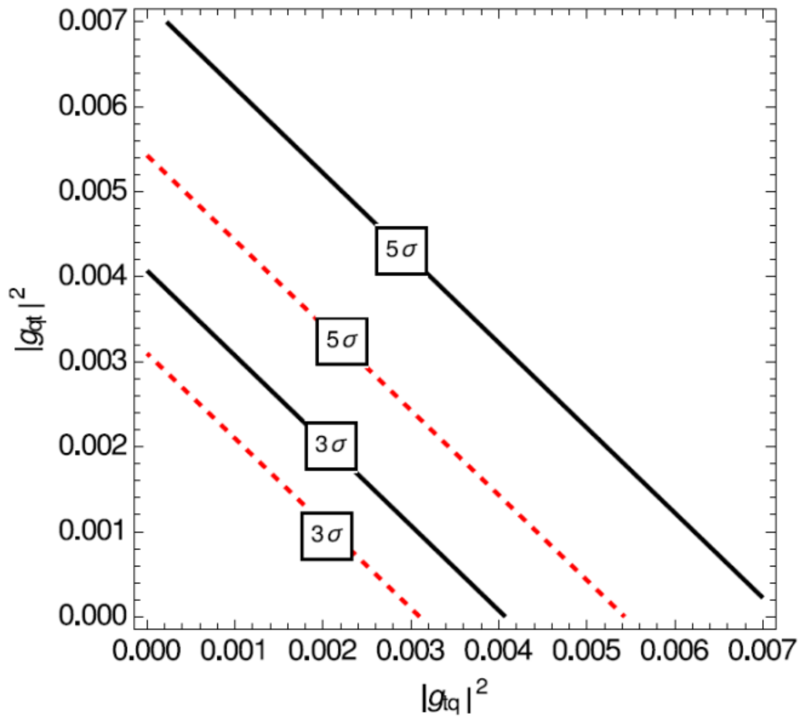
$\sim \langle O_3 \rangle = \langle 4(S_t \cdot \hat{a})(S_{\bar{t}} \cdot \hat{b}) \rangle$

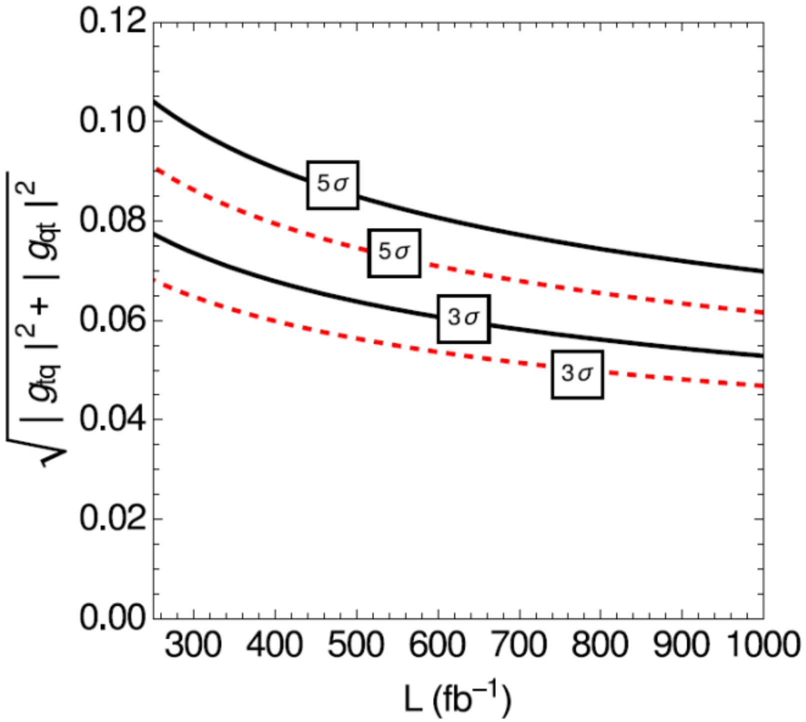


One can see asymmetrý
when compared Case 2 and Case3
- possibilty to distinquish chiral couplings

SIGNIFICANCE OF THE MEASUREMENTS

	$P^L_{e^-} = 0, P^L_{e^+} = 0$		$P^L_{e^-} = -0.8, P^L_{e^+} = 0.3$	
Significance	$\sqrt{\lvert g_{tq}\rvert^2 + \lvert g_{qt}\rvert^2}$	$BR(t \to qH)$	$\sqrt{\lvert g_{tq}\rvert^2 + \lvert g_{qt}\rvert^2}$	$BR(t \to qH)$
2σ	0.052	7.61×10^{-4}	0.046	5.96×10^{-4}
3σ	0.063	1.11×10^{-3}	0.056	8.84×10^{-4}
5σ	0.085	2.03×10^{-3}	0.074	1.54×10^{-4}





_____ 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

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