北京大學

Determining V_{tb} at e^+e^- Colliders

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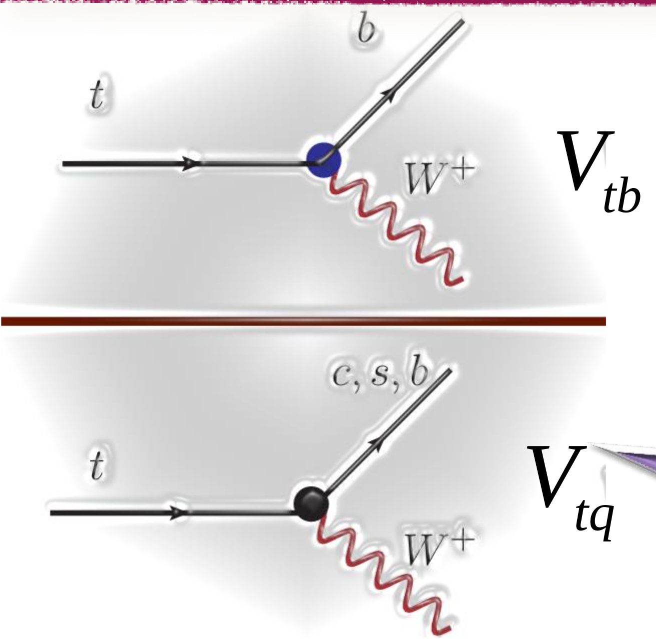
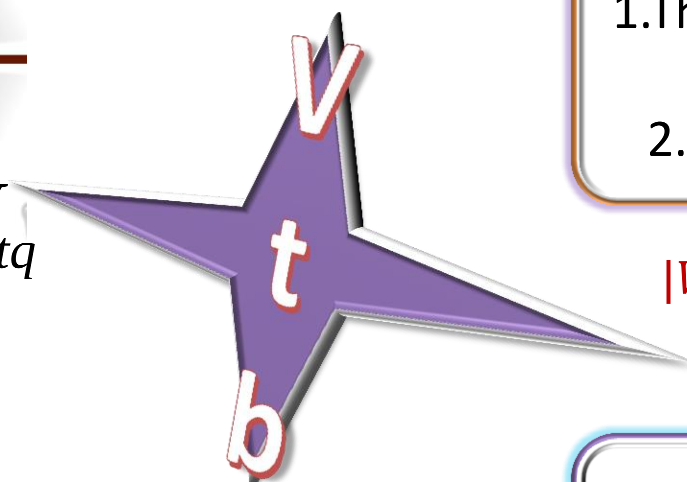
@10th TeV Physics Workshop

In collaboration with Qing-Hong Cao, arXiv: 1507.06204

V_{tb} measurements





①

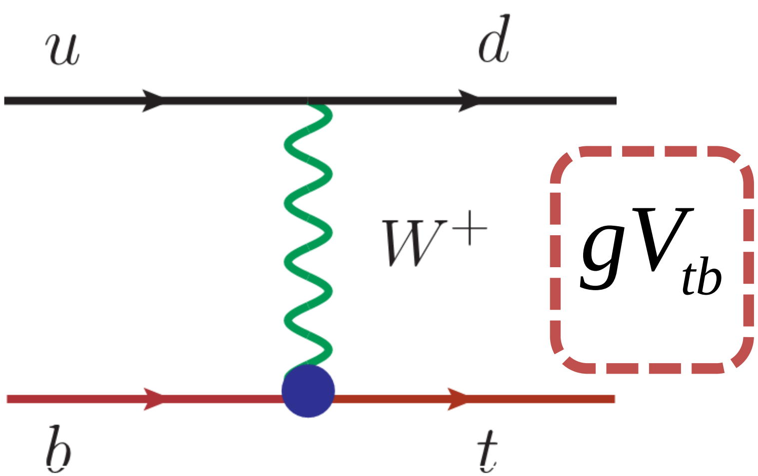
$$R \approx \frac{|V_{tb}|^2}{\sum_{q=d,s,b} |V_{tq}|^2} = |V_{tb}|^2$$

1.Three generation of quarks

2.Unitarity of CKM matrix

$|V_{tb}| = 0.99914 \pm 0.00005$

PDG2015



②

Universality of the weak gauge coupling g

$|V_{tb}| = 0.998 \pm 0.038(\mathrm{exp}) \pm 0.016(theo)$

V. Khachatryan et al. JHEP 1406,090 (2014)

V_{tb} & New Physics

New Physics models

Fourth-generation of quarks

un-unified and top-flavor models

……..

Three generation of quarks

Universality of the weak gauge coupling g

$R = ?\, |V_{tb}|^2$

$\sum_{q=d,s,b} |V_{tq}|^2 = ?\, 1$

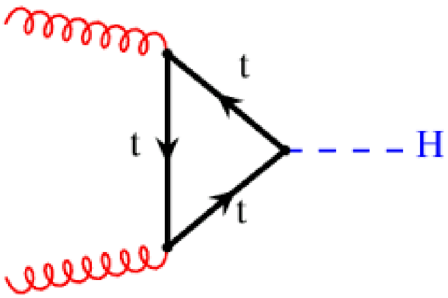
$|V_{tb}|^2 = ?\, \frac{\sigma_t}{g_W^2}$

How to determine V_{tb}?

V_{tb} & New Physics

The deviation of V_{tb}

New heavy quark
(SU(2) quantum number)



Modify the H-g-g effective coupling

Higgs Physics

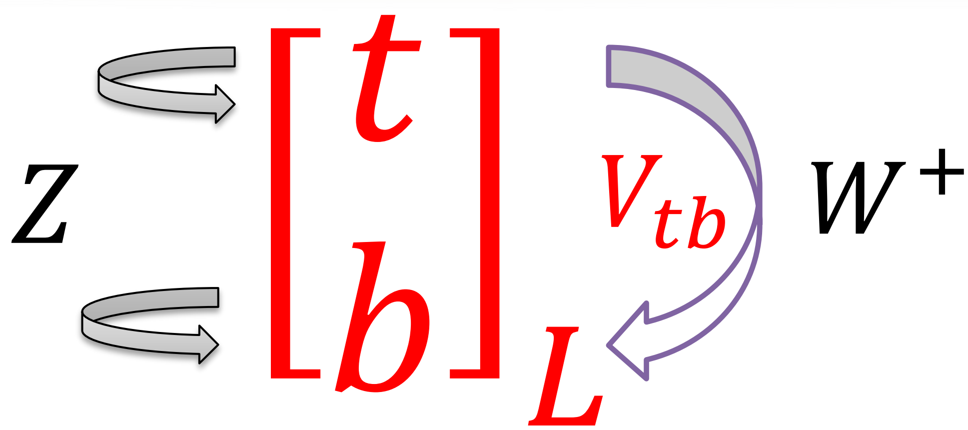
The heavy quark decouple limit?

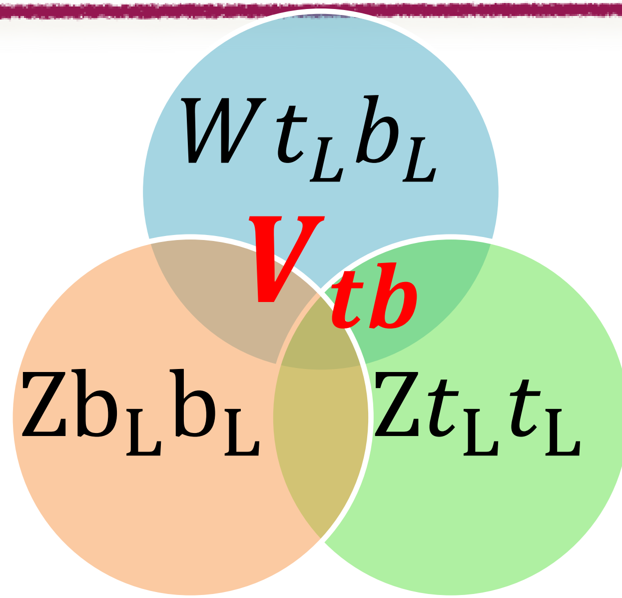
Vector-like quark

Determining V_{tb}

How to determine V_{tb} ?

V_{tb} & top gauge couplings





$g_{Zb_Lb_L} \approx g^{SM}_{Zb_Lb_L}$
LEP-II

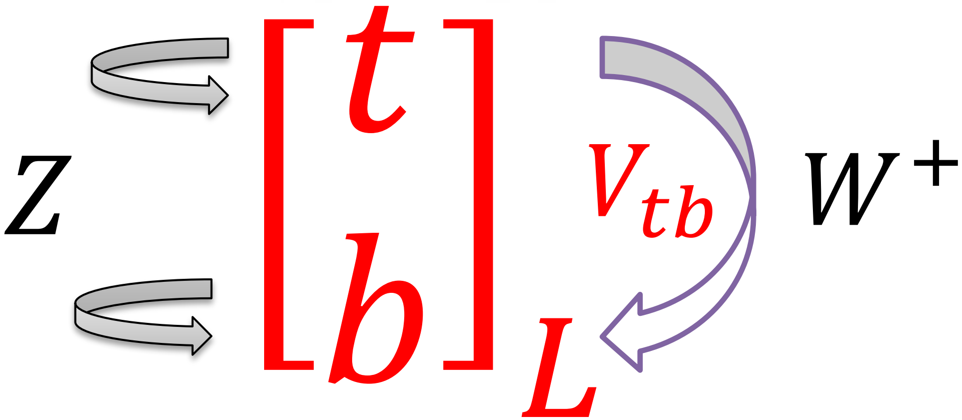
Correlation $\Longrightarrow$

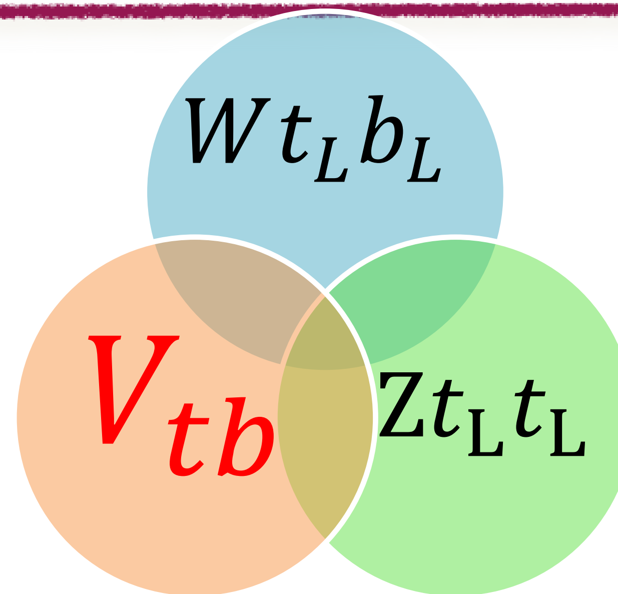
Wt_Lb_L coupling

$\mathrm{Z}t_\mathrm{L}t_\mathrm{L}$ coupling

$\blacktriangleright$ V_{tb}

Top gauge couplings & EFT





How can we measure top quark gauge couplings with a model-independent method?

Effective field theory:

$$L = L_{SM}^4 + \sum_i \frac{C_i}{\Lambda^2} O_i$$

W. Buchmuller and D. Wyler, Nucl. Phys. B268, 621(1986)

EFT (Tree-level dim-6 operators)

$$O^{(1)}_{\phi q} = i(\phi^+ D_\mu \phi)(\bar{q}\gamma^\mu q)$$

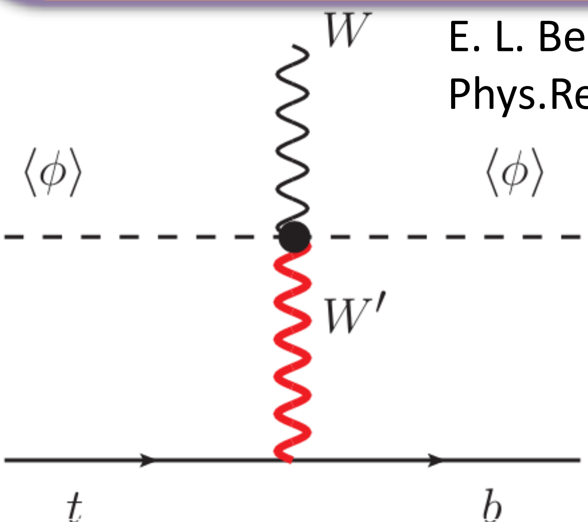
$$\boxed{O^{(3)}_{\phi q} = i(\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)}$$

$$O_{\phi t} = i(\phi^+ D_\mu \phi)(\bar{t}_R\gamma^\mu t_R)$$

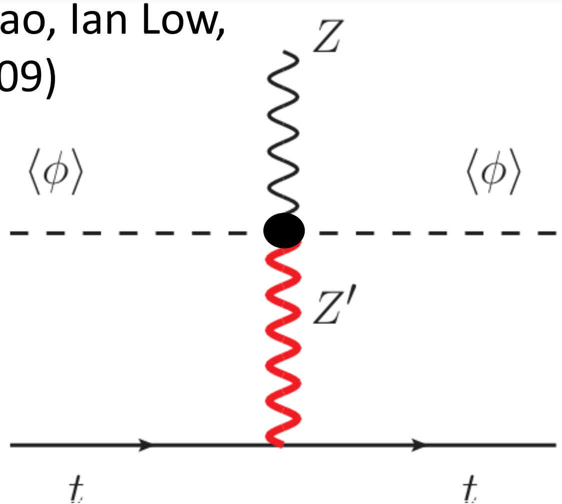
$$O_{\phi b} = i(\phi^+ D_\mu \phi)(\bar{b}_R\gamma^\mu b_R)$$

$$O_{\phi\phi} = i(\tilde{\phi}^+ D_\mu \phi)(\bar{t}_R\gamma^\mu b_R)$$

$$q = \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \tilde{\phi} = i\tau^2\phi^*$$



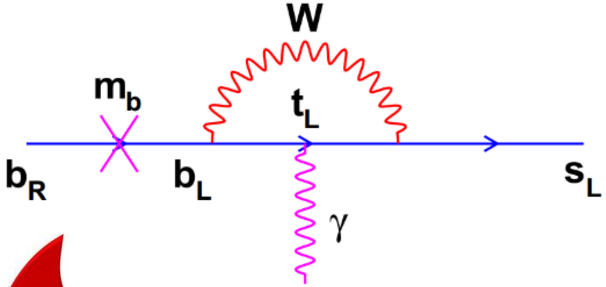
E. L. Berger, Qing-Hong Cao, Ian Low, Phys.Rev.D80:074020(2009)

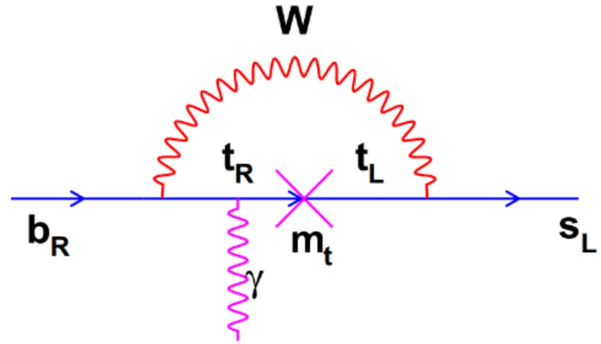


Effective Wtb, Ztt and Zbb couplings

$$-8\times10^{-4} \le \frac{c_{\phi\phi}v^2}{2\Lambda^2} \le 2.1\times10^{-3}$$

$$O_{Wtb} = \boxed{\frac{c_{\phi q}^{(3)}v^2}{\Lambda^2}\frac{g}{\sqrt{2}}W_\mu^+\bar{t}_L\gamma^\mu b_L} + \frac{c_{\phi\phi}v^2}{2\Lambda^2}\frac{g}{\sqrt{2}}W_\mu^+\bar{t}_R\gamma^\mu b_R + h.c.$$





Q.-H. Cao, B. Yan, J.-H. Yu, and C. Zhang, arxiv:1504.03785

$$O_{Ztt} = \boxed{\frac{\left(c_{\phi q}^{(3)} - c_{\phi q}^{(1)}\right)v^2}{\Lambda^2}\frac{g}{2c_W}Z_\mu\bar{t}_L\gamma^\mu t_L} - \frac{c_{\phi t}v^2}{2\Lambda^2}\frac{g}{2c_W}Z_\mu\bar{t}_R\gamma^\mu t_R$$

$$O_{Zbb} = \boxed{-\frac{\left(c_{\phi q}^{(3)} + c_{\phi q}^{(1)}\right)v^2}{\Lambda^2}\frac{g}{2c_W}Z_\mu\bar{b}_L\gamma^\mu b_L} - \frac{c_{\phi b}v^2}{2\Lambda^2}\frac{g}{2c_W}Z_\mu\bar{b}_R\gamma^\mu b_R$$

LEP-II

$$c_{\phi q}^{(3)} + c_{\phi q}^{(1)} \approx 0$$

Effective Wtb and Ztt couplings

The deviations of the Wtb and Ztt couplings：

$$g_{Wtb}^{NP} = (\Delta V_{tb} + F_L)\frac{g}{\sqrt{2}} W_\mu^+ \bar{t}_L \gamma^\mu b_L + h.c. \qquad F_L = \frac{c_{\phi q}^{(3)} v^2}{\Lambda^2}$$

$$g_{Ztt}^{NP} = 2F_L \frac{g}{2c_W} Z_\mu \bar{t}_L \gamma^\mu t_L + F_R \frac{g}{2c_W} Z_\mu \bar{t}_R \gamma^\mu t_R$$

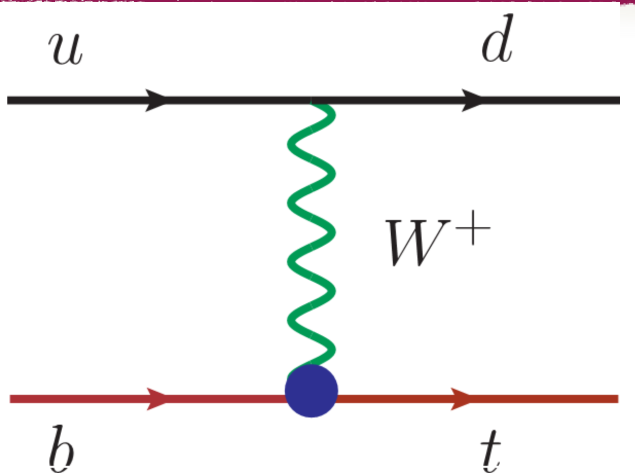
The coefficients of the left-handed neutral and charged currents are related as

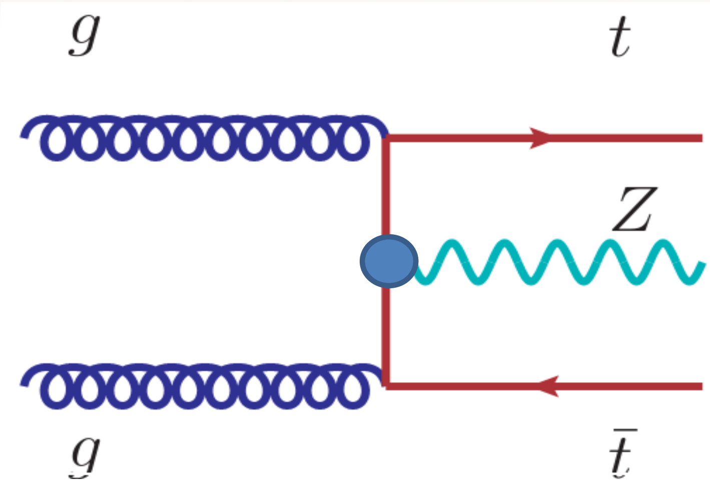
$$(g_{Ztt}^{NP})_L = 2F_L = 2\left(\left(g_{Wtb}^{NP}\right)_L - \Delta V_{tb}\right)$$

$$\Rightarrow \boxed{Ztt + Wtb}$$

How can we measure top quark gauge couplings?

V_{tb} @ LHC





$-0.06 \le \Delta V_{tb} + F_L \le 0.03$ @ 95% C.L. 8 TeV LHC

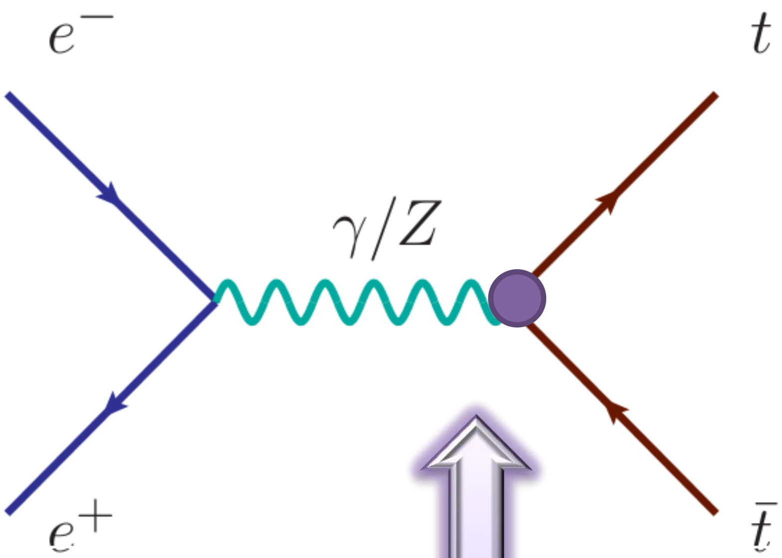
Q.-H. Cao, B. Yan, J.-H. Yu, C. Zhang, arxiv:1504.03785

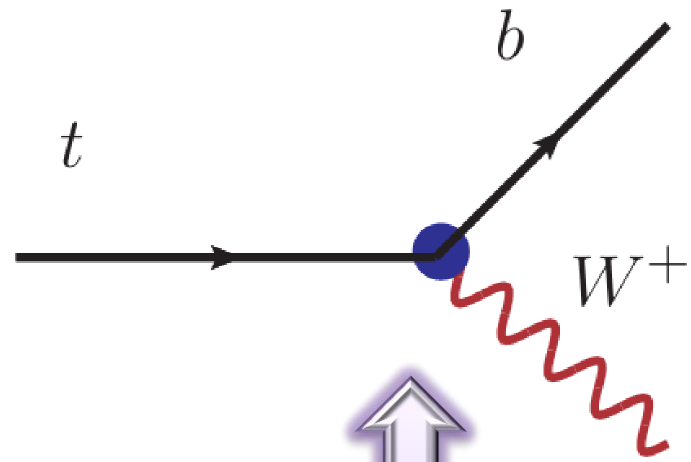
$\boxed{-0.99 \le F_L \le 0.57}$ @ 95 % C.L. 13 TeV LHC with 300 fb^{-1}

R. Rontsch and M. Schulze, JHEP 1407 (2014) 091

$$(g_{Ztt}^{NP})_L = 2F_L = 2\left(\left(g_{Wtb}^{NP}\right)_L - \Delta V_{tb}\right)$$

V_{tb} @ unpolarized e^+e^- collider





A_{FB} σ_{tt}

$\Gamma_t \propto g_{Wtb}$

$$(g_{Ztt}^{NP})_L = 2F_L = 2\left(\left(g_{Wtb}^{NP}\right)_L - \underline{\underline{\Delta V_{tb}}}\right)$$

Top quark width

Top quark width in SM at NNLO in QCD and NLO EW:

$$\Gamma_t^0 \equiv \Gamma_t^{NNLO} = 0.8926 \times \Gamma_t^{LO}$$

$$\Gamma_t^{LO} = \frac{G_F m_t^3}{8\sqrt{2}\pi} \frac{|V_{tb}|^2}{Br(t \to Wb)} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + \frac{2m_W^2}{m_t^2}\right)$$

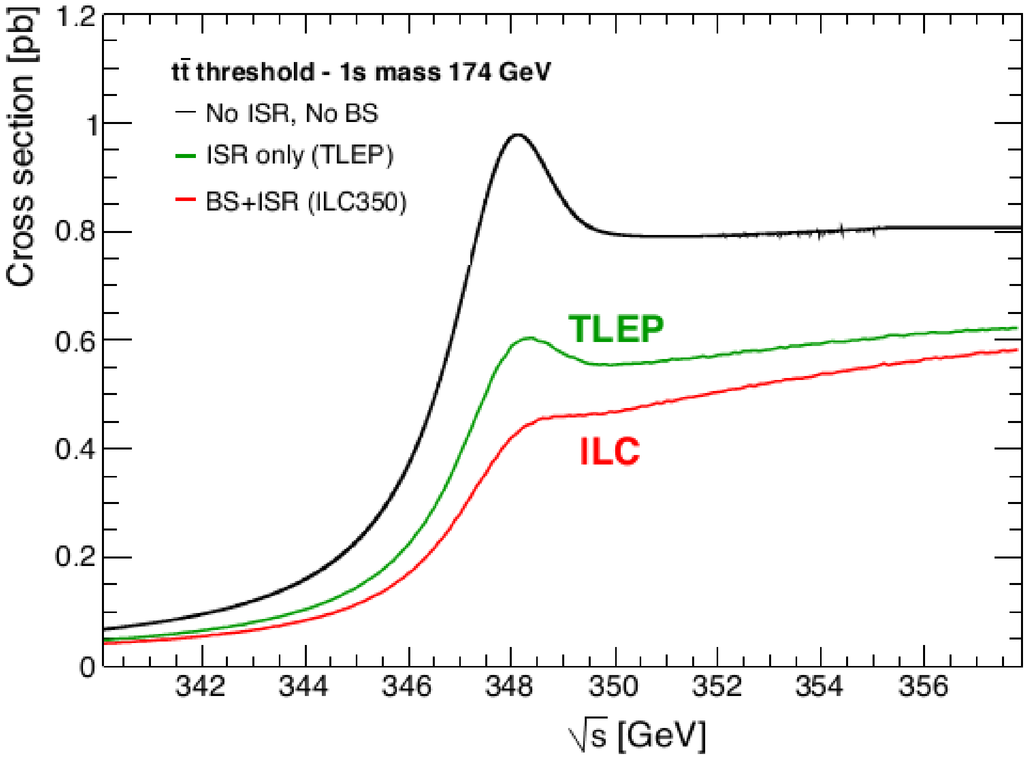
J. Gao, C. S. Li and H. X. Zhu, PRL. 119,042001 (2013)

Deviations of g, m_t and V_{tb} from the SM values modify the top quark width:

$$\frac{\Delta\Gamma_t}{\Gamma_t^0} = 3\frac{\Delta m_t}{m_t} + 2\Delta V_{tb} + 2F_L$$

$$\boxed{\Delta X = X - X^0}$$

Top quark mass and width @ ILC/TLEP



$$\frac{\Delta\Gamma_t}{\Gamma_t^0} = 3\frac{\Delta m_t}{m_t} + 2\Delta V_{tb} + 2F_L$$

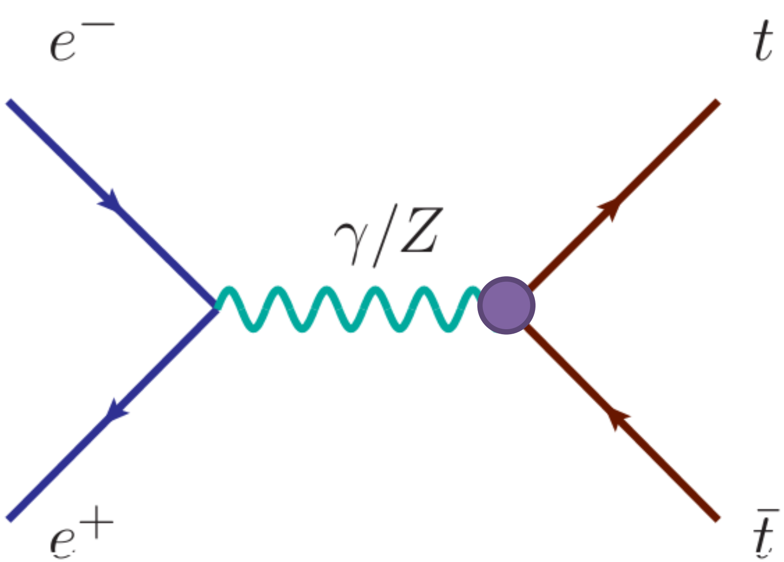
1%   0.006%

$$\Delta V_{tb} \approx \frac{\Delta\Gamma_t}{2\Gamma_t^0} - F_L$$

Bicer, M. et al. JHEP 1401(2014) 164

Parameter	Top quark mass	Top quark width
TLEP	10 MeV	11 MeV
ILC	31 MeV	34 MeV

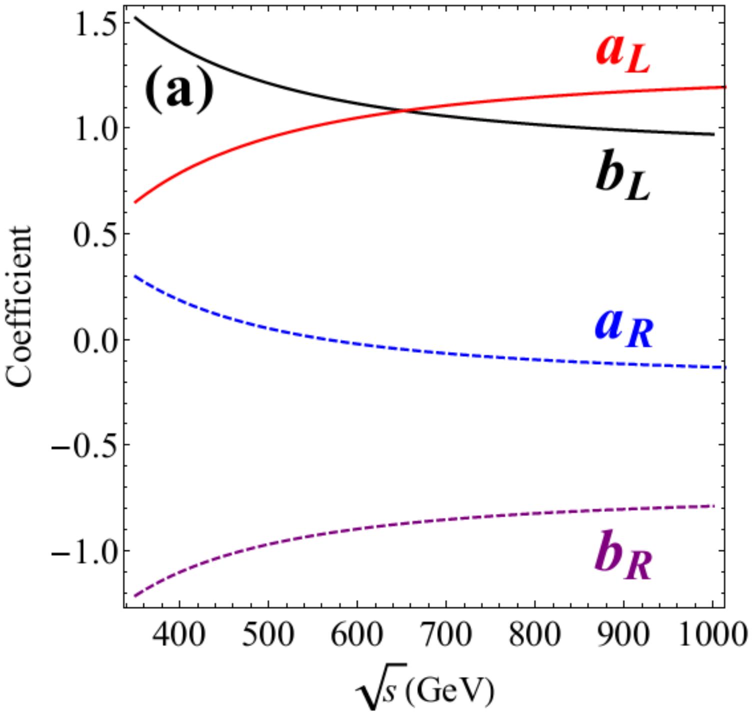
Top quark pair production @ unpolarized e^+e^- collider

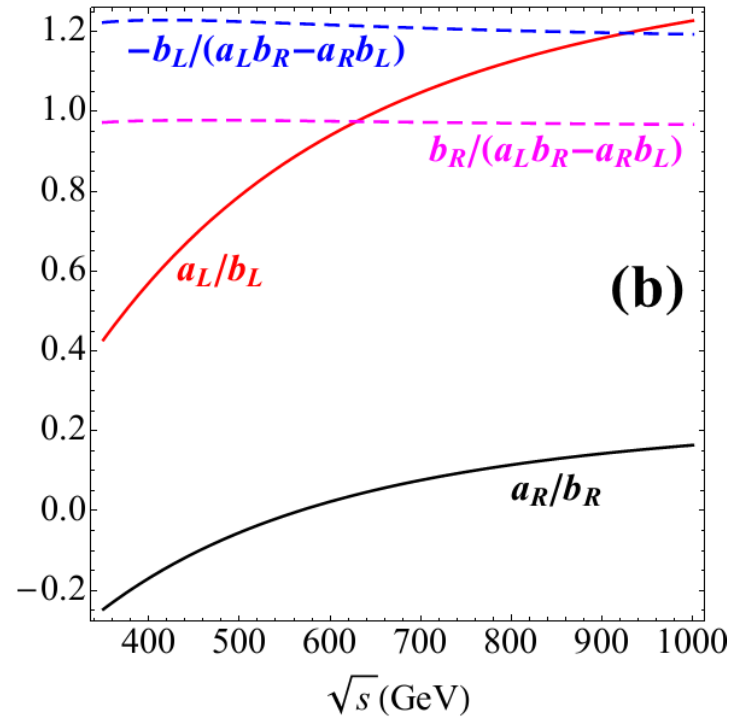


Top quark pair production @ unpolarized e^+e^- collider

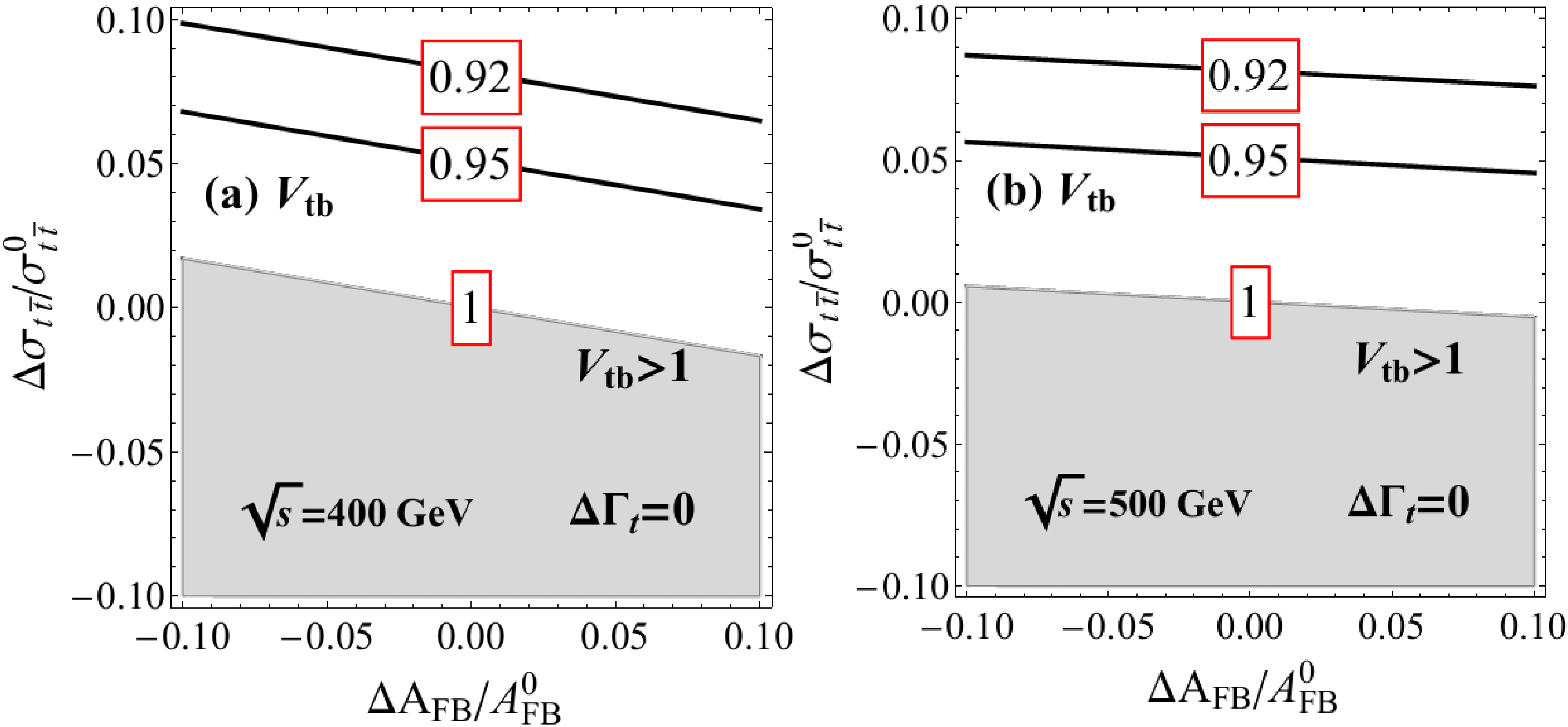
$$\sigma_{tt} = \sigma_{tt}^0(1+a_L F_L + a_R F_R) \qquad A_{FB} = A_{FB}^0(1+b_L F_L + b_R F_R)$$

$$F_L \sim 0.97\left(\frac{\Delta\sigma_{tt}}{\sigma_{tt}^0} - \frac{a_R}{b_R}\frac{\Delta A_{FB}}{A_{FB}^0}\right) \qquad F_R \sim 1.21\left(\frac{\Delta\sigma_{tt}}{\sigma_{tt}^0} - \frac{a_L}{b_L}\frac{\Delta A_{FB}}{A_{FB}^0}\right)$$





V_{tb} @ unpolarized e^+e^- collider



$$\Delta V_{tb} \approx \frac{\Delta\Gamma_t}{2\Gamma_t^0} - F_L$$

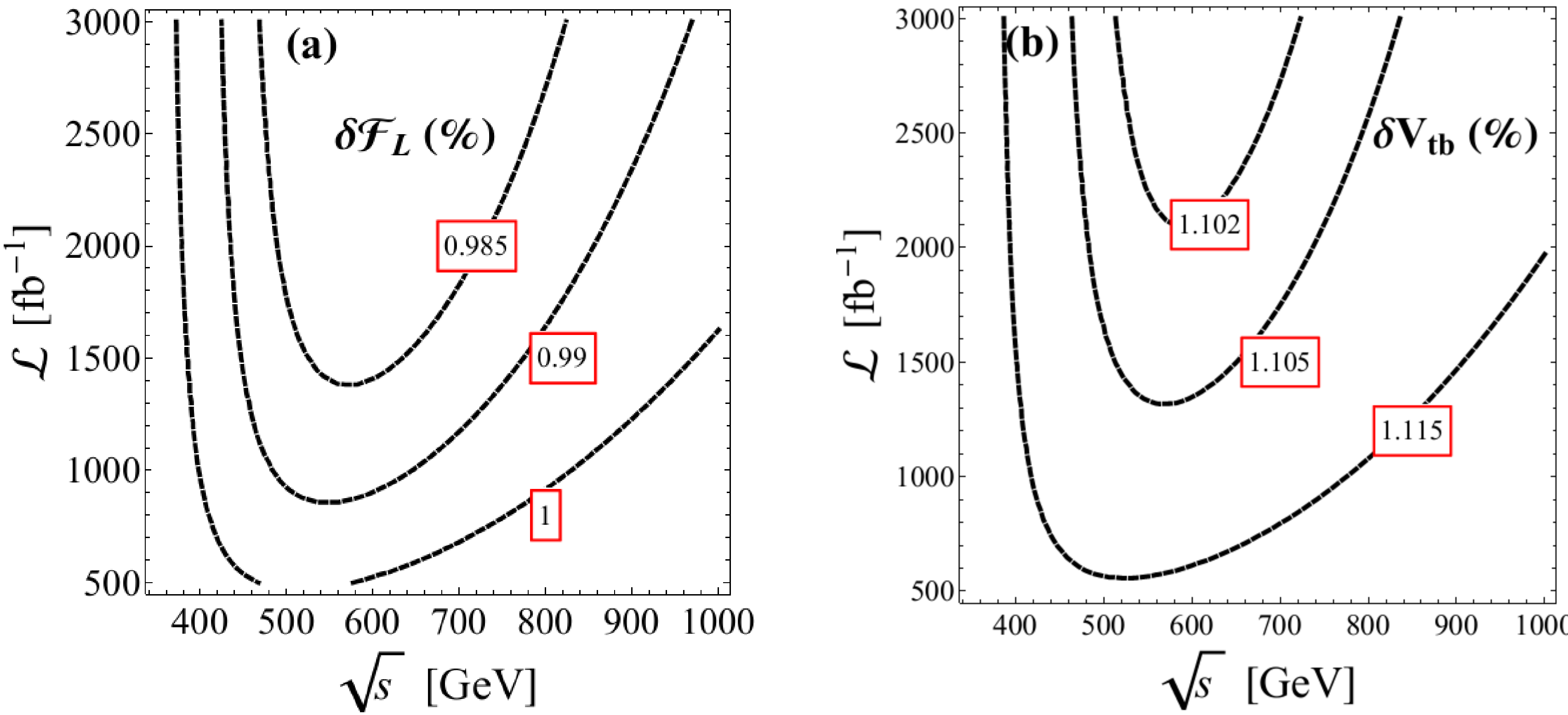
Cross section would be enhanced @ NP

Error analysis

Systematic error of σ_{tt}:

H. Baer, T. Barklow, et al. (2013), 1307.6352
M. Amjad, M. Boronat, et al. (2013), 1307.8102

$$\left(\frac{\delta\sigma_{tt}}{\sigma_{tt}^{0}}\right)_{sys.} = 0.01 \qquad \frac{\delta\Gamma_t}{\Gamma_t^0} = 0.01 \qquad \delta V_{tb} = \sqrt{\frac{1}{4}\left(\frac{\delta\Gamma_t}{\Gamma_t^0}\right)^2 + (\delta F_L)^2}$$



Summary

1.Three generation of quarks

2.Unitarity of CKM matrix

Universality of the weak gauge coupling g

Y

Model independent method to determine V_{tb}

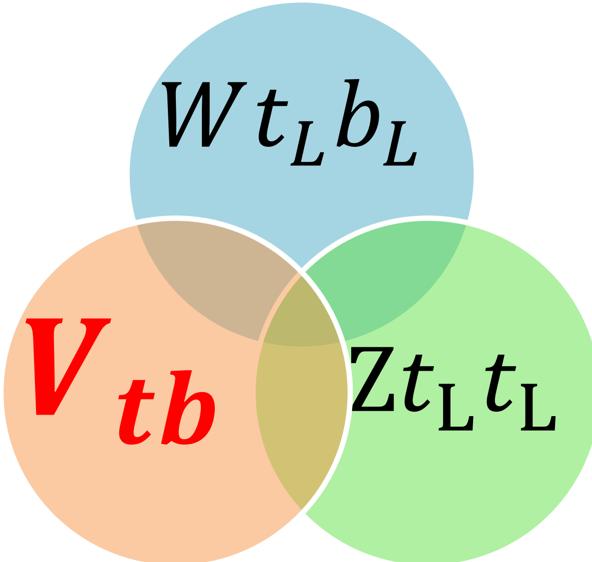
$$V_{tb}? \simeq 1$$

N

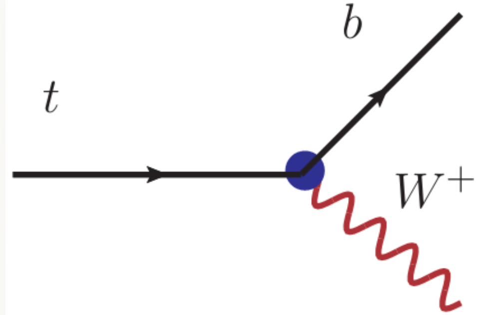
New heavy quark (SU(2) quantum number)

Higgs Physics

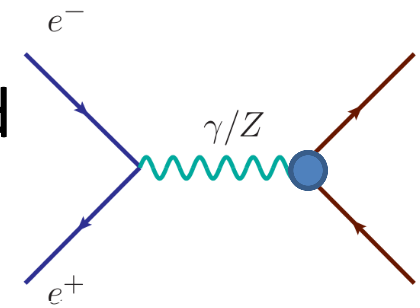
Vector-like quark



LEP-II

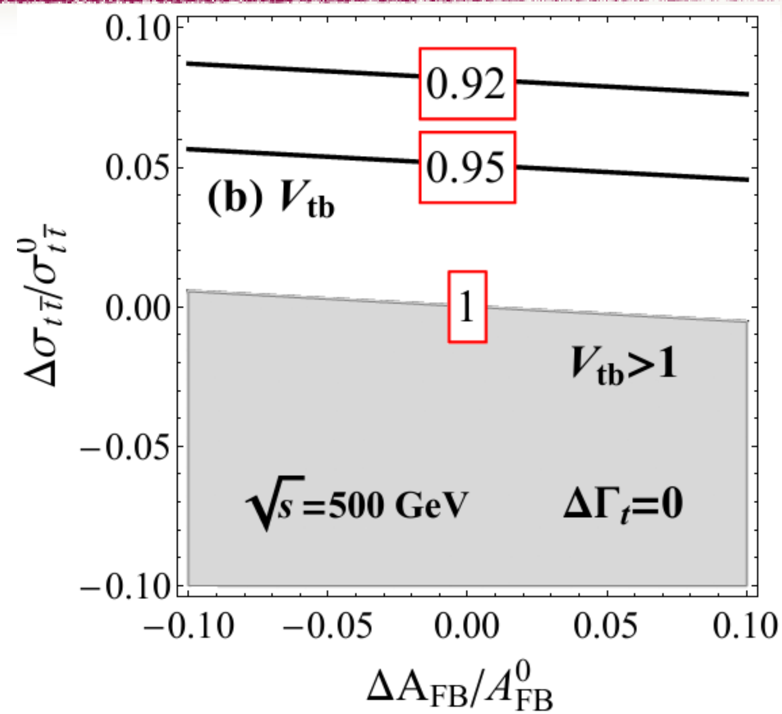


@unpolarized e^+e^- collider



Model-independent method to measure V_{tb}

$$\Delta V_{tb} \approx \frac{\Delta\Gamma_t}{2\Gamma_t^0} - F_L$$



Thank you!

Back up

R_b and A_{FB}^b

$$O_{Zbb} = \boxed{-\frac{\left(c_{\phi q}^{(3)} + c_{\phi q}^{(1)}\right) v^2}{\Lambda^2} \frac{g}{2c_W} Z_\mu \bar{b}_L \gamma^\mu b_L} - \frac{c_{\phi b} v^2}{2\Lambda^2} \frac{g}{2c_W} Z_\mu \bar{b}_R \gamma^\mu b_R$$

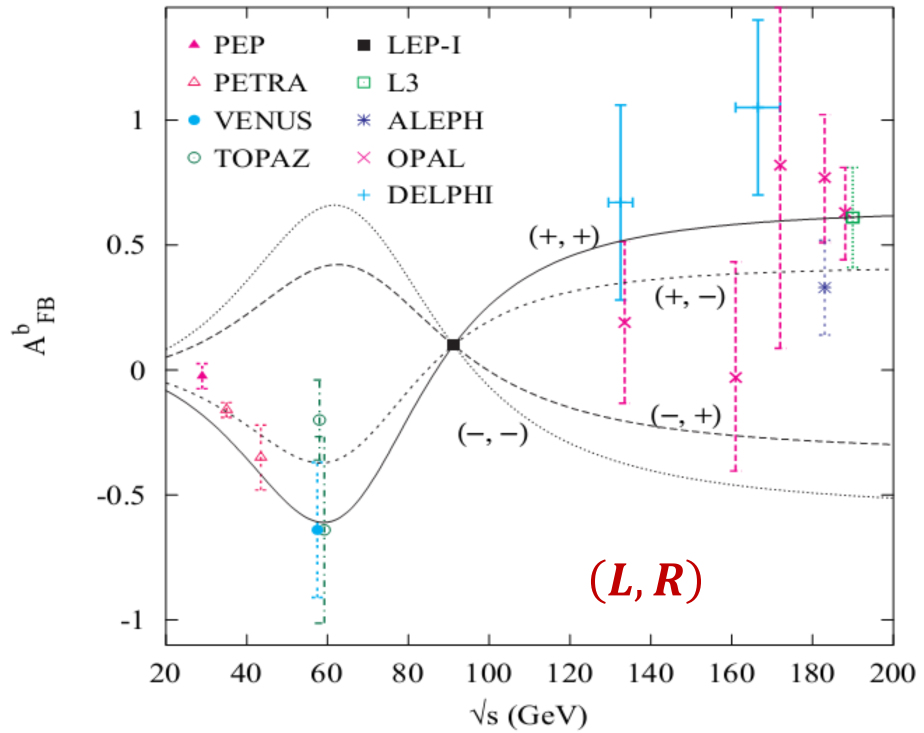
$$R_b = \frac{\sigma(e^+e^- \to b\bar{b})}{\sum_q \sigma(e^+e^- \to q\bar{q})} \qquad A_{FB}^b = \frac{\sigma_F^b - \sigma_B^b}{\sigma_F^b + \sigma_B^b}$$

Z-peak

$$g_{zbb}^L \approx \pm 0.992 g_{zbb}^{LSM}$$

$$g_{zbb}^R \approx \pm 1.26 g_{zbb}^{RSM}$$

$$c_{\phi q}^{(3)} + c_{\phi q}^{(1)} \approx 0$$



D. Choudhury, T. M. P. Tait and C. E. M. Wagner, PRD 65(2002)053002

R_b and A_{FB}^b

$$O_{Zbb} = \boxed{-\frac{\left(c_{\phi q}^{(3)} + c_{\phi q}^{(1)}\right) v^2}{\Lambda^2} \frac{g}{2c_W} Z_\mu \bar{b}_L \gamma^\mu b_L} - \frac{c_{\phi b} v^2}{2\Lambda^2} \frac{g}{2c_W} Z_\mu \bar{b}_R \gamma^\mu b_R$$

$$R_b = \frac{\sigma(e^+e^- \to b\bar{b})}{\sigma(e^+e^- \to q\bar{q})}$$

$$A_{FB}^b = \frac{\sigma_F^b - \sigma_B^b}{\sigma_F^b + \sigma_B^b}$$

$R_b(obs) = 0.21646 \pm 0.00065$

$A_{FB}^b(obs) = 0.0990 \pm 0.0017$

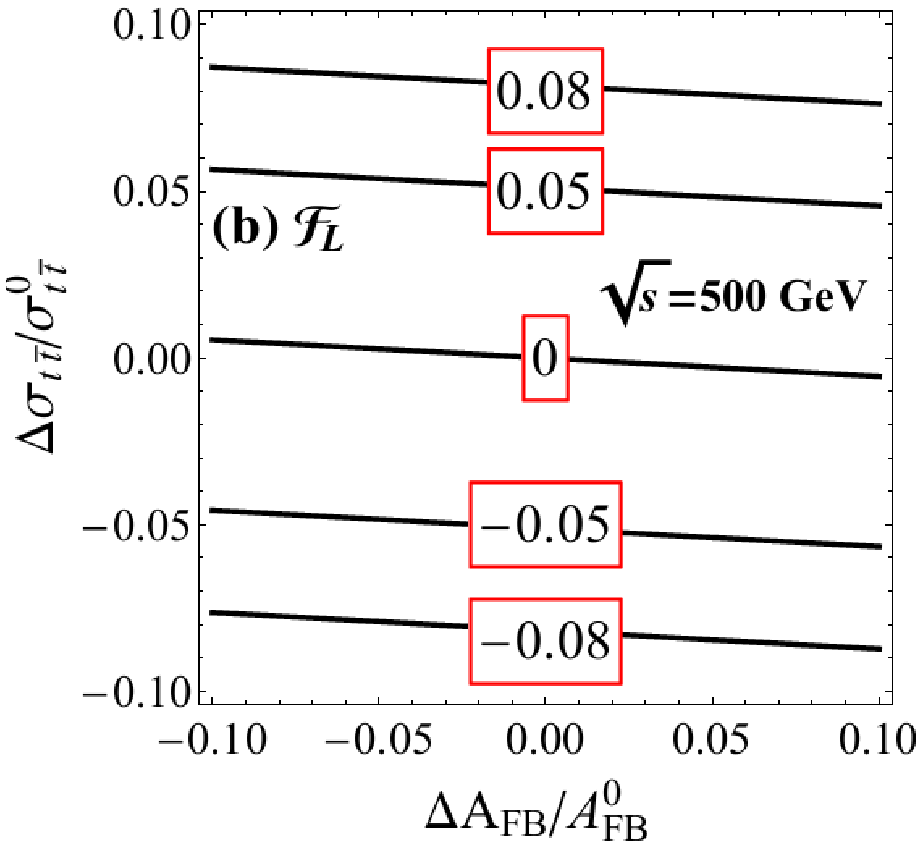
$R_b(SM) = 0.2157$

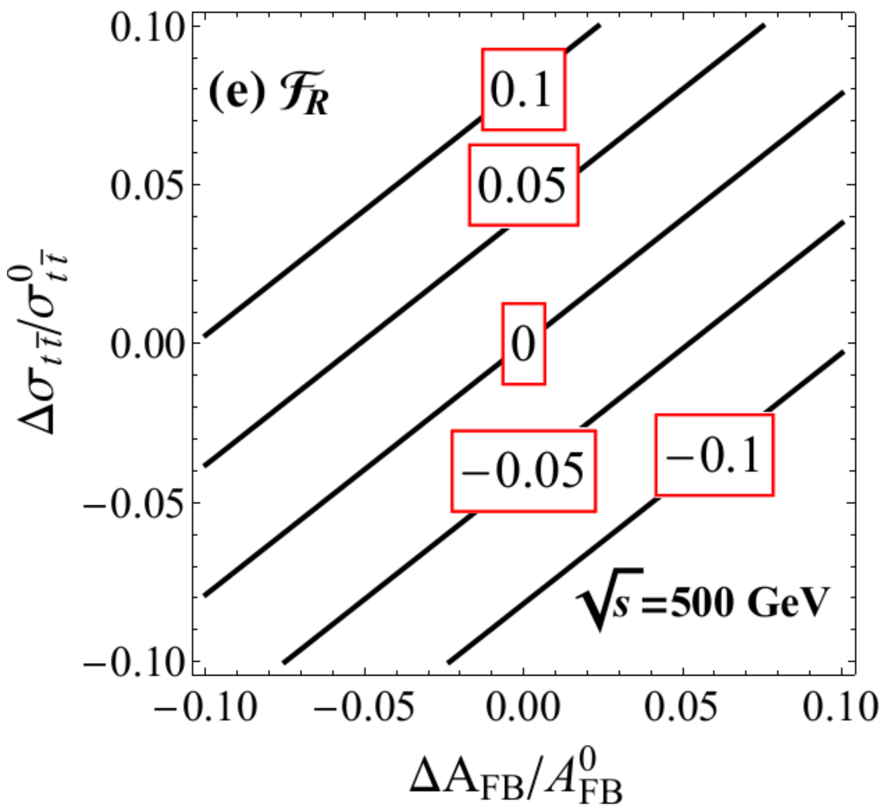
$A_{FB}^b(SM) = 0.1036$

$c_{\phi q}^{(3)} + c_{\phi q}^{(1)} \approx 0$

D. Choudhury, T. M. P. Tait and C. E. M. Wagner,
PRD 65(2002)053002

F_L and F_R @ e^+e^- collider

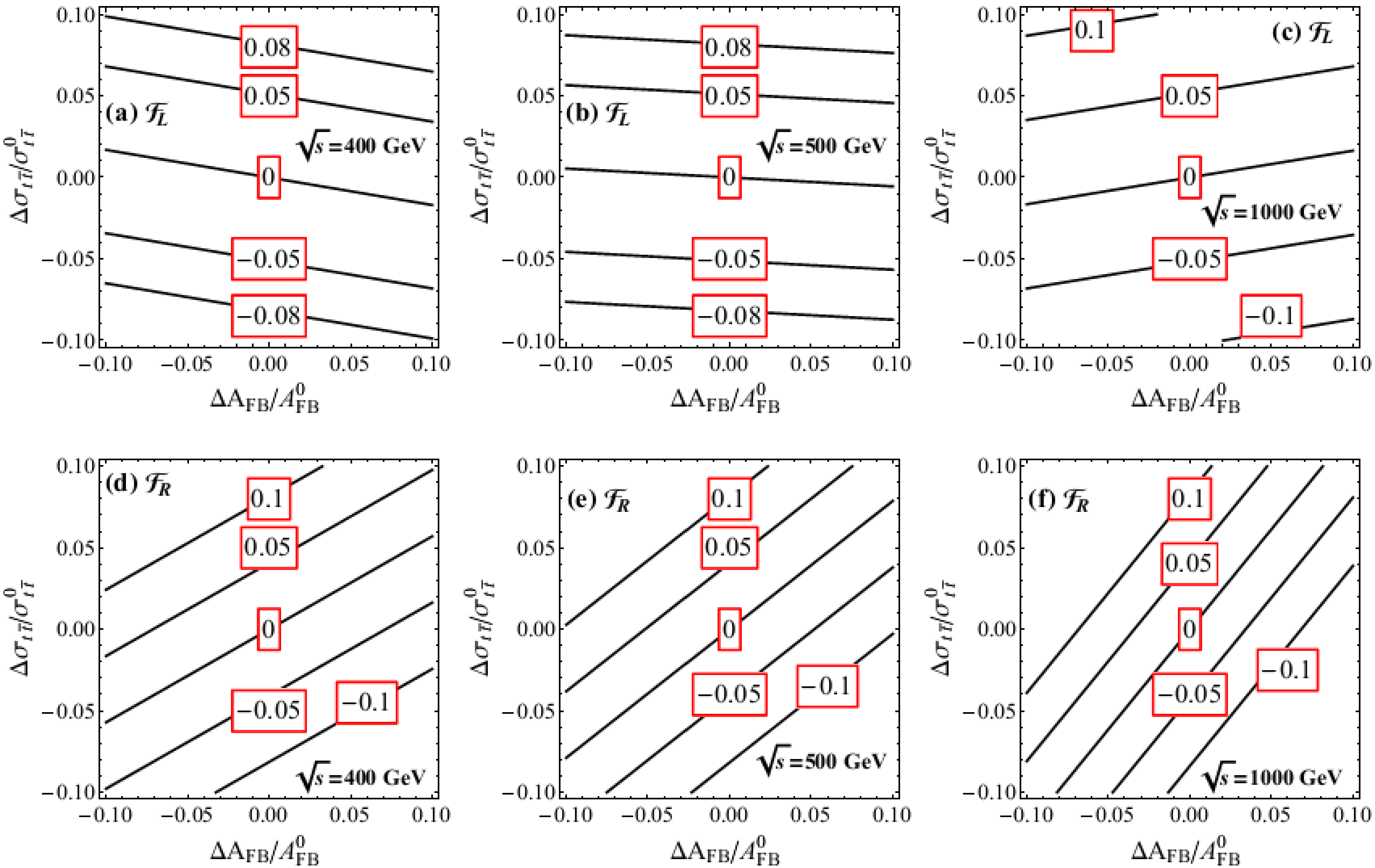




$$F_L \sim 0.97\left(\frac{\Delta\sigma_{tt}}{\sigma^0_{tt}} - \frac{a_R}{b_R}\frac{\Delta A_{FB}}{A^0_{FB}}\right)$$

$$F_R \sim 1.21\left(\frac{\Delta\sigma_{tt}}{\sigma^0_{tt}} - \frac{a_L}{b_L}\frac{\Delta A_{FB}}{A^0_{FB}}\right)$$

F_L and F_R@ e^+e^- collider



Implications on
New Physics Models

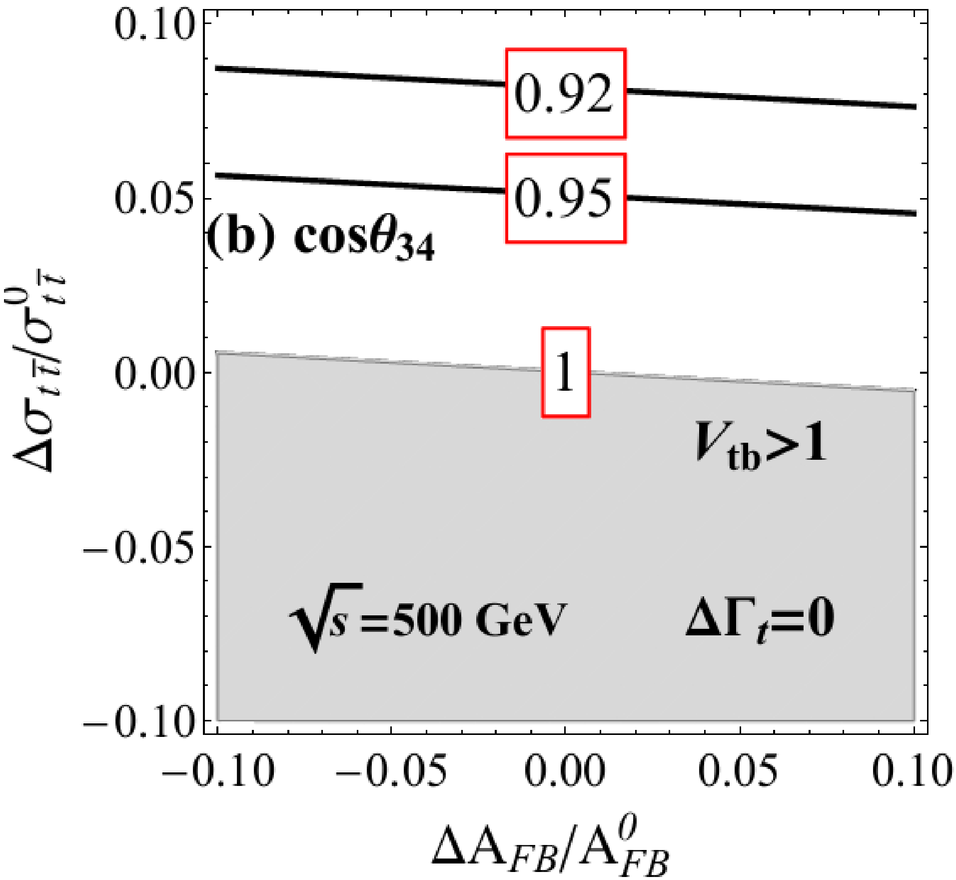
A. 4th generation of quarks

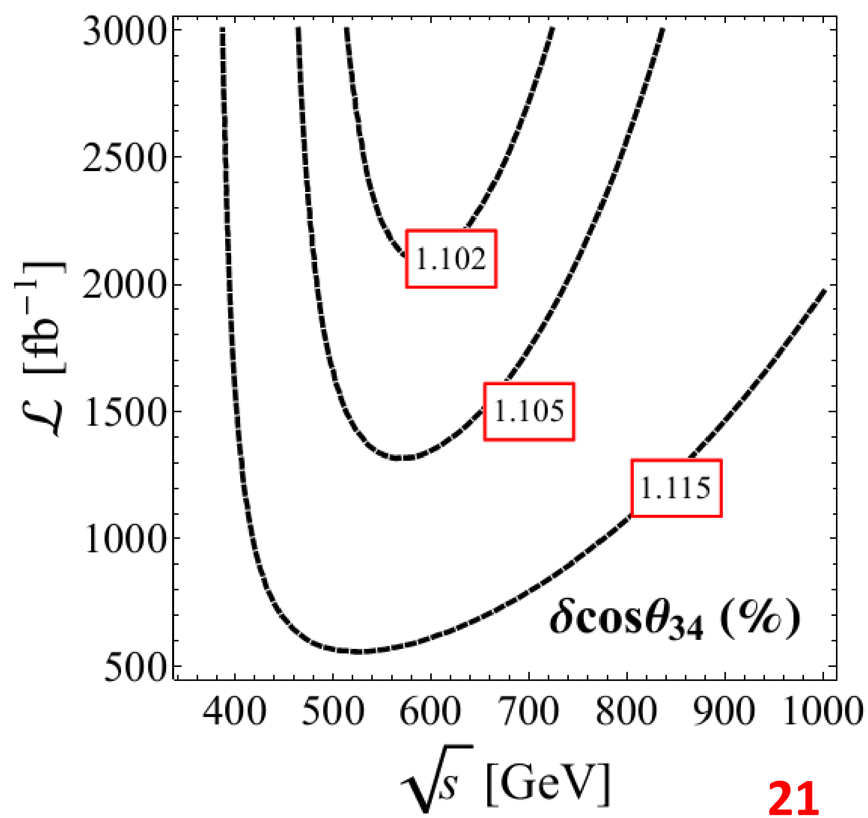
$$V_{4\times 4} = R_{34}(\theta_{34}) R_{24}(\theta_{24}) R_{14}(\theta_{14}) V_{3\times 3}$$

$$V_{tb}^{0} \approx 1 \gg V_{cb}^{0}, V_{ub}^{0}$$

$$V_{tb} = V_{tb}^{0} + \Delta V_{tb} \approx \cos\theta_{34} V_{tb}^{0} \approx \cos\theta_{34}$$

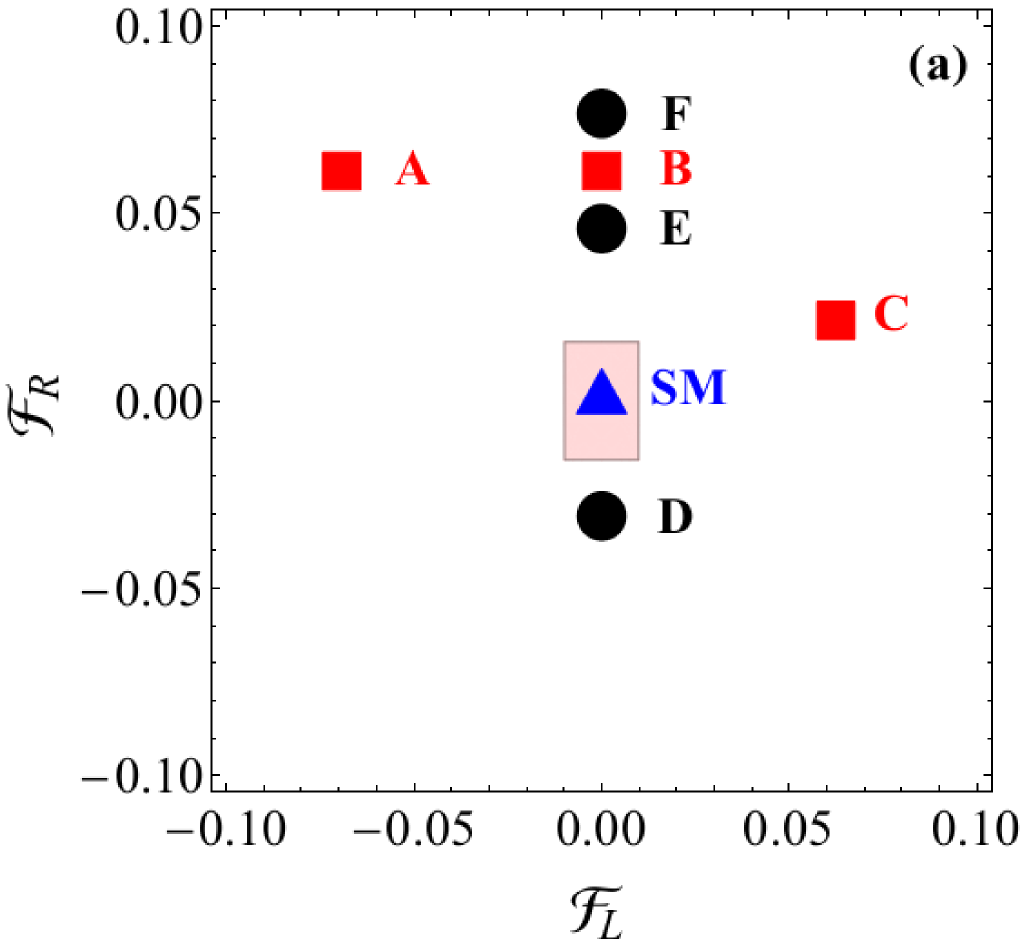
S. Bose and E. A. Paschos, Nucl. Phys. B169,384 (1980)





B. Ztt and New Physics

$$g_{Ztt}^{NP} = \underline{2F_L \frac{g}{2c_W} Z_\mu \bar{t}_L \gamma^\mu t_L} + \underline{F_R \frac{g}{2c_W} Z_\mu \bar{t}_R \gamma^\mu t_R}$$



Extra dimensional models

Composite models

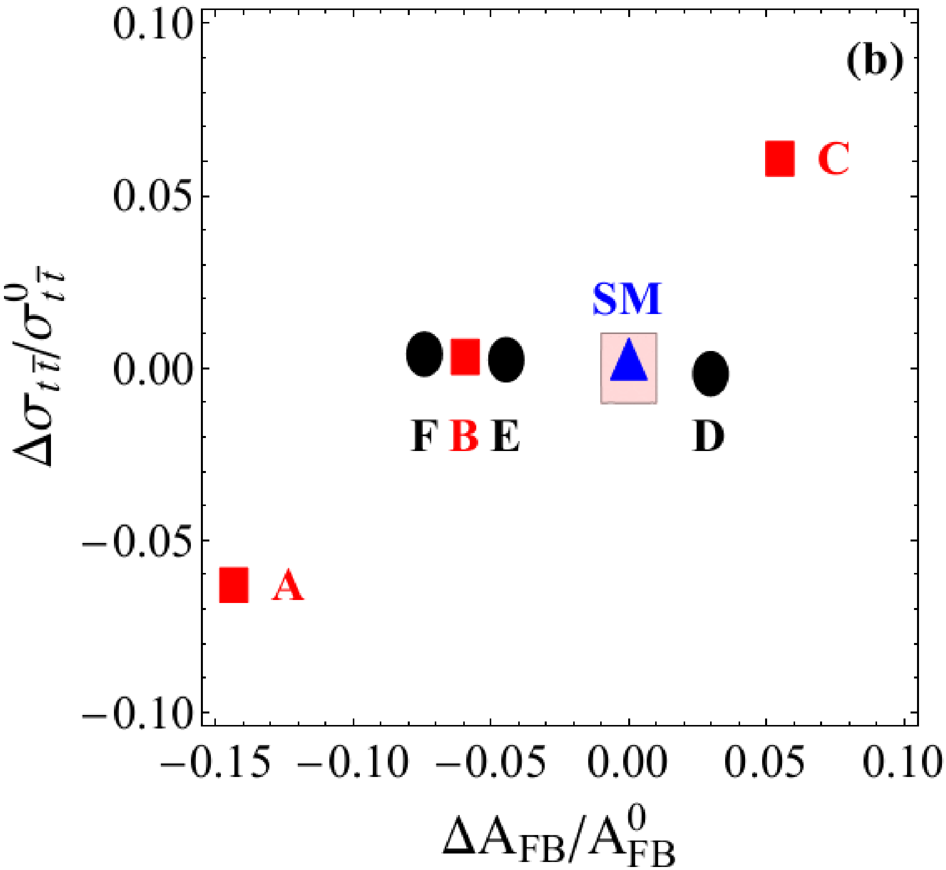
$\sqrt{s} = 500\ GeV$

$Lum = 500 fb^{-1}$

Richard, Francois, arXiv:1403.2893

B. Ztt and New Physics

$$\frac{\Delta\sigma_{tt}}{\sigma_{tt}^{0}} = a_L F_L + a_R F_R \qquad \frac{\Delta A_{FB}}{A_{FB}^{0}} = b_L F_L + b_R F_R$$



Extra dimensional models

Composite models

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

$$Lum = 500 fb^{-1}$$

Richard, Francois, arXiv:1403.2893

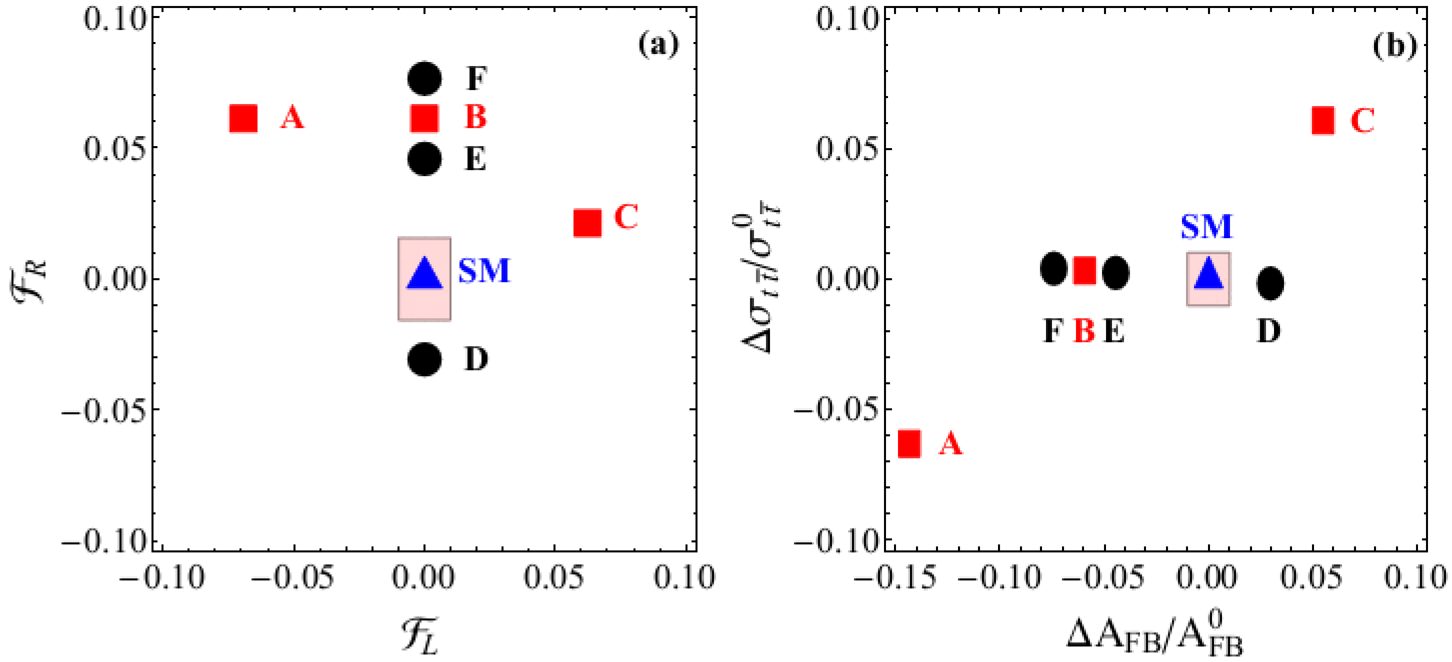


FIG. 7: *The predictions of several NP models on the deviations of left-handed and right-handed $Zt\bar{t}$ coupling from the SM predictions (a) and the deviations of the cross section and asymmetry (b) [38]. The red rectangles denote the extra dimensional models: A (Gherghetta et al [39]), B (Carena et al [40]), C (Hostanoi et al [41]), the black disks denote the composite models: D (Grojean et al [42]), E (Little Higgs [43]), F (Pomarol et al [44]). The light-blue and light-red contours indicate the precision that can be expected for the e^+e^- collider at $\sqrt{s} = 500$ GeV with luminosity $\mathcal{L} = 1000\text{fb}^{-1}$.*

Composite models

A. top quark compositeness

Partial compositeness mechanism

Elementary sector → Mass-mixing terms ← Composite sector

A. Pomarol and J. Serra
arxiv:0806.3247

Low-energy effective lagrangian for a composite top quark (Left-handed): (F)

$$i\frac{c_L^1}{f^2}H^+D_\mu H\bar{q}_L\gamma^\mu q_L \qquad \frac{\delta g_{Zbb}^L}{g_{Zbb}^L}=\frac{(c_L^3+c_L^1)\xi}{1-2/3\,s_W^2} \qquad \xi=\frac{v^2}{f^2}, f\sim O(TeV)$$

$$i\frac{c_L^3}{2f^2}H^+\sigma^i D_\mu H\bar{q}_L\gamma^\mu\sigma^i q_L \qquad \frac{\delta g_{Ztt}^L}{g_{Ztt}^L}=\frac{(c_L^3-c_L^1)\xi}{1-4/3\,s_W^2}$$

B.Littlest Higgs Model (E)

SU(5)

Gauge the subgroup

[SU(2) × U(1)]) × [SU(2) × U(1)]

Global symmetry breaking

$\langle\Sigma\rangle$

$\langle\Sigma\rangle$

Gauge symmetry breaking

New Gauge boson

Real, Eaten

SO(5)

$1_0 \oplus 3_0 \oplus 2_{\pm 1/2} \oplus 3_{\pm 1}$

$[SU(2) \times U(1)]_{SM}$

Higgs as a pseudo-Goldstone

Electroweak symmetry breaking, Coleman-Weinberg potential

$[U(1)]_{EM}$

Nambu-Goldstone bosons(NGBs) arise when a continuous global symmetry spontaneously broken

The number of NGBs:

$$N^2 - 1 - \frac{N(N-1)}{2} = 14$$

New Complex triplet Scalar

N.Arkani-Hamed et al.
JHEP 0207:034,2002