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Probing $Zt\bar{t}$ couplings using Z boson polarization in ZZ production at hadron colliders

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PRD 102 (2020) 5, 055010

Top quark as a probe of New Physics

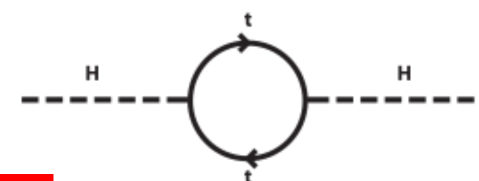
SUSY   Little Higgs   Composite   .....

Weak interacting?

Strongly interacting?

Electroweak symmetry breaking

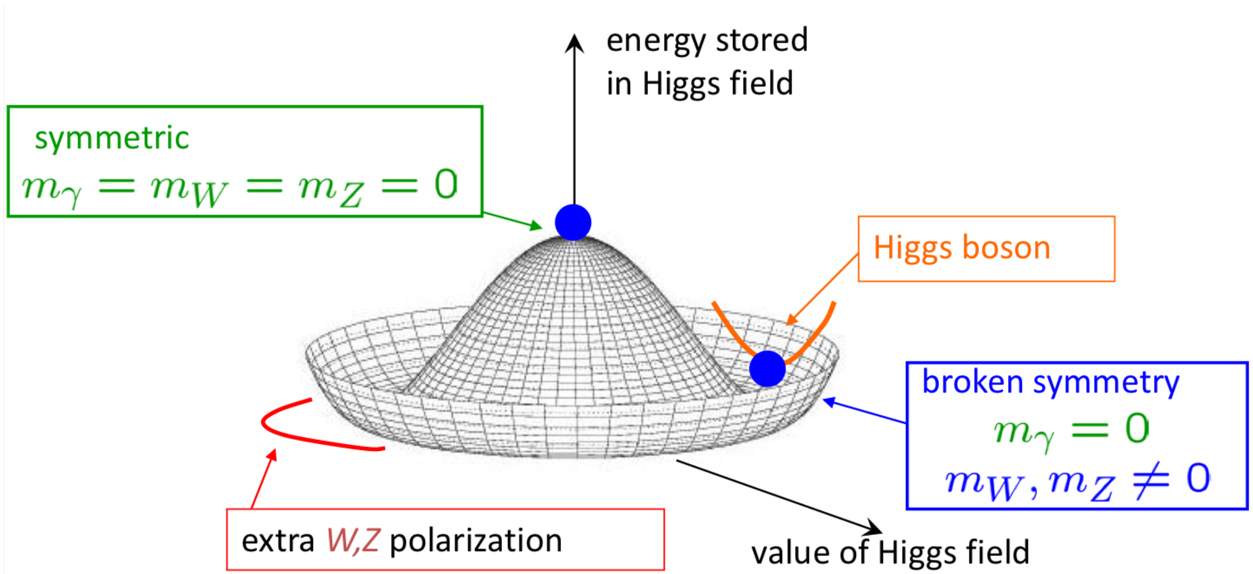
Naturalness hierarchy problem



Decay product of NP Resonances

Extra Gauge Bosons   New Heavy Quarks   Extra scalars

Top quark & EWSB

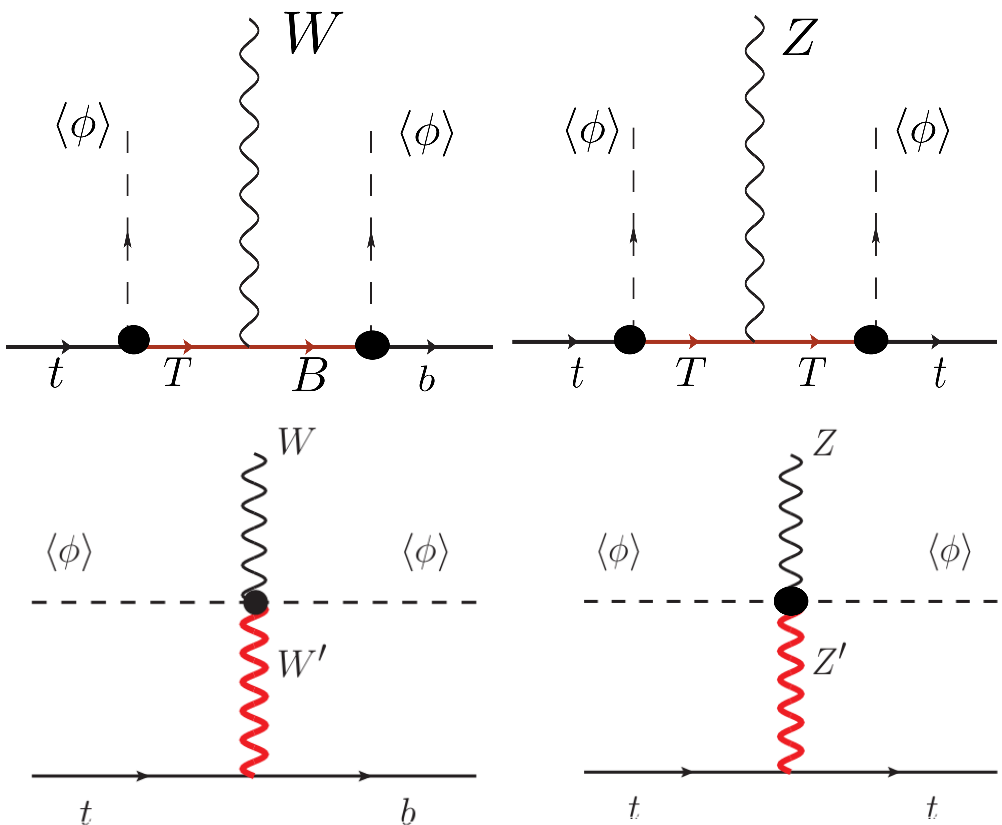


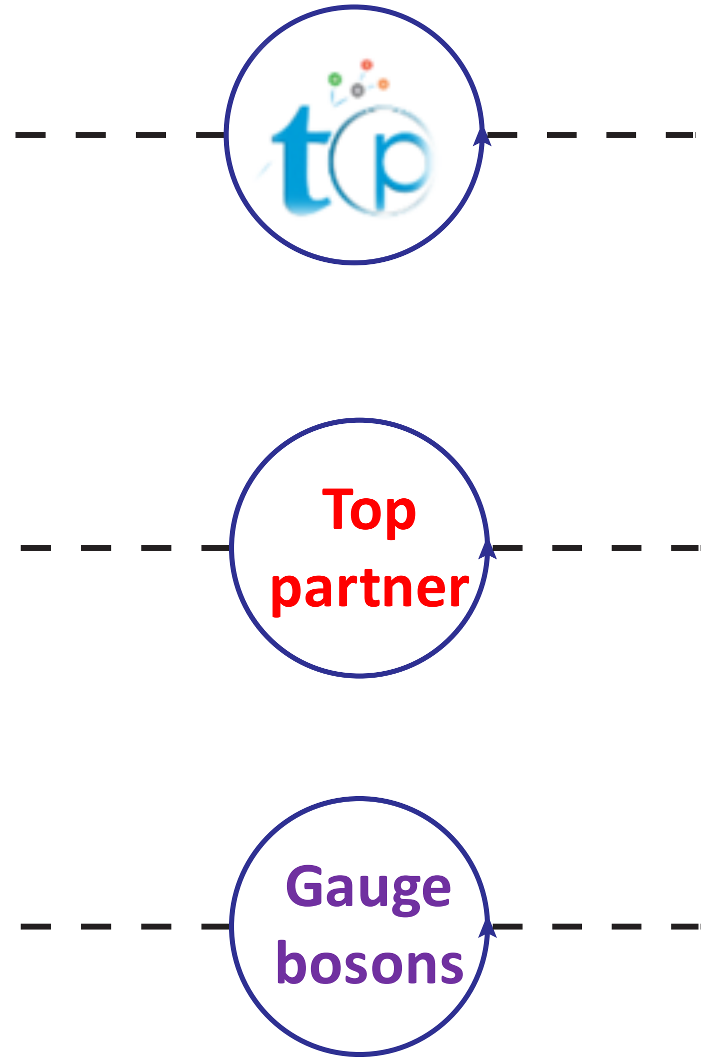
For example: in composite Higgs model

$$V = \beta \sin^4 \frac{h}{f} - \gamma \sin^2 \frac{h}{f}$$

Top quark and EWSB

$$V = \beta \sin^4 \frac{h}{f} - \gamma \sin^2 \frac{h}{f}$$

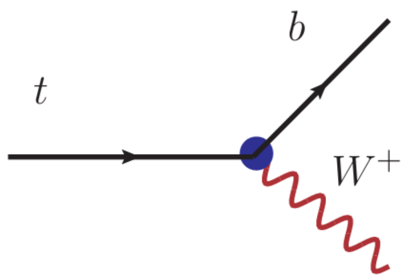


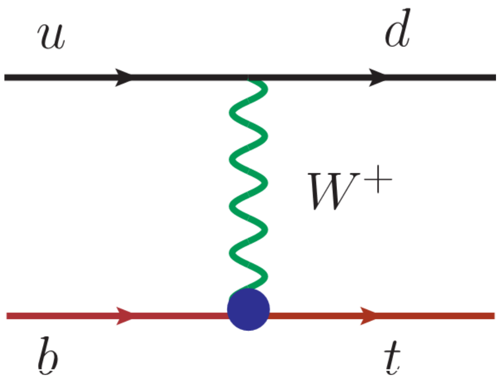


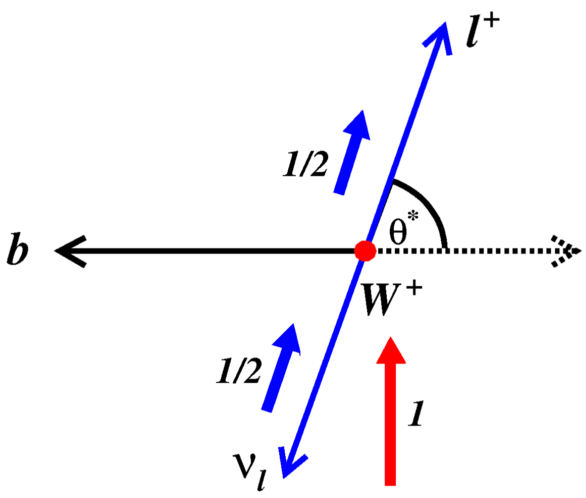
Top quark gauge couplings

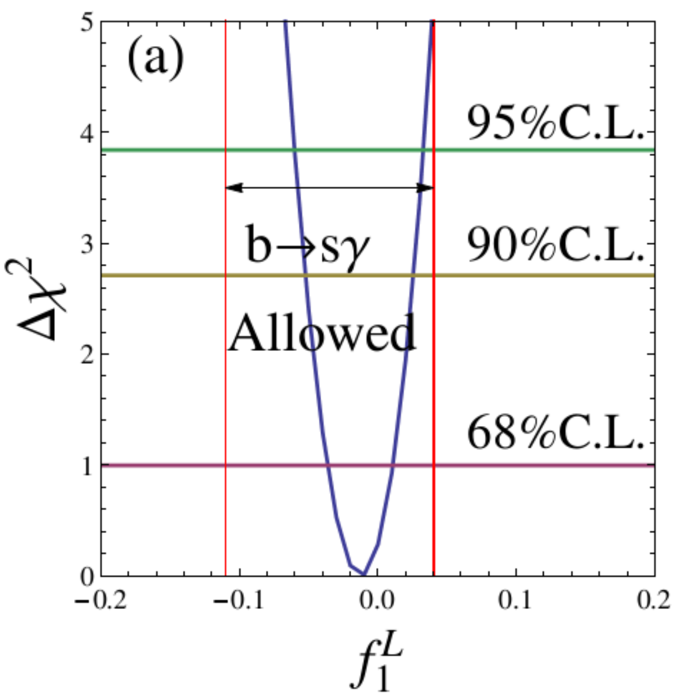
A. Charge current

Q.-H. Cao, **B. Yan**, J. H, Yu and C. Zhang, CPC41(2017)6,063101
E.L. Berger, Q.-H. Cao and I. Low, PRD80,074020(2009)









$$d^1_{1,-1} = \frac{1-\cos\theta}{2}, d^1_{1,1} = \frac{1+\cos\theta}{2} \quad d^1_{1,0} = -\frac{\sin\theta}{\sqrt{2}}$$

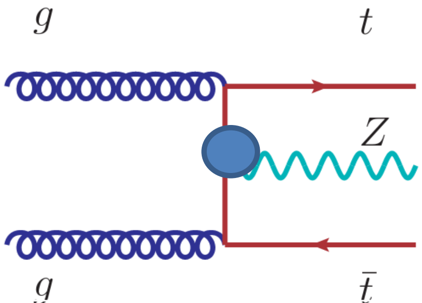
Top quark gauge couplings

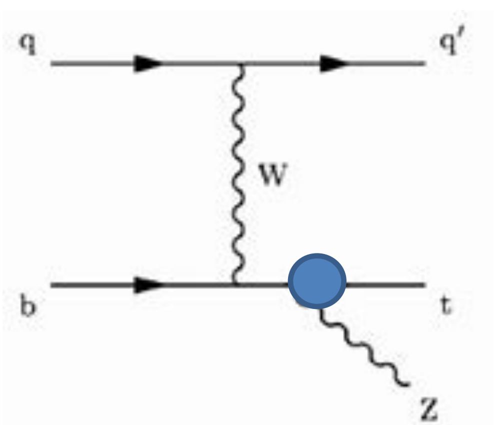
B. Neutral current

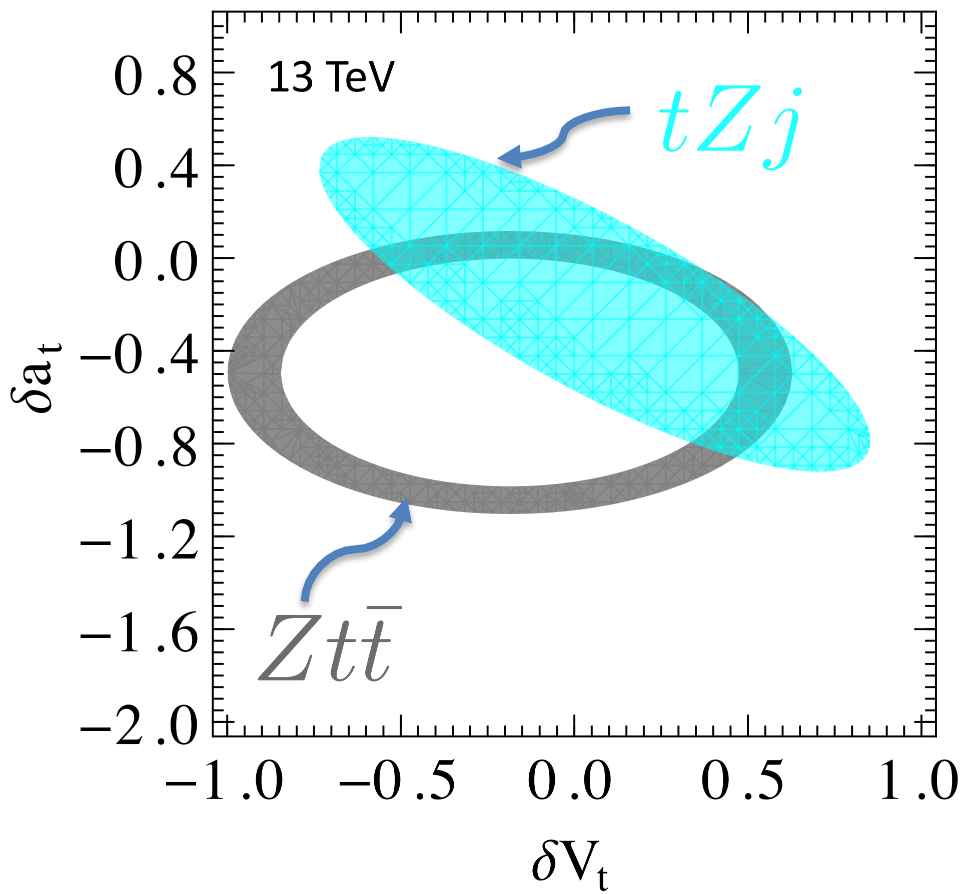
$$\mathcal{L} = \frac{g_W}{2c_W}\bar{t}(v_t - a_t\gamma_5)\gamma_\mu t Z^\mu$$

E.L. Berger, Q.-H. Cao and I. Low, PRD80,074020(2009)
R. Rontsch and M. Schulze, JHEP07,091(2014)
O. Bessidskaia Bylund et al, JHEP05,052(2016)

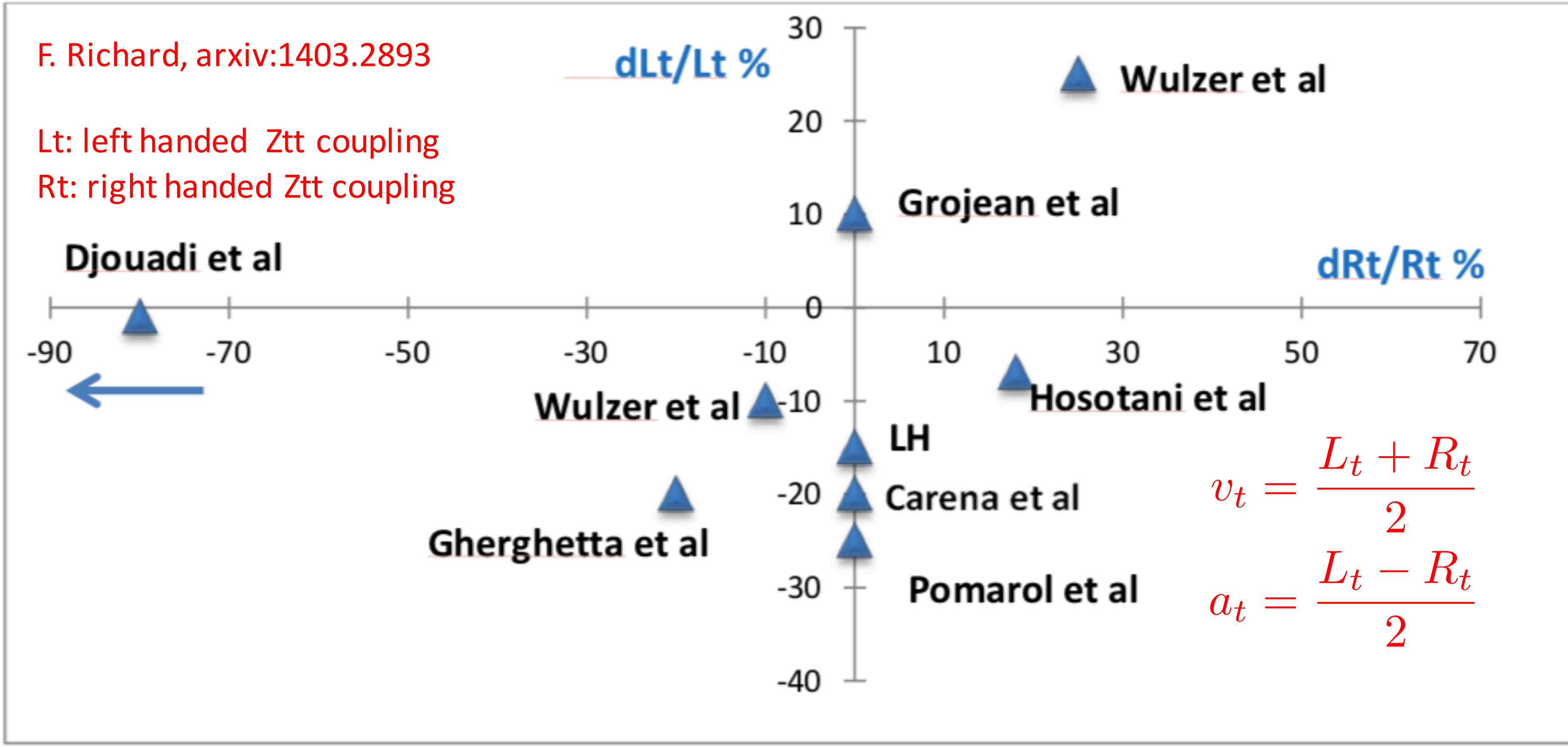
$$v_t^{\rm SM} = 0.35, \quad a_t^{\rm SM} = \frac{1}{2}$$







Top quark Neutral current & NP



$$v_t = \frac{L_t + R_t}{2}$$

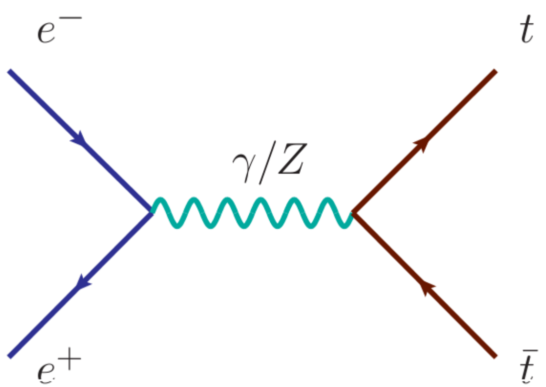
$$a_t = \frac{L_t - R_t}{2}$$

Distinguishing the vector and axial vector components of Ztt coupling=> different NP models

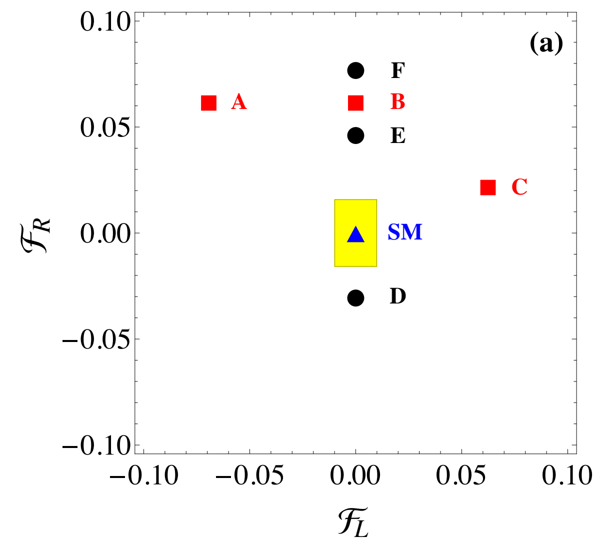
How to distinguish the top quark couplings

A, B and C: extra dimensional models

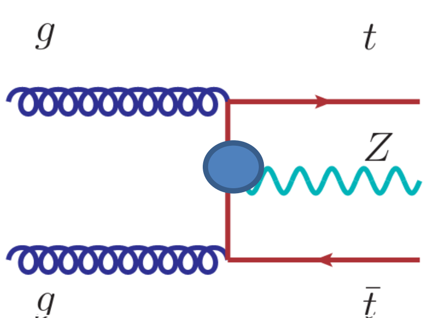
D, E and F: the composite models



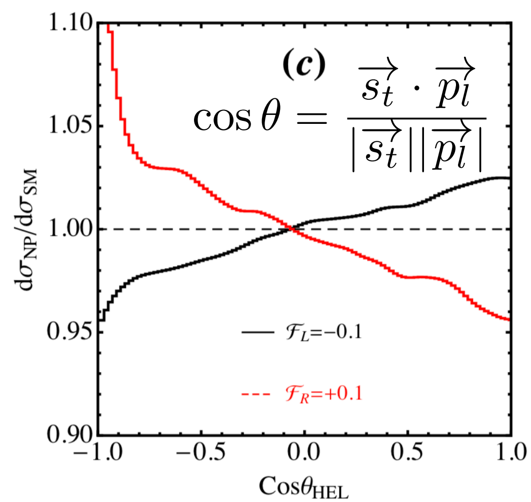
Q. H. Cao and **B. Yan**, PRD92,094018(2015)



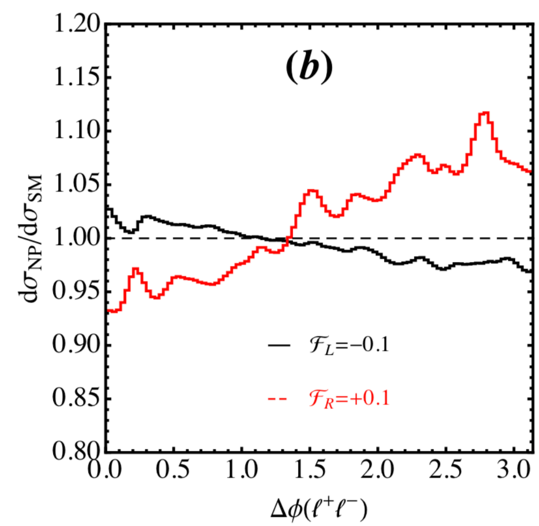
E. L. Berger, Q. H. Cao, I. Low, PRD80(2009)074020



A. Top quark Spin correlation



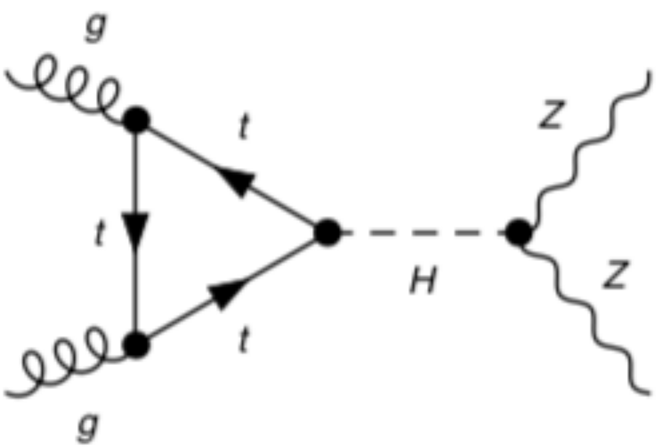
B. $\Delta\phi(\ell^+\ell^-)$

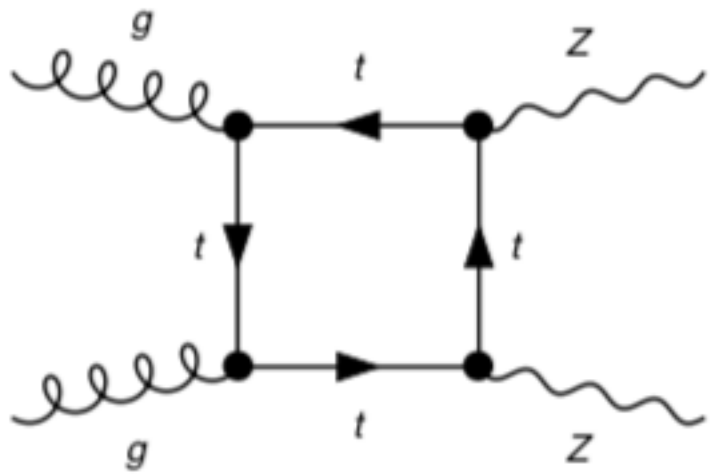


How to distinguish the top quark couplings

Other possibility:

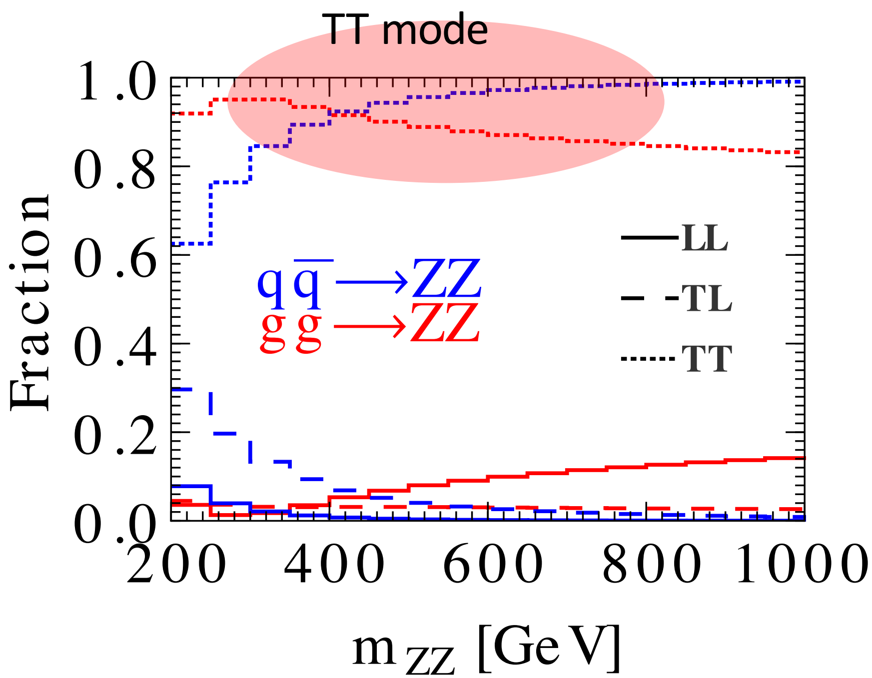
Q.-H. Cao, **B. Yan**, C.-P. Yuan and Ya Zhang,
PRD 102 (2020) 5, 055010

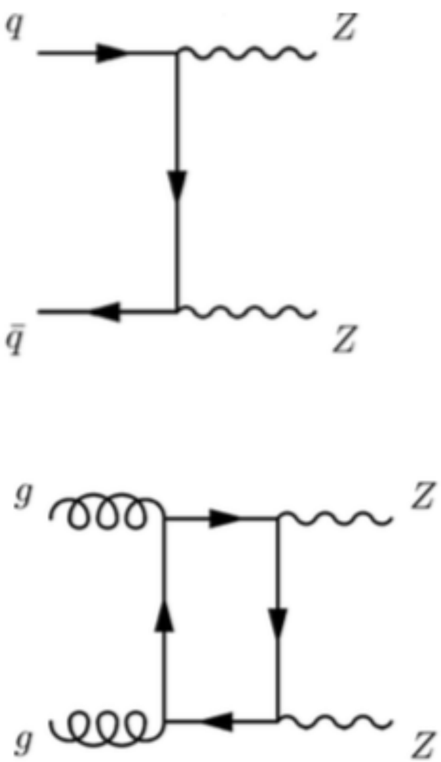




Top quark coupling will change the polarizations of Z boson pair

Polarization of ZZ scattering

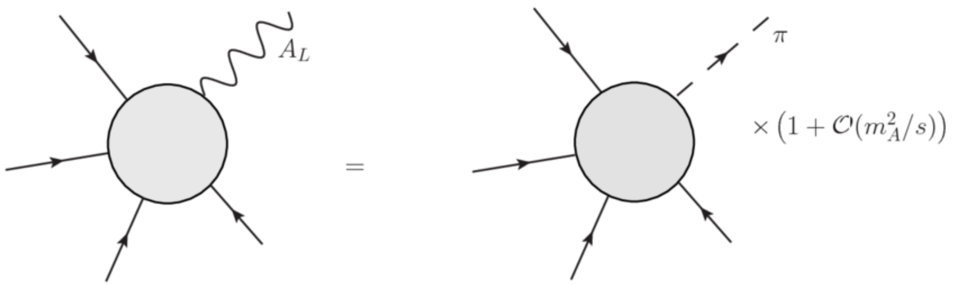


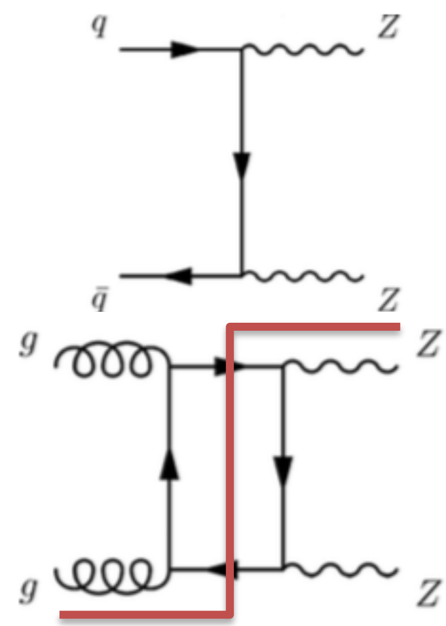


T: transverse
L: longitudinal

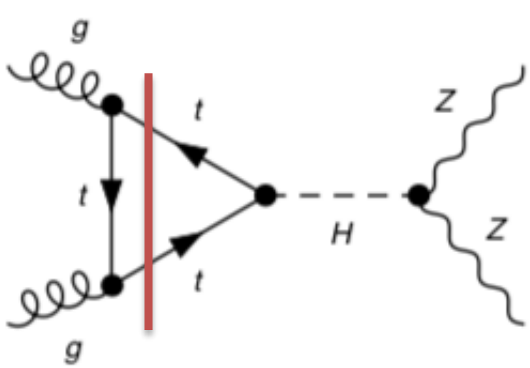
Both quark and gluon initial states are dominantly by the TT mode

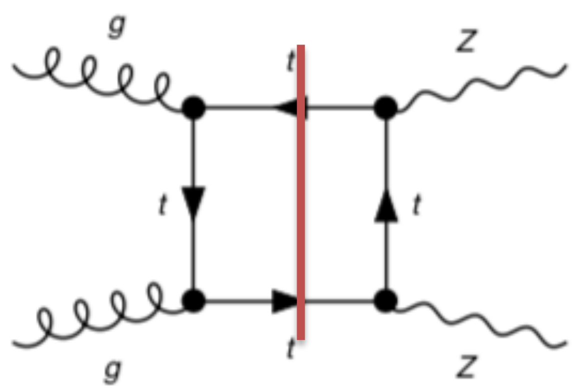
Goldstone equivalence theorem and Unitarity





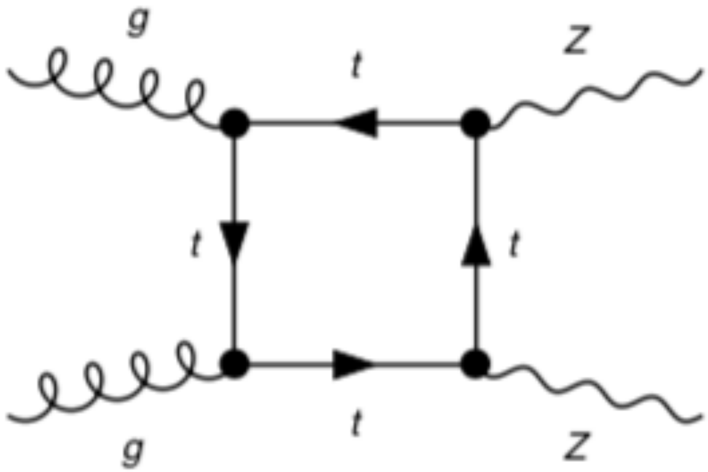
The light quark contribution to LL mode will be suppressed





There is a cancellation between the triangle and box diagrams due to the Unitarity

Axial current of top quark coupling



$$\mathcal{L} = \frac{g_W}{2c_W}\bar{t}(v_t - a_t\gamma_5)\gamma_\mu t Z^\mu$$

Energy Dependence in the high energy limit:

E. W. N. Glover and J.J. van der Bij, NPB321,561(1989)

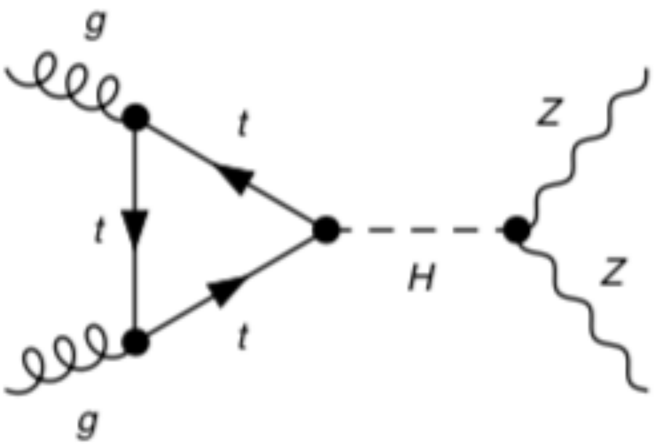
$$M^{\Box}_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} = \left(v_q^2 + a_q^2\right) A_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} + \left(v_q^2 - a_q^2\right) B_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} + a_q^2 C_{\lambda_1,\lambda_2,\lambda_3,\lambda_4}$$

$$\hat{s} = -\hat{t}/2 = -\hat{u}/2 \gg m_t, m_z$$

$$A \sim \text{Constant},$$
$$B \sim 0,$$
$$C_{\pm,\pm,0,0} \sim -\frac{m_t^2}{m_Z^2}\left[\log^2\left(\frac{\hat{s}}{m_t^2}\right) - 2i\pi \log\left(\frac{\hat{s}}{m_t^2}\right)\right]$$

Axial current is not conserved for massive top quark.

Unitarity of Gluon Fusion



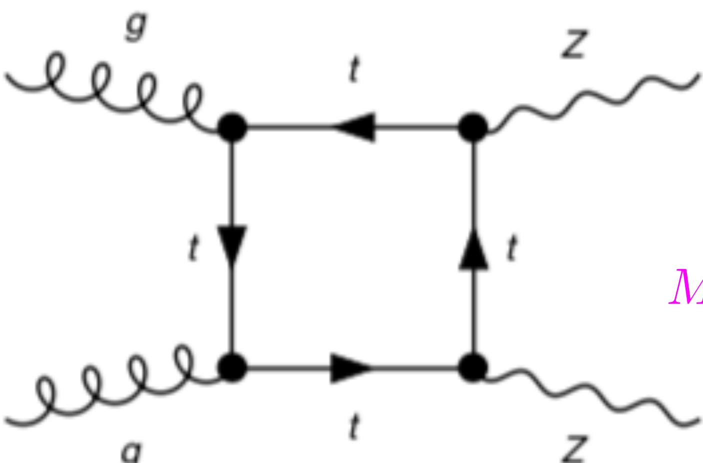
Energy Dependence in the high energy limit:

$$M^{\triangle}_{\pm,\pm,0,0} \sim \frac{m_t^2}{4m_Z^2}\left[\log^2\left(\frac{\hat{s}}{m_t^2}\right) - 2i\pi\log\left(\frac{\hat{s}}{m_t^2}\right)\right].$$

Unitarity + Axial current is not conserved

Strong cancelation

$$a_t = \frac{1}{2}$$ (SM)

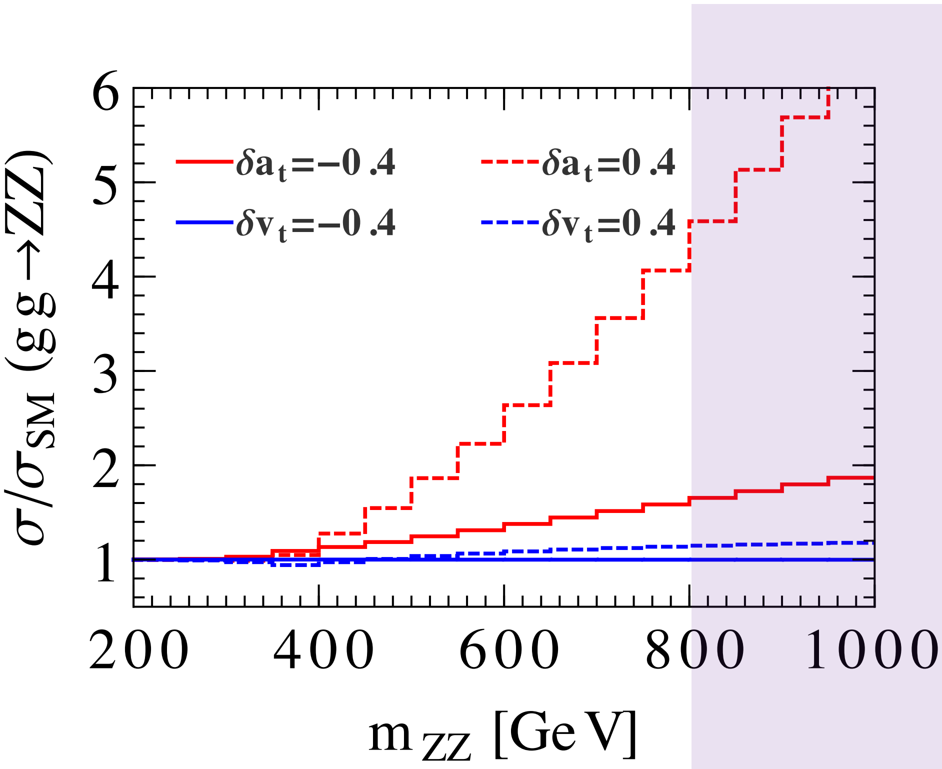


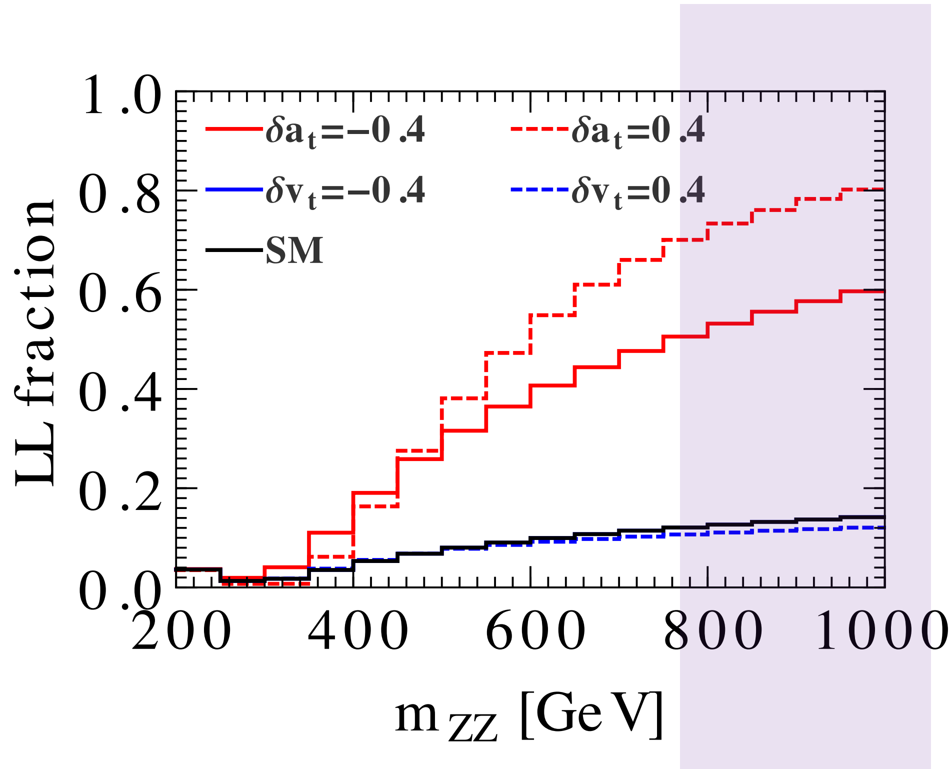
$$M^{\square}_{\pm,\pm,0,0} \sim -a_t^2\frac{m_t^2}{m_Z^2}\left[\log^2\left(\frac{\hat{s}}{m_t^2}\right) - 2i\pi\log\left(\frac{\hat{s}}{m_t^2}\right)\right].$$

LL mode is sensitive to the axial current of top quark

Cross section and polarization

$$\delta v_t = v_t - v_t^{\rm SM}, \quad \delta a_t = a_t - a_t^{\rm SM}.$$



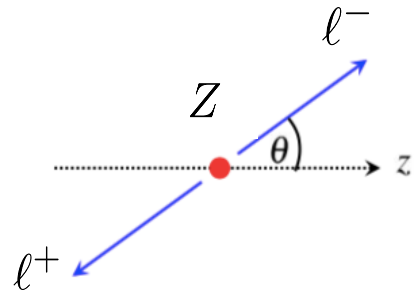


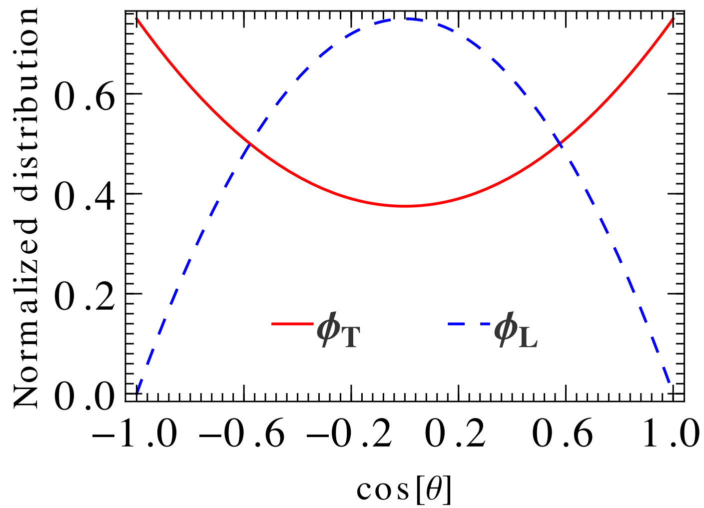
The axial current of top quark will change the total cross section and LL fraction remarkably

How to measure LL mode at the LHC?

Polarization of Z bosons in ZZ scattering

Z boson rest frame:



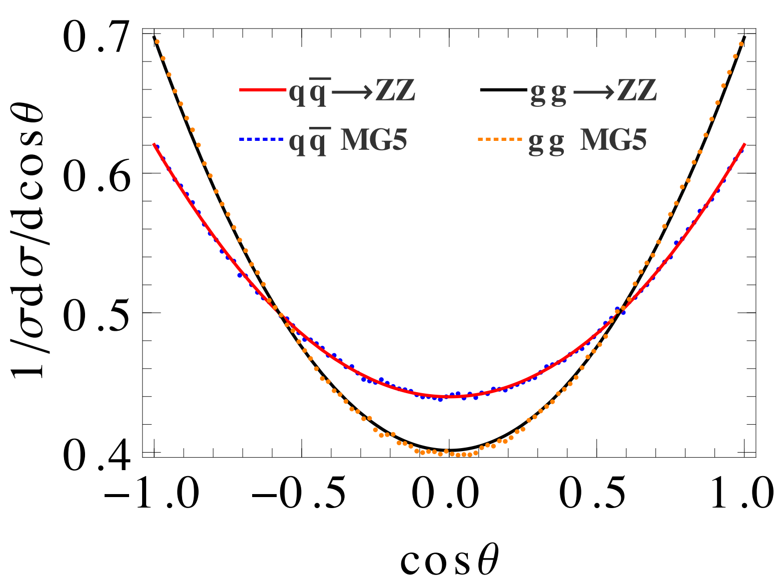


Transverse:

$$\phi_T = \frac{3}{8}(1+\cos\theta^2)$$

Longitudinal:

$$\phi_L = \frac{3}{4}(1-\cos\theta^2)$$



$$\frac{d\sigma}{\sigma d\cos\theta} = f_L\phi_L + f_T\phi_T$$

ZZ polarization fractions: $f_{L,T}$

The theoretical calculation agrees with MG5 very well

Collider Simulation@13 TeV LHC

$|\eta_l| < 2.5, P_{T\ell} > 15\ \text{GeV}$

$80 < m_{\ell^+\ell^-} < 100\ \text{GeV}$

$m_{4\ell} > 600\ \text{GeV}$

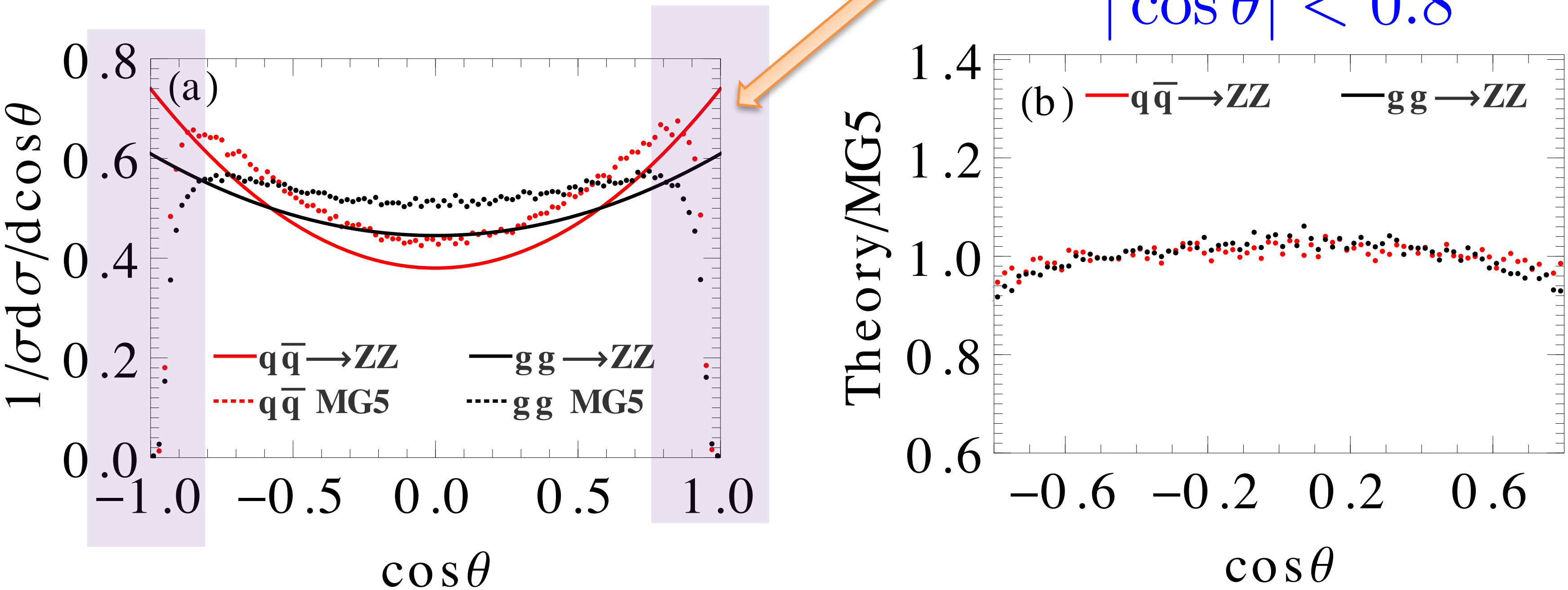
Effectively

$|\eta_Z| < 2.$

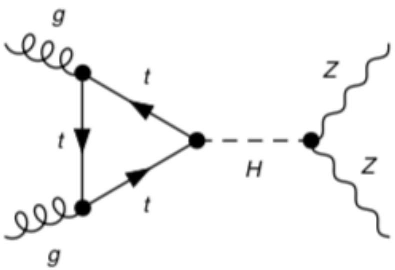
$m_{ZZ} > 600\ \text{GeV}$

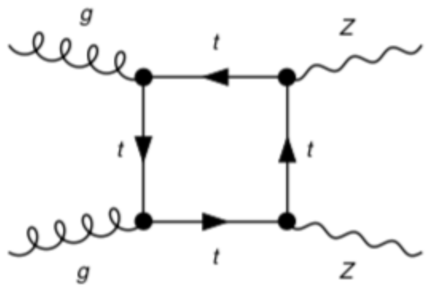
Detector effects for the edges

$|\cos\theta| < 0.8$

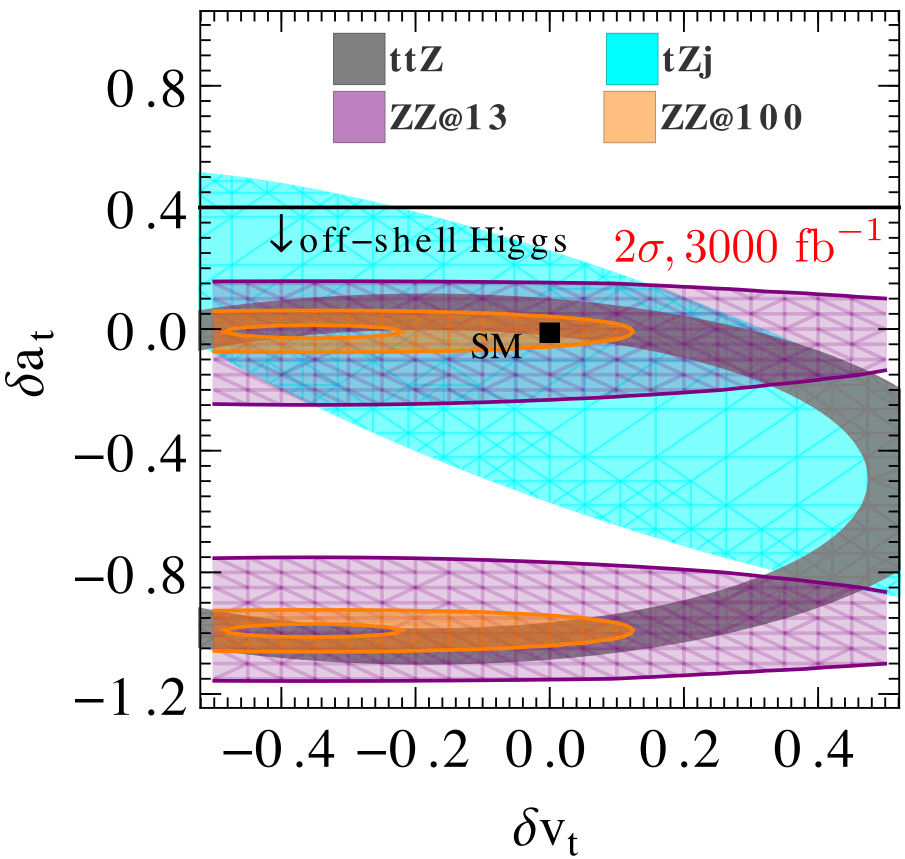


ZZ polarization and top quark





$$\mathcal{L} = \frac{g_W}{2c_W}\bar{t}(v_t - a_t\gamma_5)\gamma_\mu t Z^\mu$$



A. ZZ polarization only sensitive to the axial-vector component of Ztt coupling;

B. ZZ production is complementary to the Ztt and Ztj productions in measurements of the Ztt coupling.

Thank you!

Back up

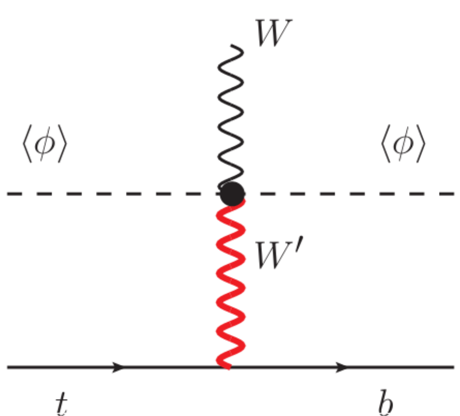
Top quark gauge couplings

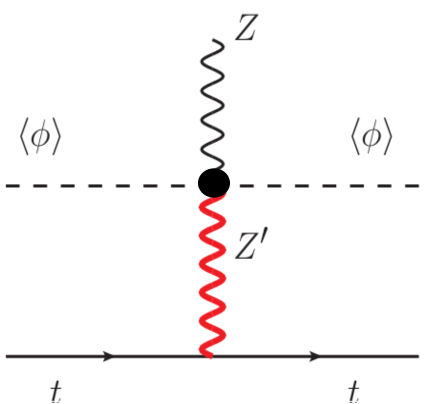
$$O_{\phi q}^{(1)} = i(\phi^{+} D_{\mu}\phi)(\bar{q}\gamma^{\mu} q) \qquad O_{\phi\phi} = i(\tilde{\phi}^{+} D_{\mu}\phi)(\bar{t}_R\gamma^{\mu} b_R)$$

$$O_{\phi t} = i(\phi^{+} D_{\mu}\phi)(\bar{t}_R\gamma^{\mu} t_R) \qquad O_{\phi q}^{(3)} = i(\phi^{+}\tau^{I} D_{\mu}\phi)(\bar{q}\gamma^{\mu}\tau^{I} q)$$

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

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

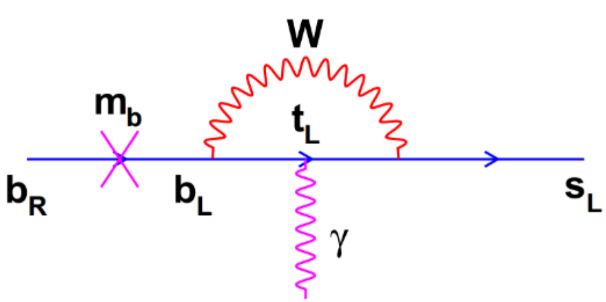


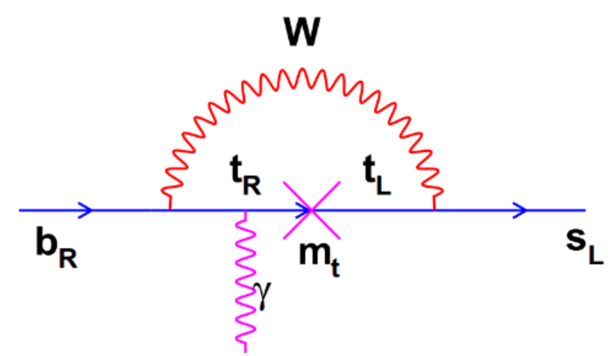


Top quark gauge couplings

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

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





Q.-H. Cao, B. Yan, J. H, Yu and C. Zhang, CPC41(2017)6,063101

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