

GUT inspired gauge-Higgs unification: CKM and ILC physics

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Funatsu, Hatanaka, YH, Orikasa, Yamatsu
1902.01603 (PRD 99, 095010, May 15 2019)
1909.00190

Scalars 2019
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$SO(5) \times U(1) \times SU(3)$ gauge-Higgs unification

GUT inspired model (B-model) $\longleftrightarrow$ A-model

Flavor mixing — CKM matrix

FCNC naturally suppressed (by 10^{-6})

Z' (7 – 8 TeV) at 250 GeV ILC
explored through interference effects

Gauge-Higgs unification

125 GeV Higgs boson

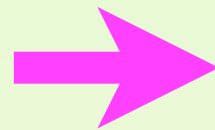


AB phase in the 5th dim

$$P \exp \left\{ ig \oint dy A_y \right\} \sim e^{i\Theta_H(x)}$$

$$\Theta_H(x) = \theta_H + \frac{H(x)}{f_H}$$

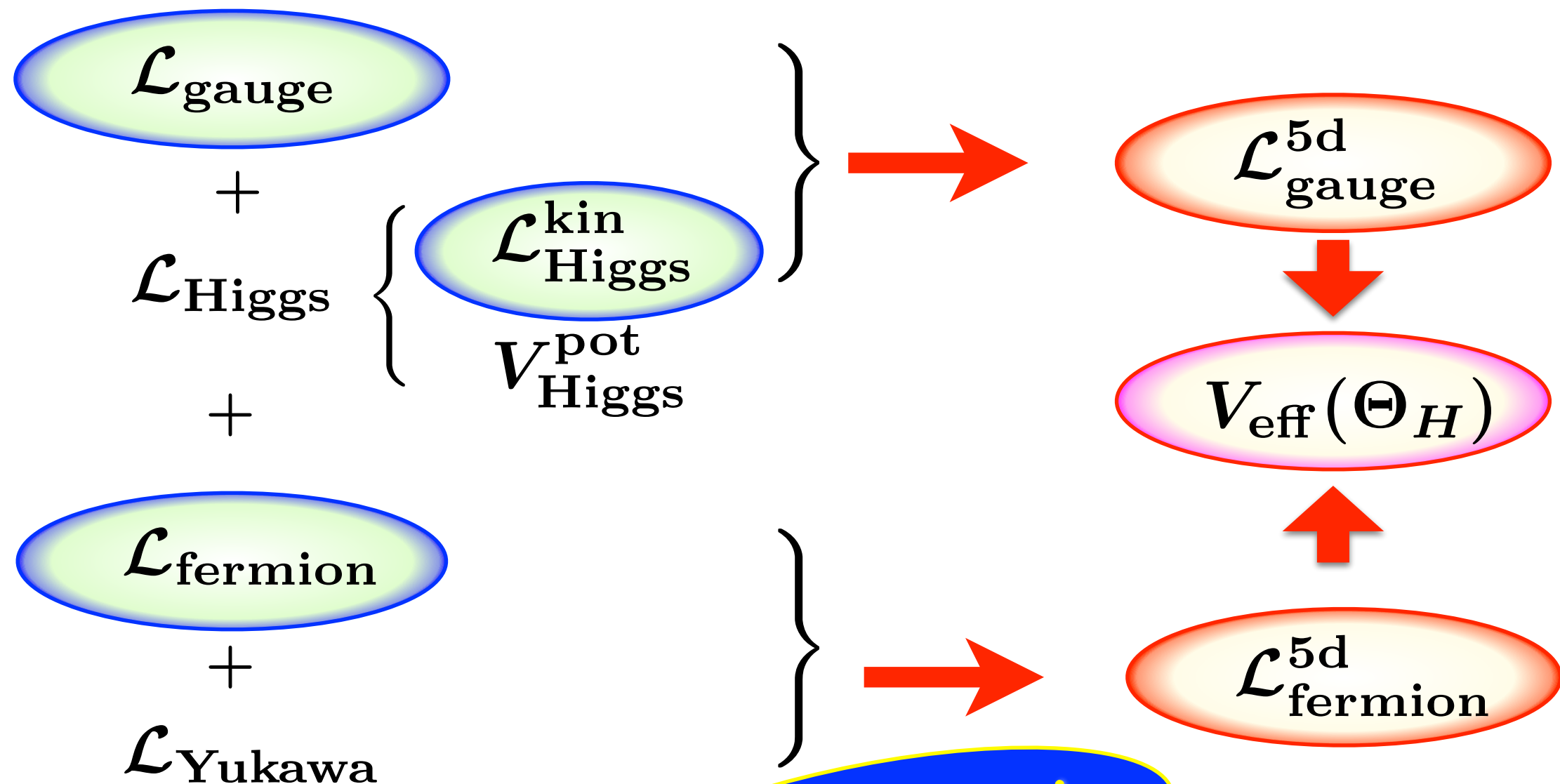
$$\theta_H \neq 0$$



EW sym. breaking

Standard Model

Gauge-Higgs Unification



$SU(3) \times SO(5) \times U(1)$
gauge-Higgs on RS

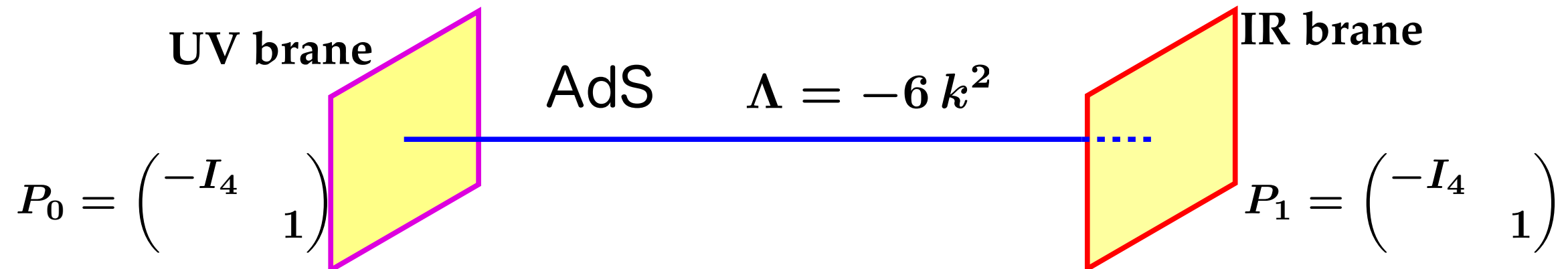
Agashe, Contino, Pomarol 2005

YH, Sakamura 2006

Medina, Shah, Wagner 2007

YH, Oda, Ohnuma, Sakamura 2008

Funatsu, Hatanaka, YH, Orikasa, Shimotani 2013



$\longrightarrow SU(3)_C \times SO(4) \times U(1)_X$

brane scalar $\langle \hat{\Phi} \rangle$

$\longrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$

Hosotani mechanism $\theta_H \neq 0$

$\longrightarrow SU(3)_C \times U(1)_{EM}$

$A_\mu \sim \left(\begin{array}{c} \boxed{W \ Z \ \gamma} \end{array} \right)$

$A_y \sim \left(\begin{array}{c} \boxed{Higgs} \end{array} \right)$

$e^{i\hat{\theta}_H(x)} \sim P \exp \left\{ ig \int dy A_y \right\}$

Matter

$$\begin{pmatrix} u \\ d \\ u' \\ d' \end{pmatrix}$$

B model
GUT inspired

$D^\pm$

A model
previous model

quark
lepton

$$(3, 4)_{\frac{1}{6}} \quad (3, 1)_{-\frac{1}{3}}^+ \quad (3, 1)_{-\frac{1}{3}}^- \quad (1, 4)_{-\frac{1}{2}}$$

$$(3, 5)_{\frac{2}{3}} \quad (3, 5)_{-\frac{1}{3}} \quad (1, 5)_0 \quad (1, 5)_{-1}$$

dark fermion

$$(3, 4)_{\frac{1}{6}} \quad (1, 5)_0^+ \quad (1, 5)_0^-$$

$$(1, 4)_{\frac{1}{2}}$$

brane fermion

$$(1, 1)_0$$

$$(3, [2, 1])_{\frac{7}{6}, \frac{1}{6}, -\frac{5}{6}} \quad (1, [2, 1])_{\frac{1}{2}, -\frac{1}{2}, -\frac{3}{2}}$$

brane scalar

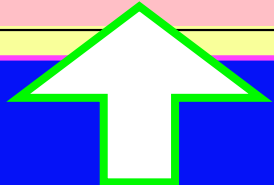
$$(1, 4)_{\frac{1}{2}}$$

$$(1, [1, 2])_{\frac{1}{2}}$$

symmetry of
brane interactions

$$SU(3)_C \times SO(5) \times U(1)_X$$

$$SU(3)_C \times SO(4) \times U(1)_X$$



Brane interactions

$$\begin{pmatrix} u \\ d \\ u' \\ d' \end{pmatrix}$$

$$\int d^5x \sqrt{-g} \delta(y) \left\{ y_B \bar{\Psi}_{(3,1)_{-\frac{1}{3}}} \hat{\Phi}_{(1,4)_{\frac{1}{2}}}^\dagger \Psi_{(3,4)_{\frac{1}{6}}} + \text{h.c.} \right\}$$

D

$$\langle \hat{\Phi}_{(1,4)} \rangle \neq 0$$

brane scalar

$$\longrightarrow SO(4) \times U(1)_X \rightarrow SU(2)_L \times U(1)_Y$$

$$\longrightarrow \mu D_L^\dagger d'_R$$

mass splitting $m_d \neq m_u$

flavor mixing $\longrightarrow$ **CKM**

Effective mass matrix

$$(\vec{\bar{d}}_L, \vec{\bar{D}}_L) \mathcal{M}_{\text{down}} \begin{pmatrix} \vec{d}'_R \\ \vec{D}_R \end{pmatrix} + h.c. \quad \vec{d} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\parallel$$

$$\begin{pmatrix} M_{\text{up}} & 0 \\ \mu & m_D \end{pmatrix} = \Omega \begin{pmatrix} M_{\text{down}} & 0 \\ 0 & M_D \end{pmatrix} \tilde{\Omega}^\dagger$$

Mass eigenstates

$$\begin{pmatrix} \vec{\hat{d}}_L \\ \vec{\hat{D}}_L \end{pmatrix} = \Omega^\dagger \begin{pmatrix} \vec{d}_L \\ \vec{D}_L \end{pmatrix} \quad \begin{pmatrix} \vec{\hat{d}}_R \\ \vec{\hat{D}}_R \end{pmatrix} = \tilde{\Omega}^\dagger \begin{pmatrix} \vec{d}'_R \\ \vec{D}_R \end{pmatrix}$$

$$\Omega \Omega^\dagger = \tilde{\Omega} \tilde{\Omega}^\dagger = 1 \quad \Omega = \begin{pmatrix} \Omega_q & \Omega_b \\ \Omega_a & \Omega_D \end{pmatrix} \quad \Omega_q \Omega_q^\dagger \neq 1$$

CKM and FCNC

$$\mathcal{L}_W \simeq \frac{g_L^W}{\sqrt{2}} W_\mu \vec{u}_L \Gamma^\mu \vec{d}_L \simeq \frac{g_L^W}{\sqrt{2}} W_\mu \vec{u}_L \Gamma^\mu \underline{\Omega_q} \vec{d}_L$$

$$\rightarrow V^{\text{CKM}} \simeq \Omega_q$$

$$\mathcal{L}_Z^{\text{down}} \sim -\frac{g_w}{\cos \theta_W} Z_\mu \left\{ -\frac{1}{2} \vec{\bar{d}}_L \Gamma^\mu \underline{\Omega_q^\dagger \Omega_q} \vec{d}_L + \frac{1}{3} \sin^2 \theta_W \left(\vec{\bar{d}}_L \Gamma^\mu \vec{d}_L + \vec{\bar{d}}_R \Gamma^\mu \vec{d}_R \right) \right\}$$

||

$$I - \Omega_a^\dagger \Omega_a$$

$$O\left(\frac{m_q^2}{m_D^2}\right) \sim 10^{-6}$$

$$m_q = m_d, m_s, m_b$$

$$m_D \sim 0.6 m_{\text{KK}}$$

FCNC : suppressed naturally

W, Z couplings

$$m_Z, z_L = 10^{10}$$

θ_H	m_{KK} (TeV)	c_u	c_c	c_t
0.10	12.08	-0.9169	-0.7545	-0.2274
0.15	8.07	-0.9170	-0.7546	-0.2294

$$\mathcal{L}_{\text{brane}} = \delta(y) \left\{ 2\mu_{\alpha\beta} \bar{d}'_R{}^\alpha D_L^{+\beta} + \text{h.c.} \right\}$$

$$\mu = \begin{pmatrix} 0.1 & & \\ & 0.1 & \\ & & 1 \end{pmatrix} U_{23}^\dagger(0.002) U_{12}^\dagger(0.106)$$

W

$$\theta_H = 0.15$$

$$g_L^W = 0.9950 g_w, \quad \hat{V}_{\text{CKM}} = \begin{pmatrix} 0.9737 & 0.2264 & 0.0043 \\ -0.2264 & 0.9736 & 0.0185 \\ 1 \times 10^{-5} & -0.0190 & 1.0004 \end{pmatrix}$$

$$g_L^W / g_{L\text{lepton}}^W = 1.00028$$

CKM**Z**

$$\begin{pmatrix} g_{Luu}^Z \\ g_{Lcc}^Z \\ g_{Ltt}^Z \end{pmatrix} = \begin{pmatrix} 0.3441 \\ 0.3441 \\ 0.3449 \end{pmatrix} g_w, \quad \begin{pmatrix} g_{Ruu}^Z \\ g_{Rcc}^Z \\ g_{Rtt}^Z \end{pmatrix} = \begin{pmatrix} -0.1533 \\ -0.1533 \\ -0.1524 \end{pmatrix} g_w$$

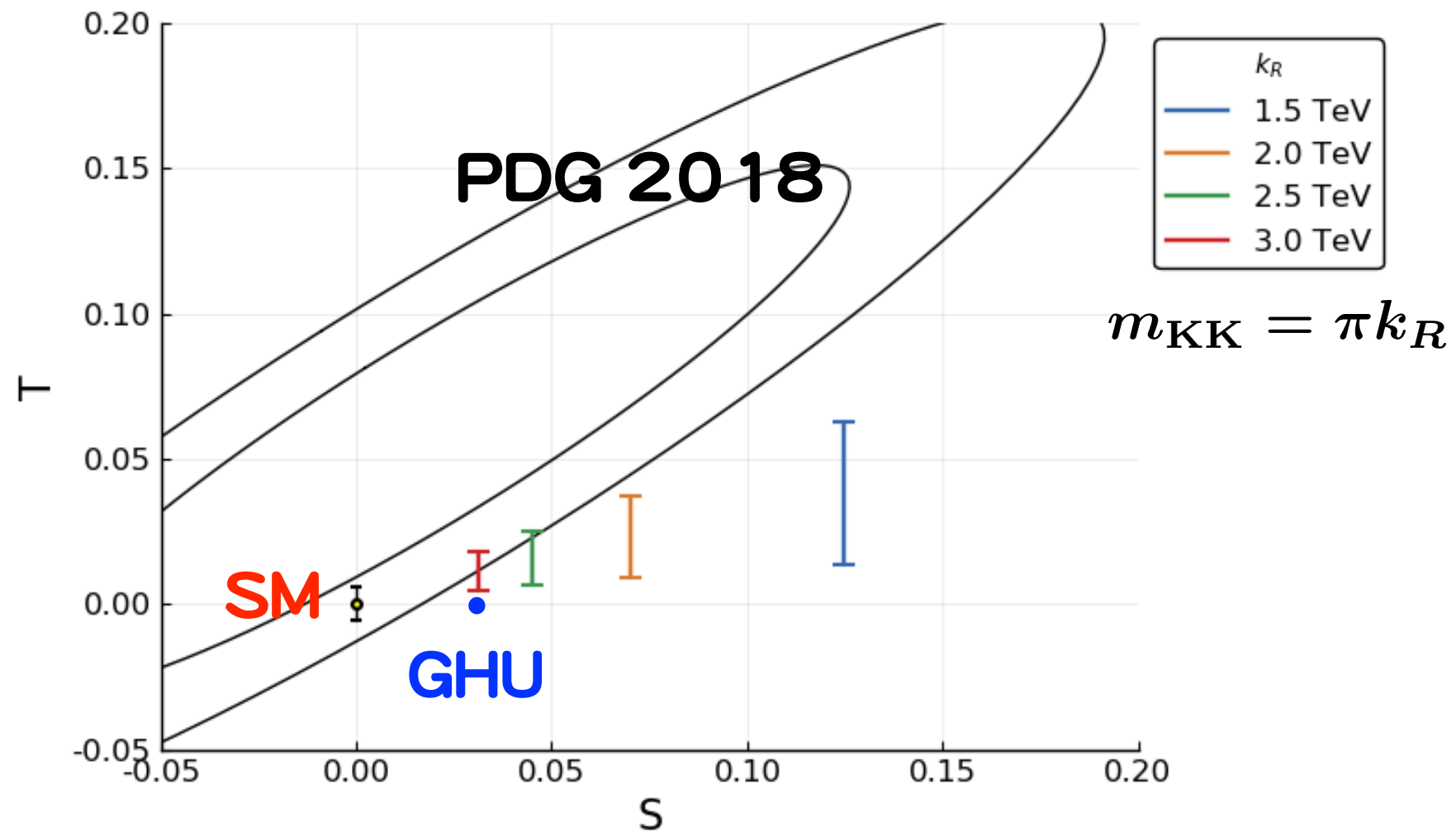
$$\hat{g}_{Ld}^Z = g_w \begin{pmatrix} -0.4208 & -7 \times 10^{-7} & -1 \times 10^{-8} \\ -7 \times 10^{-7} & -0.4208 & -4 \times 10^{-7} \\ -1 \times 10^{-8} & -4 \times 10^{-7} & -0.4207 \end{pmatrix}$$

$$\hat{g}_{Rd}^Z = g_w \begin{pmatrix} 0.0767 & -1 \times 10^{-6} & -1 \times 10^{-6} \\ -1 \times 10^{-6} & 0.0767 & -7 \times 10^{-6} \\ -1 \times 10^{-6} & -7 \times 10^{-6} & 0.0767 \end{pmatrix}$$

almost SM at low energies !

**$SO(5) \times U(1) \times SU(3)$
gauge invariance**

FCNC : suppressed



Yoon-Peskin, PRD 100, 015001 (2019), fig 6

ILC

test/observe GHU

Z' : $Z^{(1)}$ $\gamma^{(1)}$ $Z_R^{(1)}$

$m \sim 0.8 m_{\text{KK}}$
localized near IR

Large parity violation in Z' couplings

	c_ℓ , c_q	ℓ_L , q_L	ℓ_R , q_R
A model	> 0	near UV	near IR large Z' coupling
B model GUT inspired	< 0	near IR large Z' coupling	near UV

$e^+ e^- \rightarrow \mu^+ \mu^-$

Funatsu, Hatanaka, YH, Orikasa, PLB 775, 297 (2017)
Richard, 1804.02846 [hep-ex]
Yoon, Peskin, 1811.07877 [hep-ph]
Funatsu, 1905.10007 [hep-ph]

Funatsu's talk

ILC

$$\mathcal{M} = \begin{array}{c} e^- \\ e^+ \end{array} \begin{array}{c} \diagup \\ \diagdown \end{array} \begin{array}{c} Z, \gamma \\ \text{---} \end{array} \begin{array}{c} \diagdown \\ \diagup \end{array} \begin{array}{c} \mu^- \\ \mu^+ \end{array} \mathcal{M}_0 + \begin{array}{c} e^- \\ e^+ \end{array} \begin{array}{c} \diagup \\ \diagdown \end{array} \begin{array}{c} Z'^{(1)}, Z^{(1)}, \gamma^{(1)} \\ \text{---} \end{array} \begin{array}{c} \diagdown \\ \diagup \end{array} \begin{array}{c} \mu^- \\ \mu^+ \end{array} \mathcal{M}_{Z'}$$

$$m_Z^2 \ll s \ll m_{Z'}^2$$

$$(250 \text{ GeV})^2 \sim (1 \text{ TeV})^2$$

interference effects

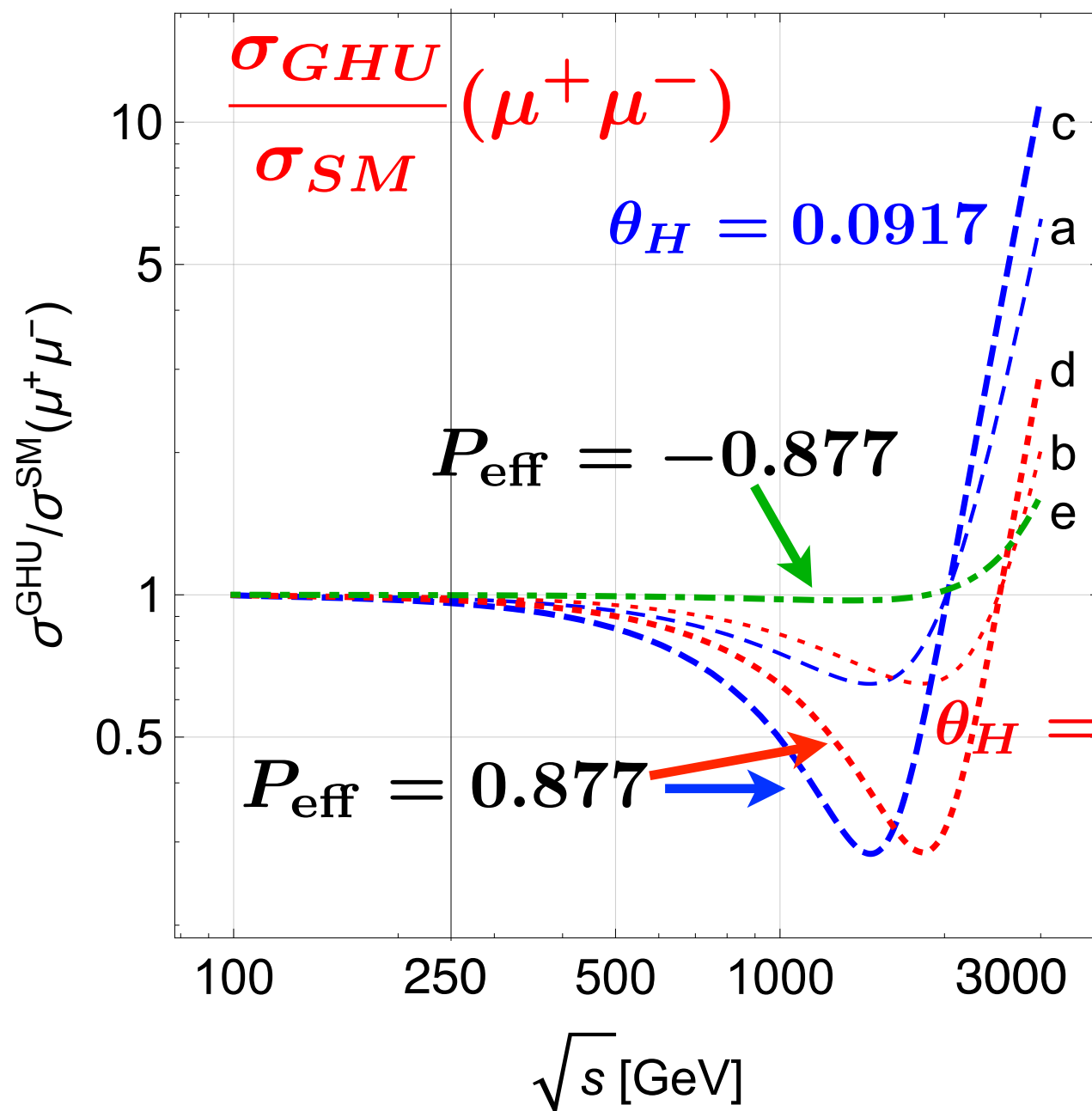
$$P_{e^-} = +1 \text{ (right-handed)}$$

$$\frac{\mathcal{M}_0 \mathcal{M}_{Z'}^*}{|\mathcal{M}_0|^2} \sim -13.6 \frac{s}{m_{Z'}^2}$$

$$\sim -0.017 \text{ at } \sqrt{s} = 250 \text{ GeV}$$

A model

$$e^+e^- \rightarrow \mu^+\mu^-$$



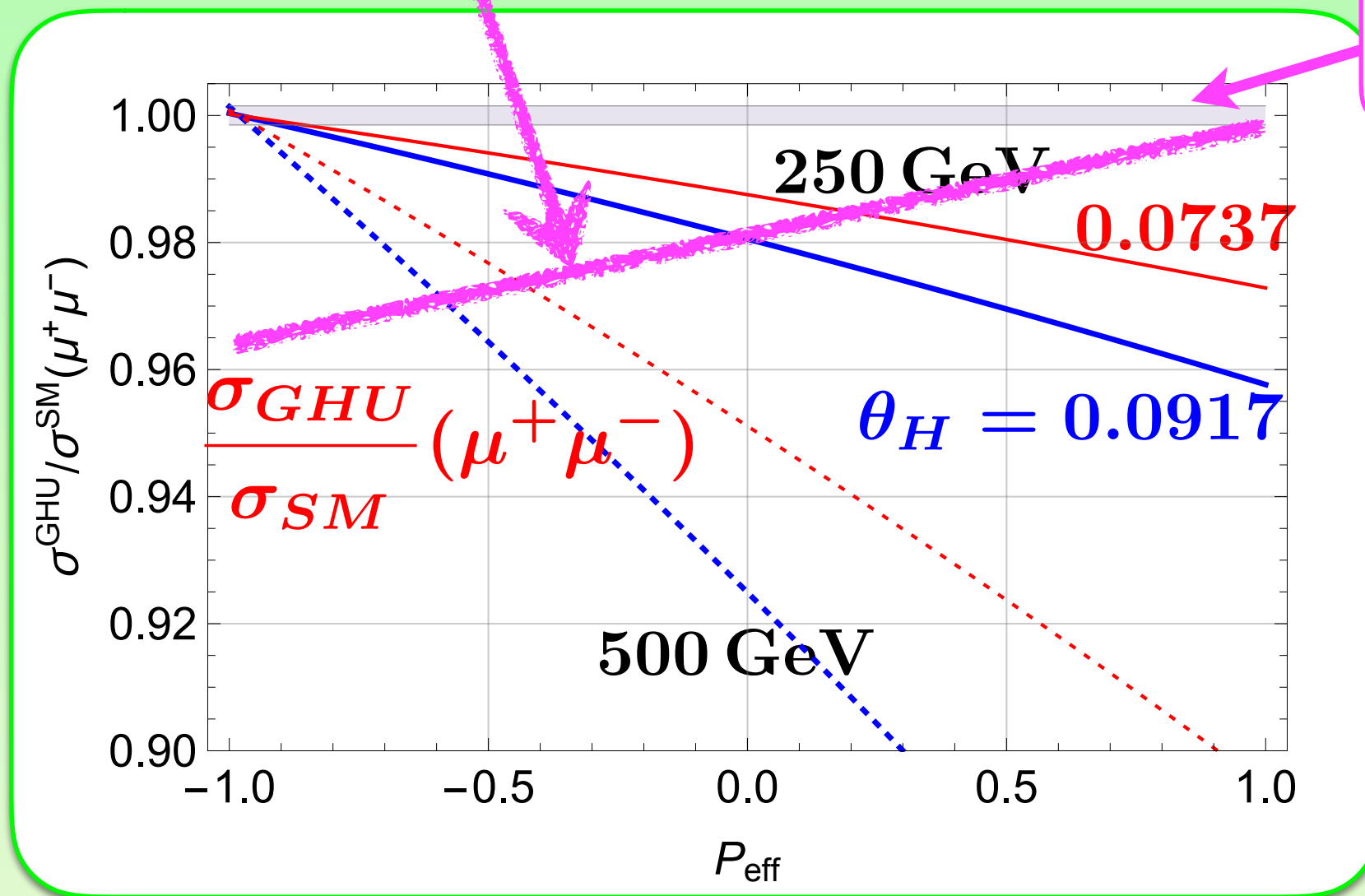
A model

$$P_{\text{eff}} = 0$$

$$P_{\text{eff}} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-}P_{e^+}}$$

Interference
among
 γ, Z, Z'

B model (GUT inspired)



statistical uncertainty
(250 GeV, 250 fb⁻¹)

A model

$$P_{eff} = \frac{P_{e-} - P_{e+}}{1 - P_{e-}P_{e+}}$$

Distinguish

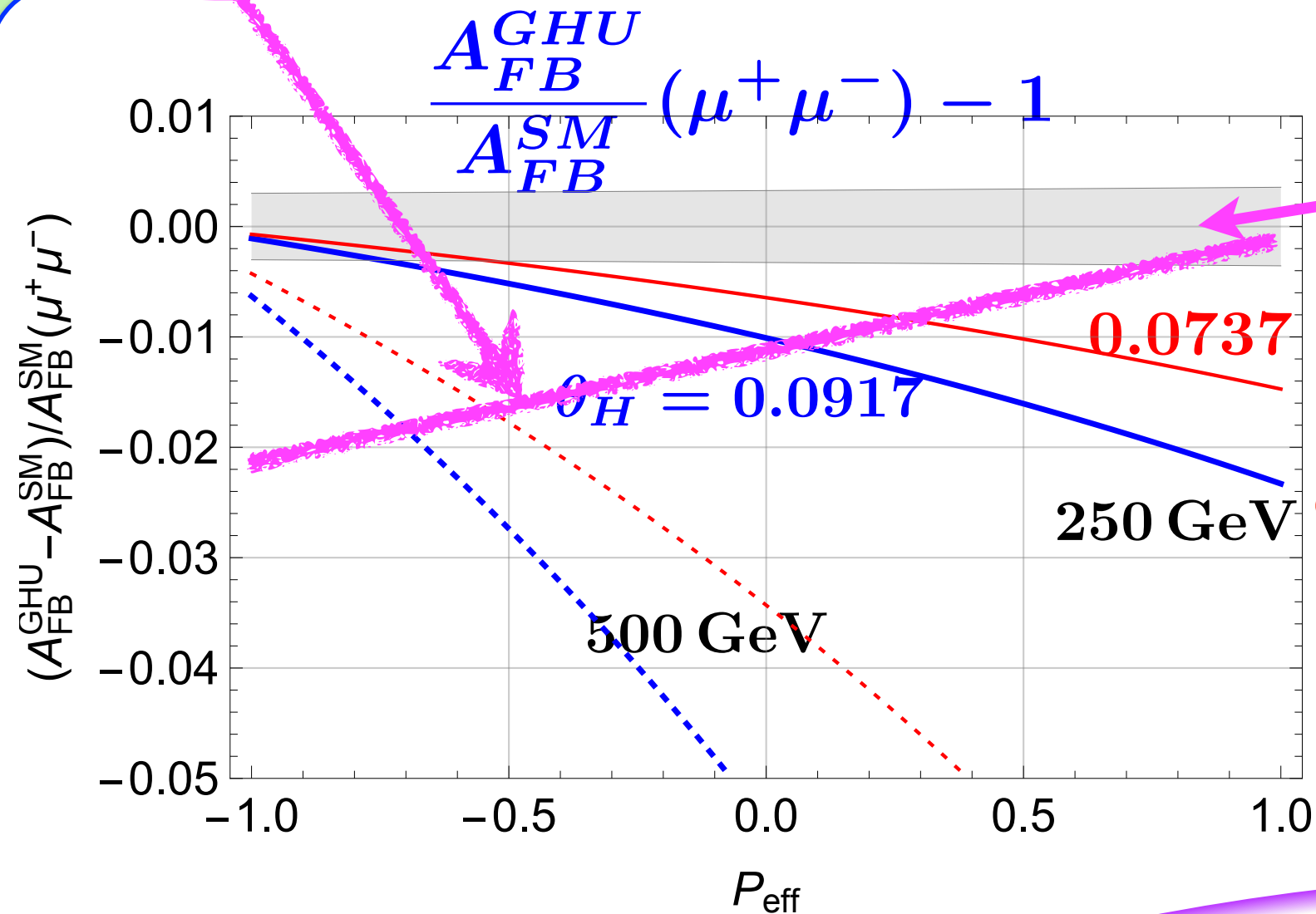
A model

B model

by polarization dependence

$$A_{FB} = \frac{\sigma_{\text{forward}} - \sigma_{\text{backward}}}{\sigma_{\text{forward}} + \sigma_{\text{backward}}}$$

B model



statistical uncertainty
(250 GeV, 250 fb⁻¹)

A model

Polarization dep !

Summary

GUT inspired gauge-Higgs unification

Flavor mixing – CKM matrix
Natural suppression of FCNC

New particles Z'

$$\left| \begin{array}{c} e^- \\ e^+ \end{array} \right\rangle \begin{array}{c} \text{---} Z, \gamma \text{---} \end{array} \begin{array}{c} f \\ \bar{f} \end{array} + \begin{array}{c} e^- \\ e^+ \end{array} \begin{array}{c} \text{---} Z_R^{(1)}, Z^{(1)}, \gamma^{(1)} \text{---} \end{array} \begin{array}{c} f \\ \bar{f} \end{array} \right|^2$$

$7 \sim 8 \text{ TeV}$

in the early stage of **ILC250**