CKM matrix and FCNC suppression in SO(5)xU(1)xSU(3) gauge-Higgs unification

Yutaka Hosotani

Physics OSAKA UNIVERSITY

Funatsu, Hatanaka, YH, Orikasa, Yamatsu

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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**

(Hosotani mechanism)

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Standard Model

Gauge-Higgs Unification

$$\mathcal{L}_{\rm gauge}$$

$$+$$

$$\mathcal{L}_{\rm Higgs} \left\{ \begin{array}{l} \mathcal{L}^{\rm kin}_{\rm Higgs} \\ V^{\rm pot}_{\rm Higgs} \end{array} \right.$$

$$+$$

$$\mathcal{L}_{\rm fermion}$$

$$+$$

$$\mathcal{L}_{\rm Yukawa}$$

$$\left.\begin{array}{l}\mathcal{L}_{\rm gauge} \\ \mathcal{L}^{\rm kin}_{\rm Higgs}\end{array}\right\} \rightarrow \mathcal{L}^{\rm 5d}_{\rm gauge}$$

$$\left.\begin{array}{l}\mathcal{L}_{\rm fermion} \\ \mathcal{L}_{\rm Yukawa}\end{array}\right\} \rightarrow \mathcal{L}^{\rm 5d}_{\rm fermion}$$

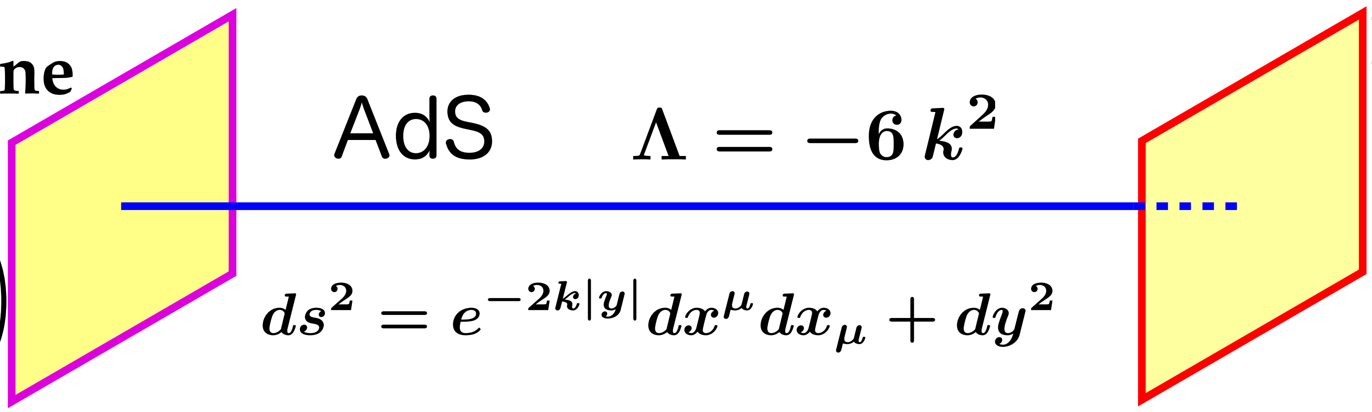
$$\mathcal{L}^{\rm 5d}_{\rm gauge} \Downarrow \quad V_{\rm eff}(\Theta_H) \quad \Uparrow \mathcal{L}^{\rm 5d}_{\rm fermion}$$

gauge principle

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

$$P_0 = \begin{pmatrix} -I_4 & \\ & 1 \end{pmatrix}$$



$$ds^2 = e^{-2k|y|} dx^\mu dx_\mu + dy^2$$

$$P_1 = \begin{pmatrix} -I_4 & \\ & 1 \end{pmatrix}$$

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

brane scalar $\langle \hat{\Phi} \rangle$ $\longrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$

Hosotani mechanism $\theta_H \neq 0$ $\longrightarrow SU(3)_C \times U(1)_{EM}$

$A_\mu \sim$ ($W \;\; Z \;\; \gamma$) $\qquad A_y \sim$ (Higgs)

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

Matter

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

$$\begin{pmatrix} \nu \\ e \\ \nu' \\ e' \end{pmatrix} \quad \begin{pmatrix} u \\ d \\ u' \\ d' \end{pmatrix}$$

	B model GUT inspired	A model previous model
quark	$(3,4)_{\frac{1}{6}}$ $(3,1)^+_{-\frac{1}{3}}$ $(3,1)^-_{-\frac{1}{3}}$ $D^\pm$	$(3,5)_{\frac{2}{3}}$ $(3,5)_{-\frac{1}{3}}$
lepton	$(1,4)_{-\frac{1}{2}}$	$(1,5)_0$ $(1,5)_{-1}$
dark fermion	$(3,4)_{\frac{1}{6}}$ $(1,5)^+_0$ $(1,5)^-_0$	$(1,4)_{\frac{1}{2}}$
brane fermion	ν_χ $(1,1)_0$	$(3,[2,1])_{\frac{7}{6},\frac{1}{6},-\frac{5}{6}}$ $(1,[2,1])_{\frac{1}{2},-\frac{1}{2},-\frac{3}{2}}$
brane scalar	$\hat{\Phi}$ $(1,4)_{\frac{1}{2}}$	$(1,[1,2])_{\frac{1}{2}}$
symmetry of brane interactions	$SU(3)_C \times SO(5) \times U(1)_X$	$SU(3)_C \times SO(4) \times U(1)_X$

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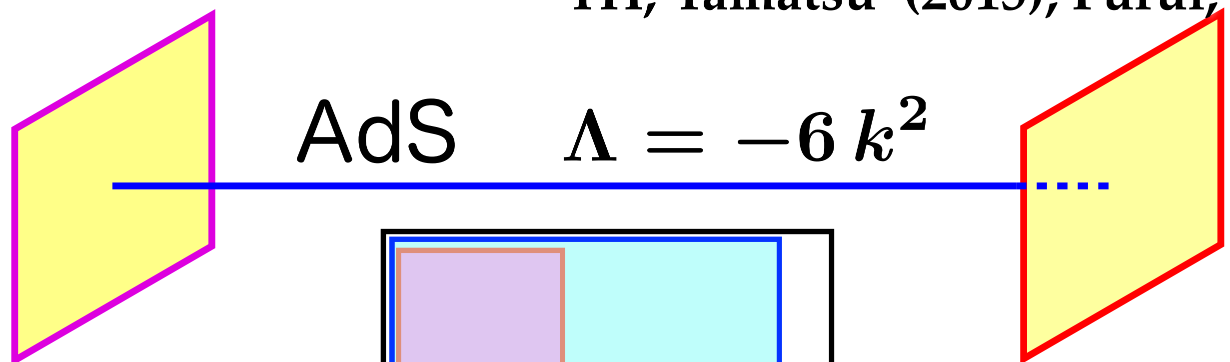
SO(11) gauge-Higgs grand unification

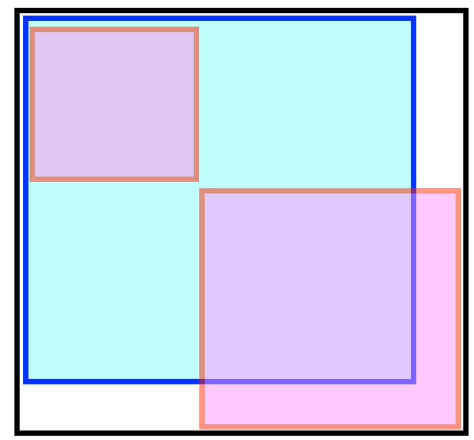
YH, Yamatsu (2015), Furui, YH, Yamatsu (2016)

UV brane



IR brane

$$P_0 = \begin{pmatrix} I_{10} & \\ & -1 \end{pmatrix}$$



$$P_1 = \begin{pmatrix} I_4 & \\ & -I_7 \end{pmatrix}$$

$$SO(4) \times SO(6) \simeq SU(2)_L \times SU(2)_R \times SU(4)$$

$$\langle \hat{\Phi}_{32} \rangle \longrightarrow \quad SU(2)_L \times U(1)_Y \times SU(3)_C$$

$$\Psi_{32} \quad \begin{pmatrix} u & \nu \\ d & e \\ u' & \nu' \\ d' & e' \end{pmatrix} \begin{pmatrix} \hat{u} & \hat{\nu} \\ \hat{d} & \hat{e} \\ \hat{u}' & \hat{\nu}' \\ \hat{d}' & \hat{e}' \end{pmatrix} \qquad \Psi_{11} \quad \begin{pmatrix} N & \hat{E} \\ E & \hat{N} \\ D^+ & D^- \\ & S \end{pmatrix}$$

Up-type quarks are only in "spinor 32".

Quark sector in B model

field	$\mathcal{G}$	G_{22}	left-handed	right-handed	name
$\Psi^{\alpha}_{(\mathbf{3},\mathbf{4})}$	$(\mathbf{3},\mathbf{4})_{\frac{1}{6}}$	$[\mathbf{2},\mathbf{1}]$	$(+,+)$	$(-,-)$	$u \;\; c \;\; t$ $d \;\; s \;\; b$
		$[\mathbf{1},\mathbf{2}]$	$(-,-)$	$(+,+)$	$u' \;\; c' \;\; t'$ $d' \;\; s' \;\; b'$
$\Psi^{\pm\alpha}_{(\mathbf{3},\mathbf{1})}$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$[\mathbf{1},\mathbf{1}]$	$(\pm,\pm)$	$(\mp,\mp)$	$D^{\pm}_{d} \; D^{\pm}_{s} \; D^{\pm}_{b}$
$\hat{\Phi}_{(\mathbf{1},\mathbf{4})}$	$(\mathbf{1},\mathbf{4})_{\frac{1}{2}}$		brane scalar		$\hat{\Phi}$

Action in the bulk

$$\sum_{\alpha=1}^{3}\left\{\overline{\Psi}^{\alpha}_{(3,4)}\mathcal{D}(c_\alpha)\Psi^{\alpha}_{(3,4)}+\left(\overline{\Psi}^{+\alpha}_{(3,1)},\overline{\Psi}^{-\alpha}_{(3,1)}\right)\begin{pmatrix}\mathcal{D}(c_{D_\alpha}) & -m_{D_\alpha}\\ -m_{D_\alpha} & \mathcal{D}(c_{D_\alpha})\end{pmatrix}\begin{pmatrix}\Psi^{+\alpha}_{(3,1)}\\ \Psi^{-\alpha}_{(3,1)}\end{pmatrix}\right\}$$

$$\mathcal{D}(c)=\gamma^A e_A{}^M\left(D_M+\frac{1}{8}\omega_{MBC}[\gamma^B,\gamma^C]\right)-c\sigma'(y)\ ,$$

$$D_M=\partial_M-ig_S A^{SU(3)}_M-ig_A A^{SO(5)}_M-ig_B Q_X A^{U(1)}_M$$

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Brane interactions

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

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

D

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

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

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

mass splitting $m_d \neq m_u$

flavor mixing $\longrightarrow$ **CKM**

FCNC ?

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Scale

$$m_W \simeq \sqrt{\frac{k}{L}}\, z_L^{-1} \sin\theta_H \simeq \frac{\sin\theta_H}{\pi\sqrt{kL}}\, m_{\rm KK}$$

$$m_t \sim \pi^{-1}\sqrt{1-4c_t^2}\, \sin\tfrac{1}{2}\theta_H\, m_{\rm KK}$$

$$m_{u,c} \sim \pi^{-1}\sqrt{4c_{u,c}^2-1}\, z_L^{-|c_{u,c}|+0.5} \sin\tfrac{1}{2}\theta_H\, m_{\rm KK}$$

$$m_{\rm KK} = \pi k z_L^{-1}\ , \ \ z_L = e^{kL}$$

$z_L = 10^{10}$

θ_H	$m_{\rm KK}$ (TeV)	k (GeV)	c_u	c_c	c_t
0.10	12.08	3.84×10^{13}	-0.9169	-0.7545	-0.2274
0.15	8.07	2.57×10^{13}	-0.9170	-0.7546	-0.2294

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CKM mixing

mass: up-type quarks

gauge interactions $(\theta_H \neq 0)$ only

$\rightarrow$ no mixing

mass: down-type quarks

gauge int. $(\theta_H \neq 0)$ + brane int.

$\rightarrow$ mass eigenstates $\neq$ gauge eigenstates

$\rightarrow$ CKM mixing

Effective mass matrix

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

$$\| $$

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

Mass eigenstates

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

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

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CKM

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

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

$$\begin{pmatrix} M_{\mathrm{up}} & 0 \\ \mu & m_D \end{pmatrix} \begin{pmatrix} \tilde{\Omega}_q^\dagger & \tilde{\Omega}_a^\dagger \\ \tilde{\Omega}_b^\dagger & \tilde{\Omega}_D^\dagger \end{pmatrix} = \begin{pmatrix} \Omega_q & \Omega_b \\ \Omega_a & \Omega_D \end{pmatrix} \begin{pmatrix} M_{\mathrm{down}} & 0 \\ 0 & M_D \end{pmatrix} \Rightarrow$$

$$\Omega_b = -\Omega_q M_{\mathrm{down}} \tilde{\Omega}_b \tilde{\Omega}_D^{-1} M_D^{-1} \rightarrow ||\Omega_b|| = O\left(\frac{m_{d,s,b}}{m_D}\right) ||\tilde{\Omega}_b|| < 10^{-3}$$

$$M_{\mathrm{up}} \tilde{\Omega}_q^\dagger = \Omega_q M_{\mathrm{down}} \rightarrow \frac{m_{dk}}{m_{uj}} |V_{jk}^{\mathrm{CKM}}| \sim |(\tilde{\Omega}_q^\dagger)_{jk}| < 1$$

$\rightarrow$ $m_u > m_d$ — **need to be solved.**

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FCNC

$$\mathcal{L}_Z^{\text{down}} \sim -\frac{g_w}{\cos\theta_W} Z_\mu \Big\{ -\frac{1}{2}\,\bar{\vec{\hat{d}}}_L \Gamma^\mu \underbrace{\Omega_q^\dagger \Omega_q}_{= I - \Omega_a^\dagger \Omega_a} \vec{\hat{d}}_L + \frac{1}{3}\sin^2\theta_W \Big(\bar{\vec{\hat{d}}}_L \Gamma^\mu \vec{\hat{d}}_L + \bar{\vec{\hat{d}}}_R \Gamma^\mu \vec{\hat{d}}_R \Big) \Big\}$$

$$\Omega_a^\dagger \Omega_a = \Omega_q^\dagger \Omega_b \Omega_b^\dagger (\Omega_q^\dagger)^{-1} = O\left(\frac{m_{d,s,b}^2}{m_D^2}\right) \lesssim 10^{-6}$$

FCNC : suppressed naturally

Rigorous evaluation of W, Z couplings

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

θ_H	$m_{\rm KK}$ (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

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

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

$$\frac{m_{D_\alpha}}{k} = 1 \qquad\qquad (c_{D_d}, c_{D_s}, c_{D_b}) \leftarrow (m_d, m_s, m_b)$$

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$$\int_1^{z_L} dz \sqrt{-\det G} \sum_{\alpha=1}^{3} \left\{ \overline{\Psi}^{\alpha}_{(3,4)} \mathcal{D}(c_\alpha) \Psi^{\alpha}_{(3,4)} + \cdots \right\}$$

W

$\theta_H = 0.10$

$$g_L^W = 0.9978\, g_w \; , \quad \hat{V}_{\rm CKM} = \begin{pmatrix} 0.9744 & 0.2245 & 0.0031 \\ -0.2245 & 0.9743 & 0.0134 \\ 9\times 10^{-6} & -0.0138 & 1.0002 \end{pmatrix}$$

$g_L^W / g_{L\,\rm lepton}^W = 1.00013$

CKM

$\theta_H = 0.15$

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

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

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Z

$\theta_H = 0.15$

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

$$\hat{g}^Z_{L\,d} = g_w \begin{pmatrix} -0.4208 & -7\times 10^{-7} & -1\times 10^{-8} \\ -7\times 10^{-7} & -0.4208 & -4\times 10^{-7} \\ -1\times 10^{-8} & -4\times 10^{-7} & -0.4207 \end{pmatrix}$$

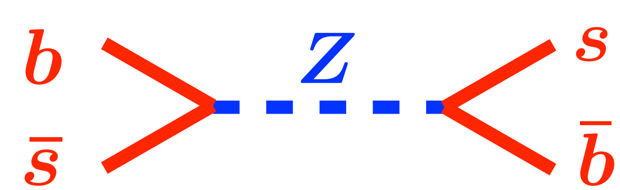
$$\hat{g}^Z_{R\,d} = g_w \begin{pmatrix} 0.0767 & -1\times 10^{-6} & -1\times 10^{-6} \\ -1\times 10^{-6} & 0.0767 & -7\times 10^{-6} \\ -1\times 10^{-6} & -7\times 10^{-6} & 0.0767 \end{pmatrix}$$

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

FCNC : suppressed

very close to SM at low energies !

$B_s^0 \bar{B}_s^0$ mixing



$$\Delta m_M \sim \frac{m_M f_M^2 (\hat{g}_d^Z|_M)^2}{3 m_Z^2}$$

$$\begin{pmatrix} \Delta m_K \\ \Delta m_{B_d} \\ \Delta m_{B_s} \end{pmatrix} \sim \begin{pmatrix} 2 \times 10^{-19} \\ 3 \times 10^{-18} \\ 3 \times 10^{-16} \end{pmatrix} \text{GeV} \quad \ll \quad \begin{pmatrix} 3.48 \times 10^{-15} \\ 3.36 \times 10^{-13} \\ 1.17 \times 10^{-11} \end{pmatrix} \text{GeV}$$

(exp)

$$\begin{array}{cccccc} & & \theta_H = 0.10 & & \theta_H = 0.15 & & SM \\ \dfrac{1}{g^W_{L\,\text{lepton}}} \begin{pmatrix} g^Z_{Luu} \\ g^Z_{Ruu} \\ g^Z_{Ldd} \\ g^Z_{Rdd} \end{pmatrix} & = & \begin{pmatrix} 0.34588 \\ -0.15413 \\ -0.42295 \\ 0.07707 \end{pmatrix} & , & \begin{pmatrix} 0.34591 \\ -0.15411 \\ -0.42298 \\ 0.07706 \end{pmatrix} & \Leftrightarrow & \begin{pmatrix} 0.3458 \\ -0.1541 \\ -0.4229 \\ 0.0771 \end{pmatrix} \end{array}$$

CKM matrix in GHU

FCNC naturally suppressed

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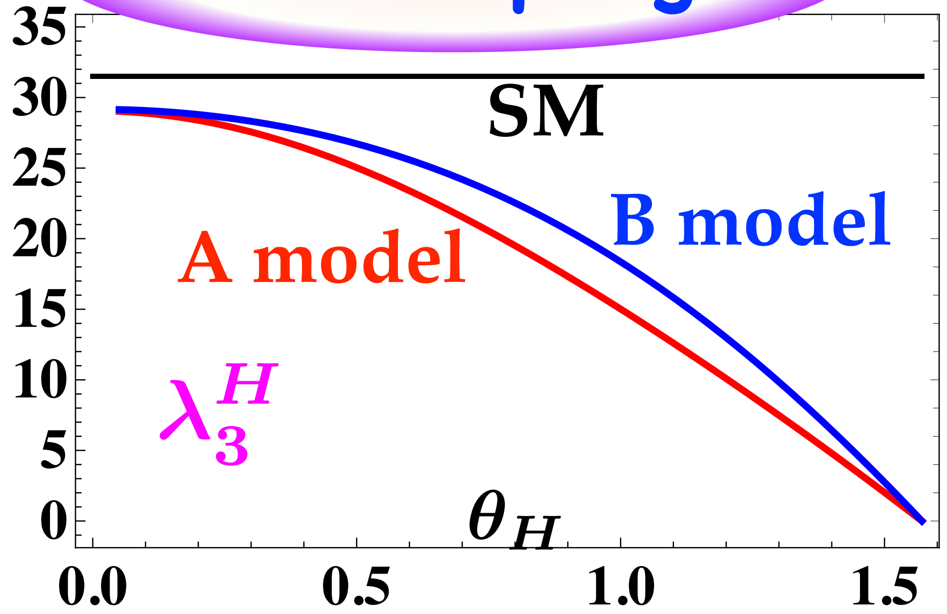
Higgs couplings

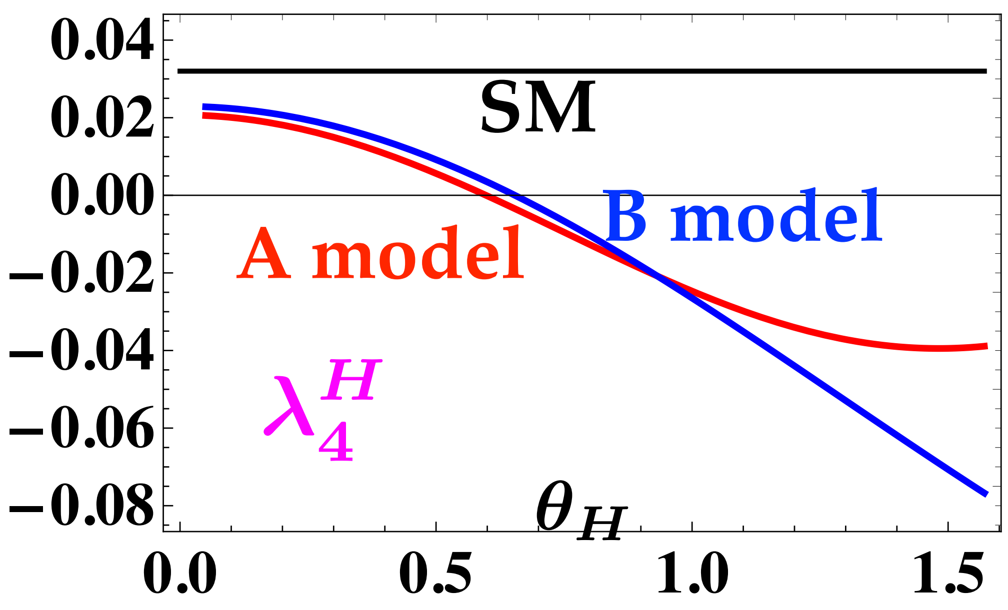
WWH, ZZH $\sim (\mathrm{SM}) \times \cos\theta_H$

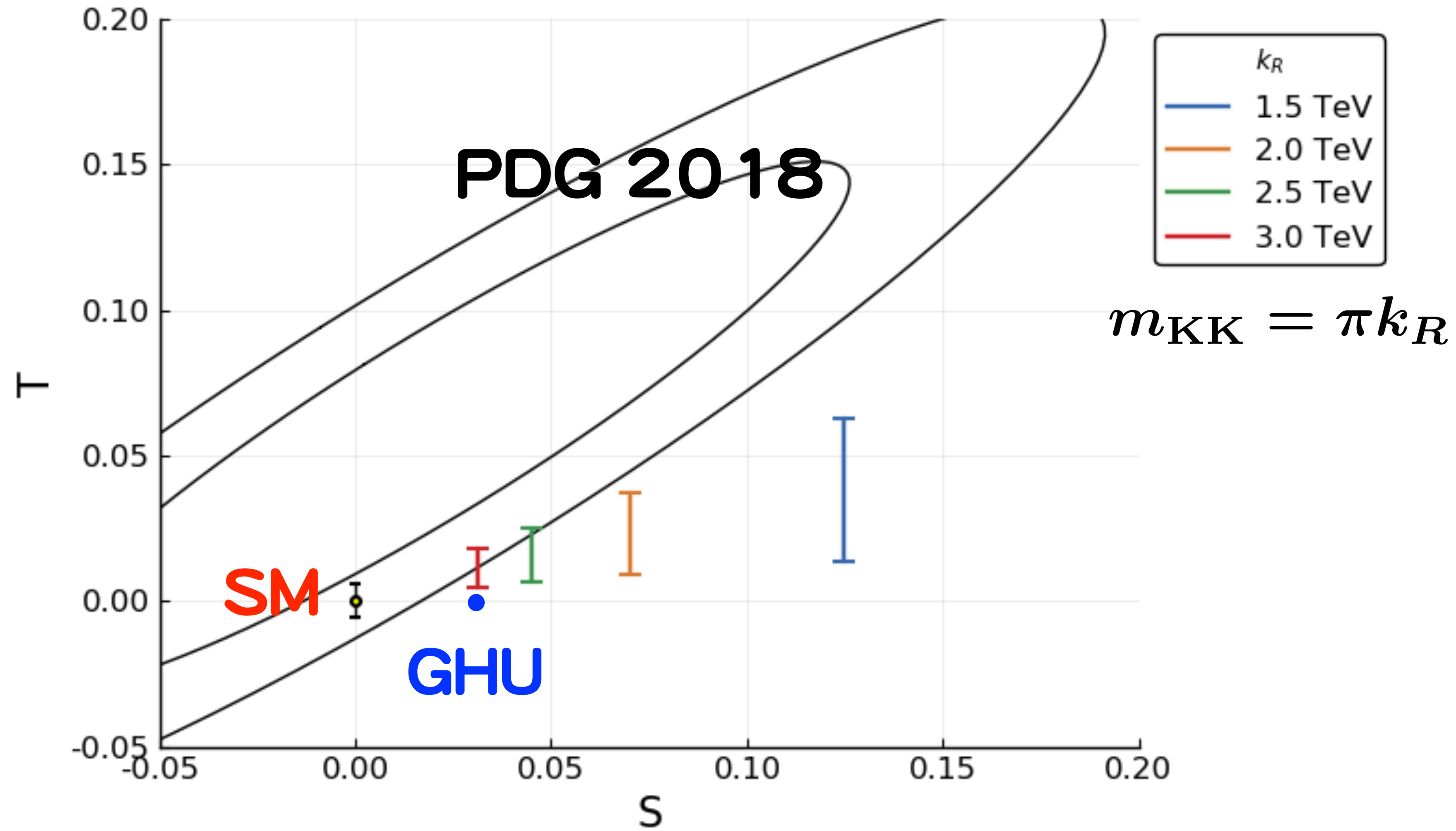
Yukawa couplings $\sim \begin{cases} (\mathrm{SM}) \times \cos\theta_H & \text{A model} \\ (\mathrm{SM}) \times \cos^2 \frac{1}{2}\theta_H & \text{B model} \end{cases}$

Deviation from SM is small for $\theta_H \sim 0.1$

self-couplings







Yoon-Peskin, PRD 100, 015001 (2019)

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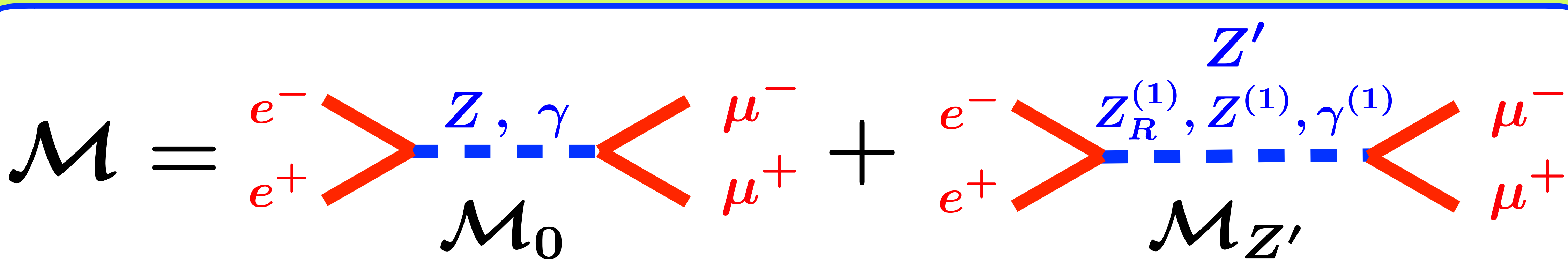
Z′ couplings in RS

Z' : $Z^{(1)}$ $\gamma^{(1)}$ $Z_R^{(1)}$ $m \sim 0.8\, m_{\rm KK}$ localized near IR

	c_ℓ , c_q	left-handed ℓ_L , q_L	right-handed 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



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

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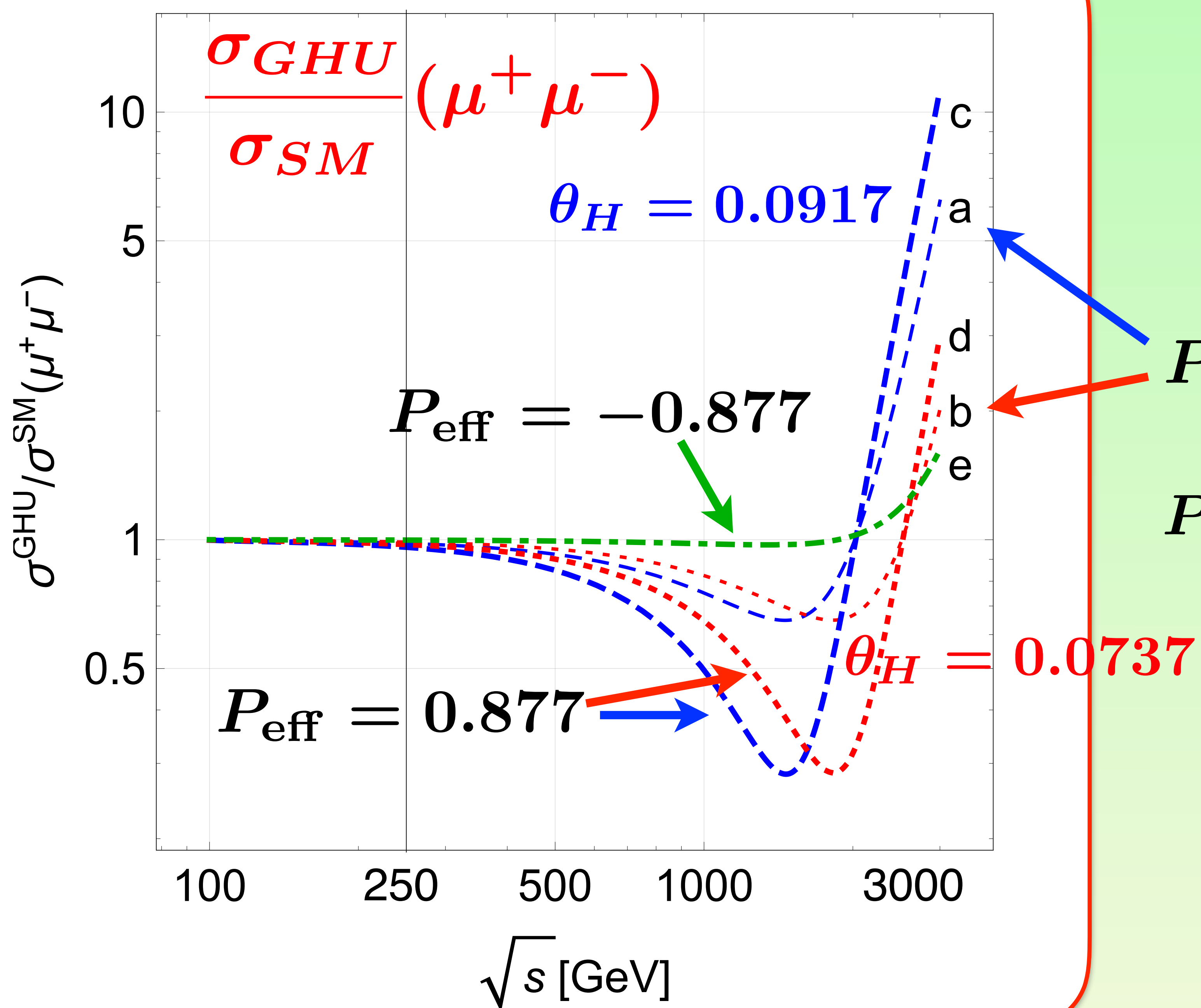
$$e^+e^- \to \mu^+\mu^-$$



A model

$P_{\rm eff} = 0$

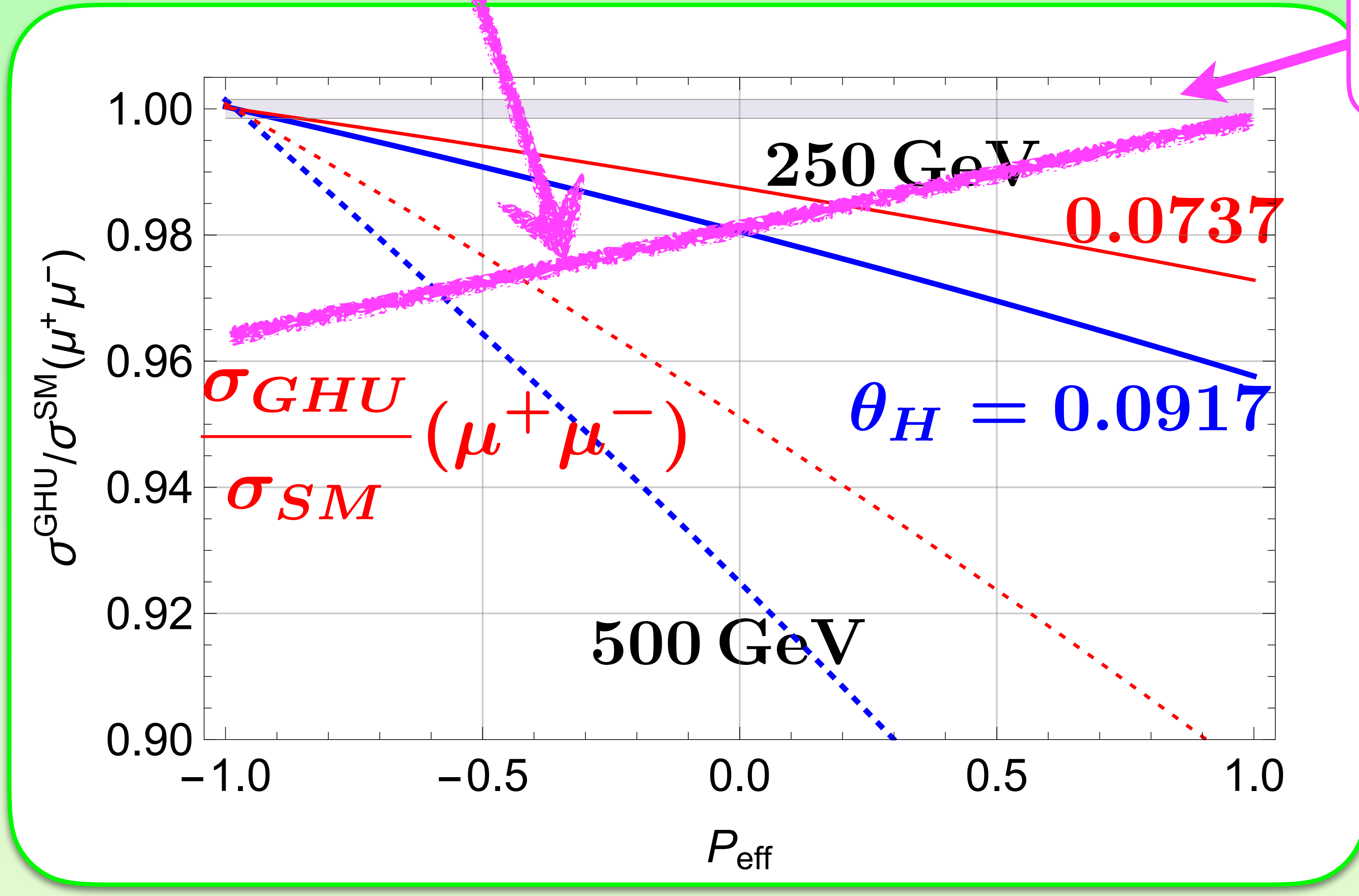
$$P_{\rm eff} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-}P_{e^+}}$$

Funatsu, Hatanaka, YH, Orikasa 1705.05282

Funatsu, 1905.10007

B model (GUT inspired)

statistical uncertainty $(250\,\mathrm{GeV}, 250\,\mathrm{fb}^{-1})$



A model

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

Distinguish A model / B model **by polarization dependence**

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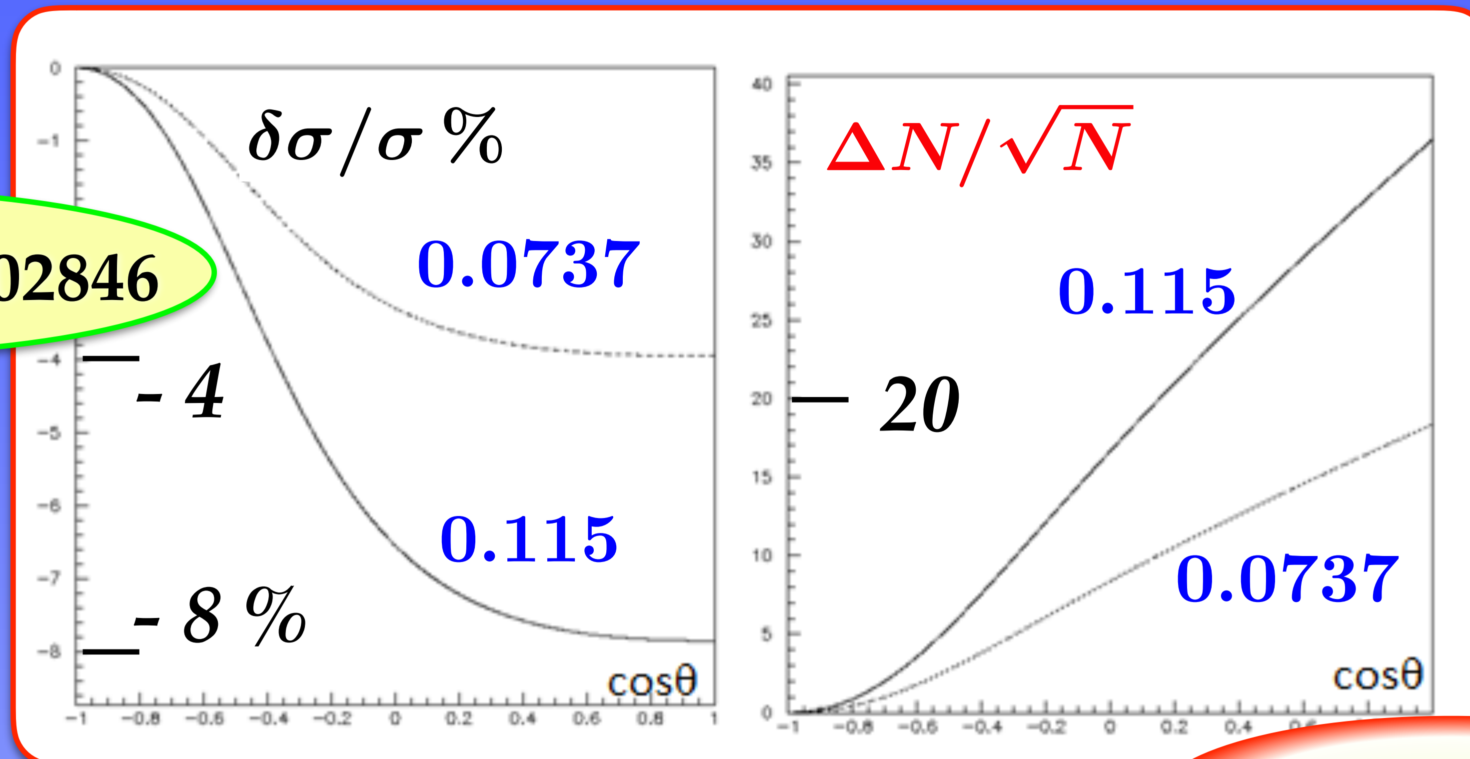
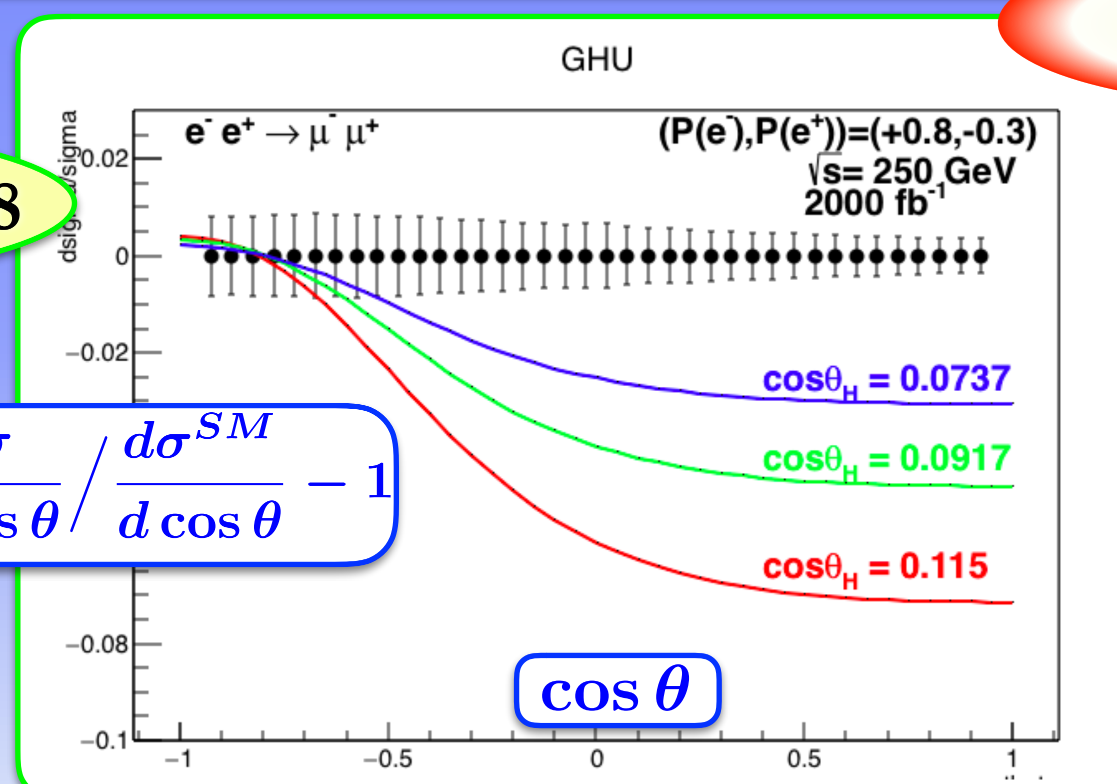
Angular distribution $e^+e^- \to \mu^+\mu^-$

F. Richard, 1804.02846



T. Suehara, ALCW2018



$$\Delta = \frac{d\sigma}{d\cos\theta} \Big/ \frac{d\sigma^{SM}}{d\cos\theta} - 1$$

A model

ILC 250

$2000\ \mathrm{fb}^{-1}$

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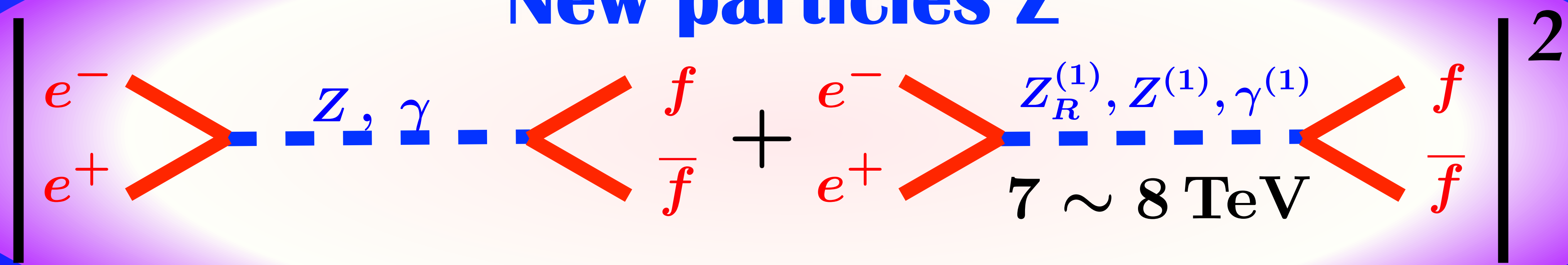
Summary

GUT inspired gauge-Higgs unification

Flavor mixing — CKM matrix

Natural suppression of FCNC

New particles Z'



in the early stage of ILC250

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