

# ILC phenomenology of gauge-Higgs unification

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# Gauge-Higgs unification

125 GeV Higgs boson

AB phase in the 5th dim

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

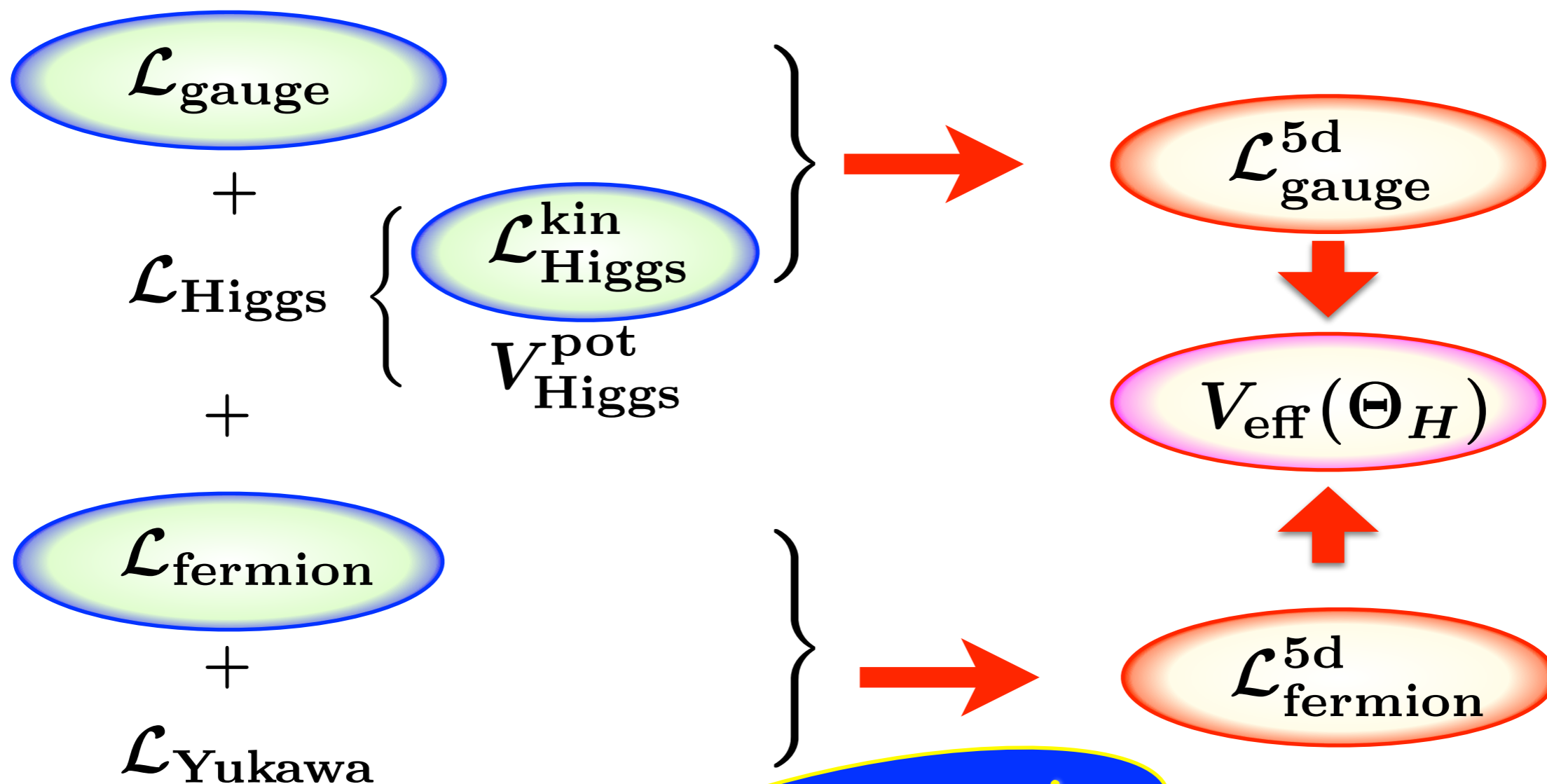
$$\Theta_H(x) = \theta_H + \frac{H(x)}{f_H}$$

$$\theta_H \neq 0$$

EW sym. breaking

# Standard Model

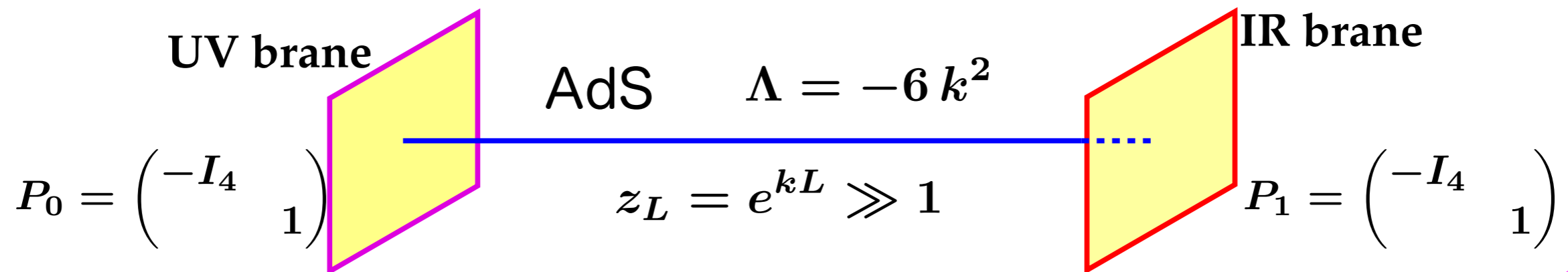
# Gauge-Higgs Unification



# $SU(3) \times SO(5) \times U(1)$ gauge-Higgs in RS warped space

Agashe, Contino, Pomarol 2005

YH, Sakamura 2006



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

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

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

Hosotani mechanism  $\theta_H \neq 0$

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

$$m_{\text{KK}} \sim \frac{\pi \sqrt{kL}}{\sin \theta_H} m_W \sim 7 \text{ to } 12 \text{ TeV}$$

$$v_{\text{SM}} \sim f_H \sin \theta_H \quad \Theta_H(x) = \theta_H + \frac{H(x)}{f_H}$$

# Matter

$[SU(3), SO(5)]_{U(1)}$

	A model	B model GUT inspired
quark	$(3, 5)_{\frac{2}{3}} (3, 5)_{-\frac{1}{3}}$ vector	$(3, 4)_{\frac{1}{6}} (3, 1)_{-\frac{1}{3}}^+ (3, 1)_{-\frac{1}{3}}^-$ spinor + singlet
lepton	$(1, 5)_0 (1, 5)_{-1}$	$(1, 4)_{-\frac{1}{2}}$
dark fermion	$(1, 4)_{\frac{1}{2}}$	$(3, 4)_{\frac{1}{6}} (1, 5)_0^+ (1, 5)_0^-$
brane scalar	$(1, [1, 2])_{\frac{1}{2}}$	$(1, 4)_{\frac{1}{2}}$

A model: Funatsu, Hatanaka, YH, Orikasa, Shimotani 2013

B model: Funatsu, Hatanaka, YH, Orikasa, Yamatsu 1902.01603

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

$D^\pm$

# gauge couplings

**B model**  $\theta_H = 0.15$

**W**

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

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

**CKM**

**Z**

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

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

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

**FCNC : suppressed**

**almost SM at low energies !**

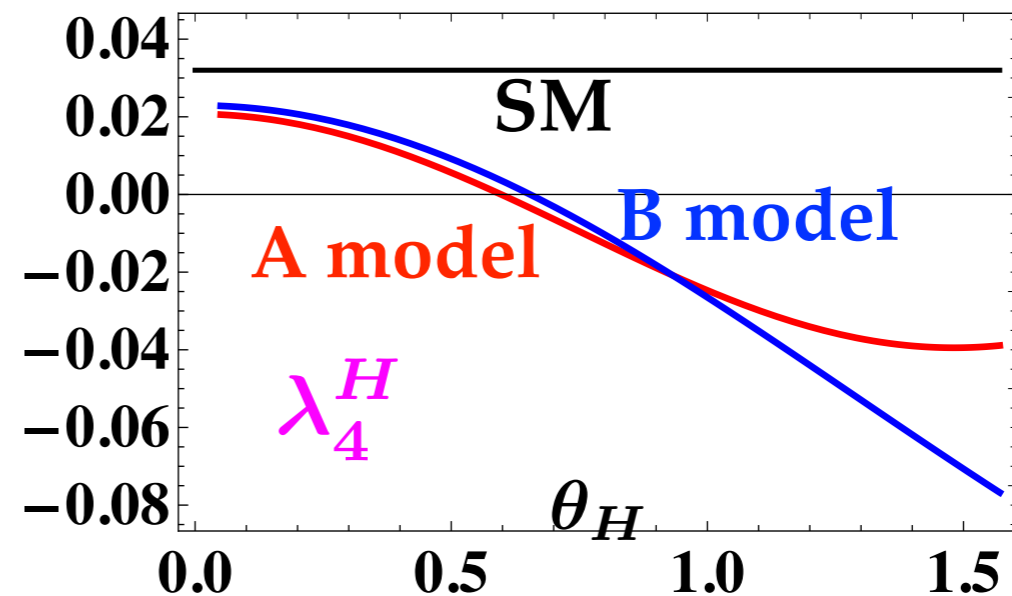
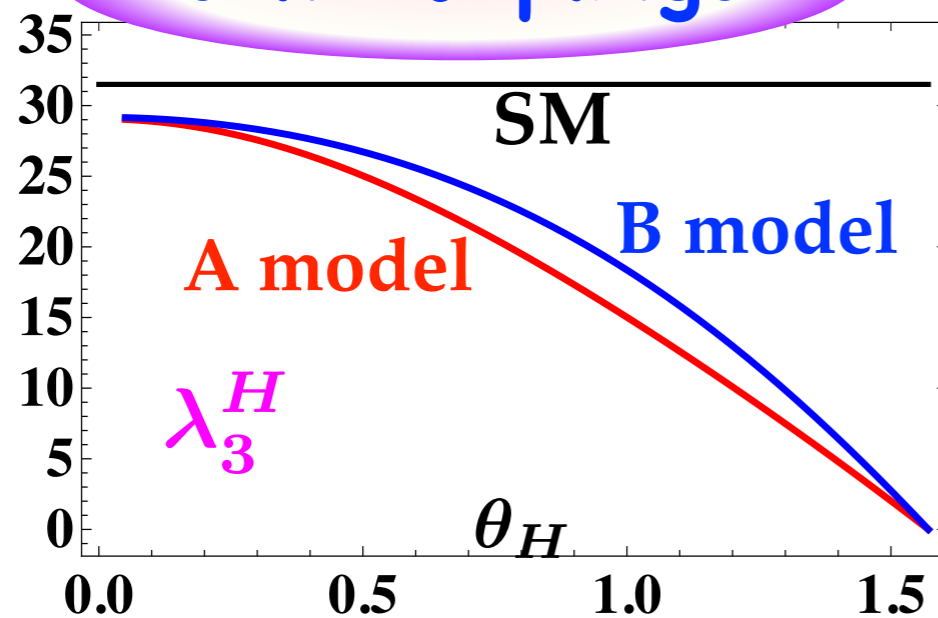
# Higgs couplings

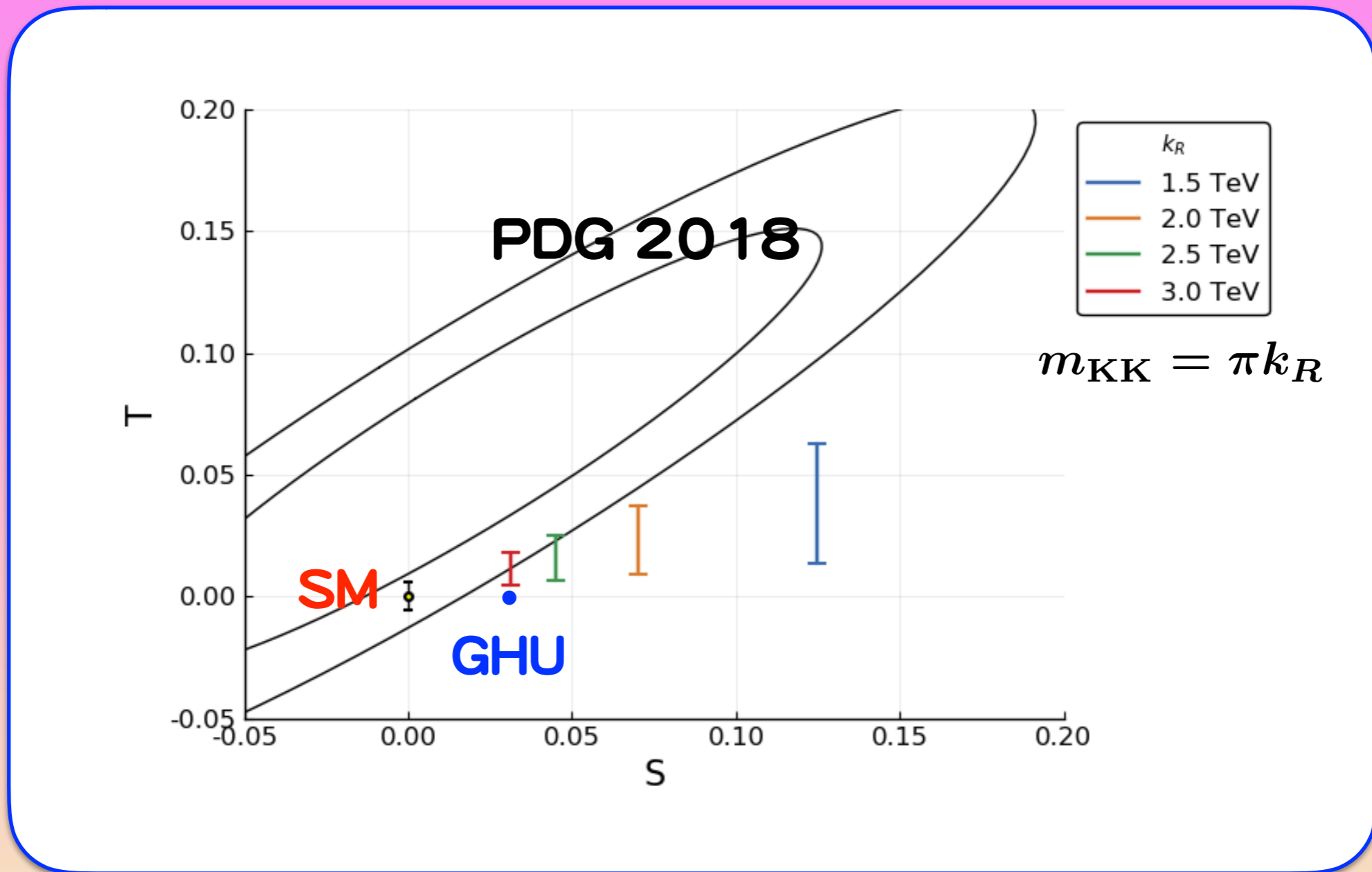
**WWH, ZZH**  $\sim (\text{SM}) \times \cos \theta_H$

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

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

## self-couplings





Yoon-Peskin, PRD 100, 015001 (2019)



# Z' couplings in RS

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

	$c_\ell, c_q$	left-handed $\ell_L, q_L$	right-handed $\ell_R, q_R$
<b>A model</b>	$> 0$	near UV	<b>near IR</b> large Z' coupling
<b>B model</b> GUT inspired	$< 0$	<b>near IR</b> large Z' coupling	near UV

$$\mathcal{M} = \begin{array}{c} e^- \\ e^+ \end{array} \left\langle \begin{array}{c} Z, \gamma \\ \mathcal{M}_0 \end{array} \right\rangle \begin{array}{c} \mu^- \\ \mu^+ \end{array} + \begin{array}{c} e^- \\ e^+ \end{array} \left\langle \begin{array}{c} Z' \\ Z_R^{(1)}, Z^{(1)}, \gamma^{(1)} \\ \mathcal{M}_{Z'} \end{array} \right\rangle \begin{array}{c} \mu^- \\ \mu^+ \end{array}$$

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

# Z' couplings : B model

$$g_{L/R}^{Z'}/g_w$$

$$\theta_H = 0.10$$

	$Z^{(1)}$		$Z_R^{(1)}$		$\gamma^{(1)}$	
	Left	Right	Left	Right	Left	Right
$\nu_e$	2.7076	$2 \times 10^{-32}$	-0.8579	$-7 \times 10^{-29}$	0	0
$\nu_\mu$	2.5687	$2 \times 10^{-31}$	-0.8163	$-5 \times 10^{-29}$	0	0
$\nu_\tau$	2.4739	$2 \times 10^{-31}$	-0.7879	$-4 \times 10^{-29}$	0	0
$e$	-1.4556	-0.0553	-0.8680	$7 \times 10^{-12}$	-2.2792	0.1014
$\mu$	-1.3809	-0.0553	-0.8260	$2 \times 10^{-7}$	-2.1623	0.1014
$\tau$	-1.3299	-0.0553	-0.7972	$5 \times 10^{-5}$	-2.0824	0.1013
$u$	1.8094	0.0369	0.2833	$-1 \times 10^{-8}$	1.4680	-0.0676
$c$	1.7369	0.0369	0.2726	$-1 \times 10^{-5}$	1.4091	-0.0676
$t$	1.3674	-0.3089	0.2177	-0.6955	1.1096	0.5685
$d$	-2.2081	0.1710	0.2731	-0.2515	-0.7325	-0.3111
$s$	-2.1283	0.0915	0.2637	-0.1457	-0.7060	-0.1663
$b$	-1.6724	0.1743	0.2109	-0.2552	-0.5547	-0.3172

left-handed: large coupling

**A model**

right-handed: large coupling

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

$$\mathcal{M} = \mathcal{M}_0 + \mathcal{M}_{Z'}$$

$m_Z^2 \ll s \ll m_{Z'}^2$   
 $(250 \text{ GeV})^2 \sim (1 \text{ TeV})^2$

**interference term**

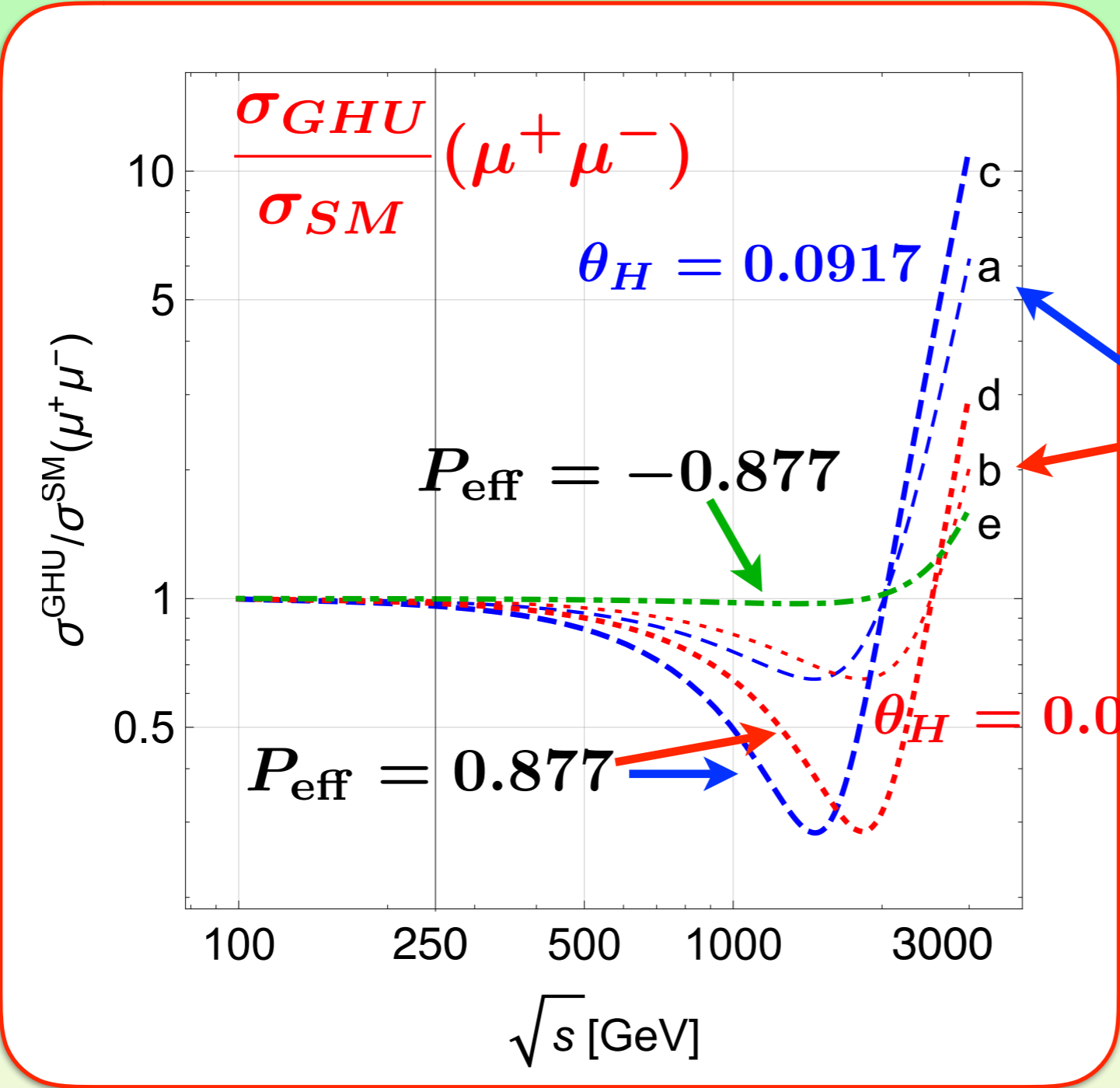
$$\sqrt{s} = 250 \text{ GeV}$$

$$\frac{\mathcal{M}_0 \mathcal{M}_{Z'}^*}{|\mathcal{M}_0|^2} \sim -13.6 \frac{s}{m_{Z'}^2} \sim -0.017 \quad (\theta_H = 0.092, \underline{P_{e^-} = +1})$$

**A model**

$$\sim -20.6 \frac{s}{m_{Z'}^2} \sim -0.014 \quad (\theta_H = 0.1, \underline{P_{e^-} = -1})$$

**B model**

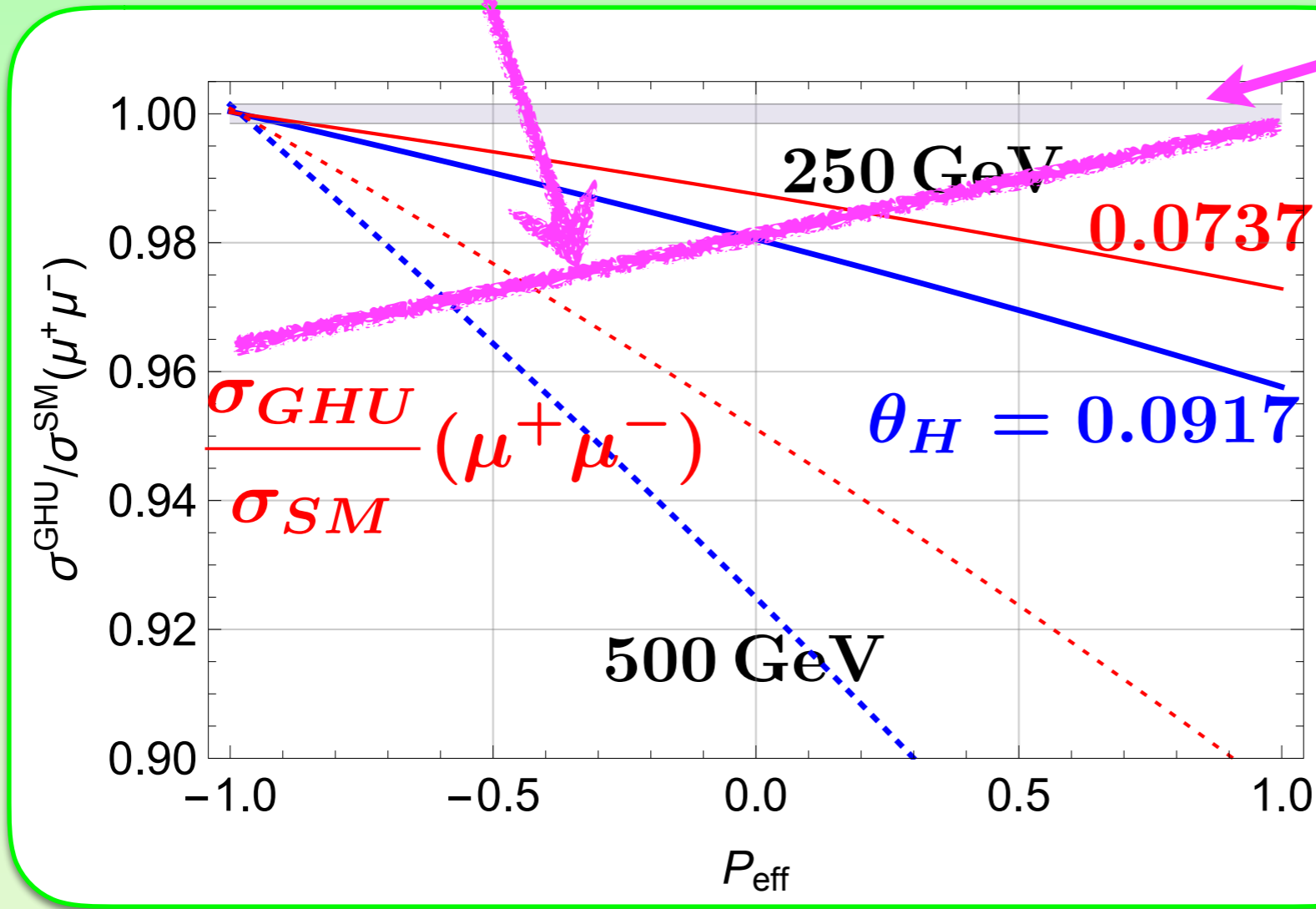


**A model**

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

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

**B model** (GUT inspired)



statistical uncertainty  
(250 GeV, 250 fb<sup>-1</sup>)

**A model**

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

**Distinguish**

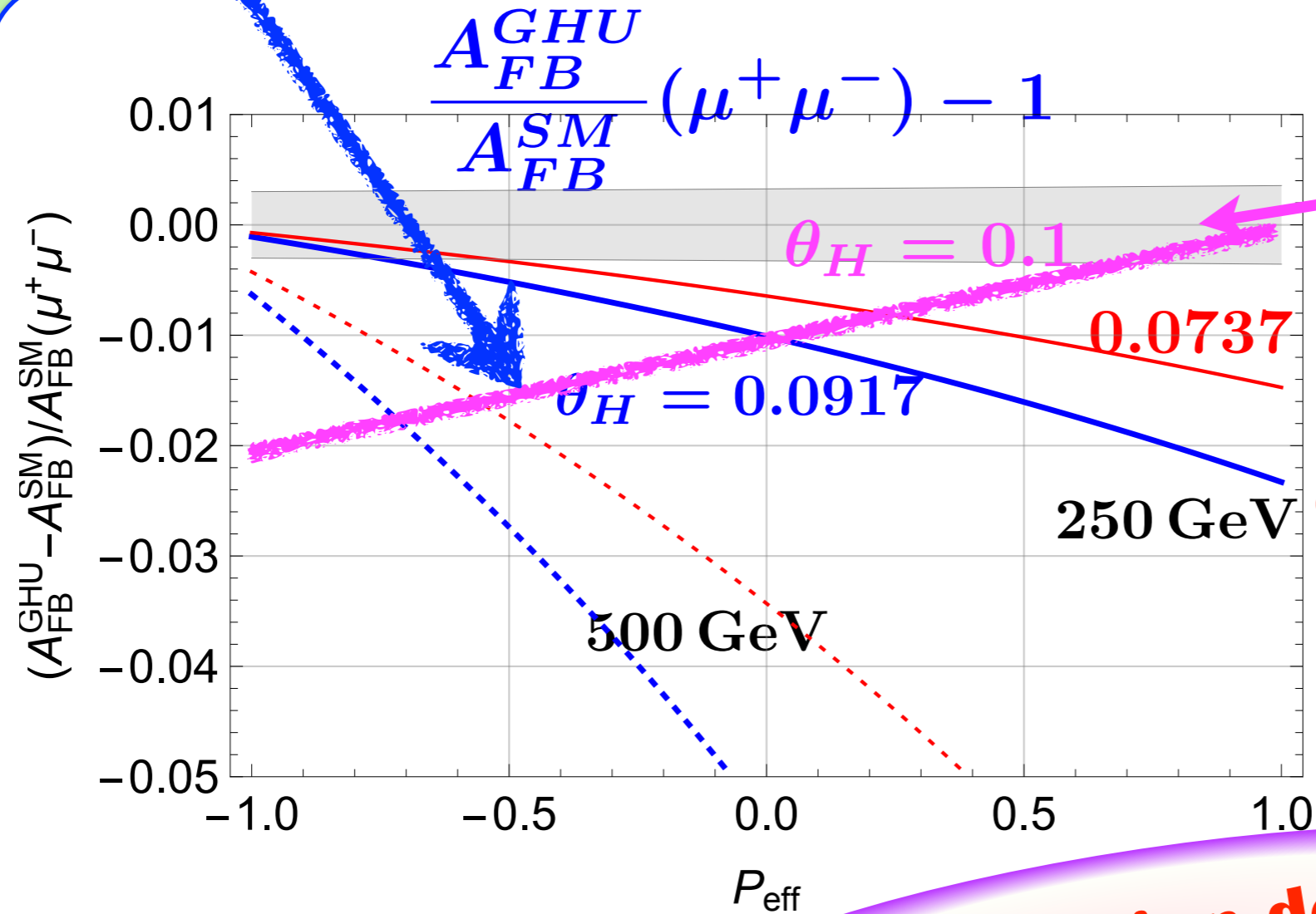
**A model**

**B model**

**by polarization dependence**

# Forward-backward asymmetry

B model



statistical uncertainty  
(250 GeV, 250 fb<sup>-1</sup>)

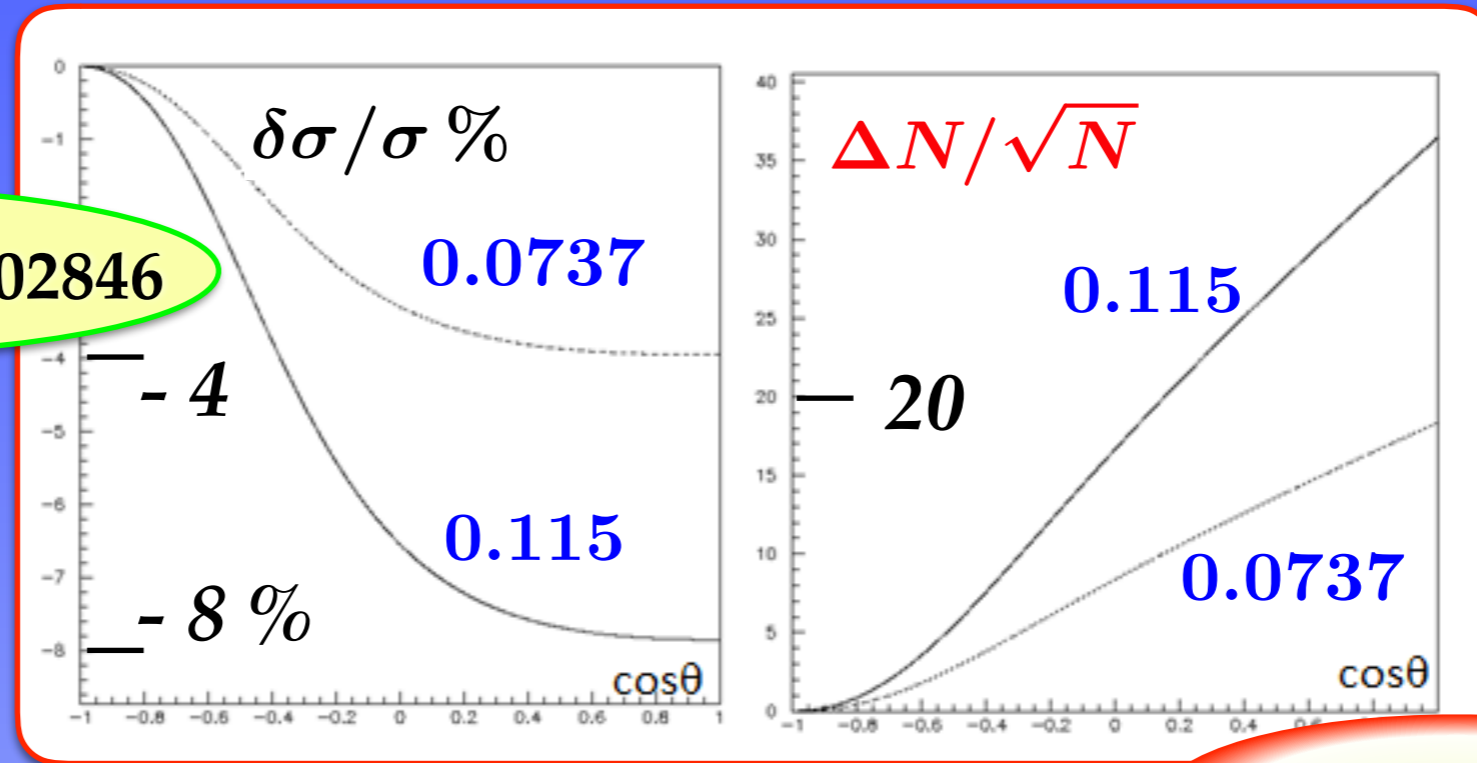
A model

Polarization dep !

→ more in Funatsu's talk

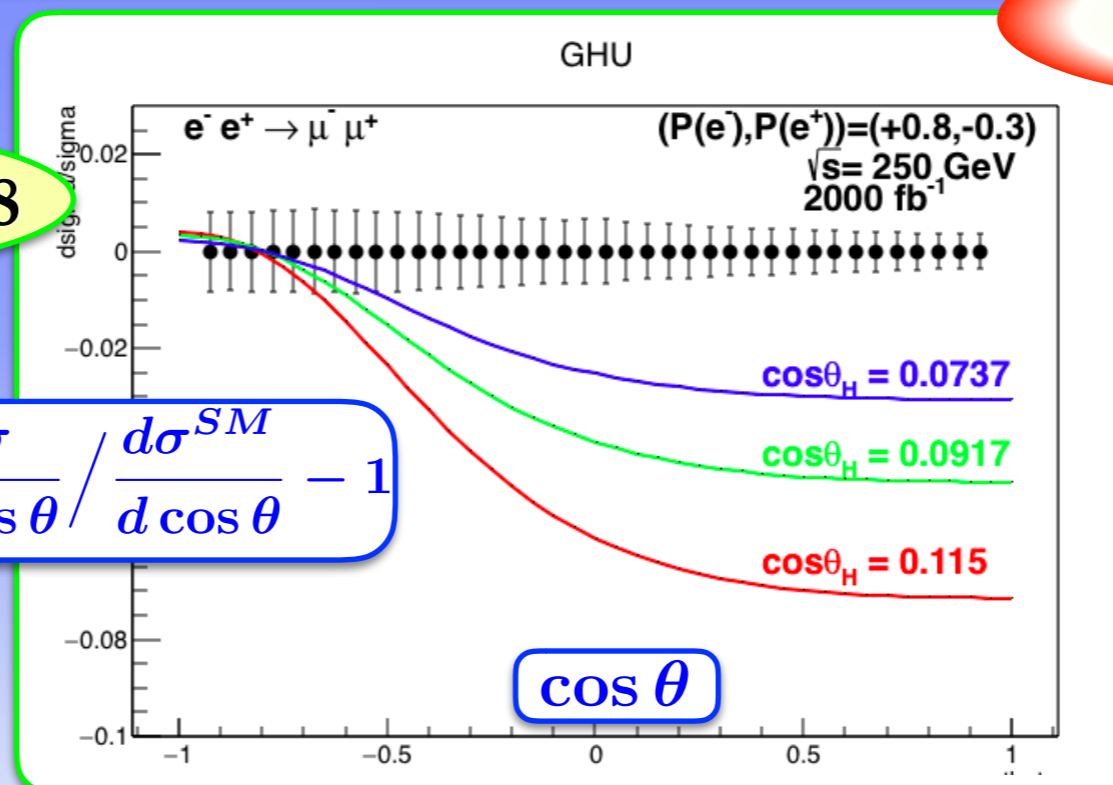
# Angular distribution $e^+e^- \rightarrow \mu^+\mu^-$

F. Richard, 1804.02846



A model

T. Suehara, ALCW2018



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

ILC 250  
 $2000 \text{ fb}^{-1}$

## Gauge-Higgs

Action & gauge principle

Higgs

gauge field  
AB phase  $\theta_H$

$$\theta_H$$

$\kappa_V$

$$\cos \theta_H$$

$\kappa_f$

$$\cos \theta_H, \cos^2 \frac{1}{2} \theta_H$$

$Z'$

$Z^{(1)}, \gamma^{(1)}, Z_R^{(1)}$   
7–9 TeV, 8–12 TeV  
large  $\mathcal{P}$

constraint

$$\theta_H \lesssim 0.1$$

restrictive  
prediction power

## Composite Higgs

Composite - strong dynamics

pseudo-NG boson

vacuum  
misalignment angle  $\frac{\langle h \rangle}{f_h}$

$\cos \langle h \rangle / f_h$  (MCHM)

not fixed

technirho meson  
no definitive prediction

$$\epsilon = \sin \langle h \rangle / f_h \lesssim 0.3$$



# Summary

$Z'$ : heavy

can be explored at 250 GeV ILC.

Polarization dep. tells details of the models.

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

ILC explores **new particles/physics.**