Gauge-Higgs unification at e^+e^- linear colliders

Yutaka Hosotani

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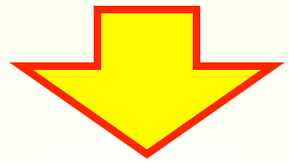
Corfu Summer Institute
Workshop on the Standard Model and Beyond
7 September 2018, Corfu, Greece

Unification



New particles

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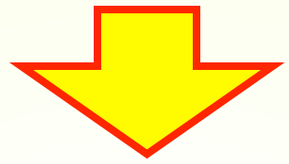
Unification



New particles

We can explore "7 - 8 TeV"

at 250 GeV ILC.

Funatsu, Hatanaka, YH, Orikasa

1705.05282 (PLB), 1612.03378 (PRD)

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Gauge-Higgs unification

125 GeV Higgs boson

||

AB phase in the 5th dim

Gauge-Higgs unification

125 GeV Higgs boson

||

AB phase in the 5th dim

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

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

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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

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

$$+$$

$$\mathcal{L}_{\text{Higgs}}$$

$$+$$

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

$$+$$

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

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Standard Model

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

$$+$$

$$\mathcal{L}_{\text{Higgs}} \begin{cases} \mathcal{L}^{\text{kin}}_{\text{Higgs}} \\ -V^{\text{pot}}_{\text{Higgs}} \end{cases}$$

$$+$$

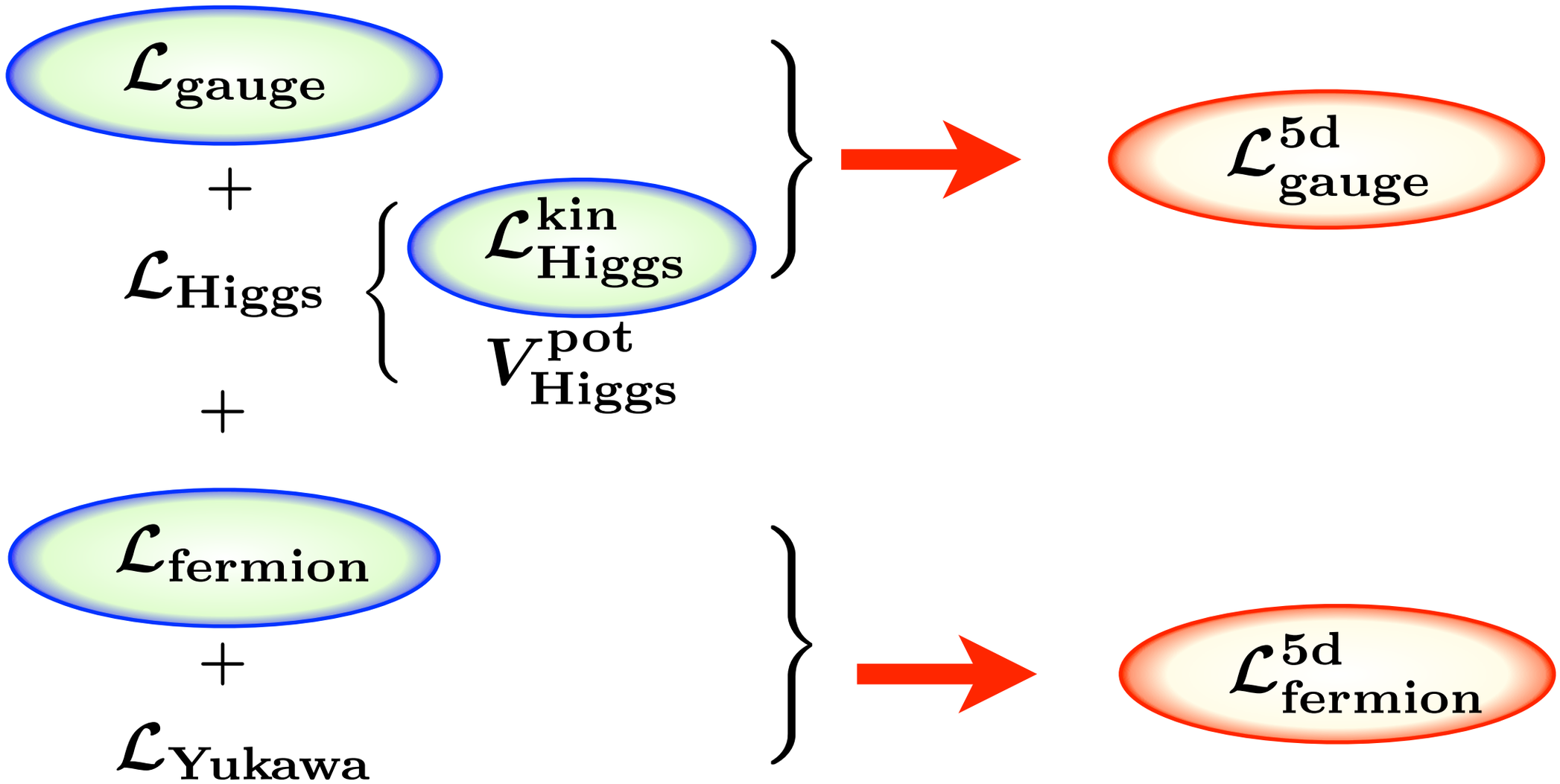
$$\mathcal{L}_{\text{fermion}}$$

$$+$$

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

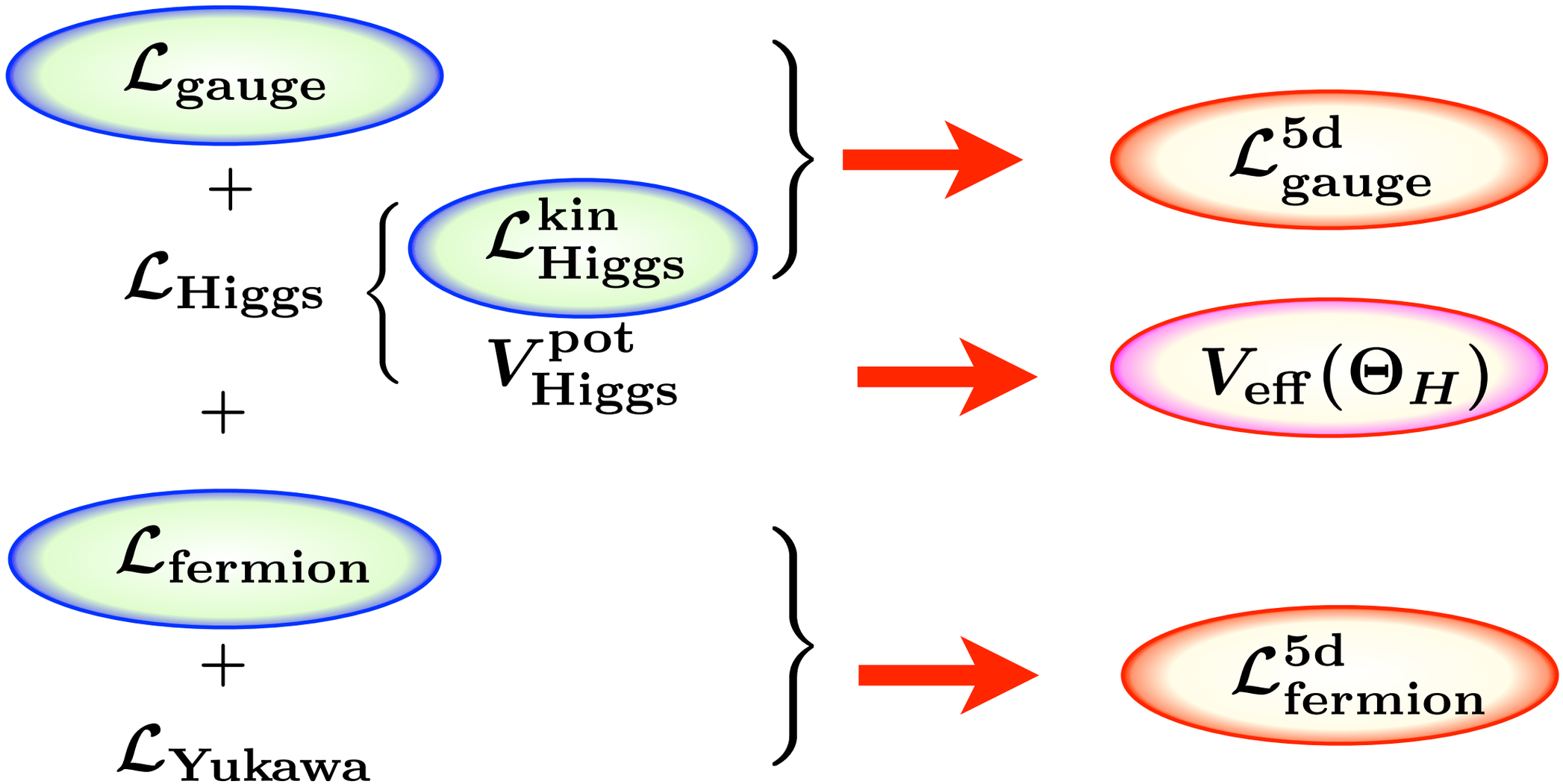
Standard Model

Gauge-Higgs Unification



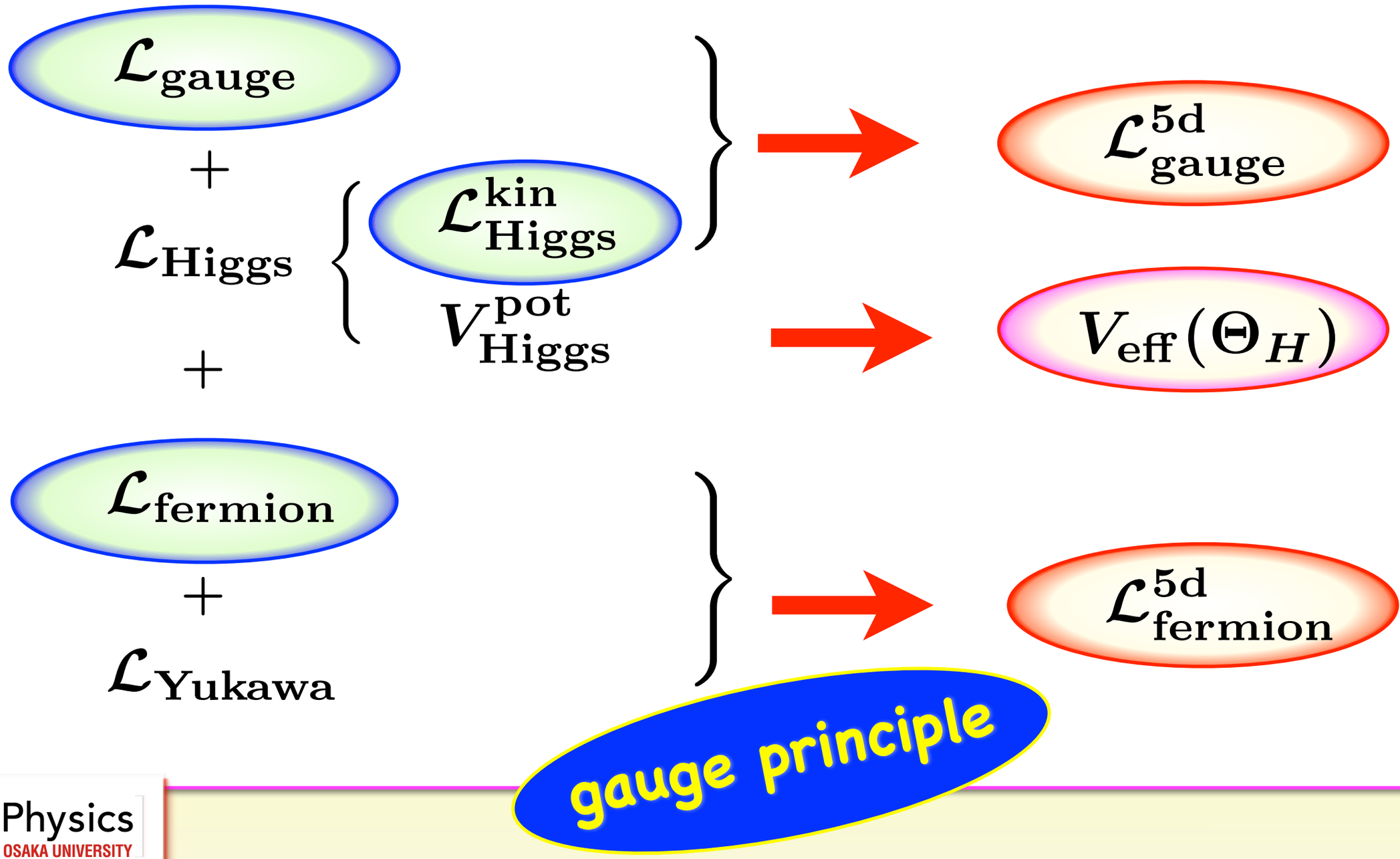
Standard Model

Gauge-Higgs Unification



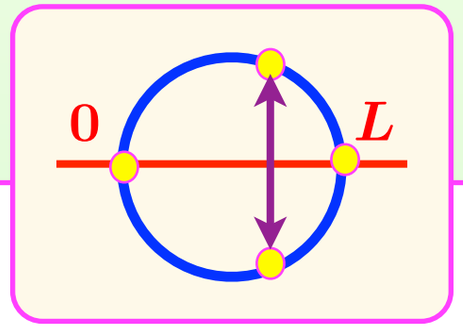
Standard Model

Gauge-Higgs Unification



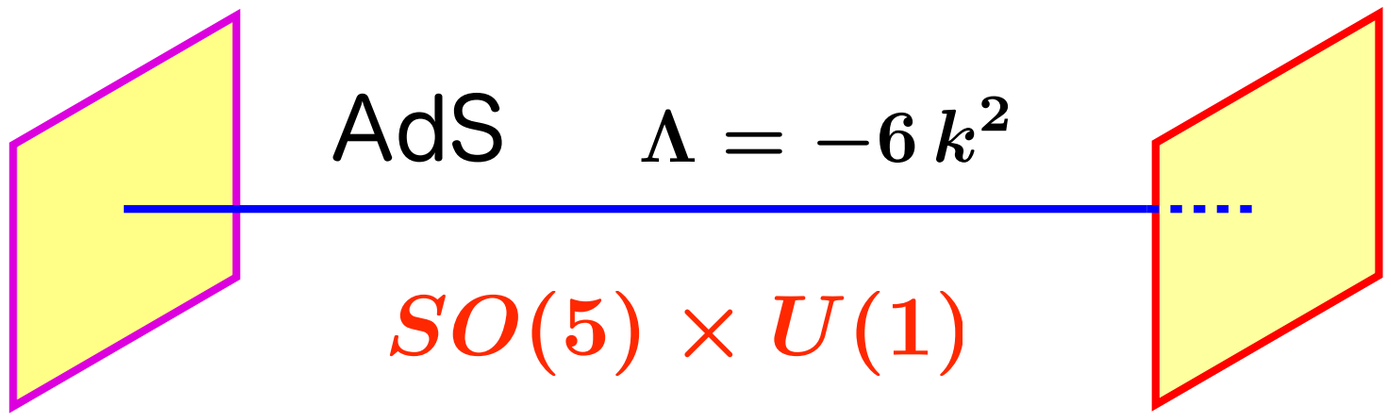
SO(5)xU(1) GHU in Randall-Sundrum

Agashe, Contino, Pomarol 2005
YH, Sakamura 2006
Medina, Shah, Wagner 2007
YH, Oda, Ohnuma, Sakamura 2008
Funatsu, Hatanaka, YH, Orikasa, Shimotani 2013



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

UV brane



IR brane

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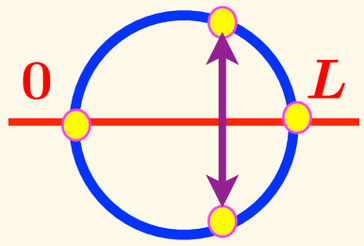

$$ds^2 = e^{-2k|y|} dx^\mu dx_\mu + dy^2$$

UV brane

IR brane

AdS $\quad \Lambda = -6\,k^2$

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

$$P_0 = \begin{pmatrix} -I_4 & \\ & 1 \end{pmatrix} \qquad P_1 = \begin{pmatrix} -I_4 & \\ & 1 \end{pmatrix}$$

SO(5)xU(1) GHU in Randall-Sundrum

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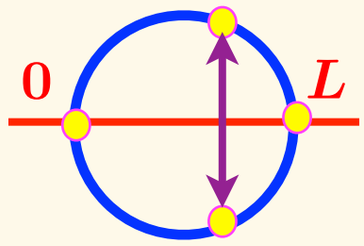

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$$SO(5) \times U(1)$$

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

quarks/leptons
vector rep Ψ_5

$$\begin{pmatrix} T \\ B \\ t_L \\ b_L \\ t'_R \end{pmatrix}_{\frac{2}{3}} \qquad \begin{pmatrix} U \\ D \\ X \\ Y \\ b'_R \end{pmatrix}_{-\frac{1}{3}}$$

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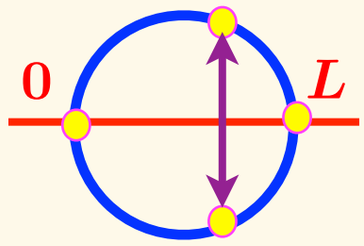

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Brane scalar
$(0, \frac{1}{2})$

Brane fermion
$(\frac{1}{2}, 0)$

quarks/leptons
vector rep Ψ_5

$$\begin{pmatrix} T \\ B \\ t_L \\ b_L \\ t'_R \end{pmatrix}_{\frac{2}{3}} \qquad \begin{pmatrix} U \\ D \\ X \\ Y \\ b'_R \end{pmatrix}_{-\frac{1}{3}}$$

dark fermions
spinor rep Ψ_4

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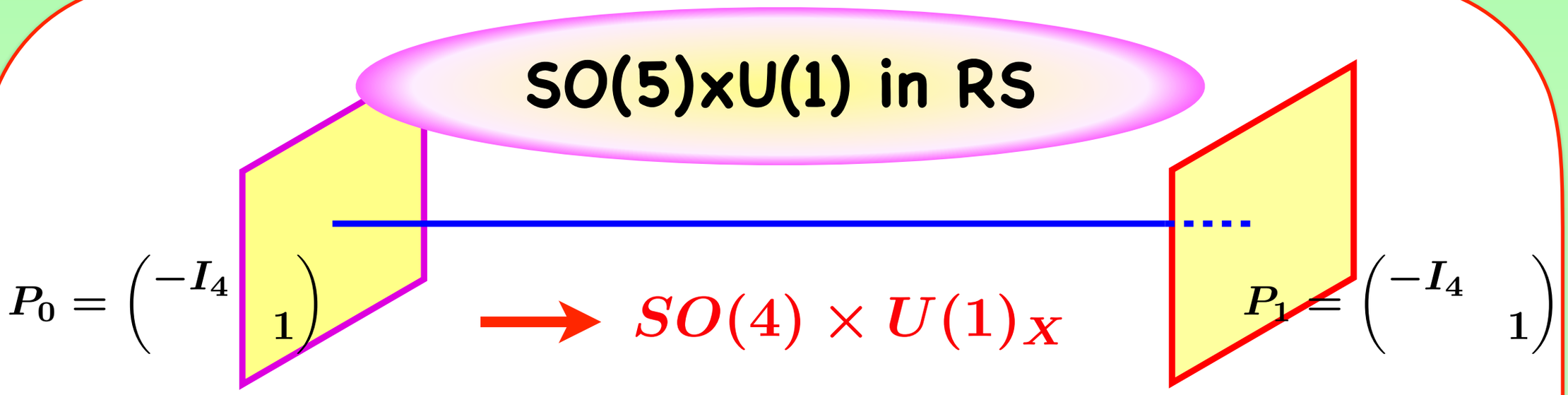
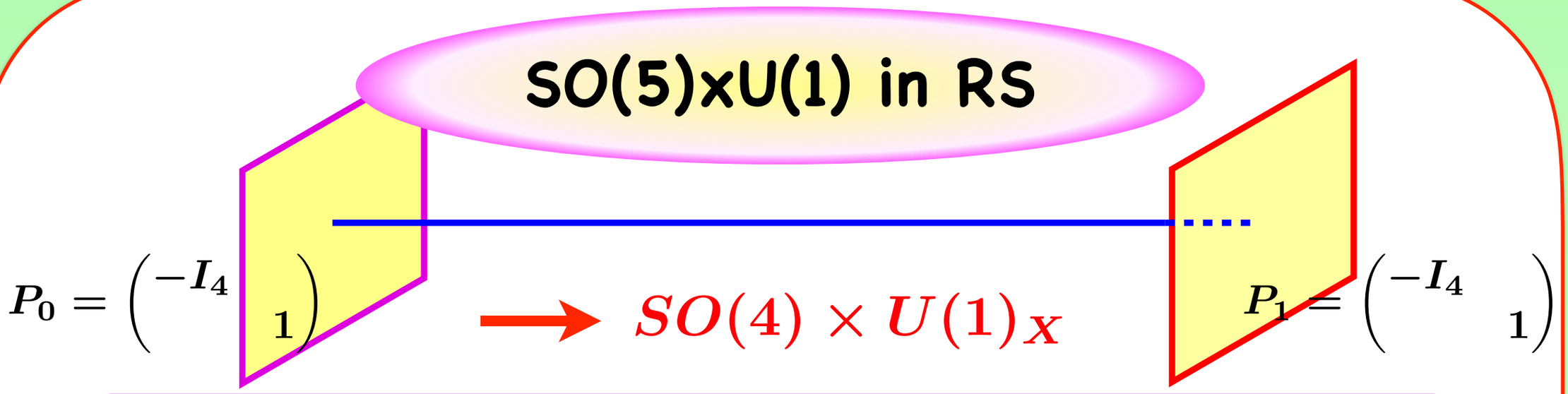
SO(5)xU(1) in RS


$P_0 = \begin{pmatrix} -I_4 & \\ & 1 \end{pmatrix}$
$SO(4) \times U(1)_X$
$P_1 = \begin{pmatrix} -I_4 & \\ & 1 \end{pmatrix}$

SO(5)xU(1) in RS



$A_\mu \sim$ (W Z γ)

$A_y \sim$ (Higgs)

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

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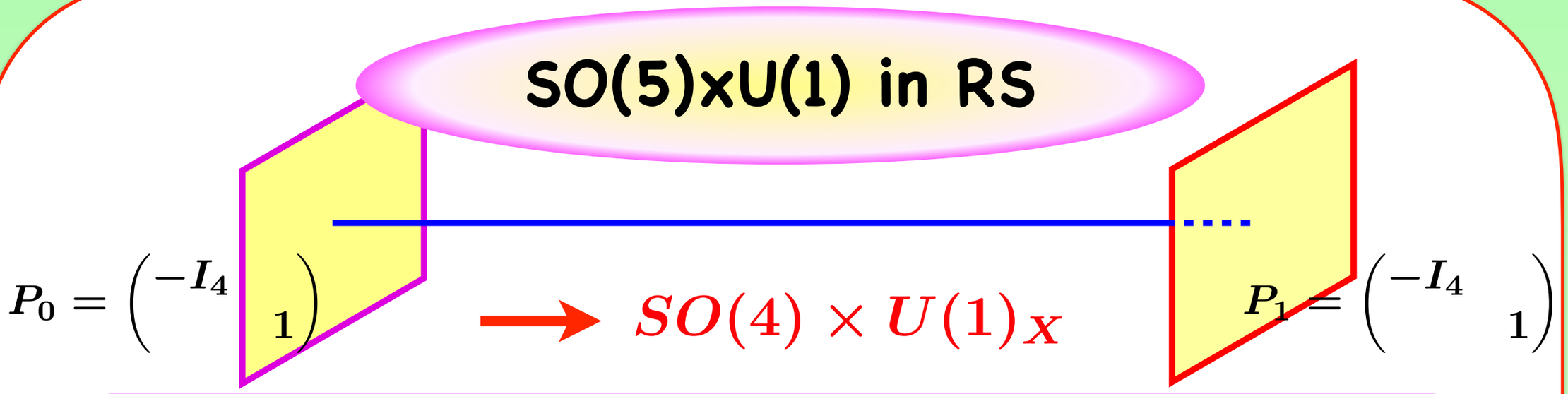
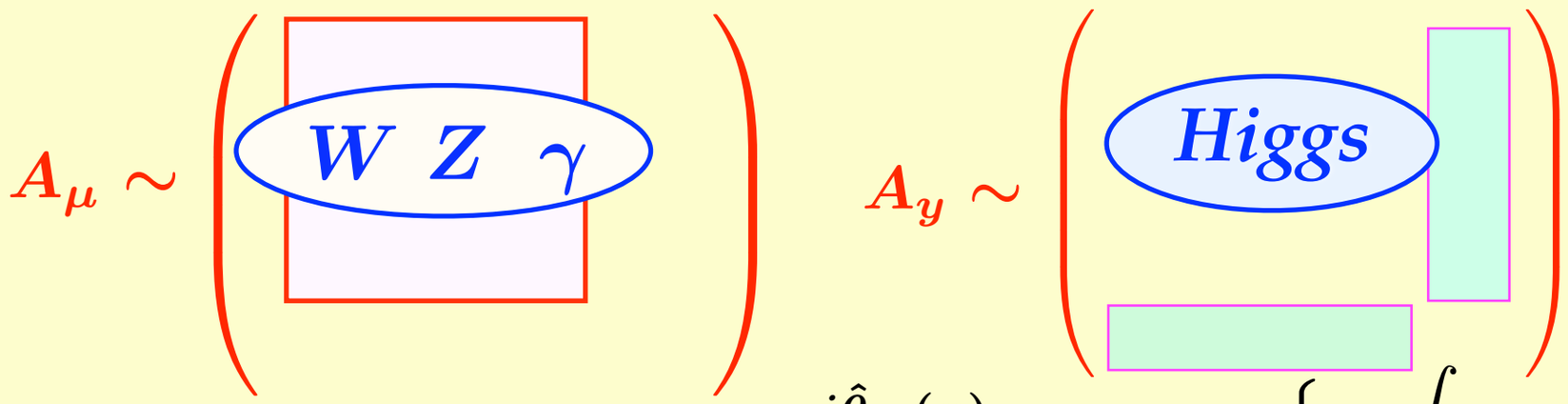
SO(5)xU(1) in RS

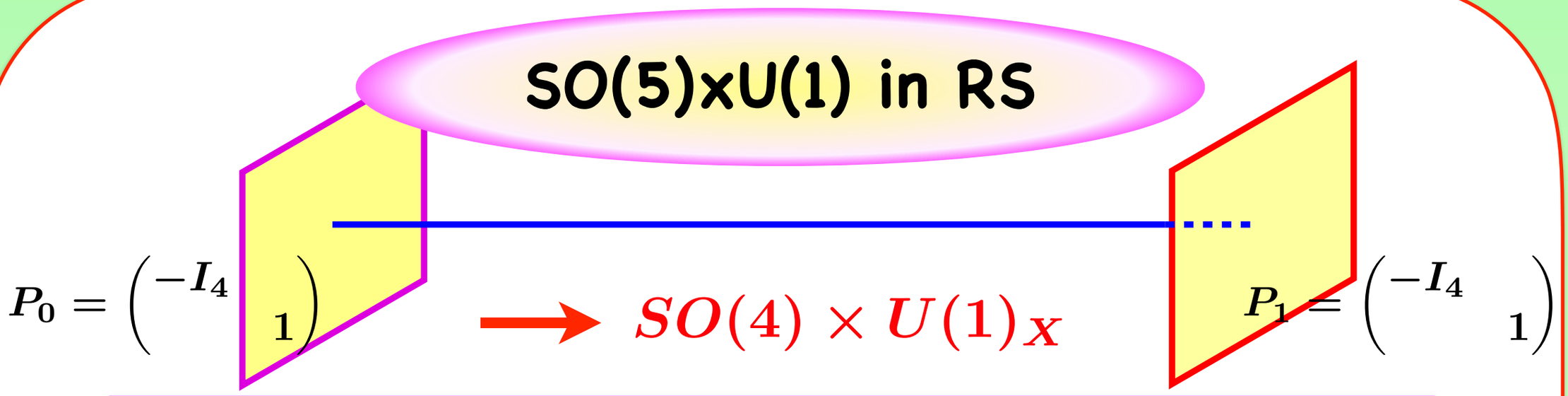


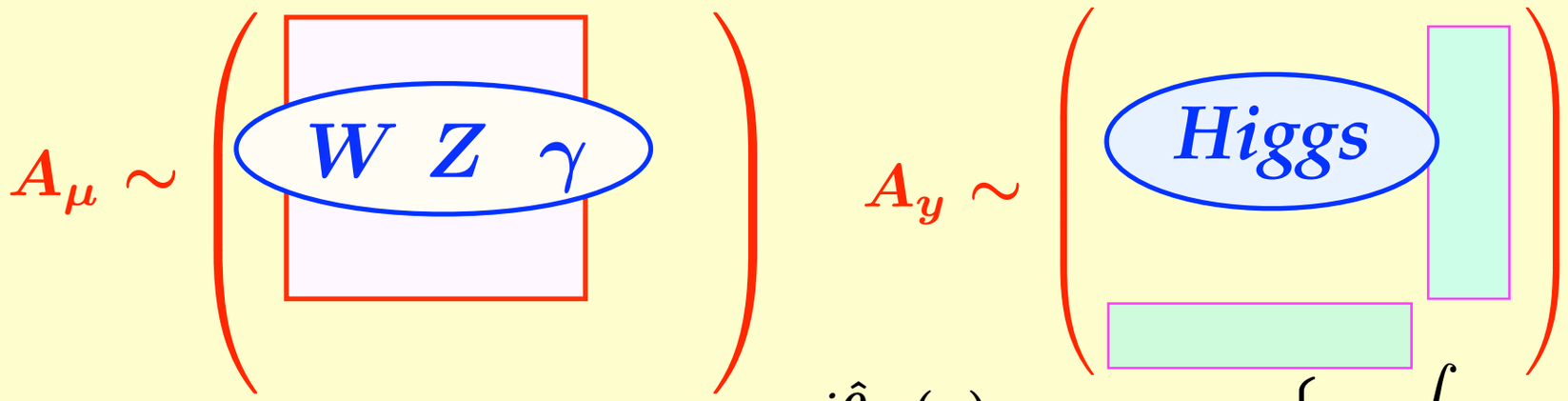


Brane scalar
$(0, \frac{1}{2})$

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

SO(5)xU(1) in RS





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Brane scalar
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$\longrightarrow$ $SU(2)_L \times U(1)_Y$

$\theta_H \neq 0$ $\longrightarrow$ $U(1)_{\rm EM}$

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Gauge couplings of SM particles

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Gauge couplings of SM particles

		$\theta_H = 0.115$		$\theta_H = 0.0737$		SM	
g_L^W/g_w	(ν_e, e)	1.00019		1.00009		1	
	(ν_μ, μ)	1.00019		1.00009			
	(ν_τ, τ)	1.00019		1.00009			
	(u, d)	1.00019		1.00009		1	
	(c, s)	1.00019		1.00009			
	(t, b)	0.9993		0.9995			
$g_{L/R}^Z/g_w$	ν_e, ν_μ, ν_τ	0.50014	0	0.50008	0	0.5	0
	e, μ, τ	-0.2688	0.2314	-0.2688	0.2313	-0.2688	0.2312
	u, c	0.3459	-0.1543	0.3459	-0.1542	0.3458	-0.1541
	t	0.3449	-0.1553	0.3453	-0.1549		
	d, s	-0.4230	0.0771	-0.4230	0.0771	-0.4229	0.0771
	b	-0.4231	0.0771	-0.4230	0.0771		
$g_{WWZ}/g_w \cos\theta_W$		0.9999998		0.99999995		1	

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$$g_{Lud}^W \sim g_w\left(1 + \frac{3\sin^2\theta_H}{16kL}\right)$$

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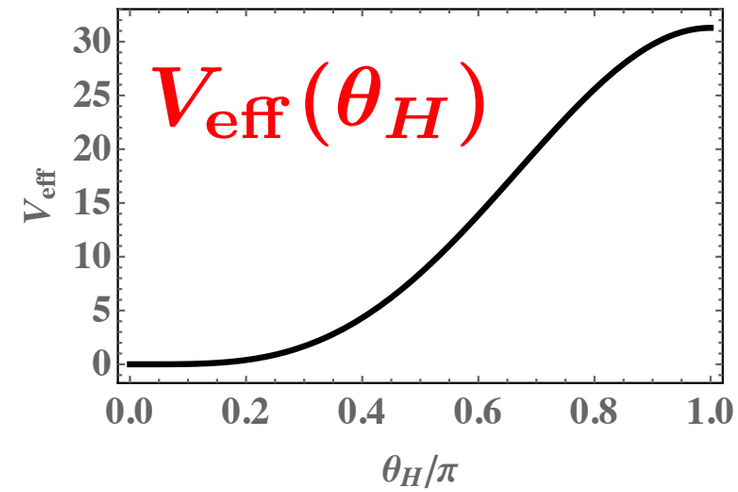
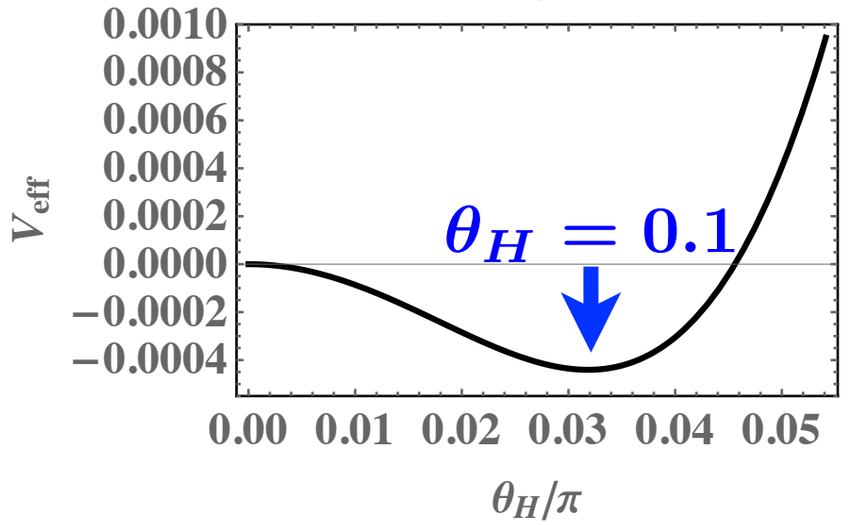
Higgs boson

$$m_H^2 = \frac{1}{f_H^2}\frac{d^2 V_{\rm eff}}{d\theta_H^2}\bigg|_{\rm min} \quad : \text{finite}$$





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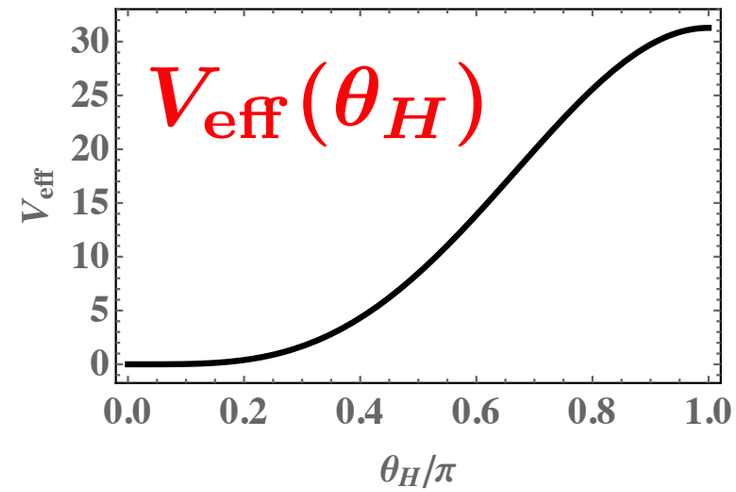
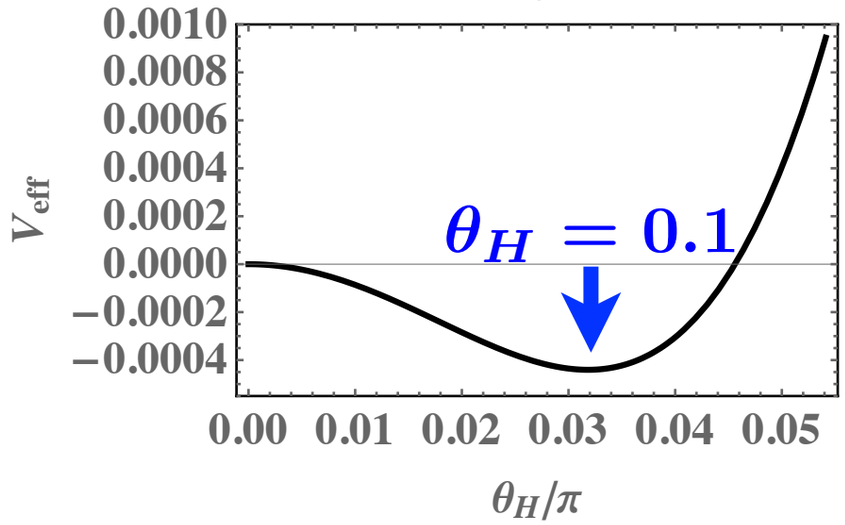
gauge hierarchy prob solved





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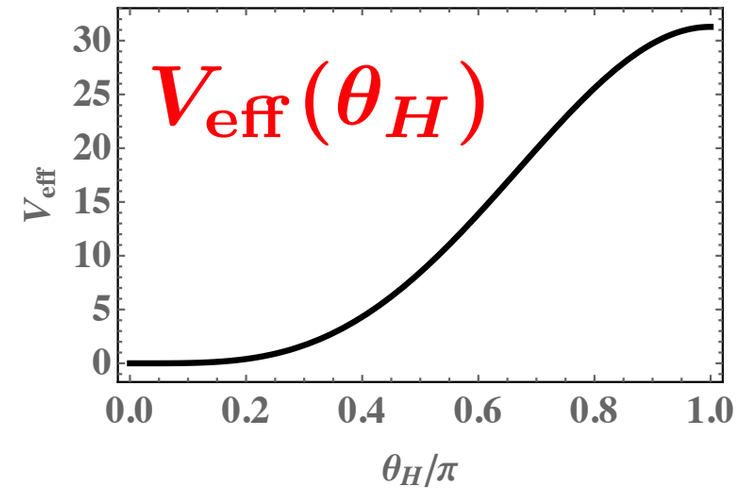

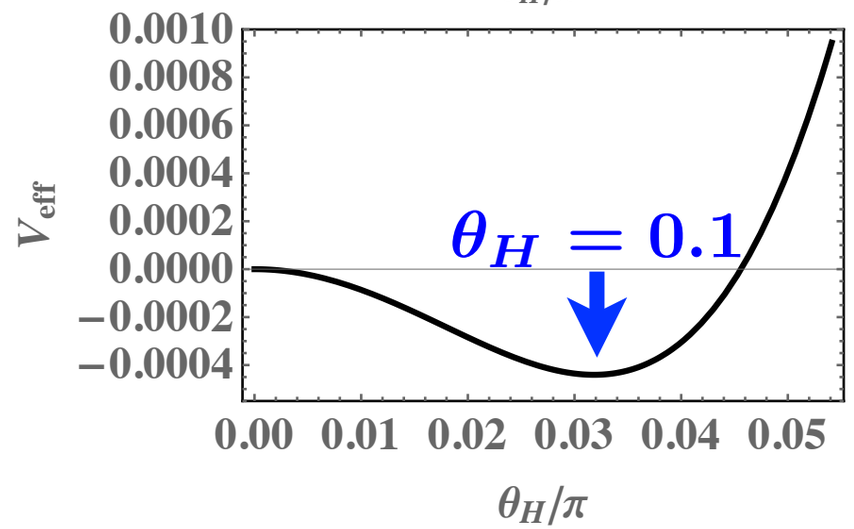

Higgs couplings :

W, Z, q, l $\sim$ (SM) $\times \cos\theta_H$

Signal strengths $\sim \mu_{\rm SM}\ \cos^2\theta_H$

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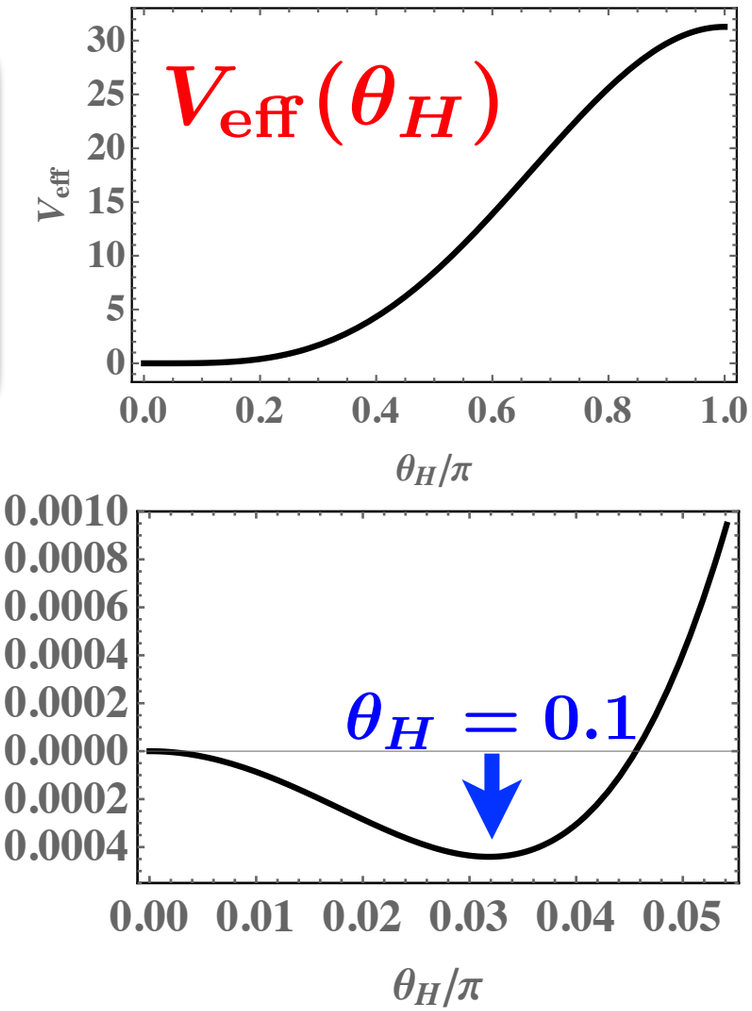

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Signal strengths $\sim \mu_{\rm SM} \cos^2\theta_H$

Phenomenology at low energies

nearly the same as in SM

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New Particles

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New Particles

Kaluza-Klein excitation modes

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New Particles

Kaluza-Klein excitation modes

$\theta_H = 0.10,\ n_F = 4,\ m_{\rm KK} = 8.144\,{\rm TeV},\ z_L = 3.56 \times 10^4$

	$Z^{(n)}$		$\gamma^{(\ell)}$	$Z_R^{(\ell)}$	$t^{(n)}$		$c^{(n)}$	$u^{(n)}$
$n\,(\ell)$	m_n	$\frac{m_n}{m_{\rm KK}}$	m_ℓ	m_ℓ	m_n	$\frac{m_n}{m_{\rm KK}}$	m_n	m_n
$1\,(1)$	6.642	0.816	6.644	6.234	7.462	0.916	8.536	10.47
2	9.935	1.220	–	–	8.814	1.082	12.01	13.82
$3\,(2)$	14.76	1.812	14.76	14.31	15.58	1.913	16.70	18.76
4	18.19	2.233	–	–	16.99	2.087	20.41	22.37

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New Particles

Kaluza-Klein excitation modes

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3 (2)	14.76	1.812	14.76	14.31	15.58	1.913	16.70	18.76
4	18.19	2.233	–	–	16.99	2.087	20.41	22.37

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

$\sim$ 7 TeV

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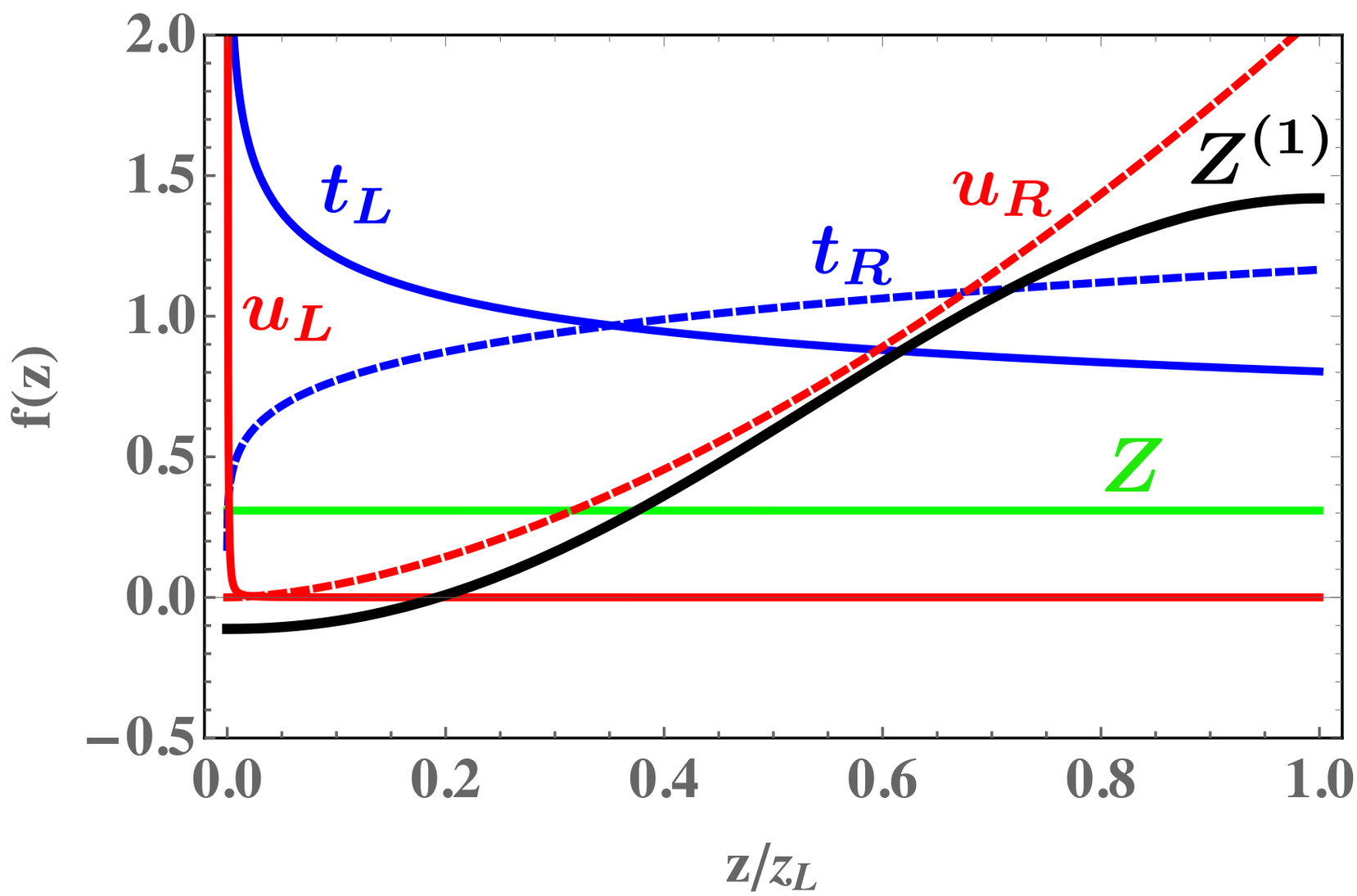
Wave functions in 5d

$$RS:\ ds^2 = \frac{1}{z^2}\left\{ dx^\mu dx_\mu + \frac{dz^2}{k^2} \right\} \quad 1 \le z \le z_L$$



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Z′ couplings

$$\frac{g_w}{\cos\theta_W} Z'_\mu \{ \hat{g}_L \bar{f}_L \gamma^\mu f_L + \hat{g}_R \bar{f}_R \gamma^\mu f_R \}$$

$\theta_H = 0.0917$

	SM: Z		$Z^{(1)}$		$Z_R^{(1)}$		$\gamma^{(1)}$	
	Left	Right	Left	Right	Left	Right	Left	Right
ν_e	0.5	0	−0.183	0	0	0	0	0
ν_μ			−0.183	0	0	0	0	0
ν_τ			−0.183	0	0	0	0	0
e	−0.2688	0.2312	0.099	0.916	0	−1.261	0.155	−1.665
μ			0.099	0.860	0	−1.193	0.155	−1.563
τ			0.099	0.814	0	−1.136	0.155	−1.479
u	0.3458	−0.1541	−0.127	−0.600	0	0.828	−0.103	1.090
c			−0.130	−0.555	0	0.773	−0.103	1.009
t			0.494	−0.372	0.985	0.549	0.404	0.678
d	−0.4229	0.0771	0.155	0.300	0	−0.414	0.052	−0.545
s			0.155	0.277	0	−0.387	0.052	−0.504
b			−0.610	0.186	0.984	−0.274	−0.202	−0.339

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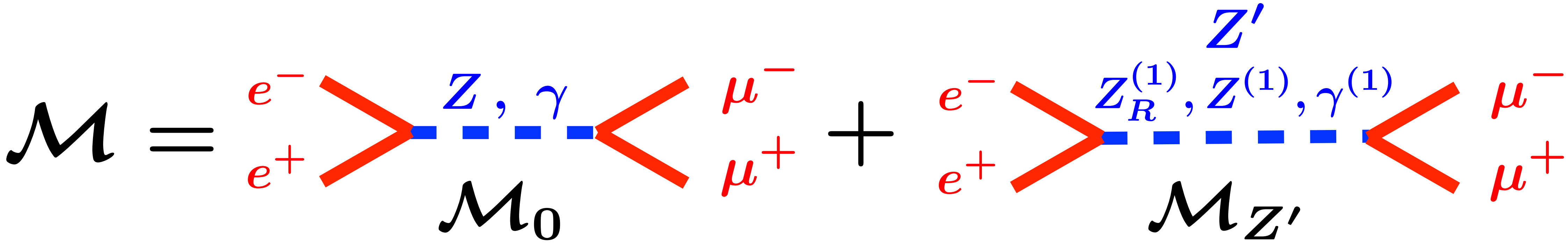
Funatsu, Hatanaka, YH, Orikasa, 1705.05282

ILC


$\mathcal{M} =$
e^-
e^+
$Z\,,\ \gamma$
μ^-
μ^+
$\mathcal{M}_0$
$+$
e^-
e^+
Z'
$Z_R^{(1)}, Z^{(1)}, \gamma^{(1)}$
μ^-
μ^+
$\mathcal{M}_{Z'}$

ILC

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

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

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

ILC

$$\mathcal{M} = \underset{\mathcal{M}_0}{\left(\begin{matrix} e^- \\ e^+ \end{matrix}\right) \xrightarrow{Z,\,\gamma} \left(\begin{matrix} \mu^- \\ \mu^+ \end{matrix}\right)} + \underset{\mathcal{M}_{Z'}}{\left(\begin{matrix} e^- \\ e^+ \end{matrix}\right) \xrightarrow{Z'\ :\ Z_R^{(1)},\,Z^{(1)},\,\gamma^{(1)}} \left(\begin{matrix} \mu^- \\ \mu^+ \end{matrix}\right)}$$

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

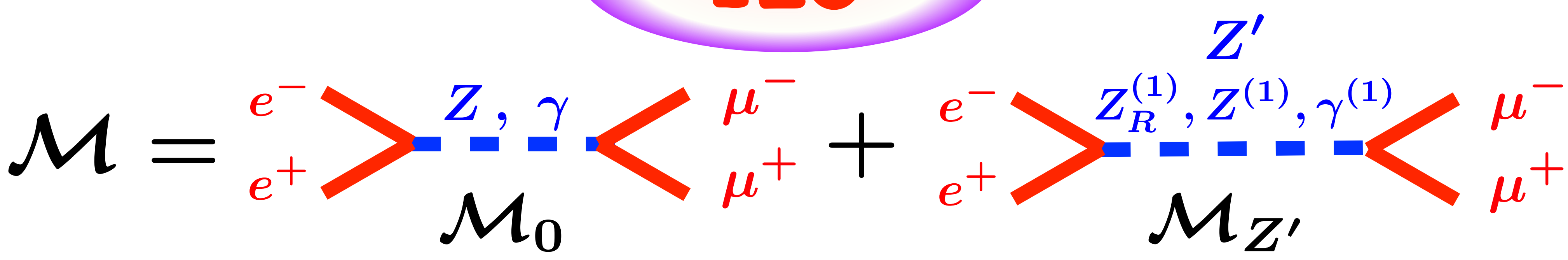
$$(250\,\mathrm{GeV})^2 \sim (1\,\mathrm{TeV})^2$$

$$= \sum_{\alpha,\beta=L,R} J_\alpha^{(e)\nu}(p,p')(A_0^{\alpha\beta} + A_{Z'}^{\alpha\beta}) J_{\beta\nu}^{(\mu)}(k,k')$$

$$\sim \frac{g_w^2}{\cos^2\theta_W}\left\{\frac{\kappa_{SM}^{\alpha\beta}}{s} - \frac{\kappa_{Z'}^{\alpha\beta}}{m_{Z'}^2}\right\}$$

$$\kappa_{Z'}^{\alpha\beta} = \sum_{V=Z'} \hat{g}_{e\alpha}^V \hat{g}_{\mu\beta}^V$$

ILC



$$(\kappa_{Z'}^{LL}, \kappa_{Z'}^{LR}, \kappa_{Z'}^{RL}, \kappa_{Z'}^{RR}) = (0.034, -0.158, -0.168, 4.895)$$

$$(\kappa_{\rm SM}^{LL}, \kappa_{\rm SM}^{LR}, \kappa_{\rm SM}^{RL}, \kappa_{\rm SM}^{RR}) = (0.25,\ 0.1156,\ 0.1156,\ 0.2312)$$

ILC

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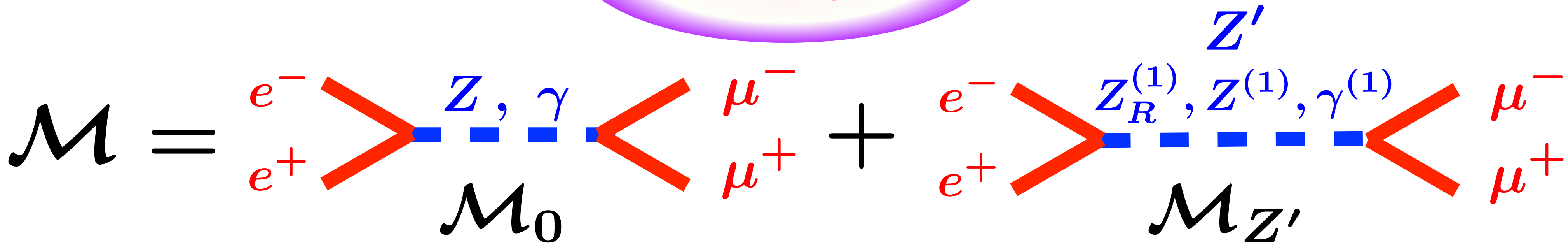
interference effects

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

$$\frac{\mathcal{M}_0 \mathcal{M}_{Z'}^*}{|\mathcal{M}_0|^2} \sim -\frac{\kappa_{Z'}^{RR} + \kappa_{Z'}^{RL}}{\kappa_{\rm SM}^{RR} + \kappa_{\rm SM}^{RL}} \frac{s}{m_{Z'}^2} \sim -13.6\, \frac{s}{m_{Z'}^2}$$

ILC



$$(\kappa_{Z'}^{LL}, \kappa_{Z'}^{LR}, \kappa_{Z'}^{RL}, \kappa_{Z'}^{RR}) = (0.034, -0.158, -0.168, 4.895)$$

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

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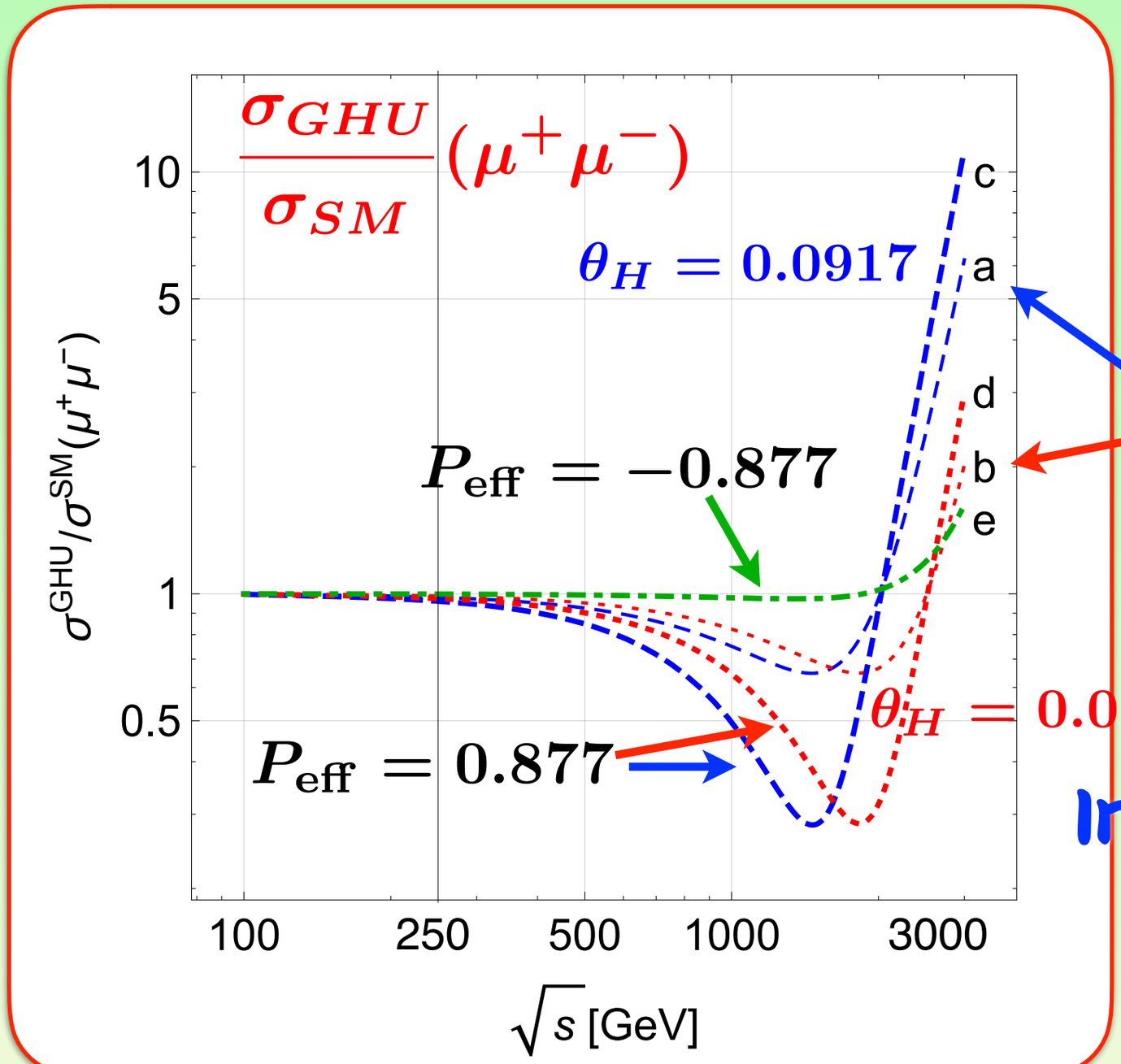
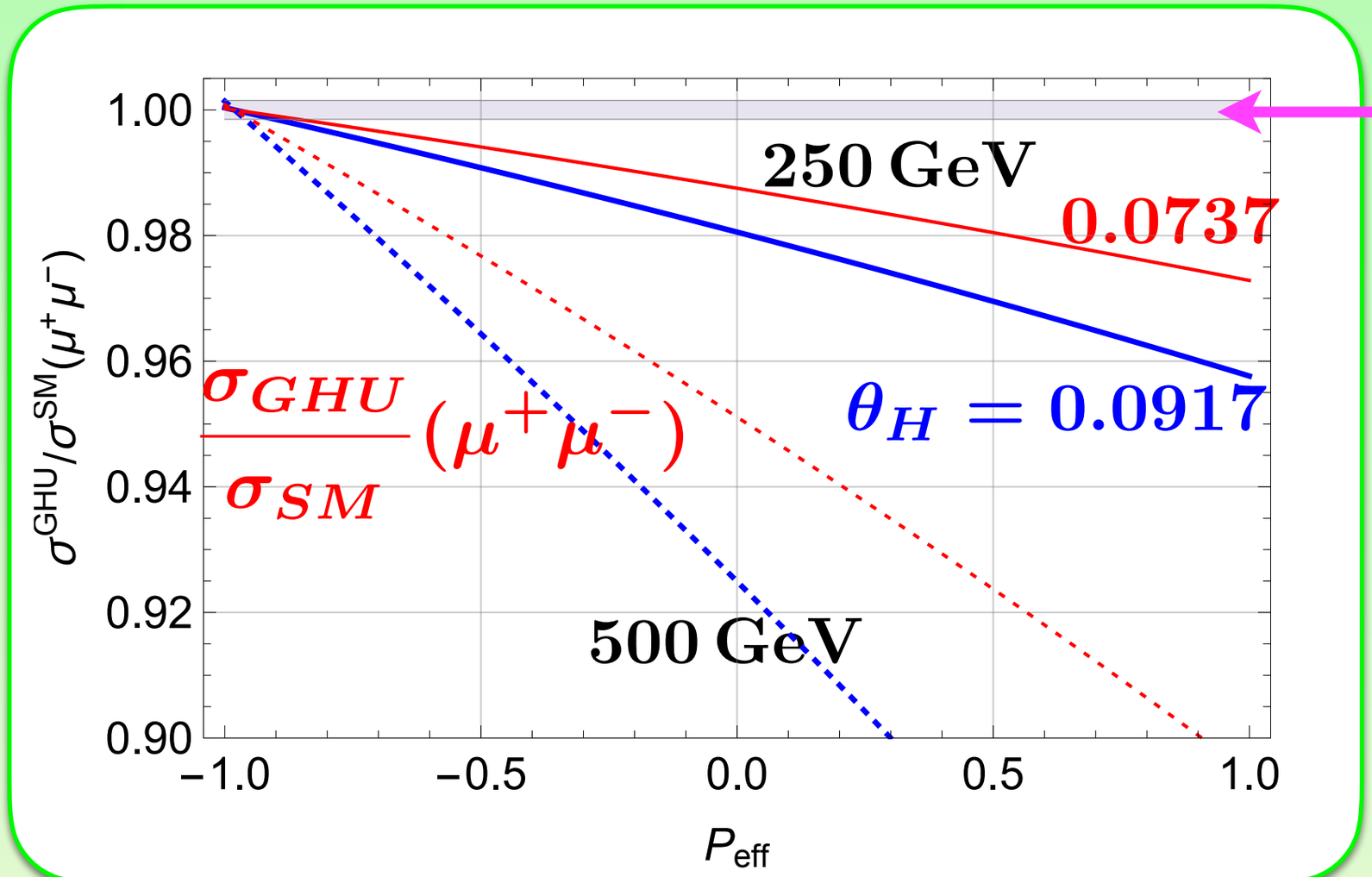
$e^+e^- \to \mu^+\mu^-$



$P_{\rm eff} = 0$

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

Interference among γ, Z, Z'



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

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

Interference among γ, Z, Z'

$4\,\%$ at $P_{\rm eff} = 0.877$ at 250 GeV

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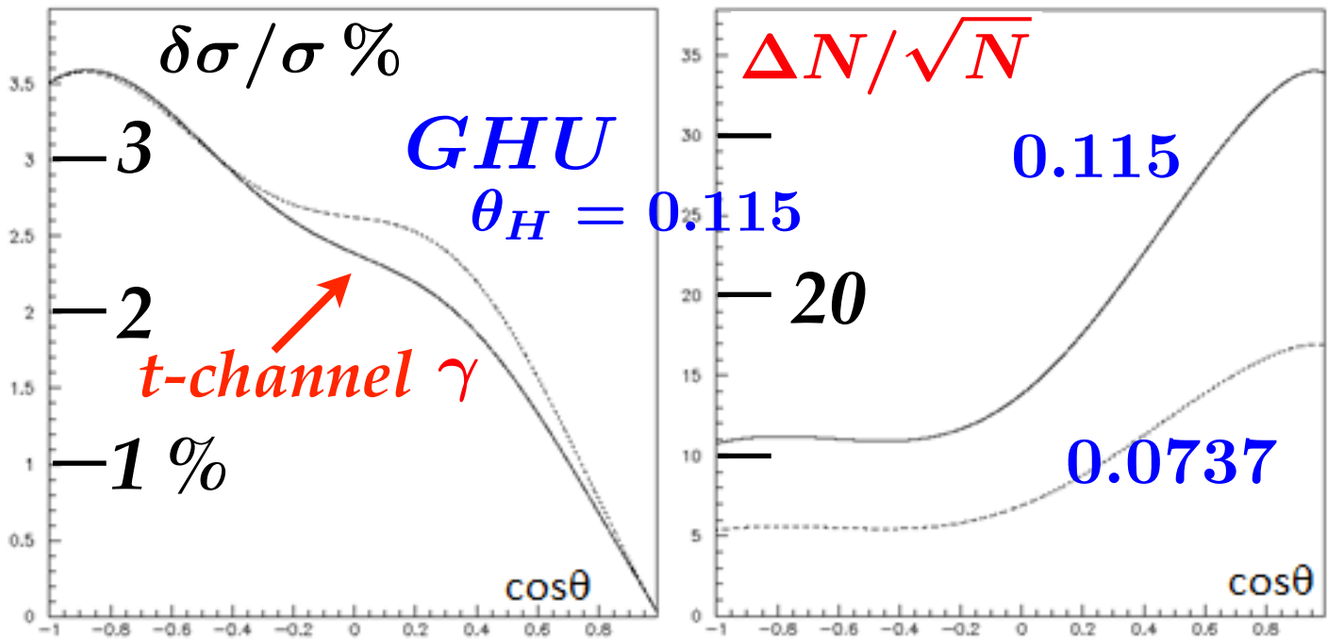
Bhabha scattering $e^+e^- \to e^+e^-$



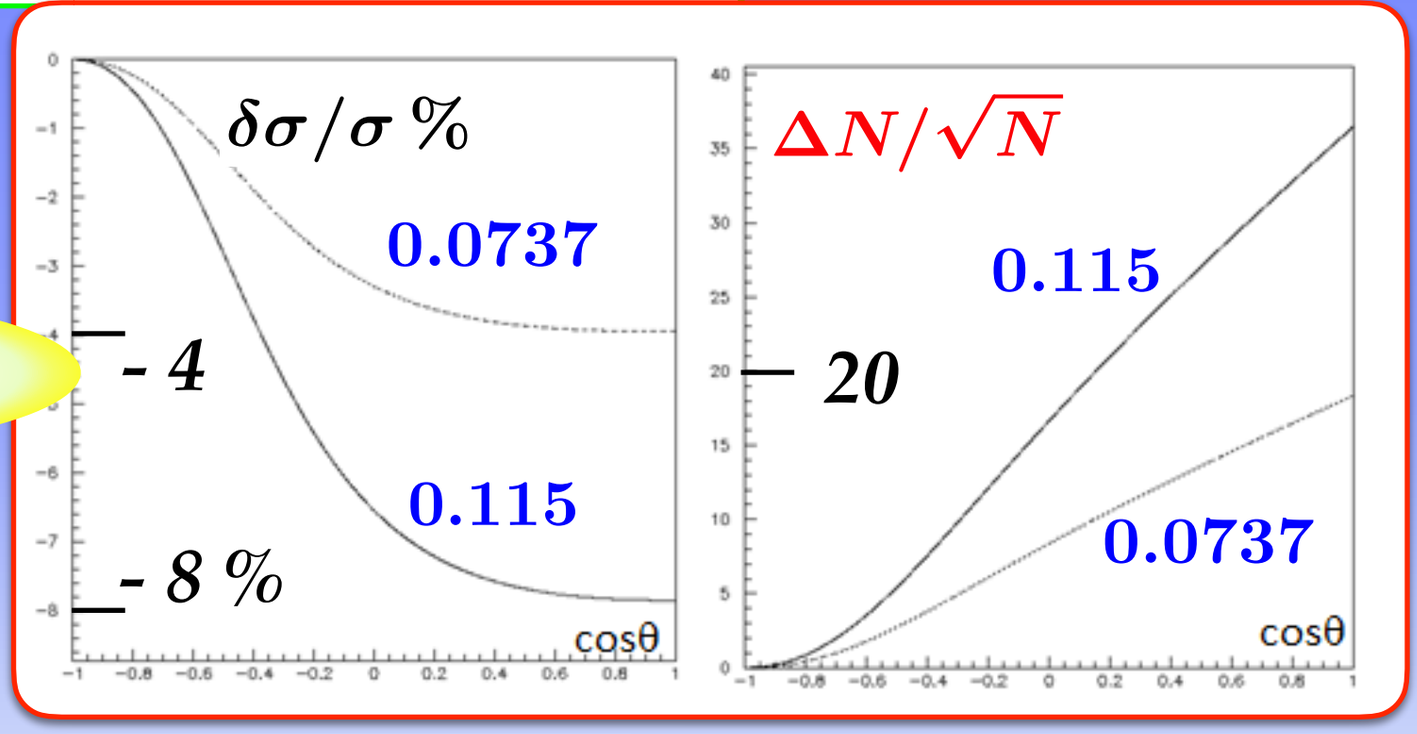
F. Richard, 1804.02846

ILC 250

2000 fb^{-1}

$\cos\theta$ bin width 0.1

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



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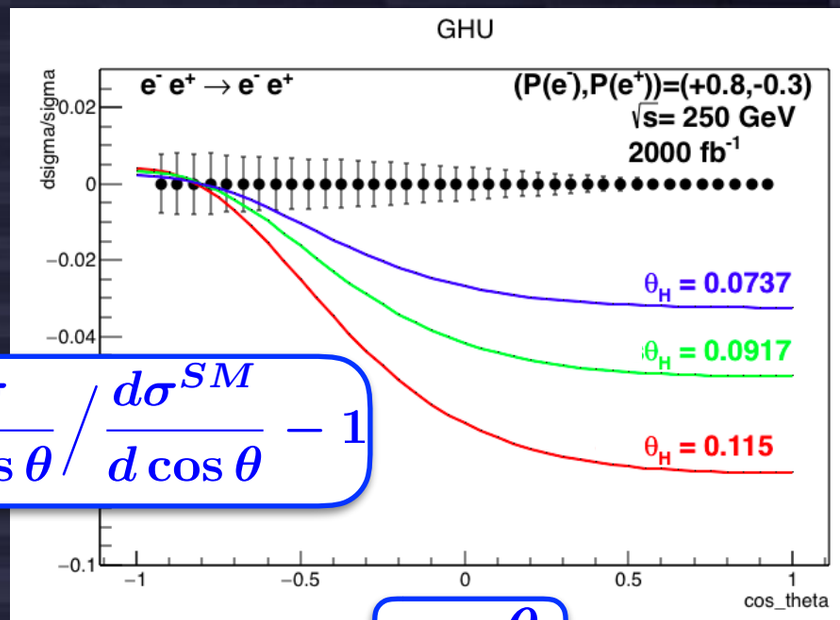
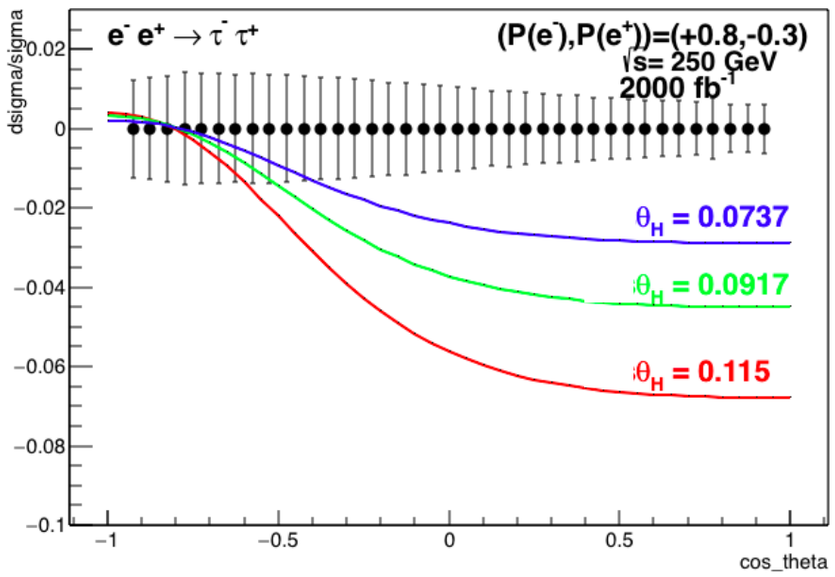
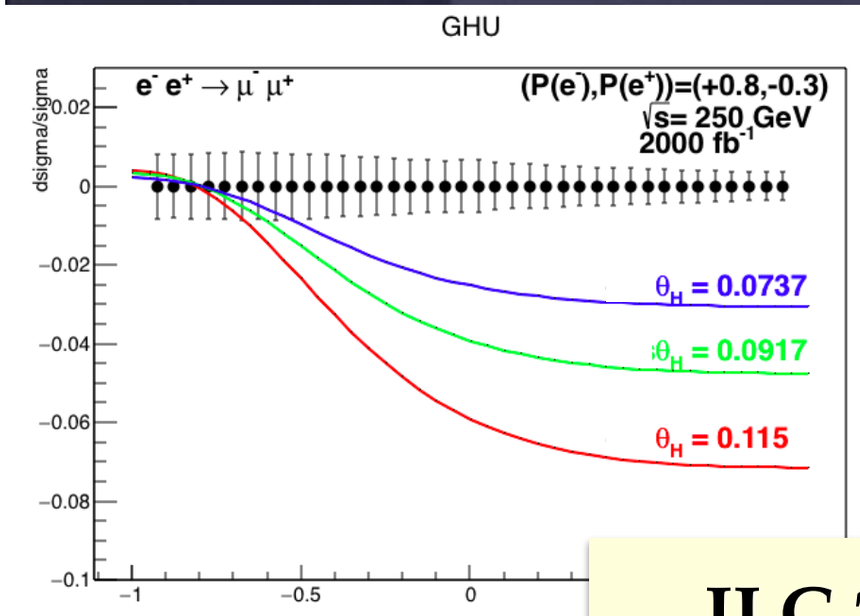
Leptonic channels – GHU sensitivity

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



$\cos\theta$





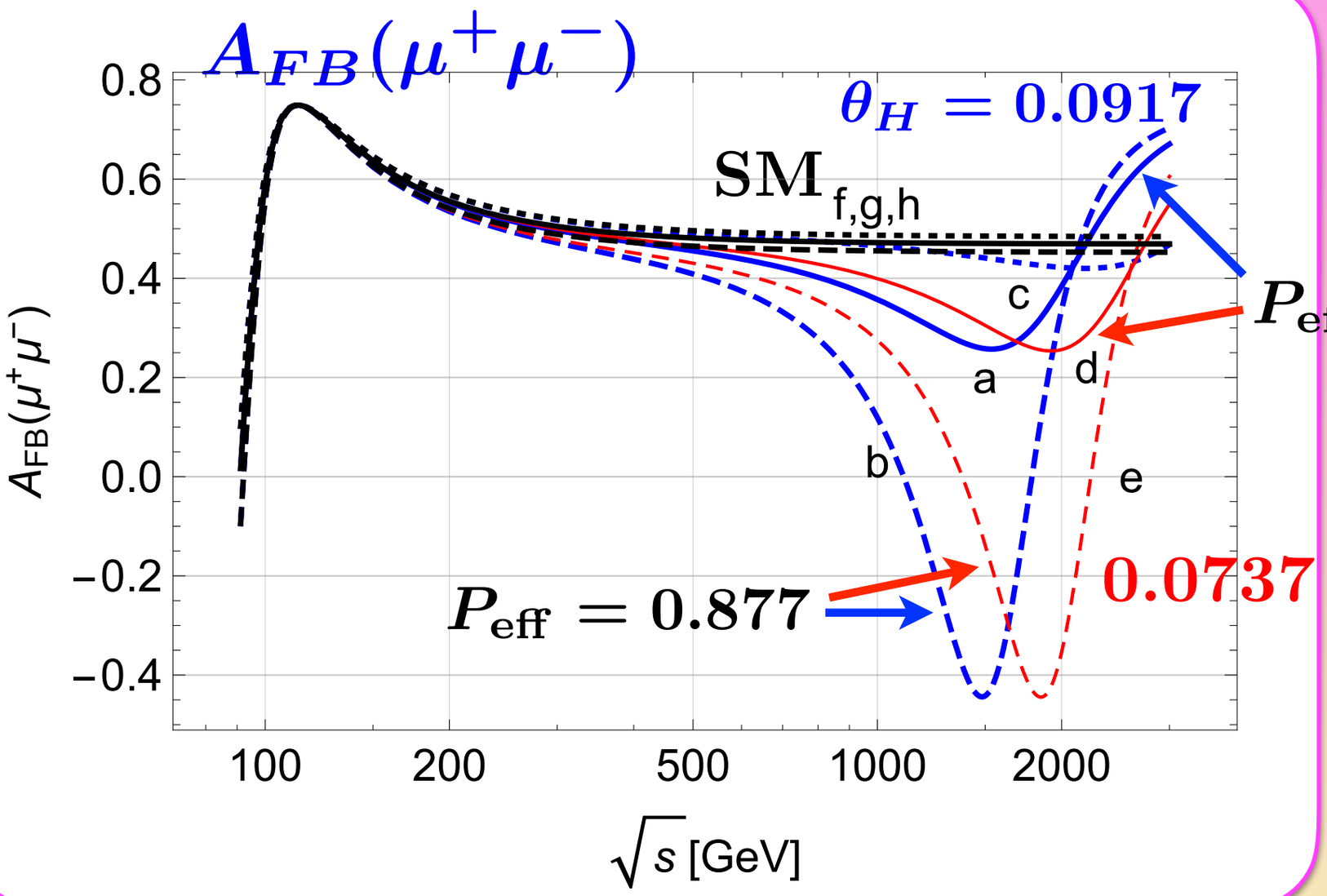
ILC 250

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

Clear separation for any favorable θ_H

T. Suehara, ALCW2018

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



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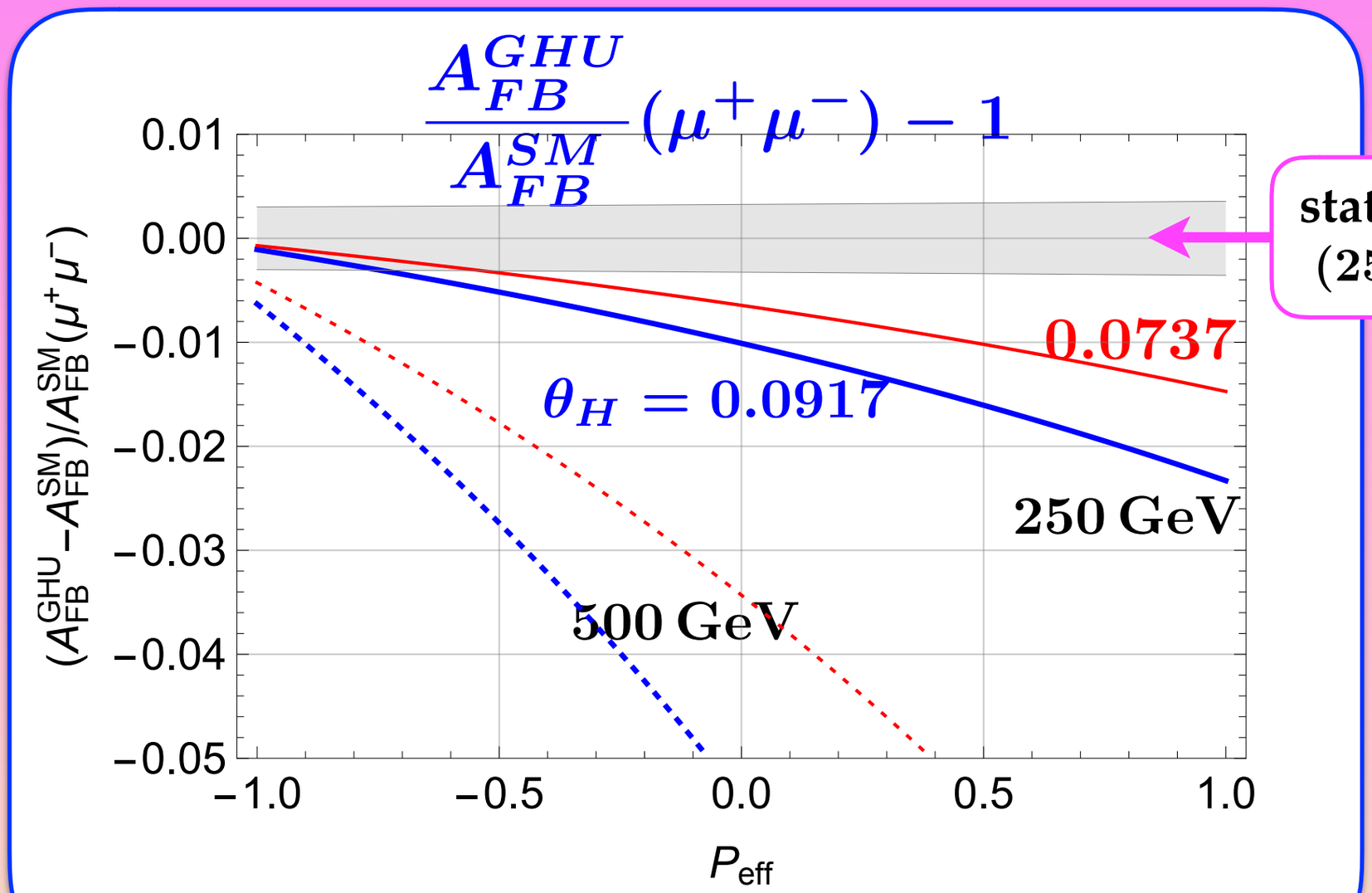

$250\,\mathrm{GeV},\ 250\,\mathrm{fb}^{-1}$ $\quad P_{\rm eff} = 0.8$ $\quad 6\,\sigma\,(4\,\sigma)$

Polarization dependence

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Left-right asymmetry

$$R_{f,RL} = \frac{\sigma(e^+e^- \to \bar{f}f; P_{e^-} = +\overline{P}, P_{e^+} = 0)}{\sigma(e^+e^- \to \bar{f}f; P_{e^-} = -\overline{P}, P_{e^+} = 0)}$$

Systematic errors reduced.

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Left-right asymmetry

$$R_{f,RL} = \frac{\sigma(e^+e^- \to \bar{f}f; P_{e^-} = +\overline{P}, P_{e^+} = 0)}{\sigma(e^+e^- \to \bar{f}f; P_{e^-} = -\overline{P}, P_{e^+} = 0)}$$

Systematic errors reduced.

$250\,\mathrm{GeV},\ \overline{P} = 0.8,\ 250\,\mathrm{fb}^{-1} \times 2$

f	SM		GHU	
	$R_{f,RL}$	$\Delta\sigma$	θ_H 0.0917	0.0737
μ	0.890	0.3%	−3.4 %	−2.2 %
b	0.349	0.3%	−3.1 %	−2.1 %

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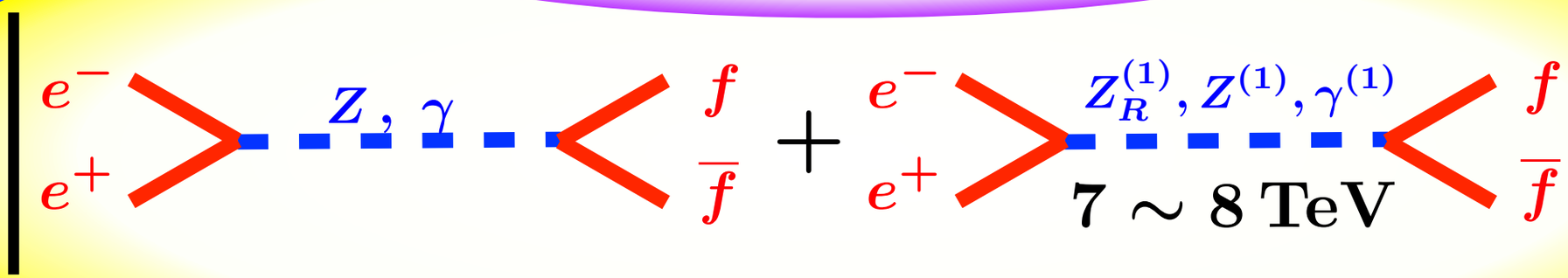
Summary

Gauge-Higgs unification

New particles



in the early stage of **ILC250**

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