ILC Symposium

New Physics Search

Yutaka Hosotani

Physics
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HPNP2019

Osaka University, 18 February 2019

ILC 250GeV

Precision measurements of 125GeV Higgs boson

with $2000\,\mathrm{fb}^{-1}$ data → { confirm SM / physics beyond SM }

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ILC 250GeV

Precision measurements of 125GeV Higgs boson

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Explore New Particles

unknown particles

heavy > 1 TeV → must be indirect.

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ILC 250GeV

Precision measurements of 125GeV Higgs boson

with $2000\,\mathrm{fb}^{-1}$ data → { confirm SM / physics beyond SM

Explore New Particles

unknown particles

heavy > 1 TeV → must be indirect.

Can be done with

$250\,\mathrm{fb}^{-1}$ in $e^+e^- \to f\,\bar{f}$ at ILC 250 GeV !

Physics
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Physics must be simple & beautiful.

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Standard Model

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

$$+$$

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

$$+$$

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

$$+$$

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

Physics
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$$+$$

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

$$+$$

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

$$+$$

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$\mathcal{L}_{\rm Higgs}$ { $\mathcal{L}^{\rm kin}_{\rm Higgs}$, $V^{\rm pot}_{\rm Higgs}$ }

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

$+$

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

Gauge-Higgs Unification

$\mathcal{L}^{\rm 5d}_{\rm gauge}$

$\mathcal{L}^{\rm 5d}_{\rm fermion}$

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$+$

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

$+$

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

Gauge-Higgs Unification

$\mathcal{L}^{\rm 5d}_{\rm gauge}$ and $\mathcal{L}^{\rm kin}_{\rm Higgs}$ $\rightarrow$ $\mathcal{L}^{\rm 5d}_{\rm gauge}$

$V^{\rm pot}_{\rm Higgs}$ $\rightarrow$ $V_{\rm eff}(\Theta_H)$

$\mathcal{L}_{\rm fermion}$ and $\mathcal{L}_{\rm Yukawa}$ $\rightarrow$ $\mathcal{L}^{\rm 5d}_{\rm fermion}$

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Standard Model

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

$+$

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$+$

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Gauge-Higgs Unification

gauge principle

$\mathcal{L}^{\rm 5d}_{\rm gauge}$

$V_{\rm eff}(\Theta_H)$

$\mathcal{L}^{\rm 5d}_{\rm fermion}$

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New particles at e^+e^- colliders

$$\text{Data} = \left| \mathcal{M}_{\text{known}} + \mathcal{M}_{\text{new}} \right|^2$$

$$= \left| \mathcal{M}_{\text{known}} \right|^2 + 2\,Re\,\mathcal{M}_{\text{known}}\mathcal{M}^*_{\text{new}} + \left| \mathcal{M}_{\text{new}} \right|^2$$

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large — *negligible*

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large — interference term — *negligible*

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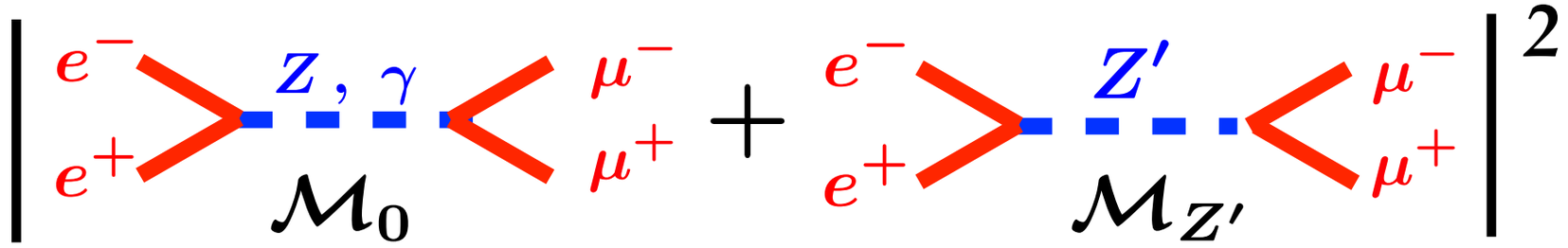
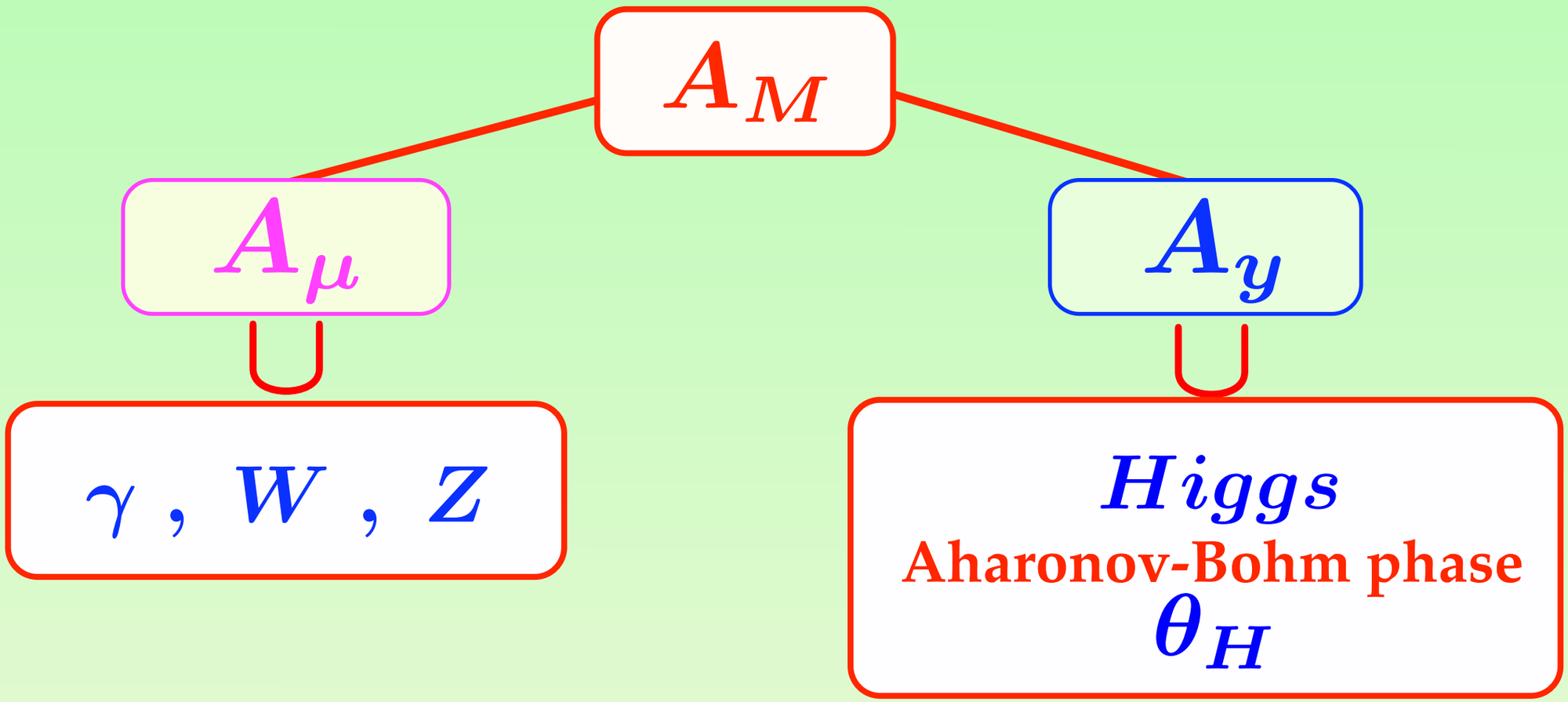
large — interference term — *negligible*



Gauge-Higgs unification



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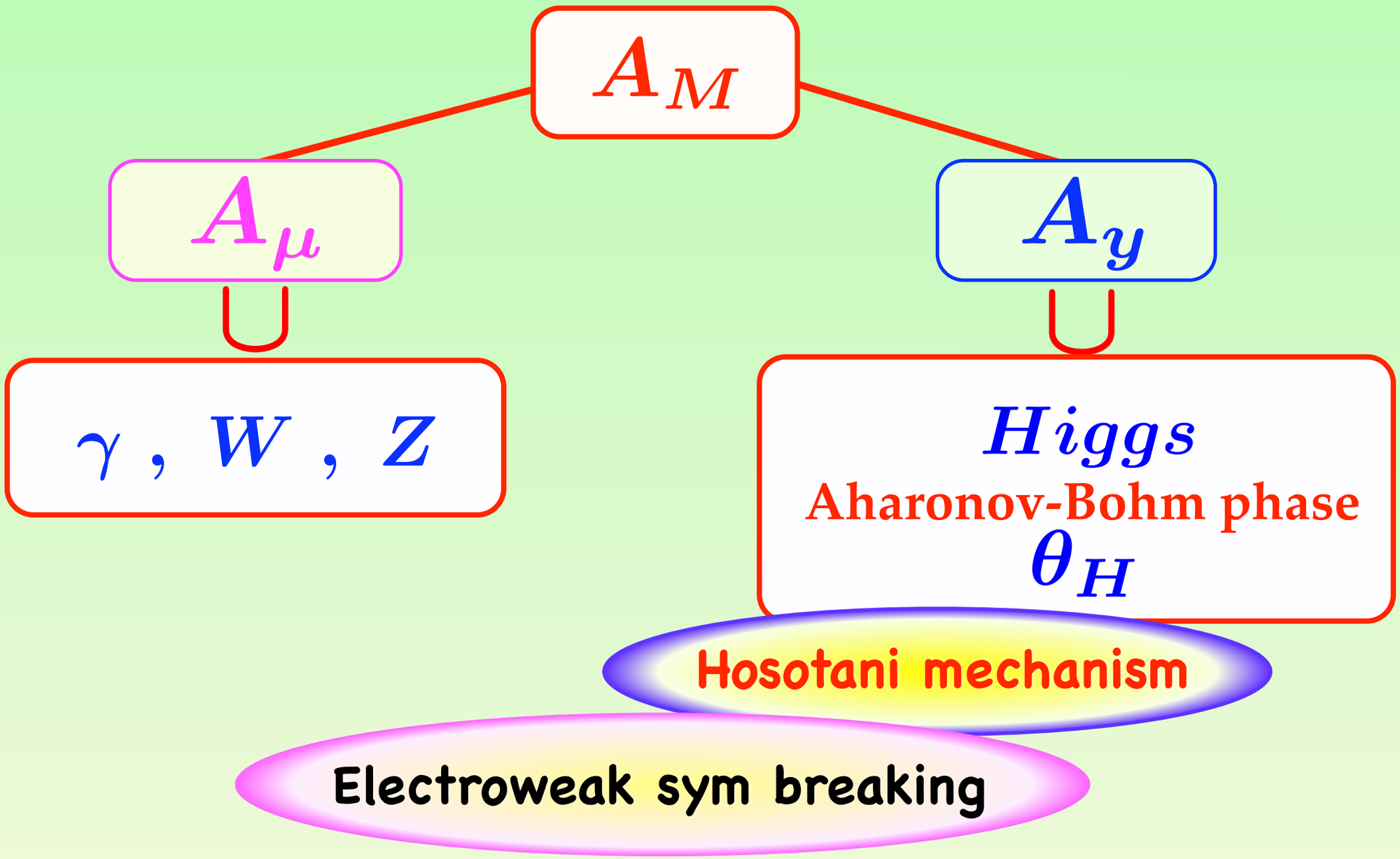

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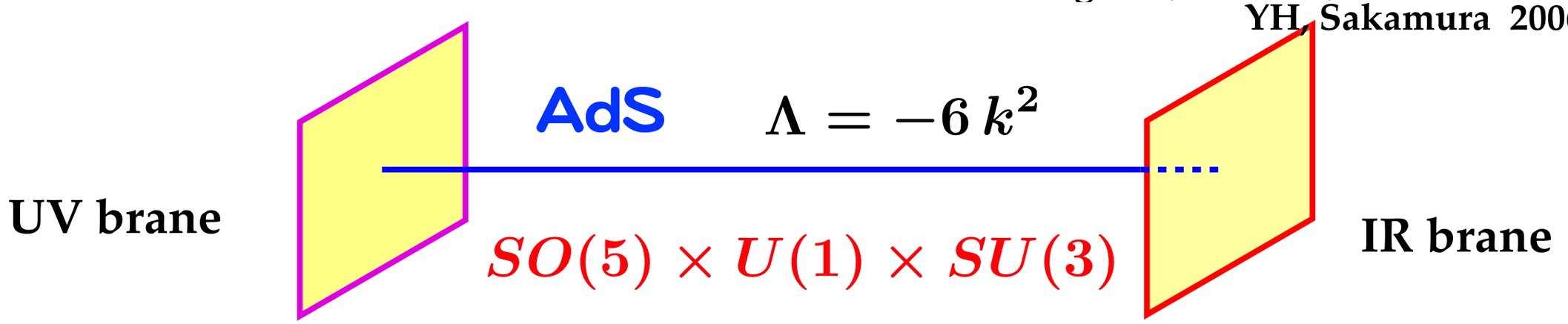
SO(5)xU(1)xSU(3) GHU in Randall-Sundrum warped space

Agashe, Contino, Pomarol 2005
YH, Sakamura 2006



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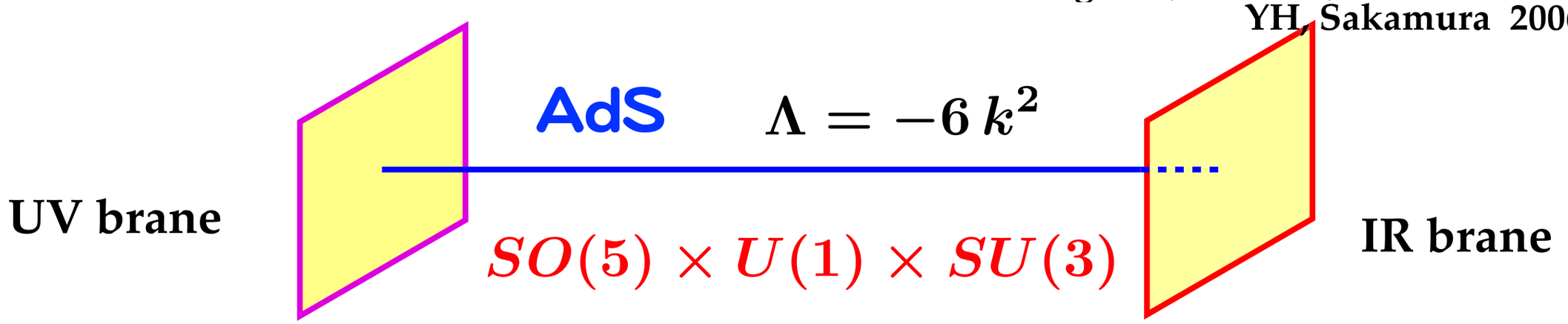

A

quarks/leptons
vector 5

YH, Oda, Ohnuma, Sakamura 2008
Funatsu, Hatanaka, YH, Orikasa, Shimotani 2013
Funatsu, Hatanaka, YH, Orikasa 2017

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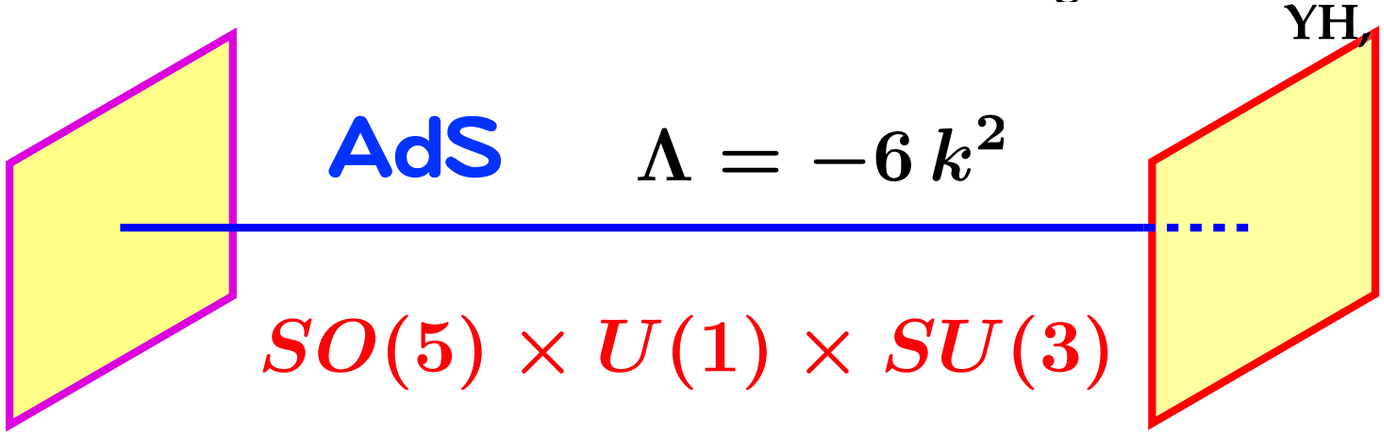

A **quarks/leptons**
vector 5

YH, Oda, Ohnuma, Sakamura 2008
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B **GUT inspired model**
spinor 4 +vector 5 + singlet 1

Funatsu, Hatanaka, YH,
Orikasa, Yamatsu 2019
(See: Funatsu's poster, Tue)

C other options Yoon, Peskin 2018

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Gauge couplings of SM particles

A

		$\theta_H = 0.115$		$\theta_H = 0.0737$		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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Funatsu, Hatanaka, YH, Orikasa, 1612.03378, 1705.05282

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	(u, d)	1.00019	1.00009	1
	(c, s)	1.00019	1.00009	
	(t, b)	0.9993		
$g_{L/R}^Z/g_w$	ν_e, ν_μ, ν_τ	0.50014		0.5 0
	e, μ, τ		0.2313	-0.2688 0.2312
	u	.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

Nearly the same as in SM

Funatsu, Hatanaka, YH, Orikasa, 1612.03378, 1705.05282

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New Particles

New Particles

Extra dims ➡ KK excitations

New Particles

Extra dims ➡ KK excitations

$n_F = 4$	$\theta_H = 0.115$ $z_L = 10^5$		$\theta_H = 0.0917$ $z_L = 3 \times 10^4$		$\theta_H = 0.0737$ $z_L = 10^4$	
Z'	m (TeV)	Γ (GeV)	m (TeV)	Γ (GeV)	m (TeV)	Γ (GeV)
$Z_R^{(1)}$	5.67	729	6.74	853	7.92	1058
$Z^{(1)}$	6.00	406	7.19	467	8.52	564
$\gamma^{(1)}$	6.01	909	7.20	992	8.52	1068

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

$\sim$ 7 TeV

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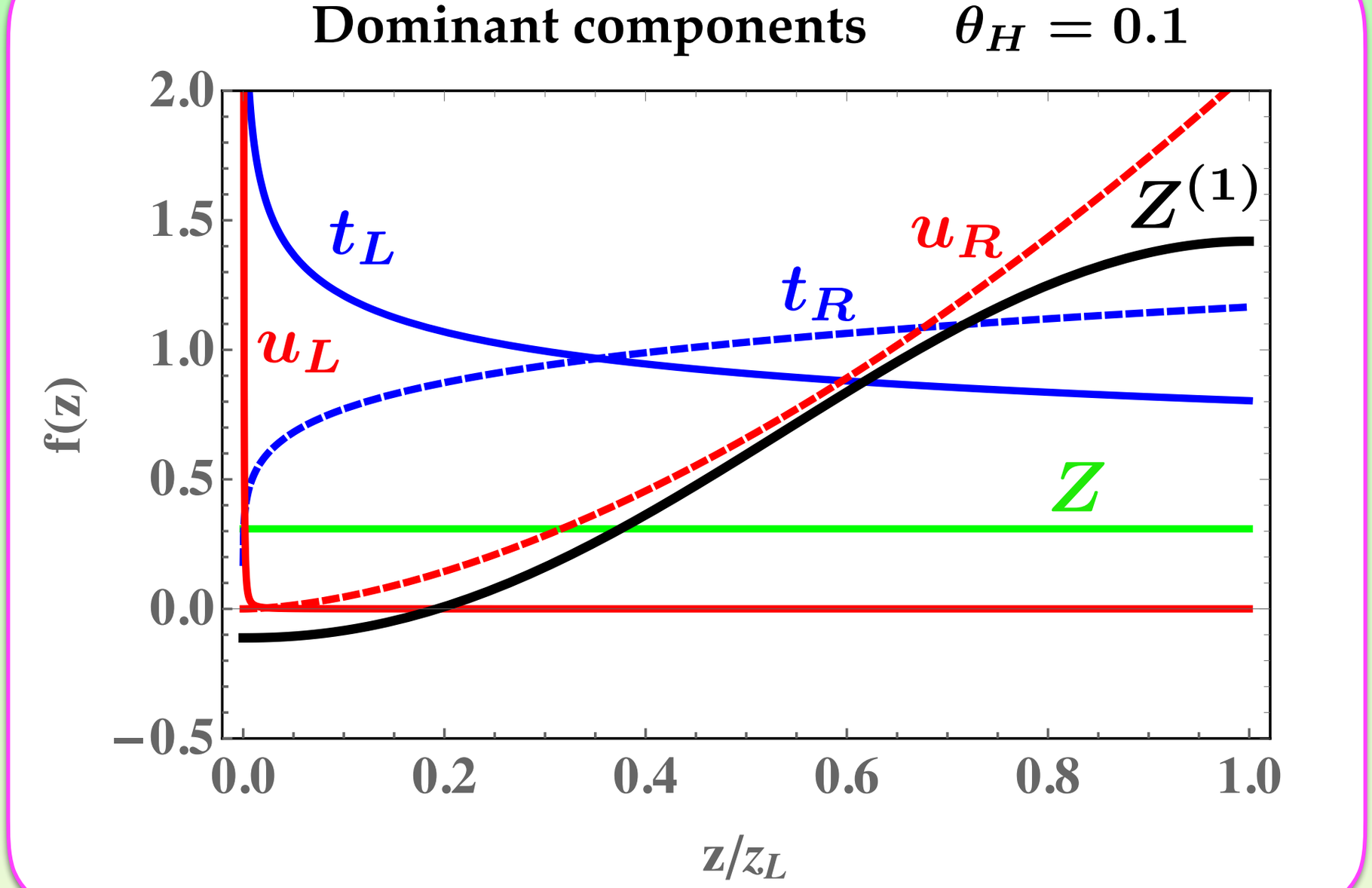
Wave functions in 5d



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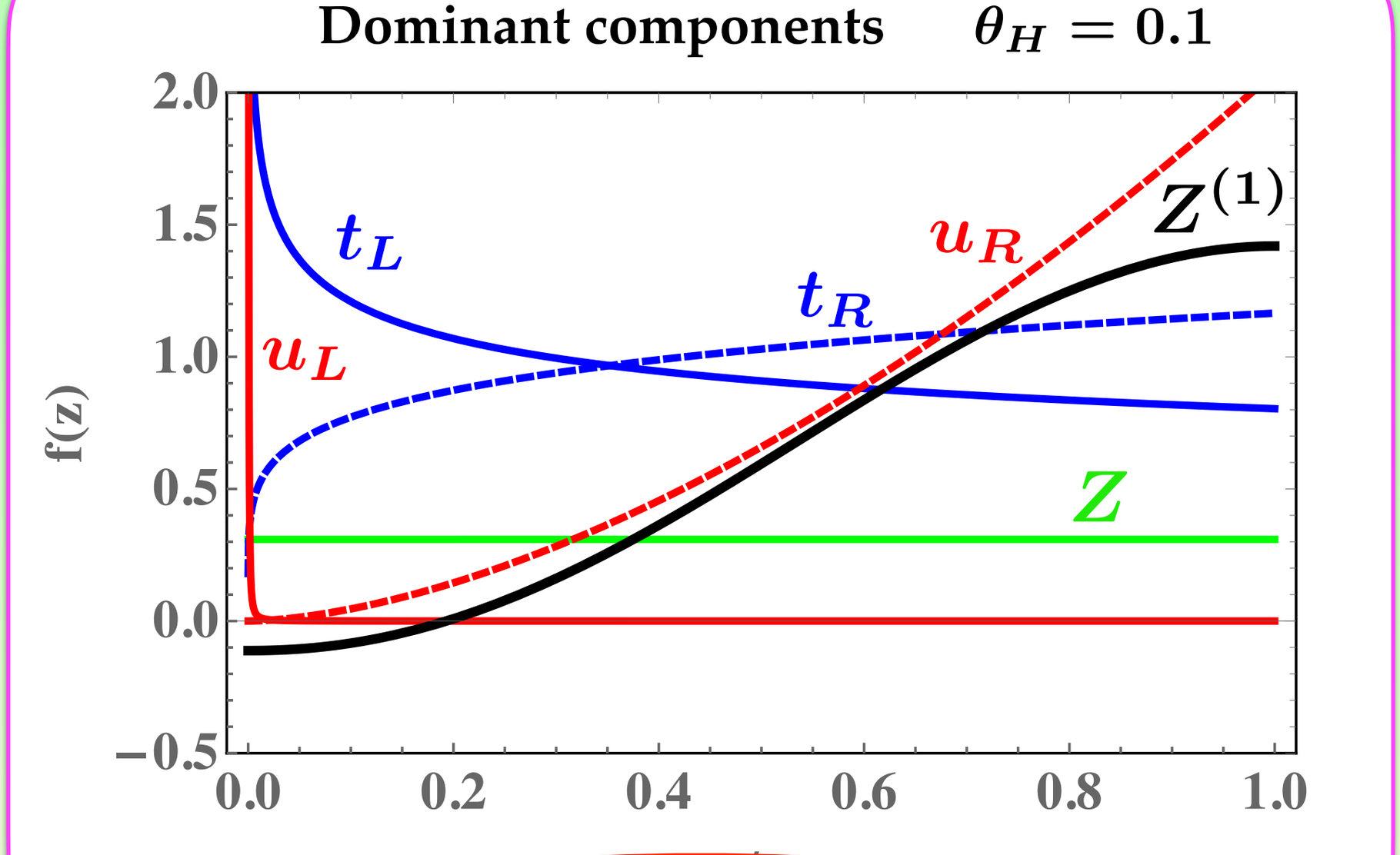

right-handed q, l
couple to Z′ strongly

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Z′ couplings

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

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Z′ couplings

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

$\theta_H = 0.0917$

A

	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

Z′ couplings

large !

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

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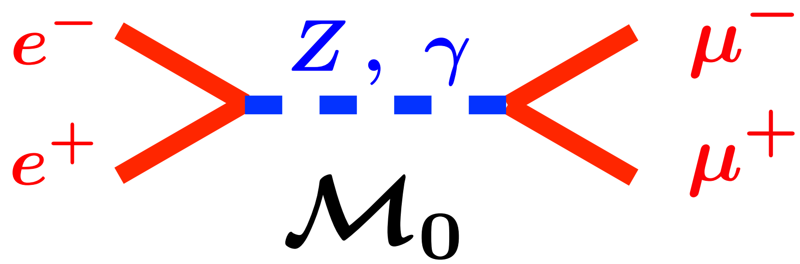
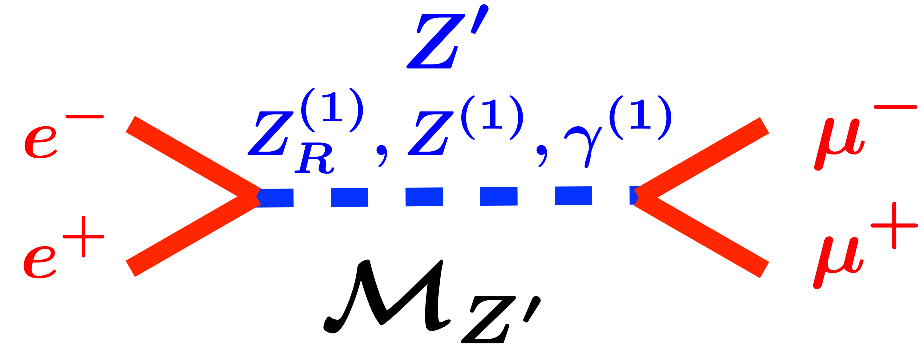
e^+e^- collisions (ILC, ...)

$\mathcal{M} =$  $+$ 

e^+e^- collisions (ILC, ...)

$$\mathcal{M} = \underbrace{\begin{matrix} e^- \\ e^+ \end{matrix} \!\!>\!\!\!-\!\!\!-\!\!\!<\!\!\!\begin{matrix} \mu^- \\ \mu^+ \end{matrix}}_{\mathcal{M}_0} + \underbrace{\begin{matrix} e^- \\ e^+ \end{matrix} \!\!>\!\!\!-\!\!\!-\!\!\!-\!\!\!-\!\!\!<\!\!\!\begin{matrix} \mu^- \\ \mu^+ \end{matrix}}_{\mathcal{M}_{Z'}}$$

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

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

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

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e^+e^- collisions (ILC, ...)

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Z, γ over $\mathcal{M}_0$; $Z', Z_R^{(1)}, Z^{(1)}, \gamma^{(1)}$ over $\mathcal{M}_{Z'}$

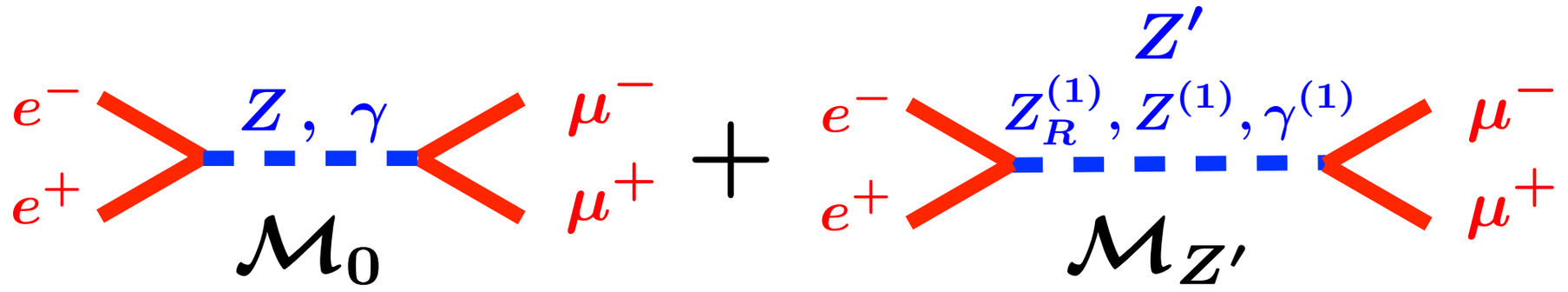
$$m_Z^2 \ll s \ll m_{Z'}^2$$

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

Look at: interference

e^+e^- collisions (ILC, ...)

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



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

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

Look at: interference

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

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

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

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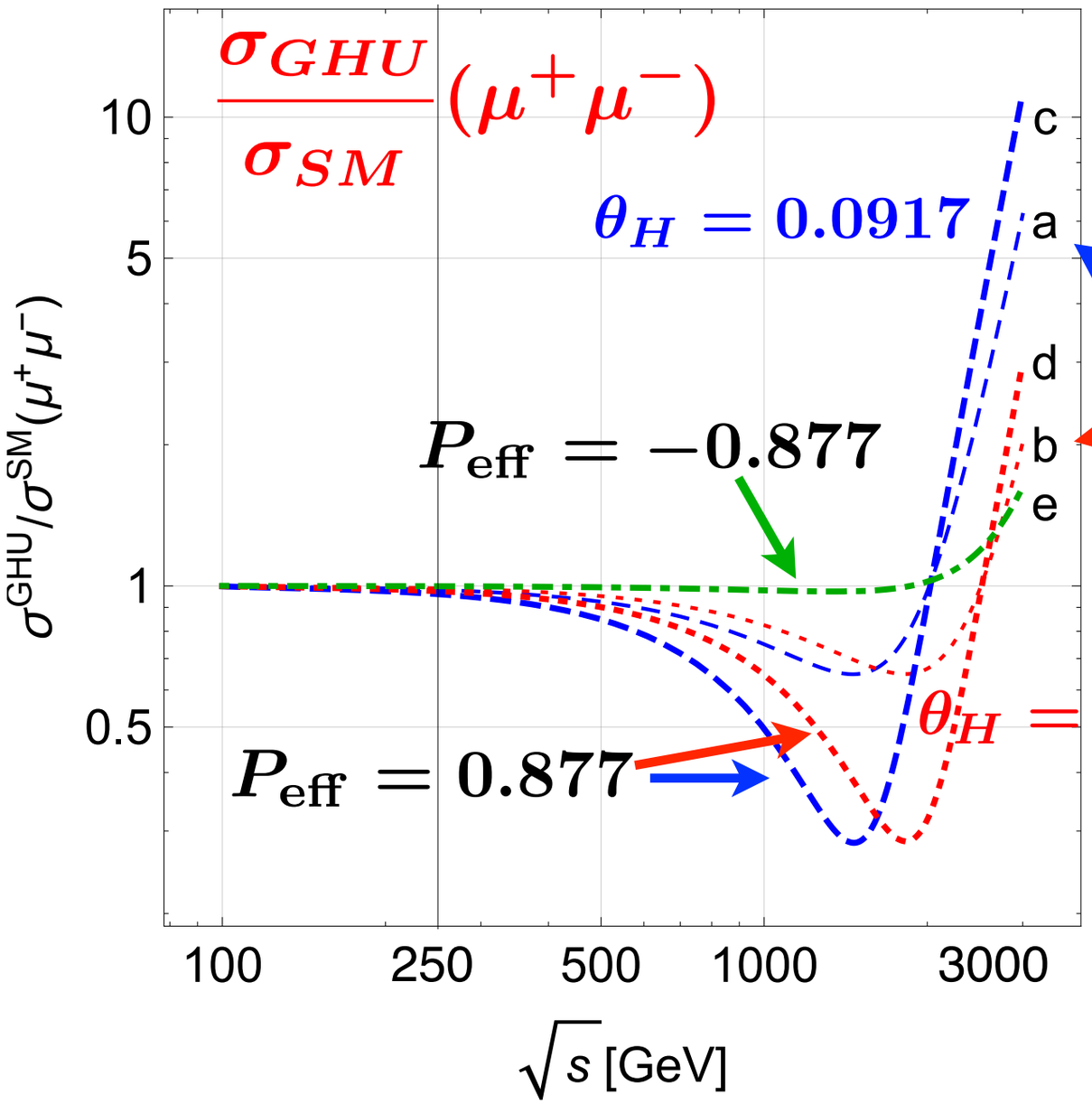
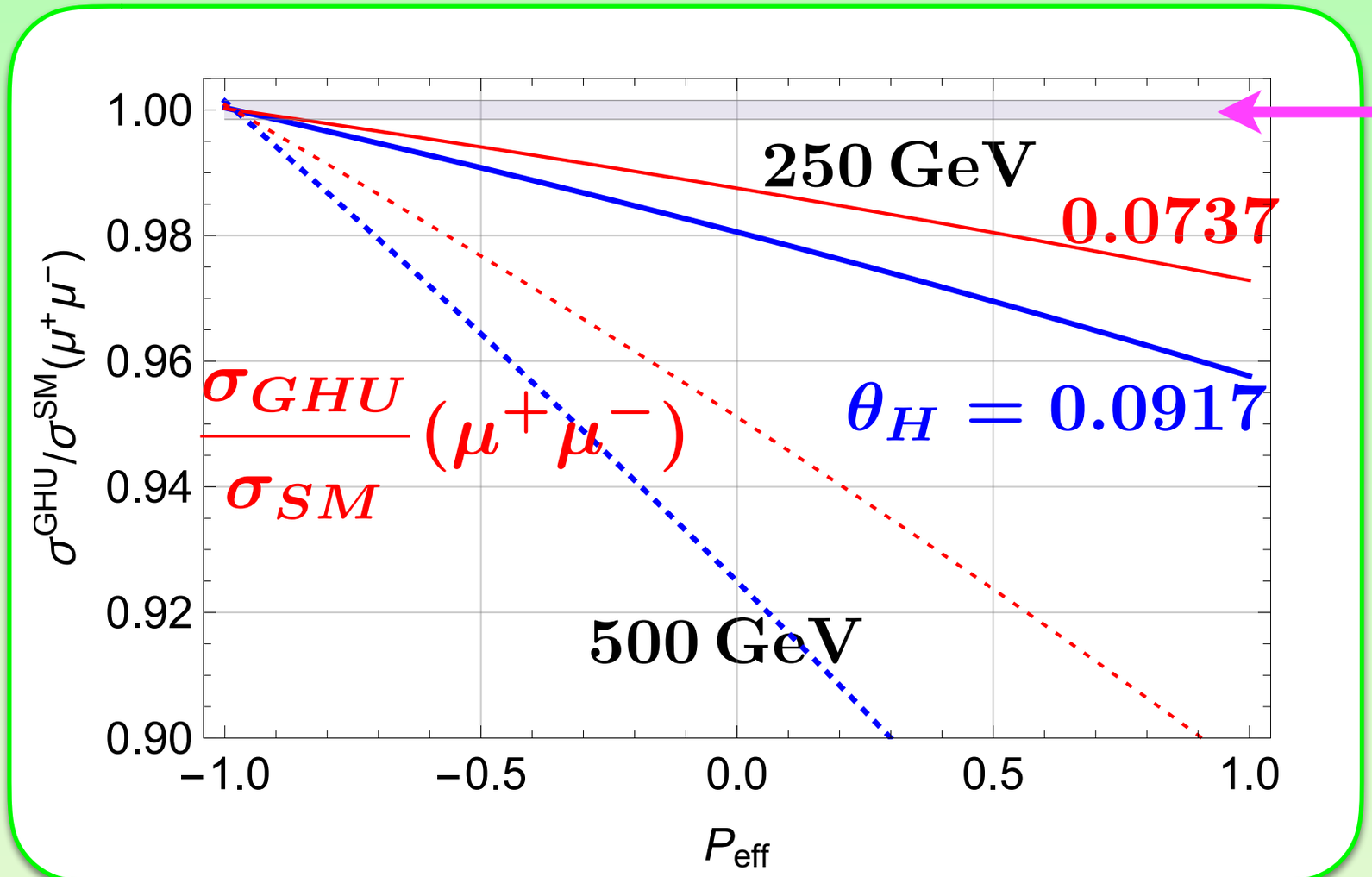
$e^+e^- \to \bar{f}f$



$P_{\rm eff} = 0$

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

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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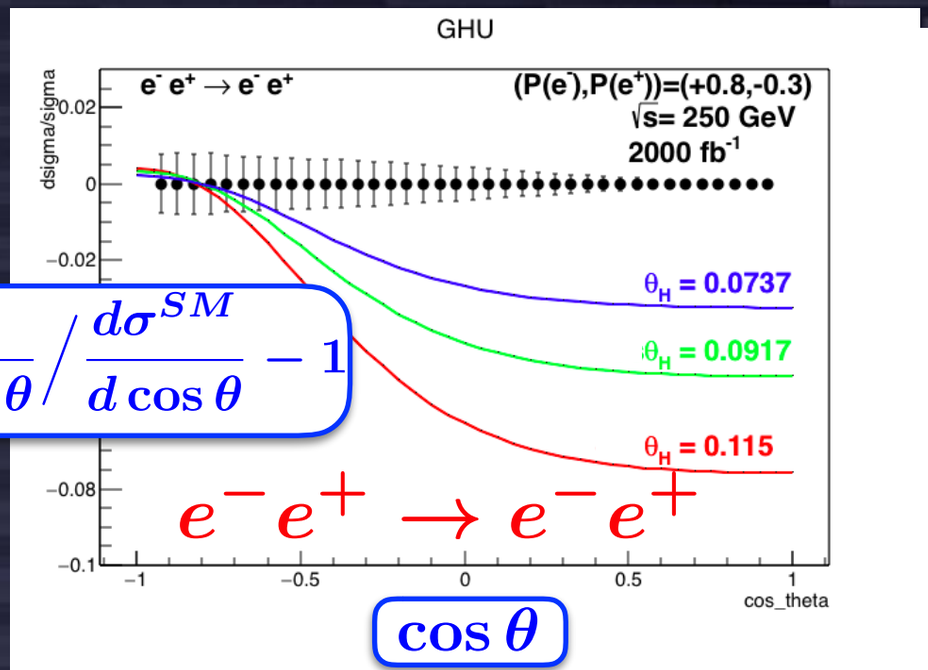
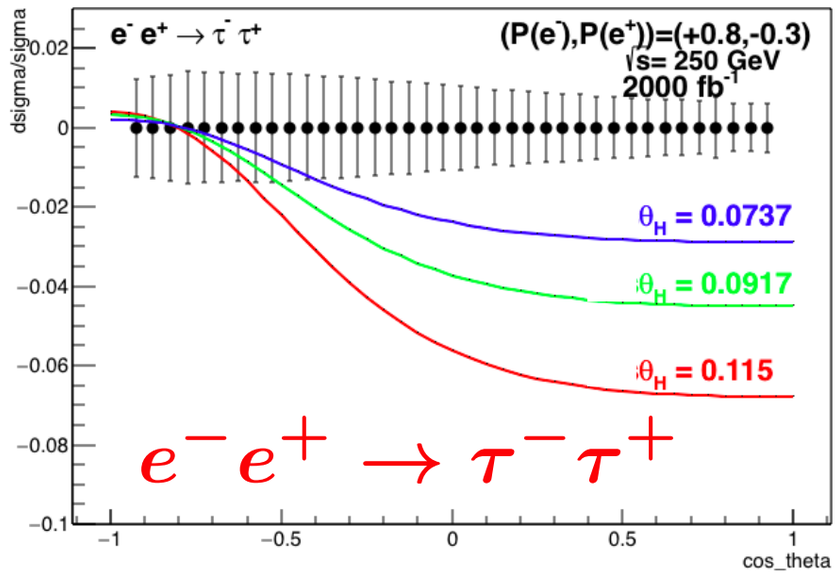
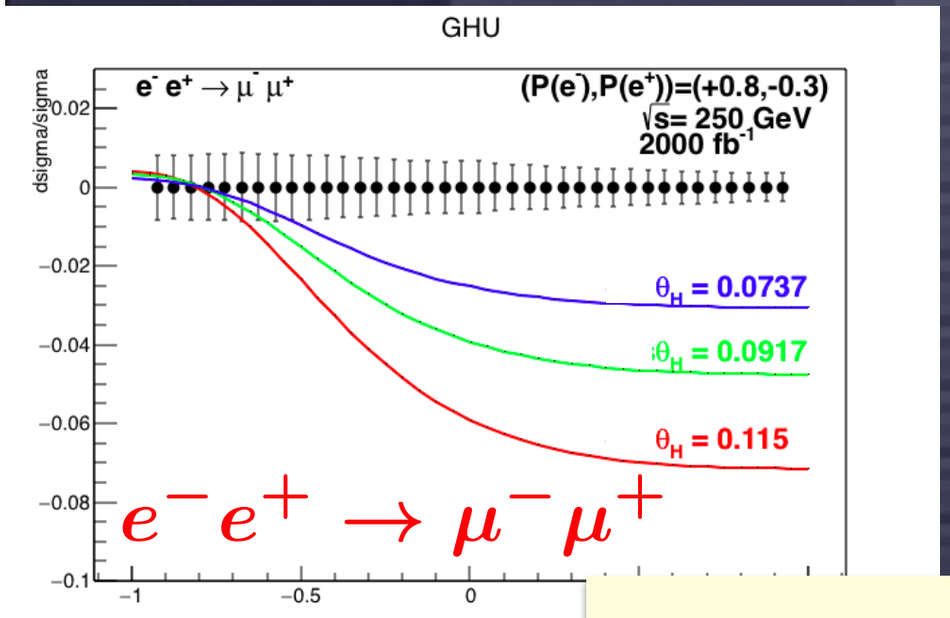
Leptonic channels – GHU sensitivity

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



$\cos\theta$





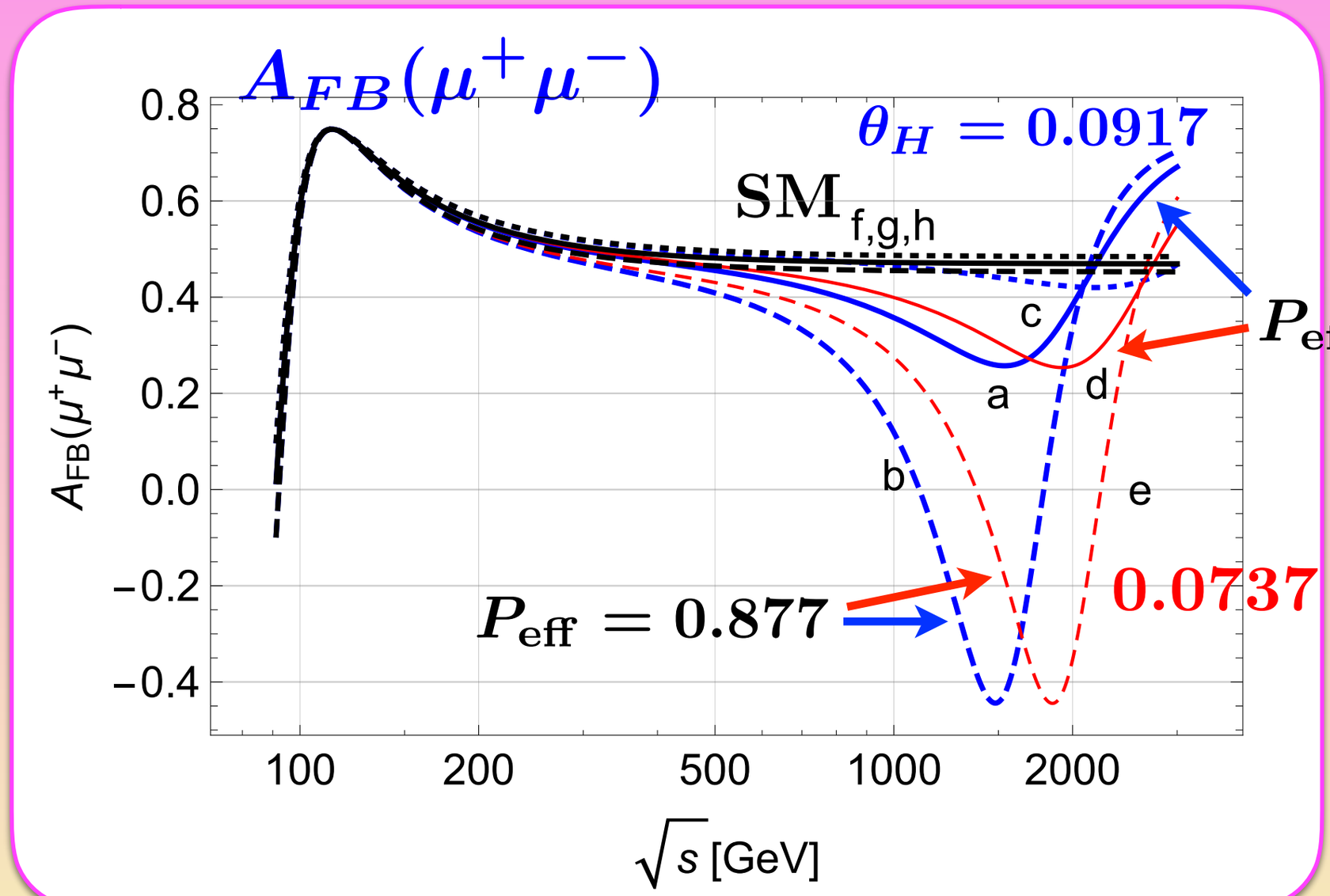
ILC 250

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

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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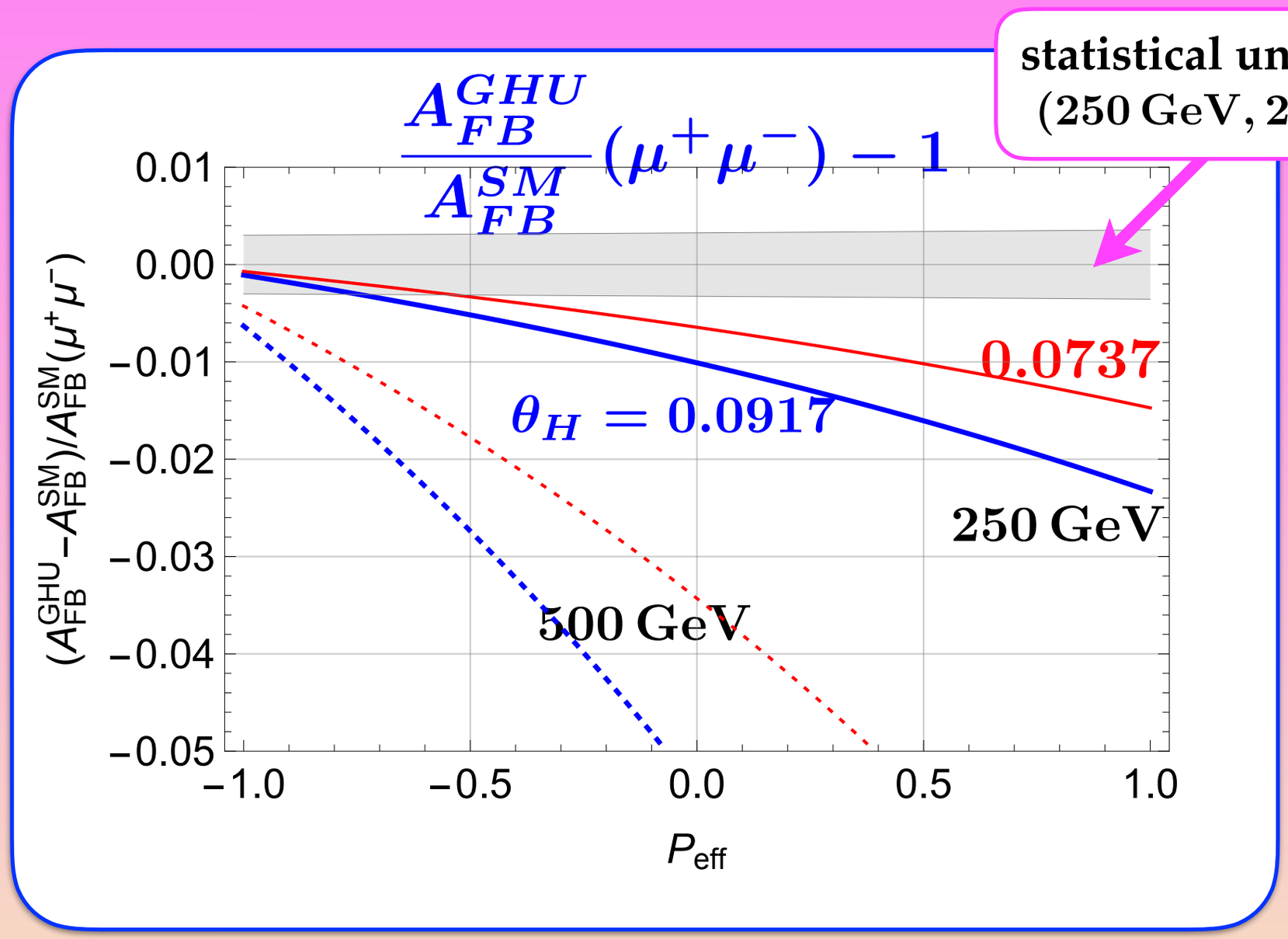

250 GeV, 250 fb^{-1} $P_{\rm eff} = 0.8$ **6 σ (4 σ)**

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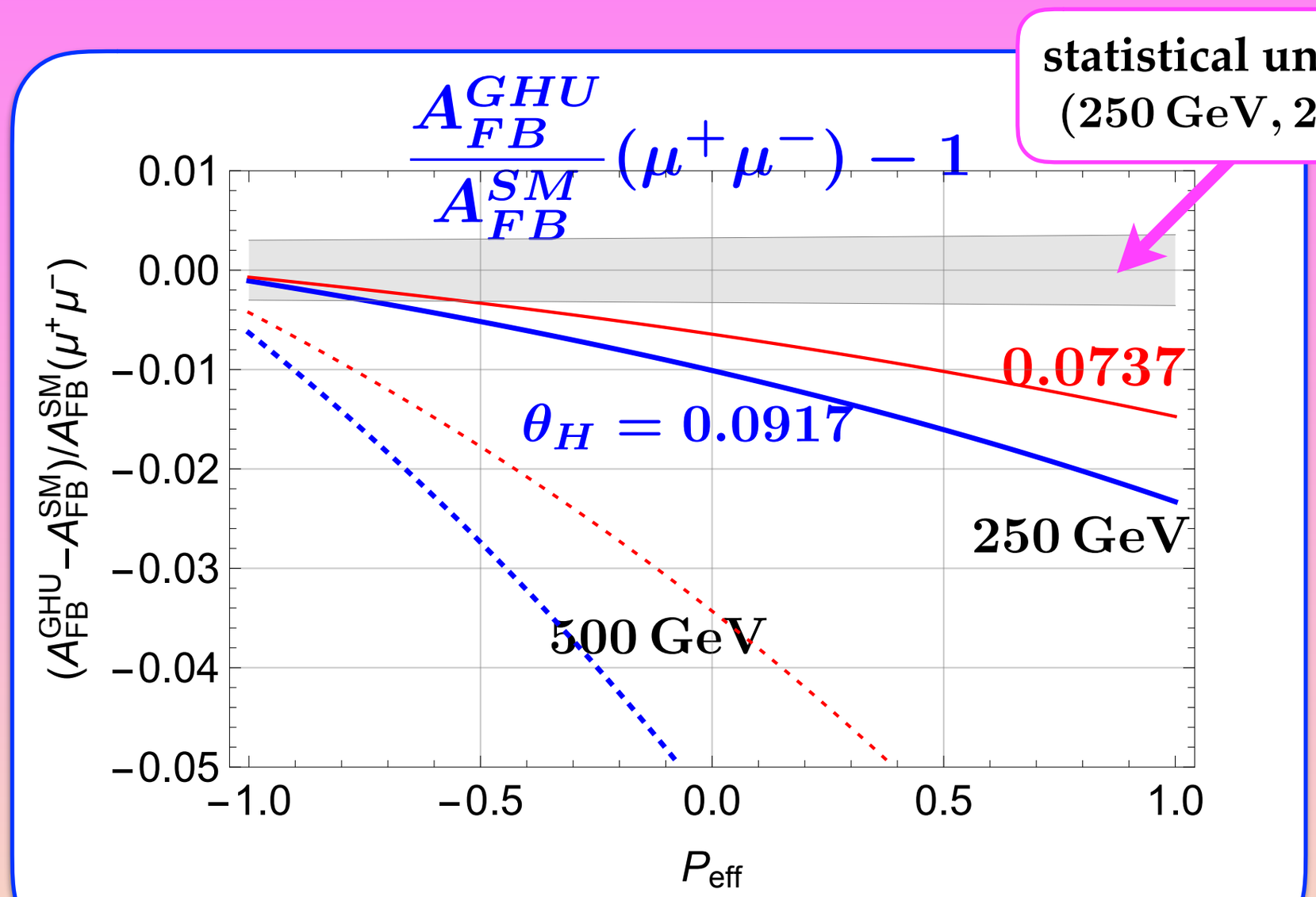

$250\,\mathrm{GeV},\ 250\,\mathrm{fb}^{-1}$ $\quad P_{\mathrm{eff}} = 0.8$ $\quad 6\,\sigma\,(4\,\sigma)$

Polarization dependence is the key.

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ILC 250GeV

Precision measurements of Higgs couplings

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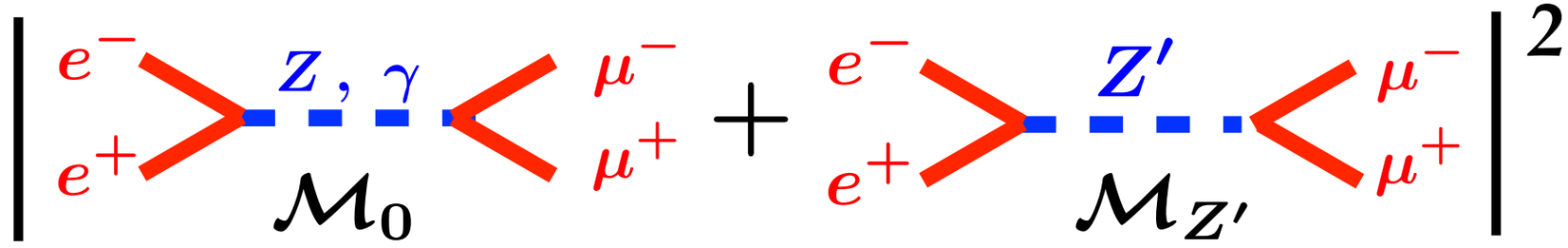
ILC 250GeV

Precision measurements of Higgs couplings

Explore New Particles (7 - 8 TeV)



e^+e^- 250 fb^{-1}, polarized e^- → $3\sigma-5\sigma$ signals

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