Gauge-Higgs unification : signals at LHC/ILC

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Physics
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LAL, Orsay, 5 December 2017

Unification of forces

$SU(3)_C$

Strong int.

$U(1)_{EM}$

EM

Electroweak

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

Weak int.

(SUSY) GUT

$SU(5)$?

Gravity

Superstrings

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Unification of gauge forces

Large gauge symmetry

Spontaneous symmetry breaking

Higgs mechanism

Higgs boson

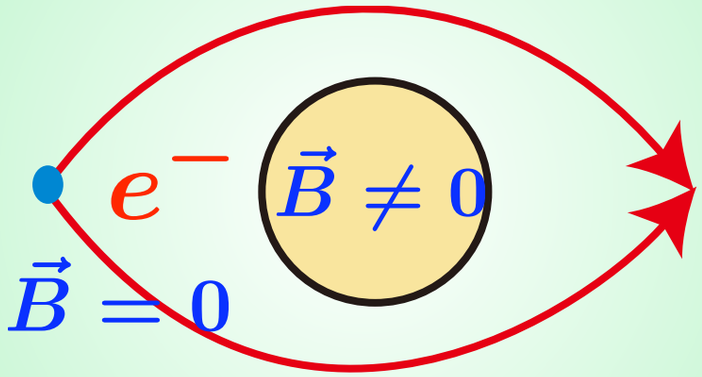
Smaller gauge symmetry at low energies

Large gauge symmetry

Spontaneous symmetry breaking

Smaller gauge symmetry at low energies

Aharonov-Bohm effect



$$\oint \vec{A}\, d\vec{x} = \int \vec{B}\, d\vec{S} = \Phi$$

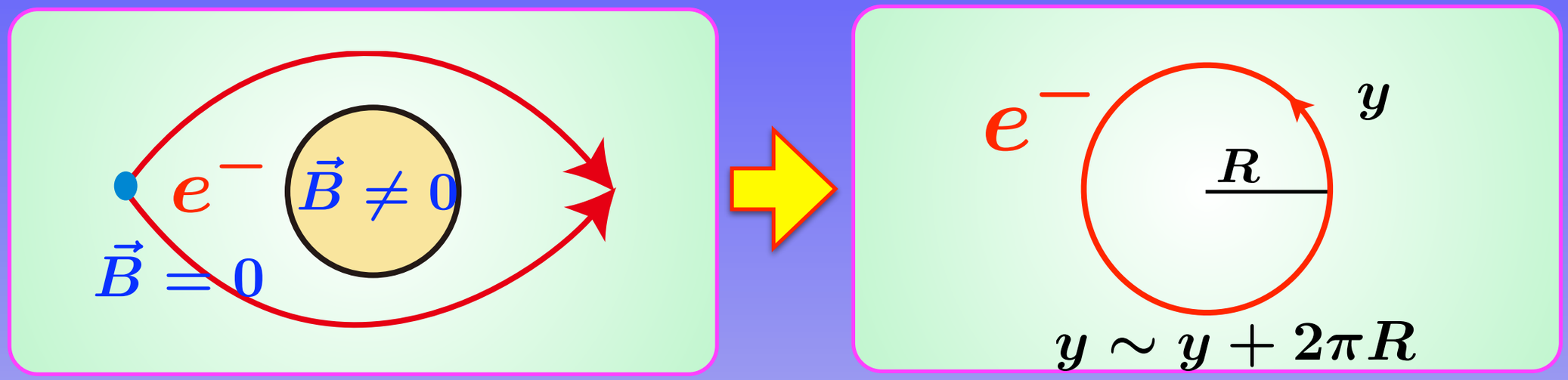
$$A_\theta = \frac{\Phi}{2\pi r}$$

$$F_{\mu\nu} = 0\ , \quad \text{but nontrivial.}$$

$$\exp\left\{ i \frac{e}{\hbar c} \oint \vec{A}\, d\vec{x} \right\} = e^{i\theta_{AB}} \qquad \theta_{AB} = \frac{e\Phi}{\hbar c}$$

AB phase

e^- on S^1



$$\exp\left\{ i\frac{e}{\hbar c}\int_0^{2\pi R} dy A_y \right\} = e^{i\theta_{AB}}$$

Gauge transformation

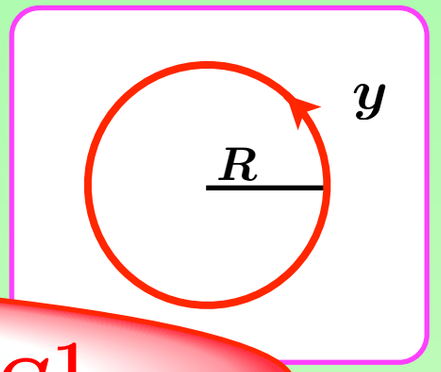
$$A_\mu \to A'_\mu = A_\mu + \partial_\mu \Lambda$$

$$\psi \to \psi' = e^{i(e/\hbar c)\Lambda}\,\psi$$

$$\Lambda = \beta y\ , \quad A'_y = A_y + \beta$$

$$e^{i(e/\hbar c)\beta \cdot 2\pi R} = 1$$

AB phase θ_{AB} cannot be gauged away.



Non-Abelian gauge fields on $M^4 \times S^1$

$$A_y = \text{const}\ , \quad F_{MN} = 0$$

$$W = P e^{ig \oint A_y dy} \quad \not\propto I$$

eigenvalues : AB phases

example: SU(3)

$$\{e^{i\theta_1}, e^{i\theta_2}, e^{i\theta_3}\} \quad (\Sigma\theta_j = 0)$$

$\theta_1 = \theta_2 = \theta_3$	$SU(3)$
$\theta_1 = \theta_2 \neq \theta_3$	$SU(2) \times U(1)$
$\theta_j \neq \theta_k$	$U(1) \times U(1)$

$\{\ \theta_j\ \}$ undetermined at the classical level

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

$\theta_H = \{\,\theta_j\,\}$ **determined at the quantum level**

$$A_M(x,y) = \sum_n A_M^{(n)}(x)\, e^{iny/R}$$

$$\mathcal{L} = -\tfrac{1}{2}\mathrm{tr}\, F_{MN}F^{MN} \Rightarrow \mathrm{tr}\,(\partial_y A_\mu + ig[A_\mu, A_y^c])^2$$

$$A_\mu^{(jk)(n)}\ :\ m_n^2 = \frac{1}{R^2}\left(n + \frac{\theta_j - \theta_k}{2\pi}\right)^2$$

$$V_{\rm eff}^{1\,loop}(\theta_H) = \sum\sum_n \int \frac{d^3p}{(2\pi)^3}(\pm)\frac{1}{2}\sqrt{\vec{p}^{\,2} + m_n(\theta_H)^2}$$

zero point energies

θ_H-dependent part : **finite**

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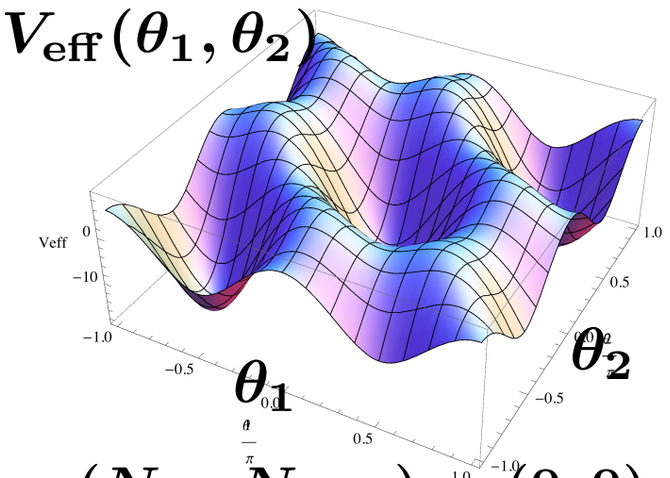
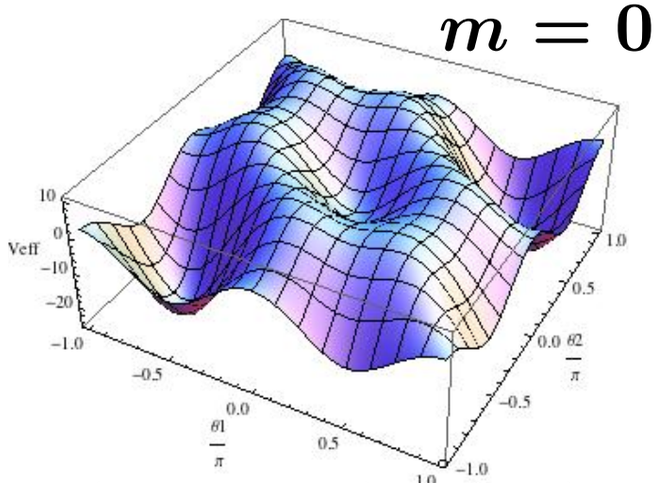
SU(3) $V_{\rm eff}(\theta_1, \theta_2)^{1\ \rm loop}$

$D = 5$



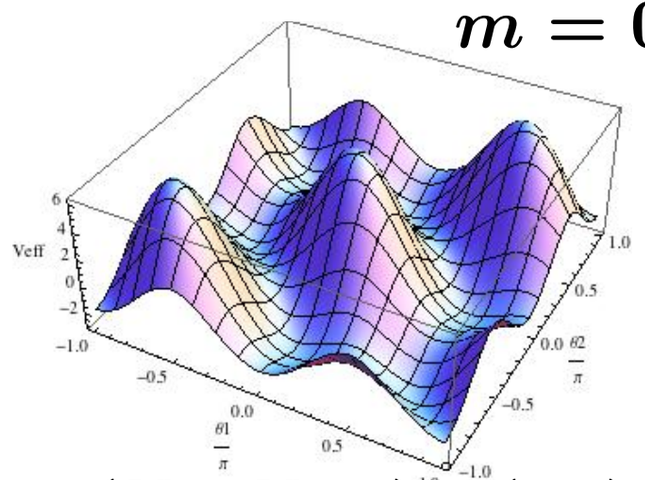
$(N_{\rm ad}, N_{\rm fund}) = (0, 0)$

$SU(3)$



$(N_{\rm ad}, N_{\rm fund}) = (0, 1)$

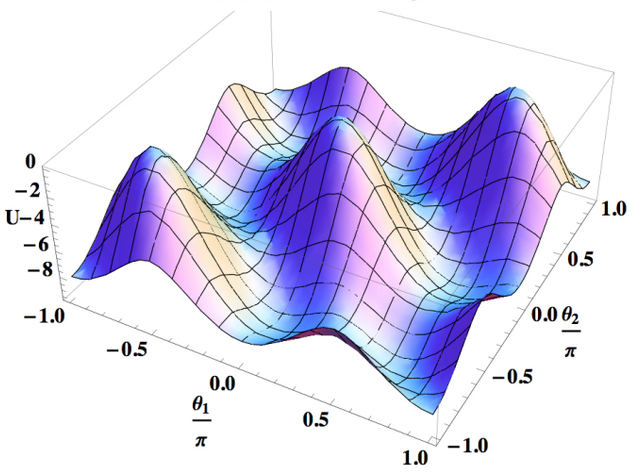
$SU(3)$



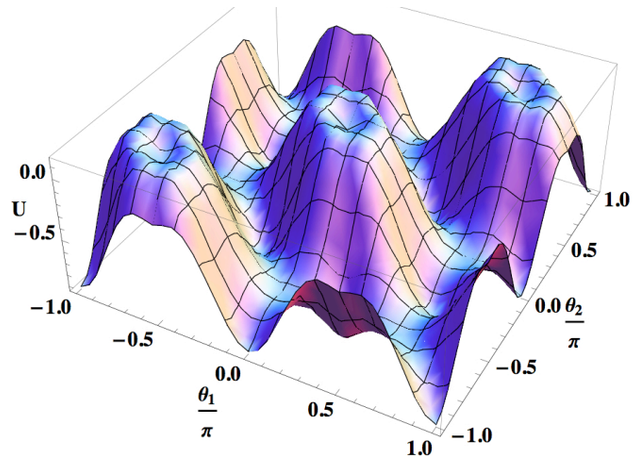
$(N_{\rm ad}, N_{\rm fund}) = (1, 0)$

$U(1) \times U(1)$

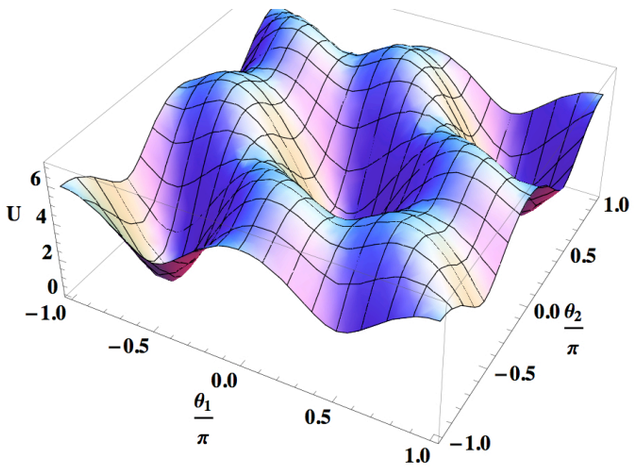
$D = 4 \quad (N_{\rm ad}, N_{\rm fund}) = (1, 0)$



$U(1) \times U(1)$



$SU(2) \times U(1)$



$SU(3)$

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Hosotani mechanism

(1983)

Non-Abelian gauge theory in $M^4 \times S^1$, $M^4 \times (S^1/Z_2)$, RS, $\cdots$

→ AB phase θ_H

$V_{\rm eff}(\theta_H)$: finite

$\theta_H \neq 0 \Rightarrow$ gauge symmetry dynamically broken

fluctuations of θ_H ⟷ 4d Higgs field

finite m_H generated

gauge hierarchy prob. solved

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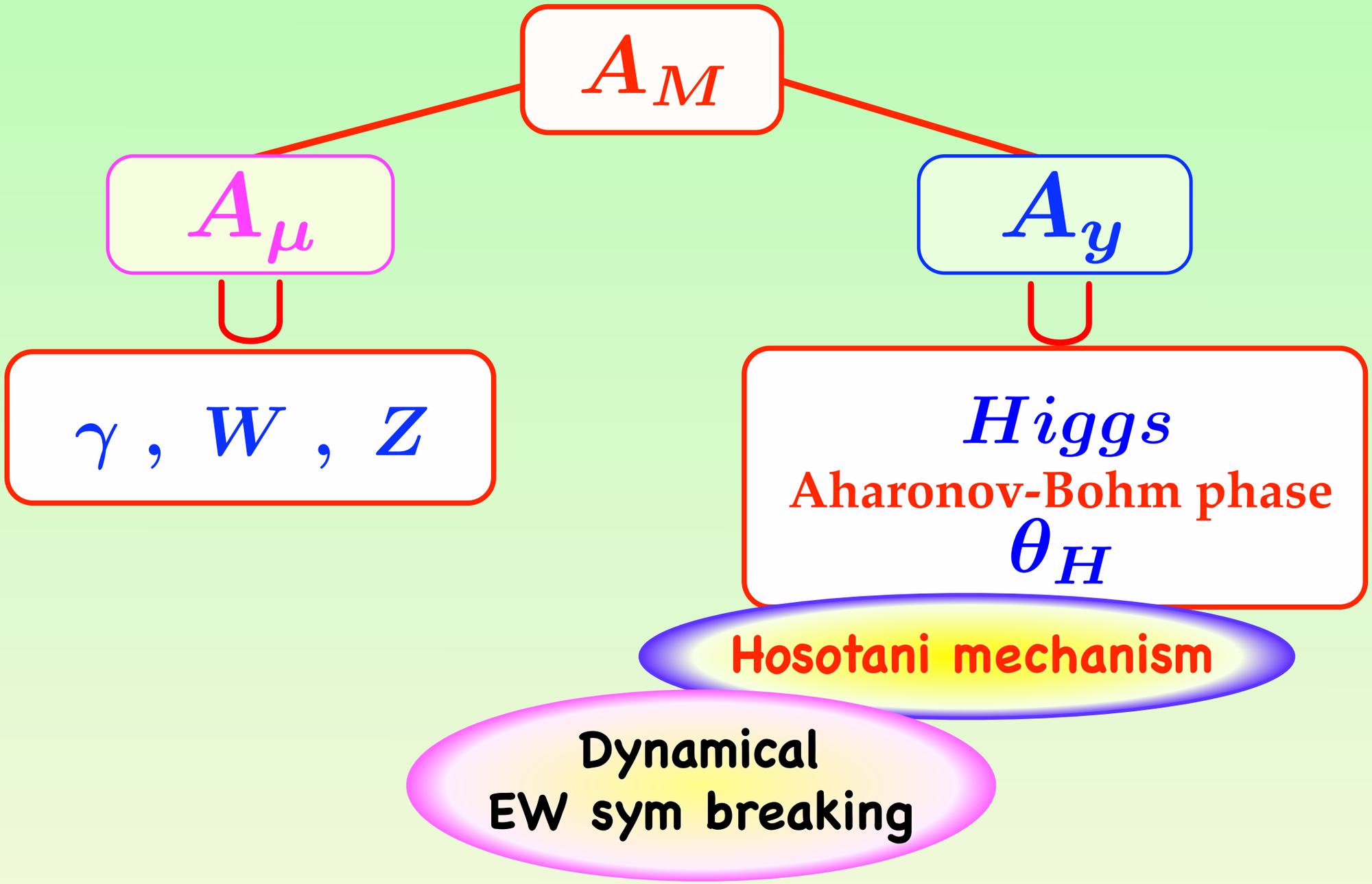
Gauge-Higgs unification



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Standard Model

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

$+$

$\mathcal{L}_{\rm Higgs}$ no principle

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

$+$

$\mathcal{L}_{\rm Yukawa}$ no principle

Gauge-Higgs Unification

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

gauge principle

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

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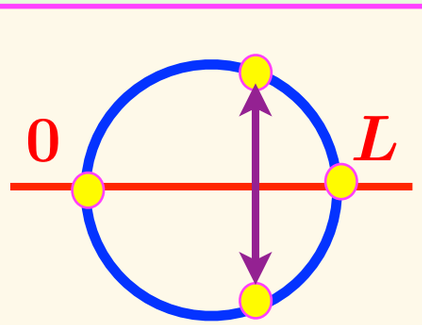
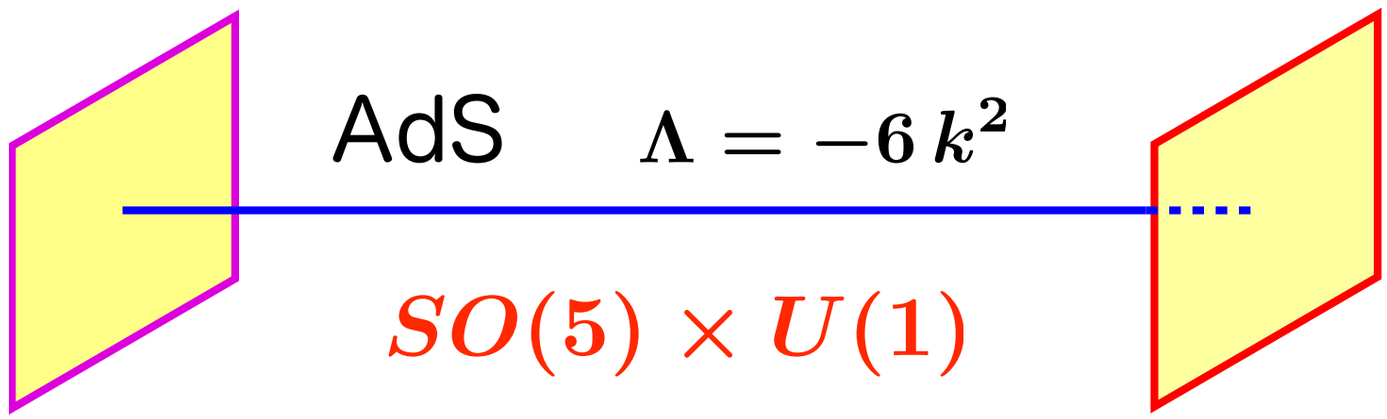
SO(5)xU(1) GHU in Randall-Sundrum

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

$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x, y_j - y) = P_j \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x, y_j + y) P_j^\dagger$$

$$(y_0, y_1) = (0, L)$$

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4D gauge bosons and Higgs

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

$$SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)_R$$

$$A_\mu \sim \begin{pmatrix} W\ Z\ \gamma & \\ & \end{pmatrix} \qquad A_y \sim \begin{pmatrix} \text{Higgs} & \\ & \end{pmatrix}$$

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

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SO(5)xU(1) EW

UV brane

IR brane

quarks/leptons
vector rep Ψ_5

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

Brane scalar

$\hat{\Phi}\ (0, \frac{1}{2})$

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

$\begin{pmatrix} \hat{T}_R \\ \hat{B}_R \end{pmatrix}$ $\begin{pmatrix} \hat{U}_R \\ \hat{D}_R \end{pmatrix}$ $\begin{pmatrix} \hat{X}_R \\ \hat{Y}_R \end{pmatrix}$

dark fermions
spinor rep Ψ_4

At low energies

Nearly the same as SM

gauge couplings of quarks/leptons~ SM

	g_{GHU}/g_{SM} $(\theta_H = 0.115)$
W to $\ell\nu$, ud , cs	1.00019
tb	0.9993
WWZ	0.9999998

Higgs couplings to W, Z, quarks/leptons ~ $(SM) \times \cos\theta_H$

$$\cos\theta_H \sim 0.995 \quad \text{for } \theta_H = 0.1$$

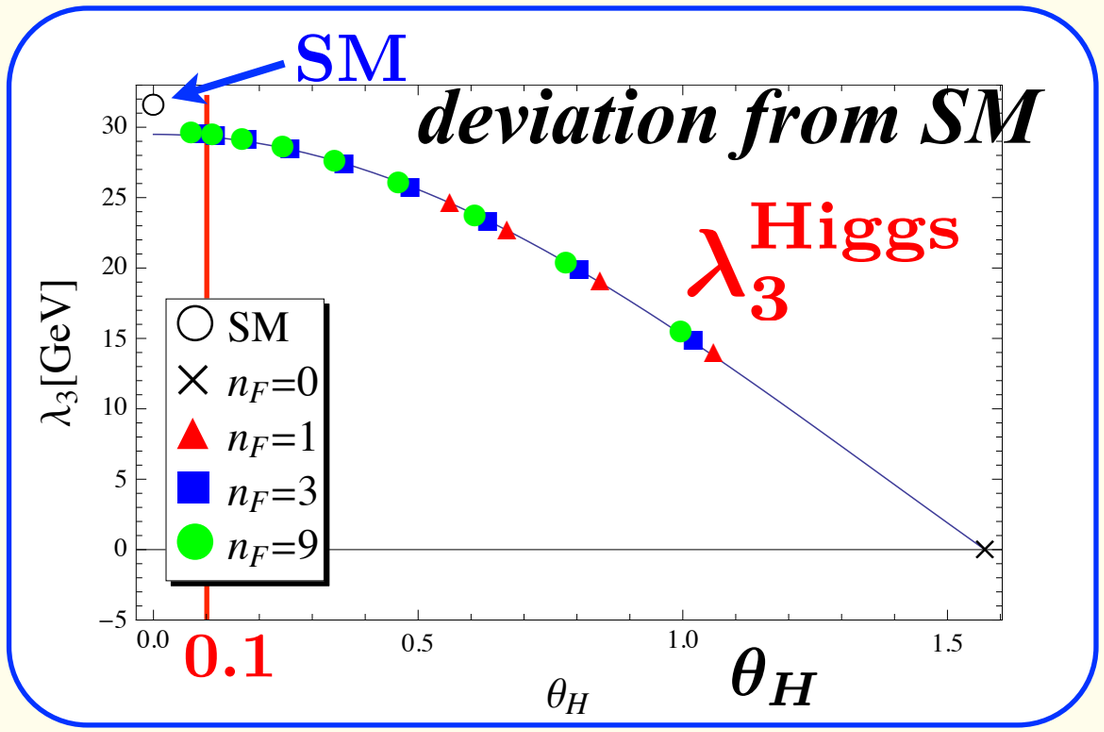
Higgs decays:

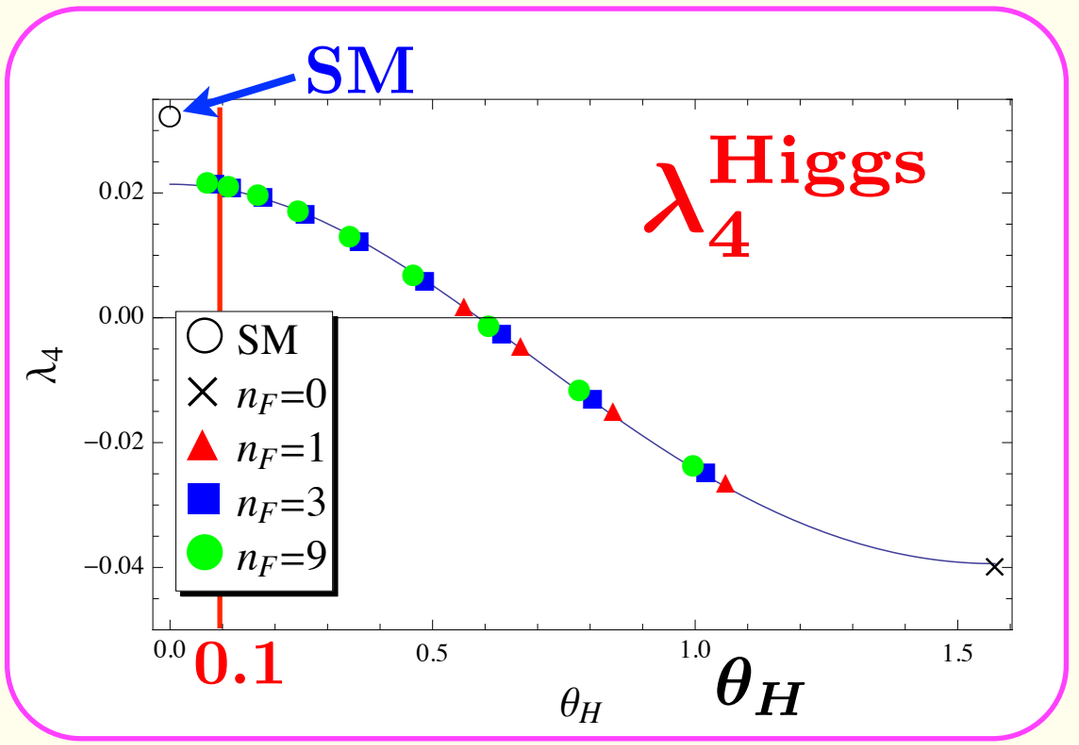
$$\Gamma(H \to \gamma\gamma), \mu(H \to \gamma\gamma) \sim (SM) \times \cos^2\theta_H$$

corrections due to KK modes < 0.2%

Branching fractions ~ (SM)

Higgs self-couplings





FHHOS 1301.1744, 1404.2748

Small deviation for $\theta_H \sim 0.1$

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Extra dims ➡ KK excitations

KK gluons, W', Z'

$n_F = 4$	$\theta_H = 0.115$ $z_L = 10^5$		$\theta_H = 0.0917$ $z_L = 3 \times 10^4$		$\theta_H = 0.0737$ $z_L = 10^4$	
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

Funatsu, Hatanaka, YH, Orikasa,

LHC : 1612.03378 (PRD) ILC : 1705.05282v3 (PLB)

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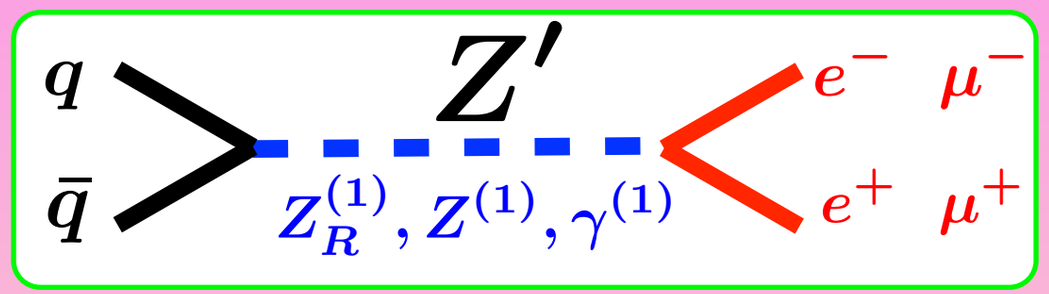
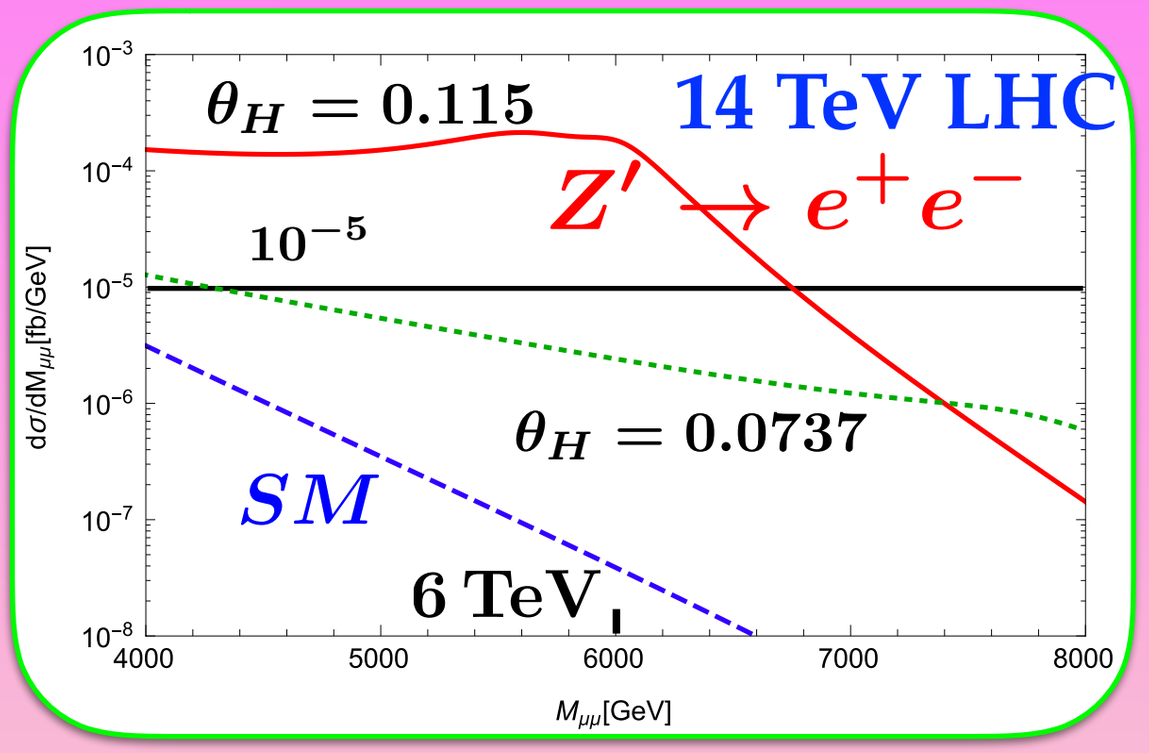
LHC

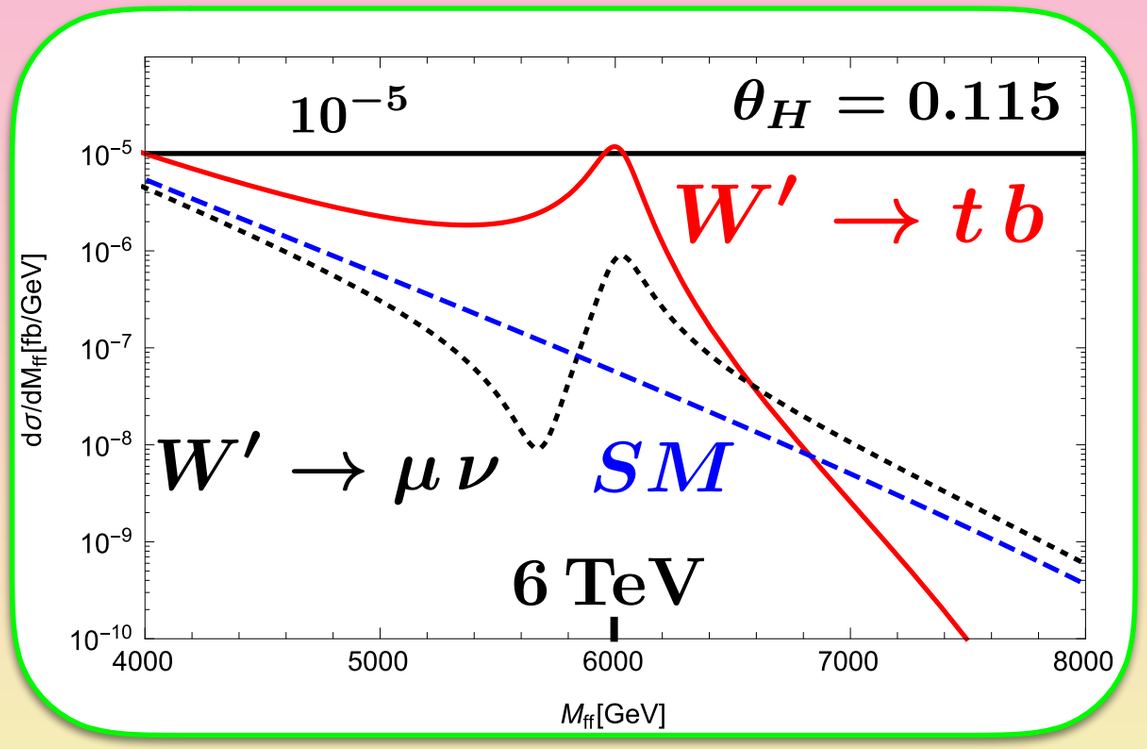




ATLAS-CONF-2017-027
(9 April 2017)
$\sqrt{s} = 13\,\text{TeV}, \quad 36.1\,\text{fb}^{-1}$

no event for > 3000 GeV

$\Rightarrow \quad \theta_H < 0.1$



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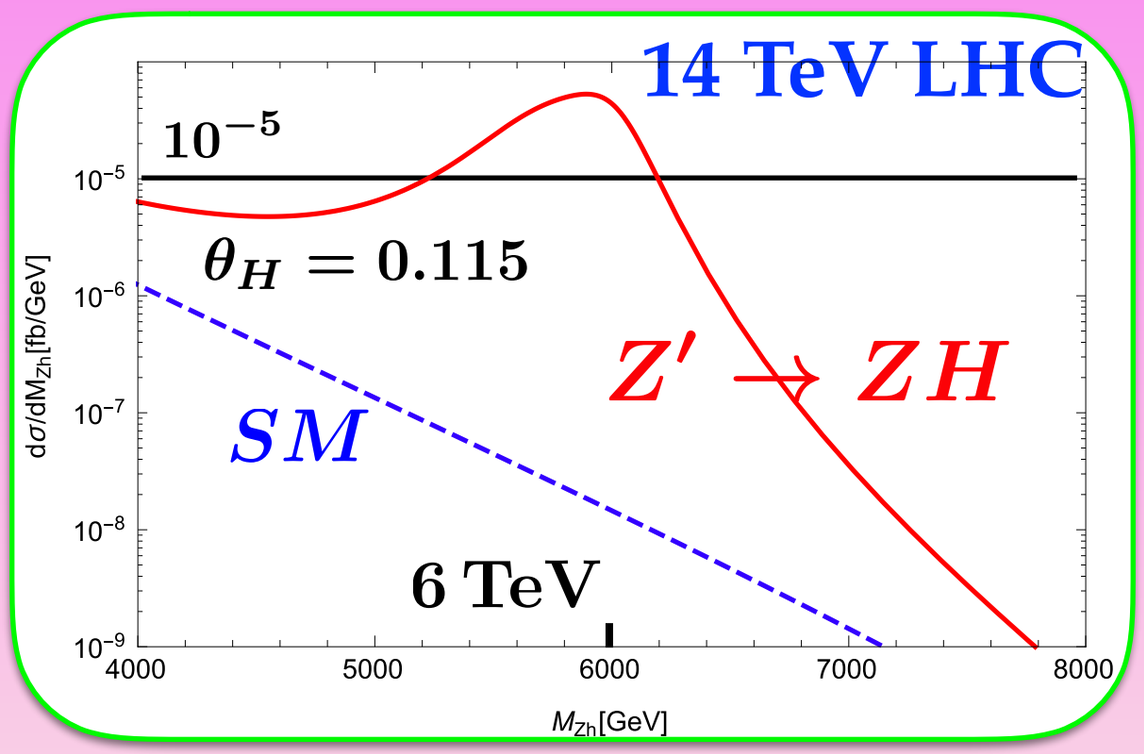

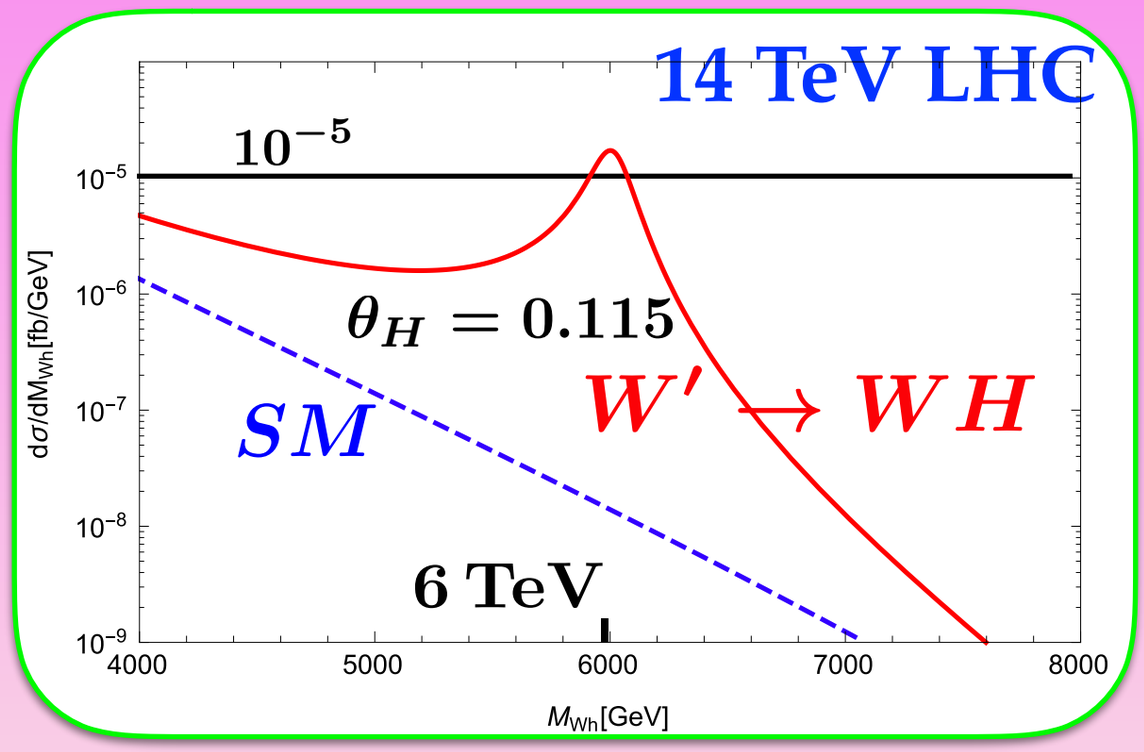

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Left-right asymmetry in the couplings to Z′

Wave functions

Z' : **localized near IR brane**

q_R , ℓ_R **near IR brane**

⇒ **large**

q_L , ℓ_L **near UV brane**

⇒ **small**

light quarks, leptons: sharply localized
top, bottom quarks : spread with long tails

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Couplings to Z′

	Z		Z'					
f	g^L_{Zf}	g^R_{Zf}	$g^L_{Z^{(1)}f}$	$g^R_{Z^{(1)}f}$	$g^L_{Z^{(1)}_R}$	$g^R_{Z^{(1)}_R f}$	$g^L_{\gamma^{(1)}f}$	$g^R_{\gamma^{(1)}f}$
ν_e	0.5704	0	−0.209	0	0	0	0	0
ν_μ	0.5704	0	−0.209	0	0	0	0	0
ν_τ	0.5704	0	−0.209	0	0	0	0	0
e	−0.3066	0.2639	0.112	1.044	0	−1.438	0.177	−1.869
μ	−0.3066	0.2639	0.112	0.980	0	−1.361	0.177	−1.783
τ	−0.3066	0.2639	0.112	0.973	0	−1.296	0.177	−1.687
u	0.3945	−0.1759	−0.145	−0.684	0	0.944	−0.118	1.243
c	0.3945	−0.1759	−0.148	−0.624	0	0.882	−0.118	1.151
t	0.3937	−0.1759	0.564	−0.425	1.124	0.626	0.461	0.773
d	−0.4824	0.08796	0.177	0.342	0	−0.472	0.059	−0.622
s	−0.4824	0.08796	0.177	0.316	0	−0.441	0.059	−0.575
b	−0.4825	0.08795	−0.696	0.213	1.122	−0.313	−0.230	−0.387

in unit of g_w ($\theta_H = 0.0917$)

Funatsu, Hatanaka, YH, Orikasa, 1705.05282

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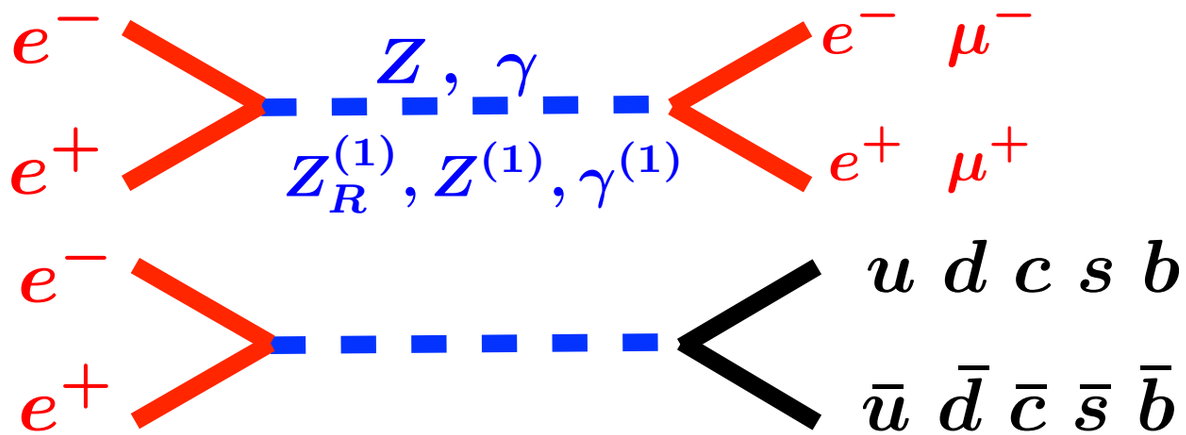
ILC

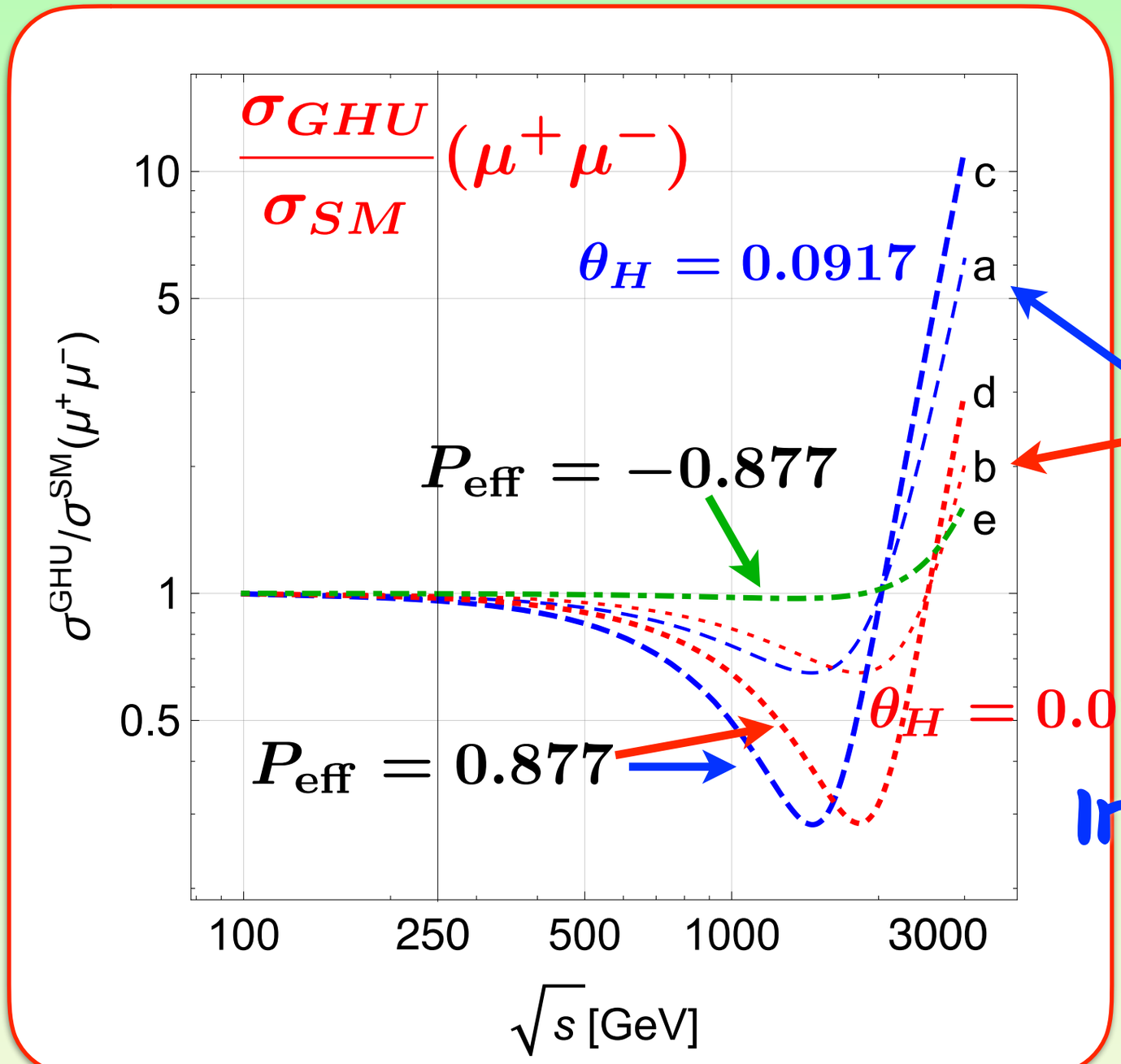
ILC (e^+e^- linear collider)



Energies at 250 GeV, 500 GeV, 1 TeV

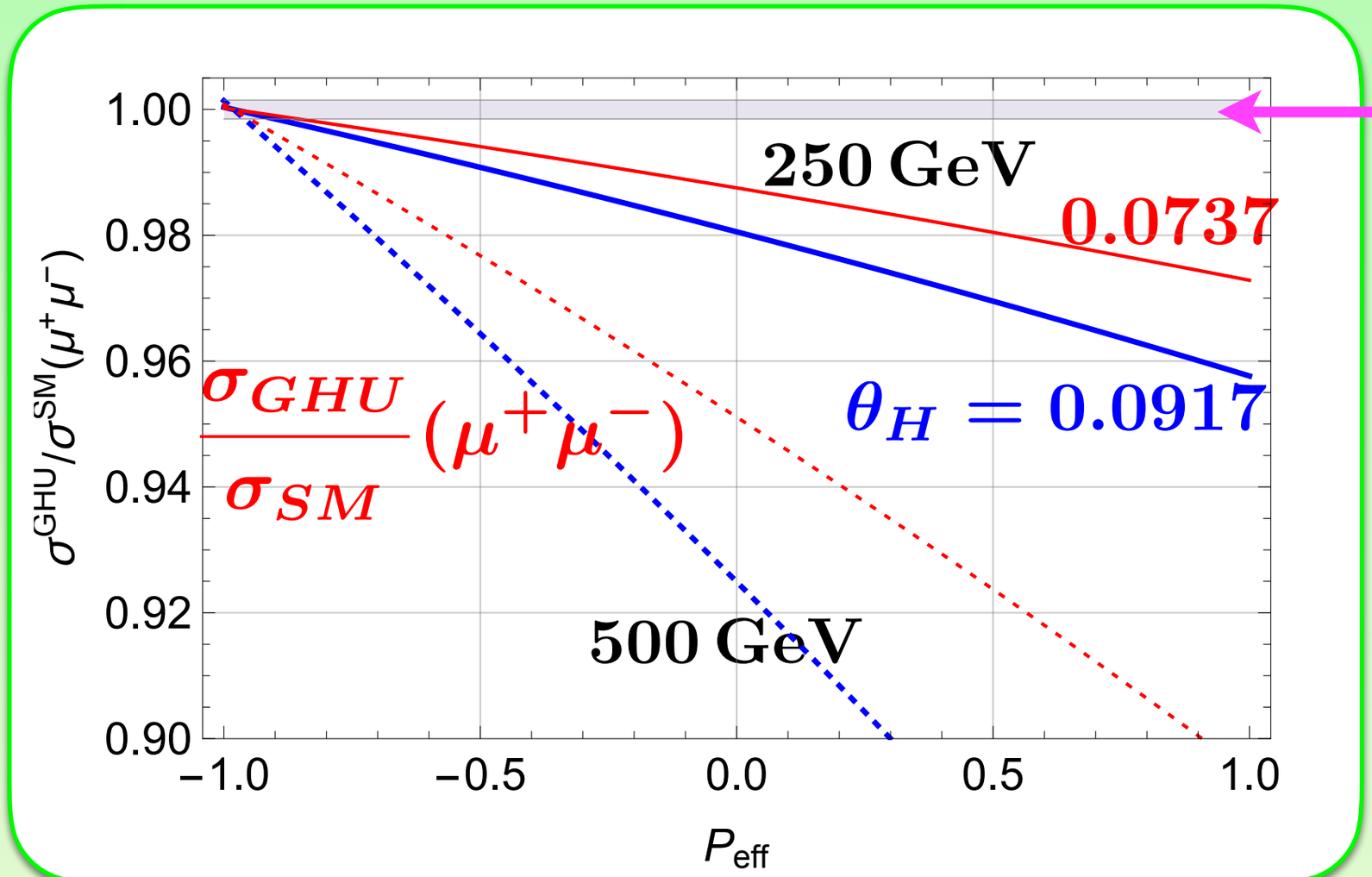
Polarized electron/positron beams

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



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

Interference among γ, Z, Z'



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

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

Interference among γ, Z, Z'

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

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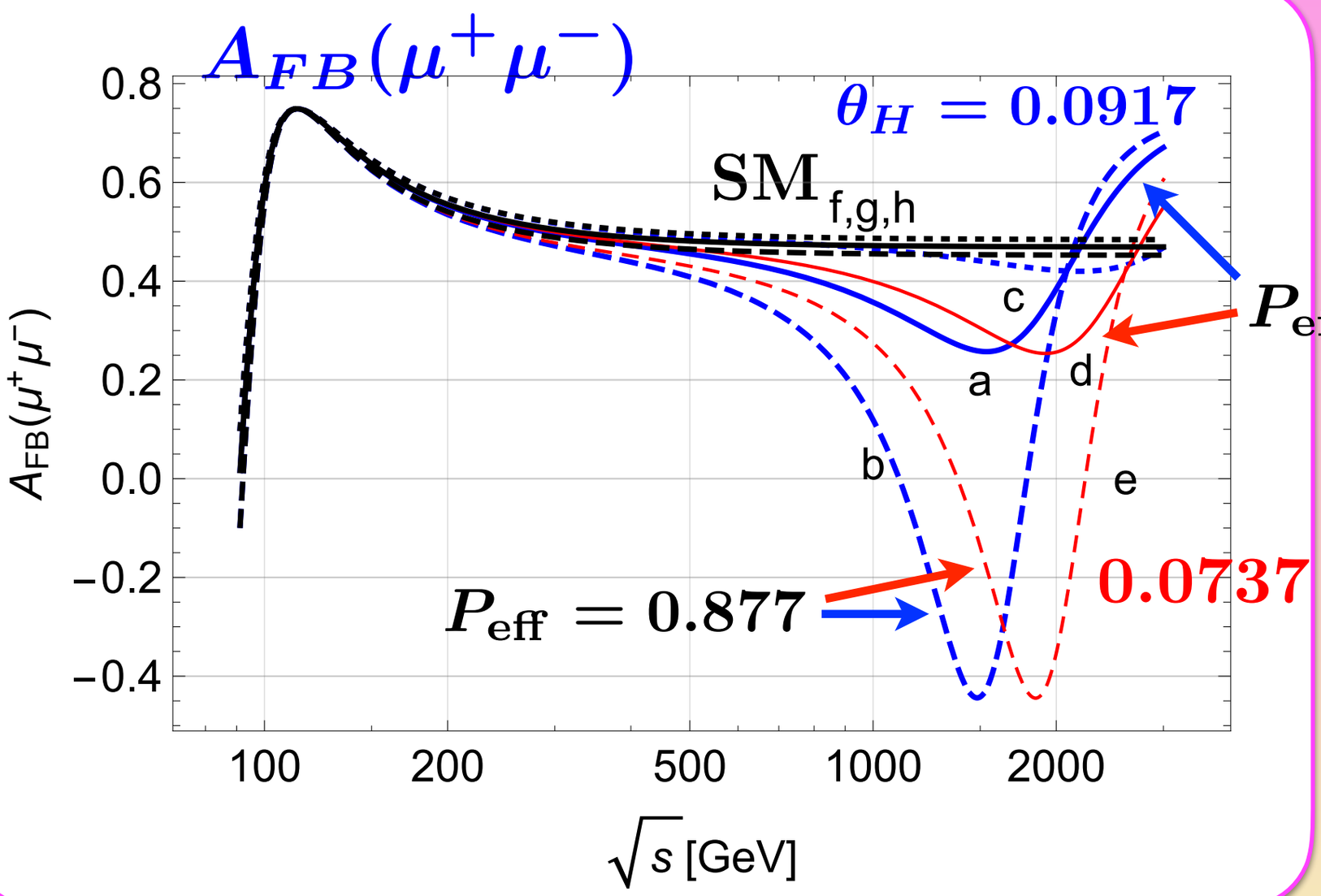
$$A_{FB} = \frac{\sigma_{\text{forward}} - \sigma_{\text{backward}}}{\sigma_{\text{forward}} + \sigma_{\text{backward}}}$$



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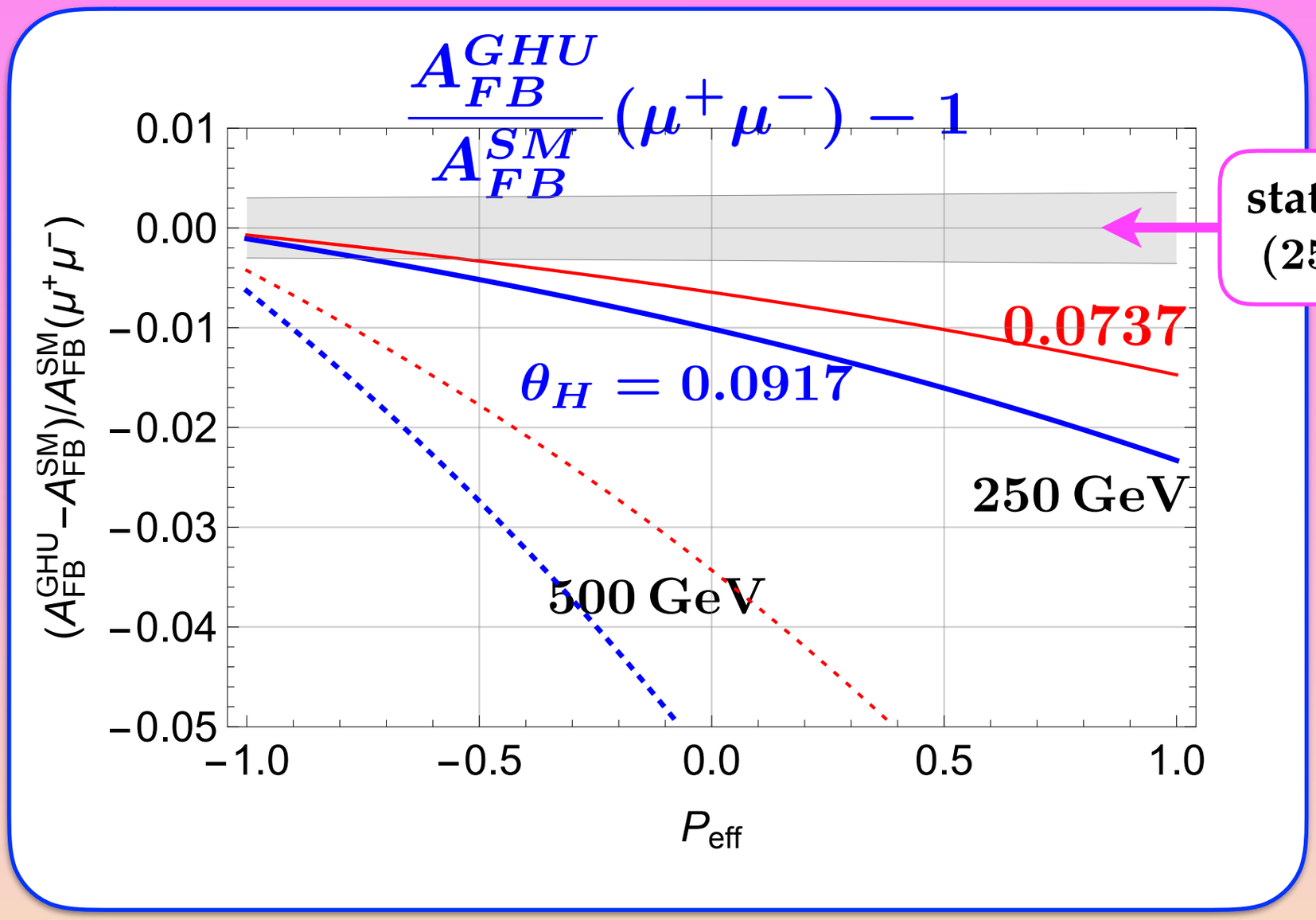

$250\,\mathrm{GeV},\ 250\,\mathrm{fb}^{-1}$ $\quad P_{\mathrm{eff}} = 0.8$ $\quad 6\,\sigma\,(4\,\sigma)$

Polarization dependence

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	θ_H 0.0737
μ	0.890	0.3%	−3.4 %	−2.2 %
b	0.349	0.3%	−3.1 %	−2.1 %

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Gauge-Higgs　　Composite Higgs

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

	5d gauge theory	Composite picture
Higgs	gauge field AB phase θ_H	**pseudo-NG boson**
	θ_H	vacuum misalignment angle $\frac{\langle h \rangle}{f_\pi}$
κ_V κ_f	$\cos\theta_H$	$\cos\theta_H$ (MCHM) not fixed
Z'	$Z^{(1)}, \gamma^{(1)}, Z_R^{(1)}$ $7 \sim 10\,\mathrm{TeV}$ large widths, $\not{p}$	technirho meson
constraint	$\theta_H < 0.1$ from Z'	$\epsilon = \sin\theta_H < 0.3$ $(\xi = \theta_H^2 < 0.1)$ from S parameter

Summary

Gauge-Higgs unification

Higgs = gauge boson in 5d

Large left-right asym. in Z′ couplings
Signals can be seen at LHC/ILC.

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extra

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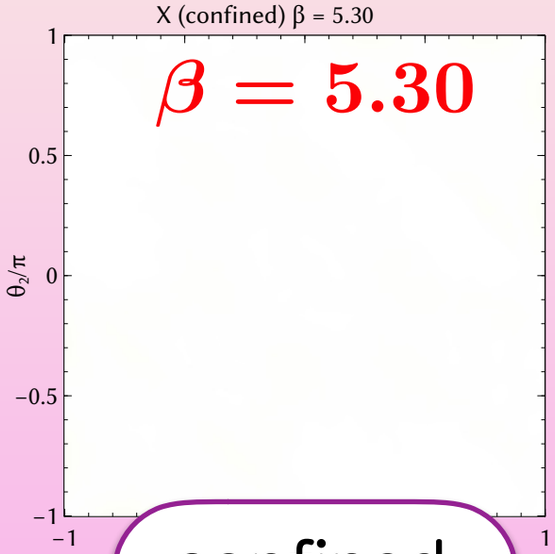
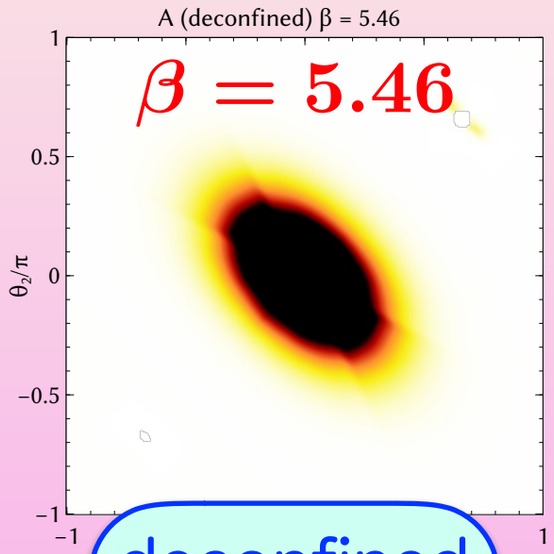
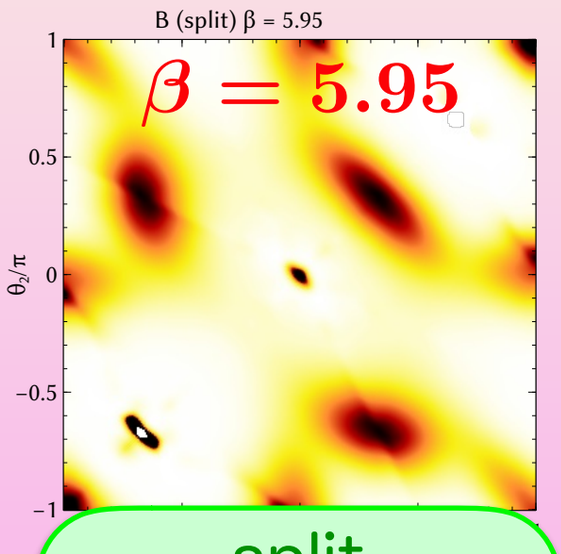
Normalized density: $\rho^{\text{normalized}}$



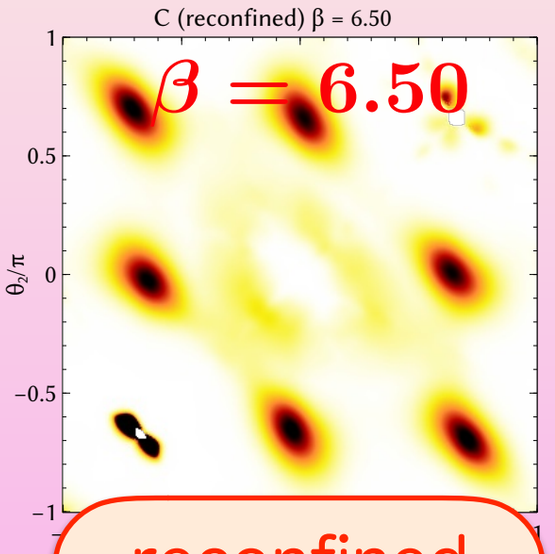
confined
uniform
$SU(3)$



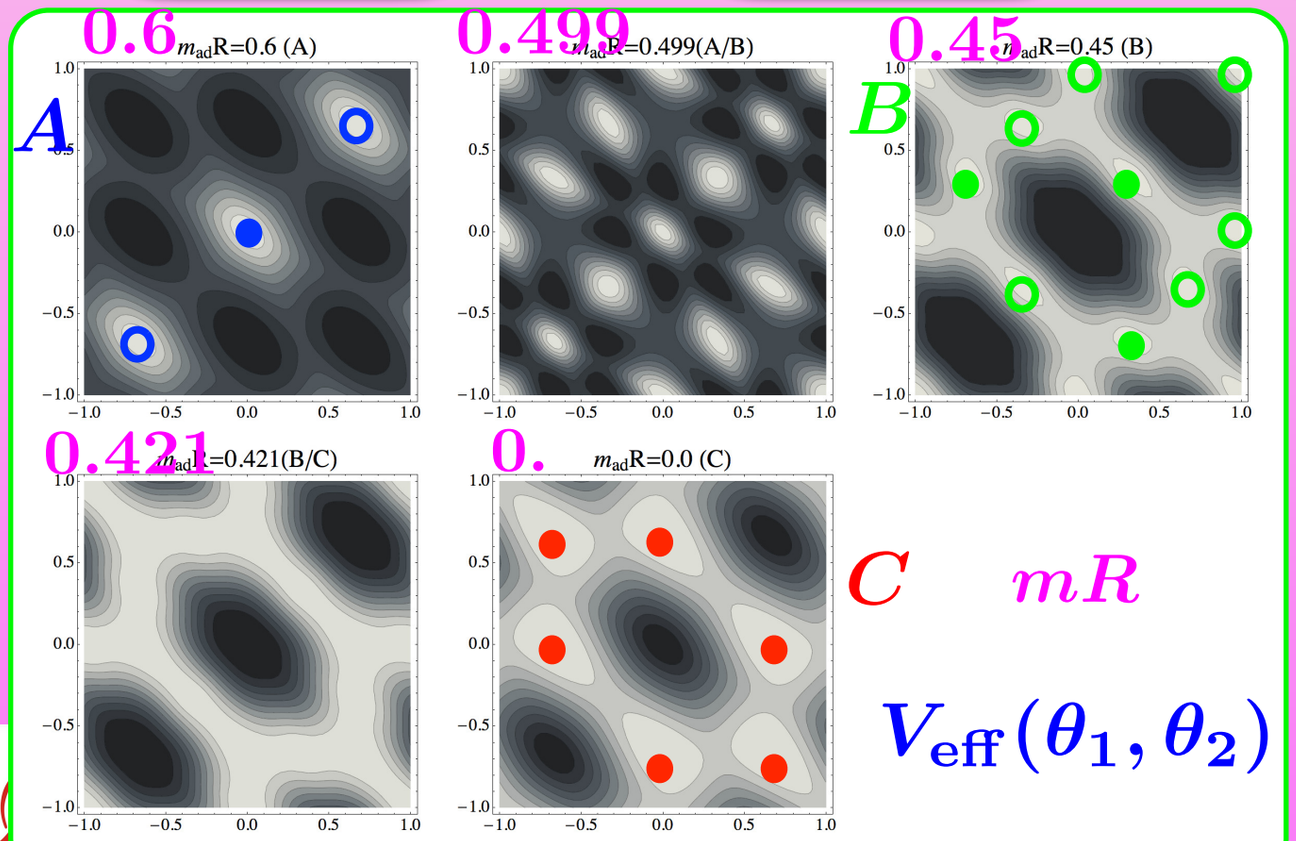
deconfined
A_1
$SU(3)$



split
B_2
$SU(2) \times U(1)$



reconfined
C
$U(1) \times U(1)$



Strong indication of
Hosotani mechanism
on the lattice

Cossu, Noaki, Hatanaka, YH, 1309.4198

Higgs couplings

$$\theta_H + \frac{H(x)}{f_H} \qquad\qquad f_H \sim \frac{2}{g_w}\sqrt{\frac{k}{L}}\, z_L^{-1}$$

$$m_W \sim \sqrt{\frac{k}{L}}\, z_L^{-1} \sin\theta_H = \frac{1}{2} g_w f_H \sin\theta_H \quad \equiv \frac{1}{2} g_w v_{\rm SM}$$

$$v_{\rm SM} = f_H \sin\theta_H$$

$$\mathcal{L}^q_{\rm eff} = a \sin\left(\theta_H + \frac{H}{f_H}\right) \bar{q}\, q$$

$$m_q = a \sin\theta_H$$

$$y_q = \frac{a}{f_H}\cos\theta_H = \frac{m_q}{v_{\rm SM}}\cos\theta_H \qquad y_q = y_q^{\rm SM}\cos\theta_H$$

EW sym breaking

$z_L = 10^5,\ \theta_H = 0.115$
$n_F = 4$

$\theta_H = 0.115$ (example)

$m_Z,\ \alpha,\ \sin^2\theta_W$

$\rightarrow m_{\rm KK} = 7.41\,{\rm TeV}$

$m_t = 171\,{\rm GeV},\ m_H = 125\,{\rm GeV}$

$\rightarrow c_t = 0.227,\ c_F = 0.332$

$m_\tau,\ m_e = 0.511\,{\rm MeV}$

$\rightarrow c_\tau = 0.950,\ c_e = 1.72$

Physics
OSAKA UNIVERSITY

Universality in θ_H

We discover

$$m_{\rm KK} \sim \frac{1352\,{\rm GeV}}{(\sin\theta_H)^{0.786}}$$

$$m_{Z_R^{(1)}} \sim \frac{1038\,{\rm GeV}}{(\sin\theta_H)^{0.784}}$$

$$m_{Z^{(1)}} \sim \frac{1044\,{\rm GeV}}{(\sin\theta_H)^{0.808}}$$

$$m_{\gamma^{(1)}} \sim \frac{1056\,{\rm GeV}}{(\sin\theta_H)^{0.804}}$$