Z' signals at e^-e^+ linear colliders in gauge-Higgs unification

Yutaka Hosotani

Physics
OSAKA UNIVERSITY

S. Funatsu, H. Hatanaka, YH, Y. Orikasa, N. Yamatsu

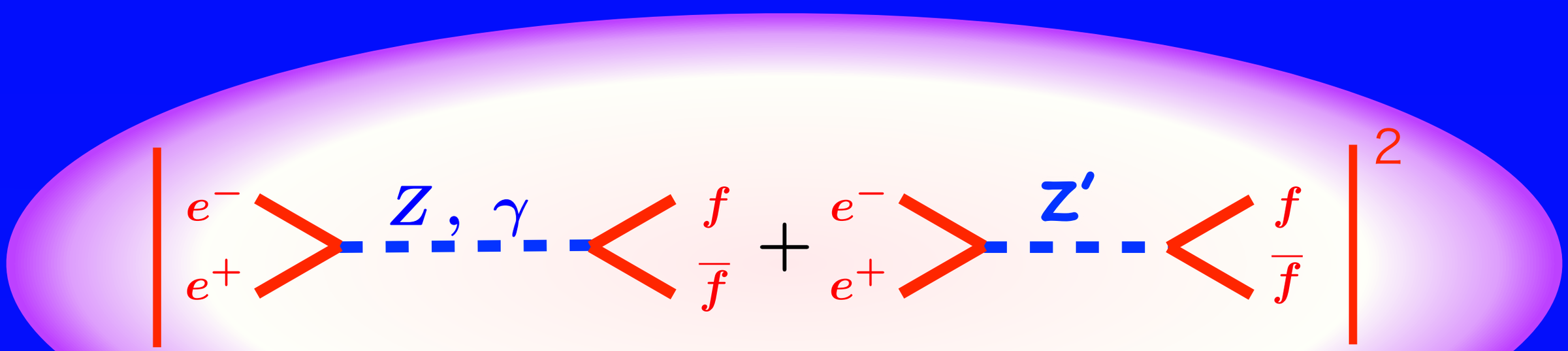
PRD102, 015029 (2020) [arXiv: 2006.02157]

IFIC, Valencia, April 27, 2021

Z' (10 TeV) signals can be seen in

$$e^- e^+ \to \mu^- \mu^+ \ (f \bar{f})$$

in the early stage of 250 GeV ILC



Interference terms : large enough

Gauge-Higgs unification

A_M

A_μ

γ , W , Z

A_y

125 GeV Higgs boson

AB phase in the 5th dim

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

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

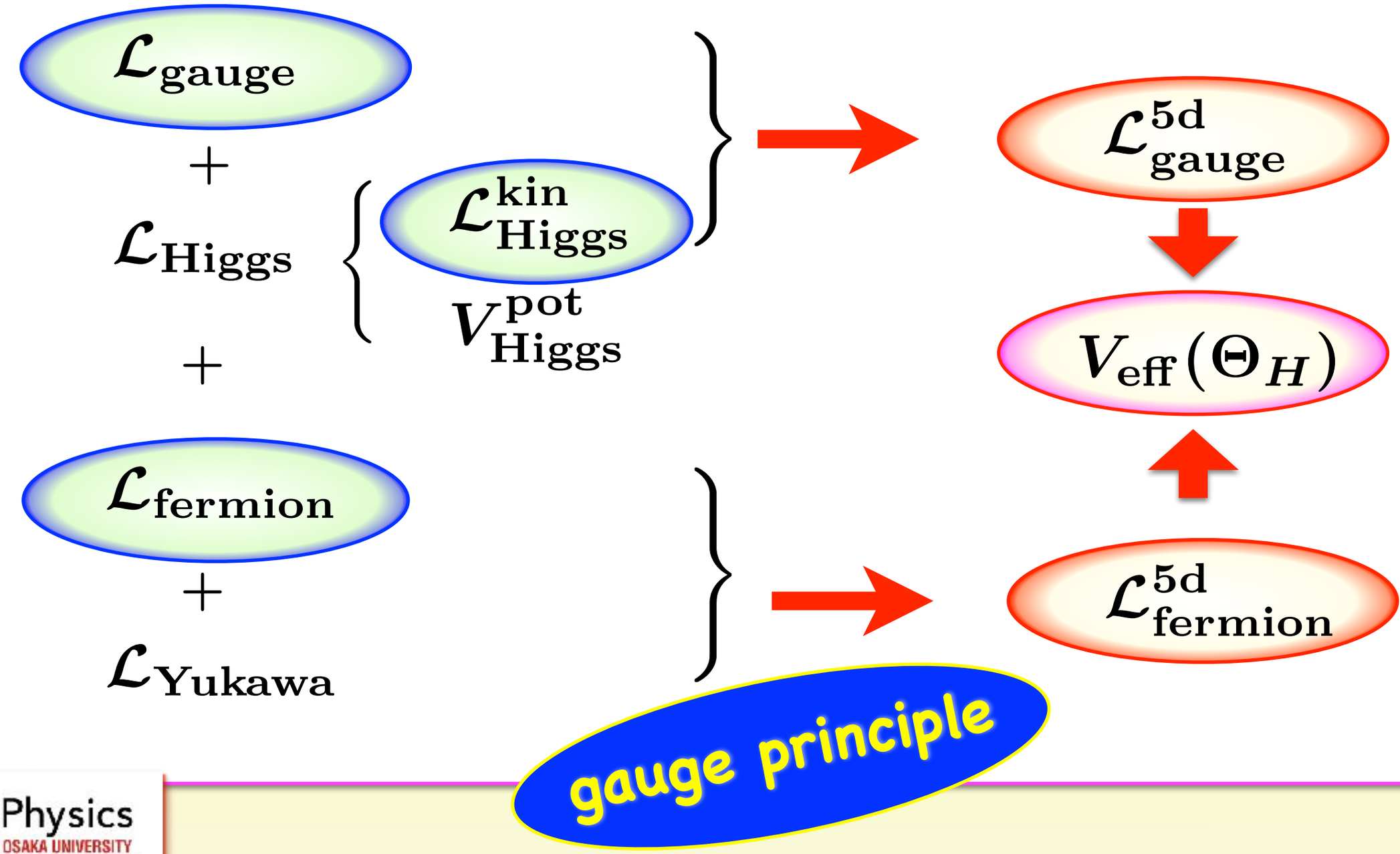
$\theta_H \neq 0$ → EW sym. breaking

Gauge hierarchy prob. solved

Physics
OSAKA UNIVERSITY

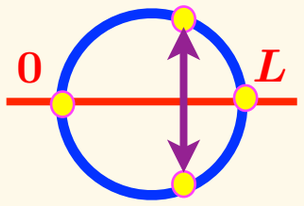
Standard Model

Gauge-Higgs Unification



$SU(3) \times SO(5) \times U(1)$ gauge-Higgs on RS

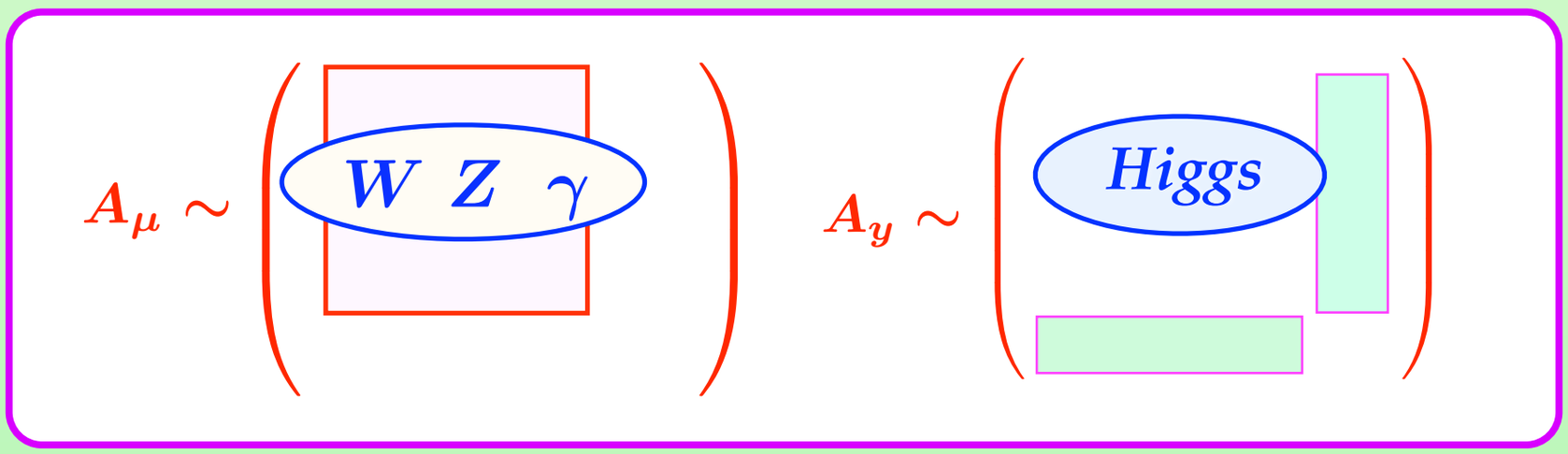
Agashe, Contino, Pomarol 2005
Medina, Shah, Wagner 2007
YH, Oda, Ohnuma, Sakamura 2008
Funatsu, Hatanaka, YH, Orikasa, Shimotani 2013



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

brane scalar $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$

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



Physics
OSAKA UNIVERSITY

Matter

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

$\begin{pmatrix} \nu \\ e \\ \nu' \\ e' \end{pmatrix}$

	B-model (GUT inspired)
Quark	$(\mathbf{3},\mathbf{4})_{\frac{1}{6}}$ $(\mathbf{3},\mathbf{1})^{+}_{-\frac{1}{3}}$ $(\mathbf{3},\mathbf{1})^{-}_{-\frac{1}{3}}$ $D^{\pm}$
Lepton	$(\mathbf{1},\mathbf{4})_{-\frac{1}{2}}$
Dark fermion	$(\mathbf{3},\mathbf{4})_{\frac{1}{6}}$ $(\mathbf{1},\mathbf{5})^{+}_{0}$ $(\mathbf{1},\mathbf{5})^{-}_{0}$ $(\mathbf{1},\mathbf{4})_{-\frac{1}{2}}$
Brane fermion	$(\mathbf{1},\mathbf{1})_{0}$ ν_χ
Brane scalar	$(\mathbf{1},\mathbf{4})_{\frac{1}{2}}$ $\hat{\Phi}$

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

Physics
OSAKA UNIVERSITY

GUT inspired B-model

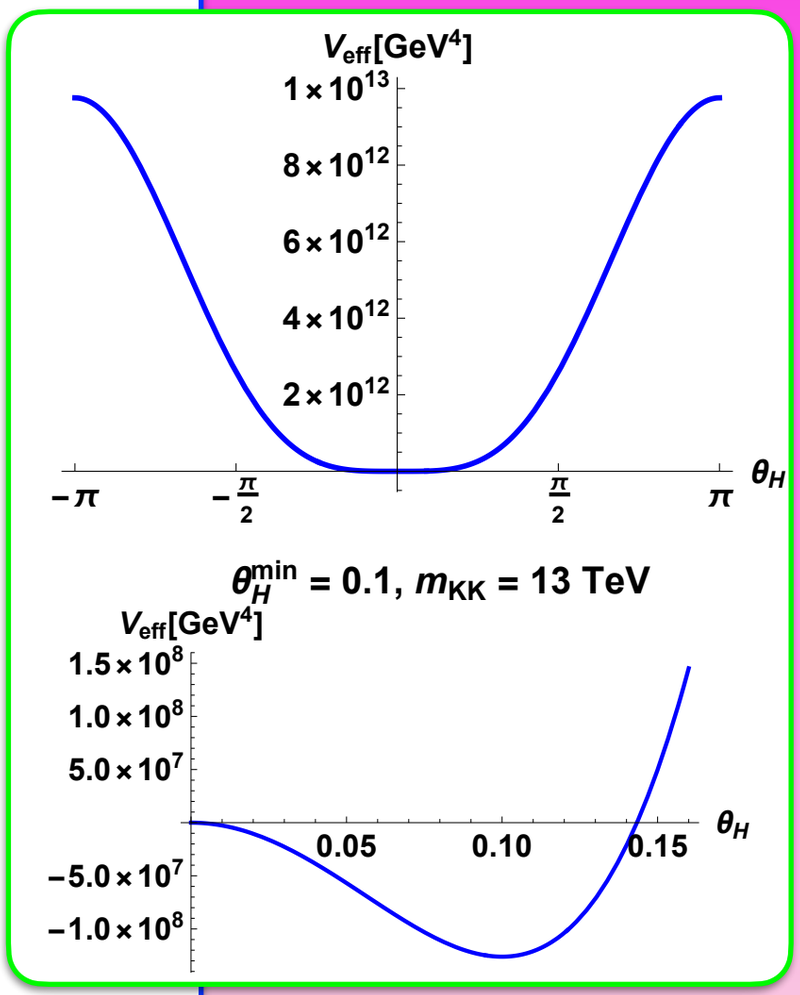
EW sym breaking

$\theta_H \sim 0.1\ ,\ m_H = 125.1\,\mathrm{GeV}$

Mass spectrum

CKM

FCNC naturally suppressed



Physics
OSAKA UNIVERSITY

W, Z couplings of quarks/leptons

— nearly the same as in the SM

$$\frac{1}{g^W_{L\,\mathrm{lepton}}}\begin{pmatrix} g^Z_{Luu} \\ g^Z_{Ruu} \\ g^Z_{Ldd} \\ g^Z_{Rdd} \end{pmatrix} = \begin{pmatrix} 0.34588 \\ -0.15413 \\ -0.42295 \\ 0.07707 \end{pmatrix}, \begin{pmatrix} 0.34591 \\ -0.15411 \\ -0.42298 \\ 0.07706 \end{pmatrix} \Leftrightarrow \begin{pmatrix} 0.3458 \\ -0.1541 \\ -0.4229 \\ 0.0771 \end{pmatrix}$$

$\theta_H = 0.10$ $\theta_H = 0.15$ SM

Physics OSAKA UNIVERSITY

GHU : signals (deviation from SM)

- Higgs
- New particles

KK states $Z^{(n)}, \gamma^{(n)}, W^{(n)}, gluon^{(n)}, q^{(n)}, \cdots$

Physics
OSAKA UNIVERSITY

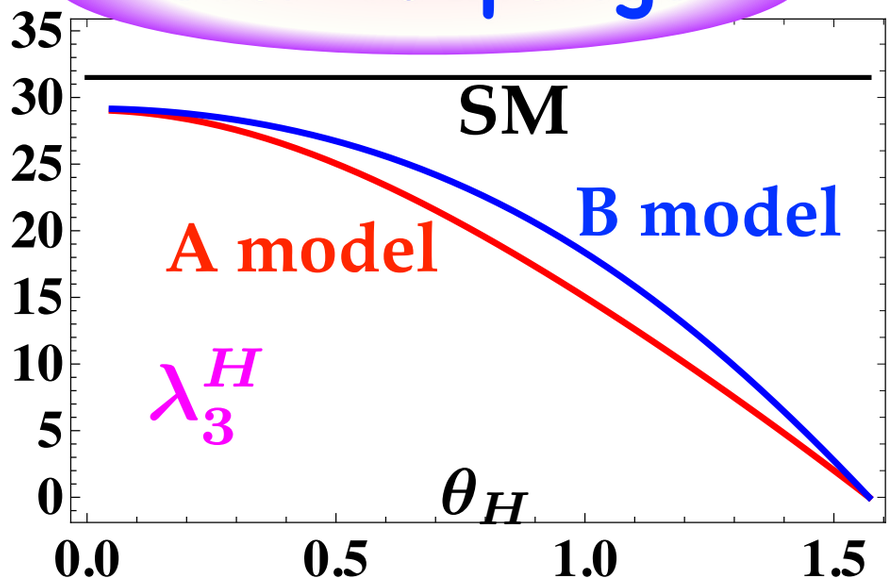
Higgs couplings

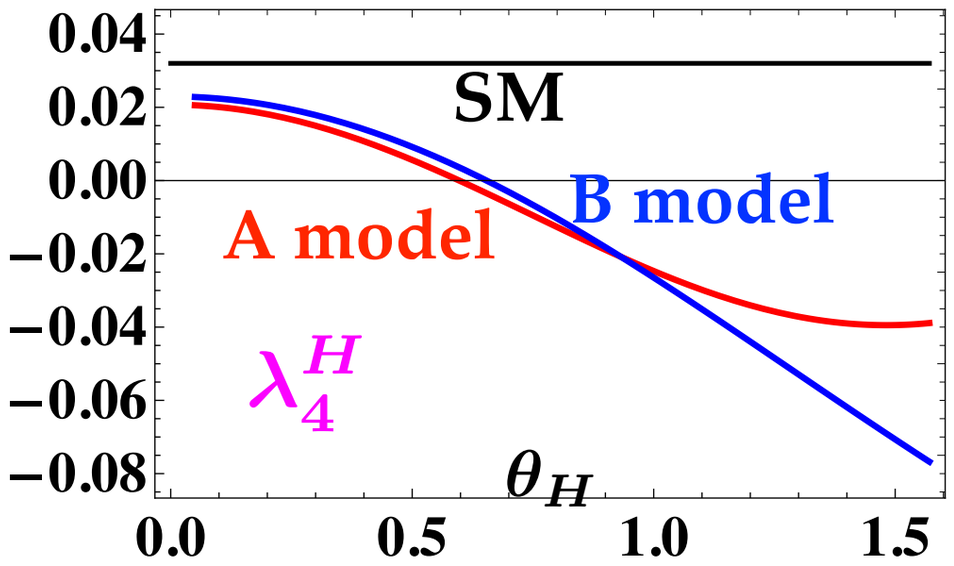
WWH, ZZH $\sim (\mathrm{SM}) \times \cos\theta_H$

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





Physics
OSAKA UNIVERSITY

New Particles

Kaluza-Klein excitation modes

	θ_H [rad.]	$m_{\rm KK}$ [TeV]	z_L	k [GeV]	$m_{\gamma^{(1)}}$ [TeV]	$\Gamma_{\gamma^{(1)}}$ [TeV]	$m_{Z^{(1)}}$ [TeV]	$\Gamma_{Z^{(1)}}$ [TeV]	$m_{Z_R^{(1)}}$ [TeV]	$\Gamma_{Z_R^{(1)}}$ [TeV]
B^L	0.10	11.00	1.980×10^{8}	6.933×10^{11}	8.715	2.080	8.713	4.773	8.420	0.603
B	0.10	13.00	3.865×10^{11}	1.599×10^{15}	10.20	3.252	10.20	7.840	9.951	0.816
B^H	0.10	15.00	2.667×10^{15}	1.273×10^{19}	11.69	4.885	11.69	11.82	11.48	1.253

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

$\sim$10 TeV

Physics
OSAKA UNIVERSITY

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

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

Physics OSAKA UNIVERSITY

Z′ couplings in RS

$\boldsymbol{\theta_H = 0.1}$, $\boldsymbol{m_{KK} = 13\,\mathrm{TeV}}$

f	g^L_{Zf}	g^R_{Zf}	$g^L_{Z^{(1)}f}$	$g^R_{Z^{(1)}f}$	$g^L_{Z^{(1)}_R f}$	$g^R_{Z^{(1)}_R f}$	$g^L_{\gamma^{(1)}f}$	$g^R_{\gamma^{(1)}f}$
ν_e	0.5687	0	3.2774	0	−1.0322	0	0	0
ν_μ	0.5687	0	3.1207	0	−0.9852	0	0	0
ν_τ	0.5687	0	3.0165	0	−0.9539	0	0	0
e	−0.3058	0.2629	−1.7621	−0.0584	−1.0444	0	−2.7587	0.1071
μ	−0.3058	0.2629	−1.6778	−0.0584	−0.9969	0	−2.6268	0.1071
τ	−0.3058	0.2629	−1.6218	−0.0584	−0.9652	0.0001	−2.5391	0.1070
u	0.3934	−0.1753	2.1951	0.0390	0.3415	0	1.7807	−0.0714
c	0.3934	−0.1753	2.1147	0.0389	0.3296	0	1.7154	−0.0714
t	0.3938	−0.1749	1.7406	−0.3269	0.2740	−0.7395	1.4121	0.6017
d	−0.4811	0.0876	−2.6842	0.1162	0.3297	−0.1801	−0.8904	−0.2113
s	−0.4811	0.0876	−2.5858	0.1460	0.3182	−0.2197	−0.8577	−0.2657
b	−0.4811	0.0876	−2.1284	0.2900	0.2646	−0.4096	−0.7059	−0.5279

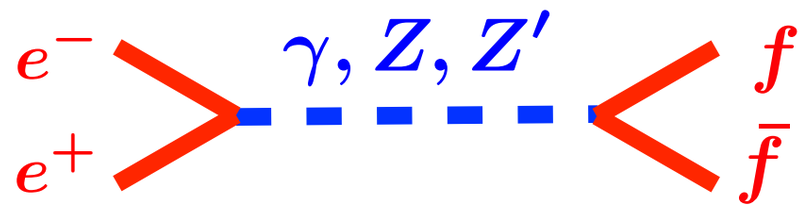
Z large

$Z^{(1)}$ large

$Z^{(1)}_R$ large

$\gamma^{(1)}$ large

in units of g_w

$$\mathcal{M} =$$ 

$$\frac{d\sigma^{f\bar{f}}}{d\cos\theta} = \frac{1-P_{e^-}P_{e^+}}{4}\left\{(1-P_{\rm eff})\frac{d\sigma^{f\bar{f}}_{LR}}{d\cos\theta} + (1+P_{\rm eff})\frac{d\sigma^{f\bar{f}}_{RL}}{d\cos\theta}\right\}$$

$$\sigma^{f\bar{f}}_{LR} \ : \ e^-_L e^+_R \to f\bar{f}$$
$$\sigma^{f\bar{f}}_{RL} \ : \ e^-_R e^+_L \to f\bar{f}$$

$$P_{\rm eff} \equiv \frac{P_{e^-}-P_{e^+}}{1-P_{e^-}P_{e^+}} \qquad \begin{matrix}|P_{e^-}| \le 0.8 \\ |P_{e^+}| \le 0.3\end{matrix} \ \text{at ILC}$$

$$\frac{d\sigma^{f\bar{f}}_{LR}}{d\cos\theta} \simeq \frac{s}{32\pi}\left\{(1+\cos\theta)^2|Q_{e_Lf_L}|^2 + (1-\cos\theta)^2|Q_{e_Lf_R}|^2\right\}$$

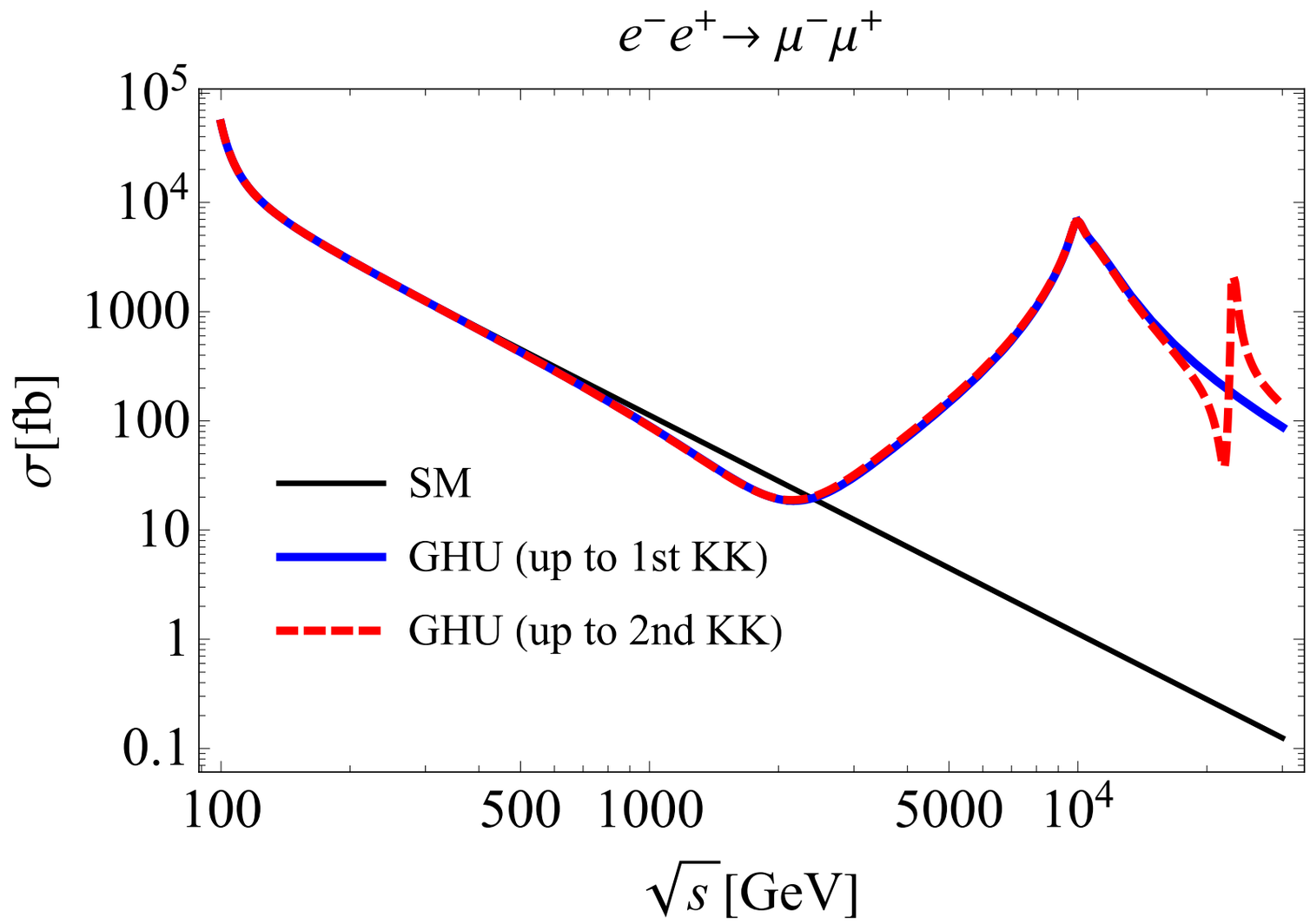
(RL; e_Rf_R; e_Rf_L)

$$Q_{e_Lf_L} \equiv \sum_i \frac{g^L_{V_ie}g^L_{V_if}}{(s-m^2_{V_i})+im_{V_i}\Gamma_{V_i}},$$

(R R above; R R below)

$|Q_{e_Lf_L}|$: large

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

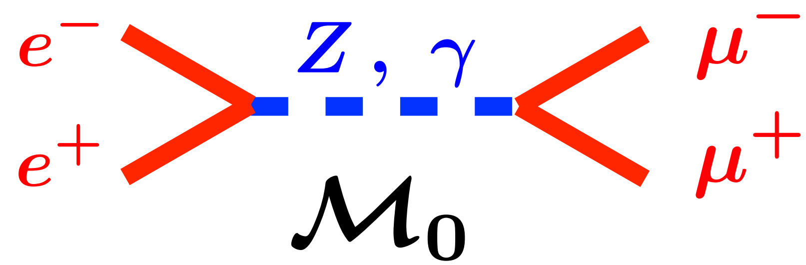
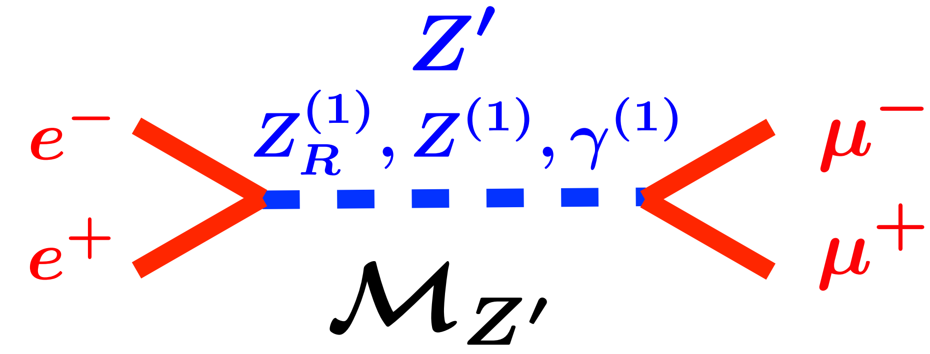


$\theta_H = 0.1\ ,\ m_{\rm KK} = 13\,{\rm TeV}$

Contributions from 2nd KK modes small for $\sqrt{s} < 3\,{\rm TeV}$

Physics
OSAKA UNIVERSITY

ILC

$\mathcal{M} =$  $+$ 

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

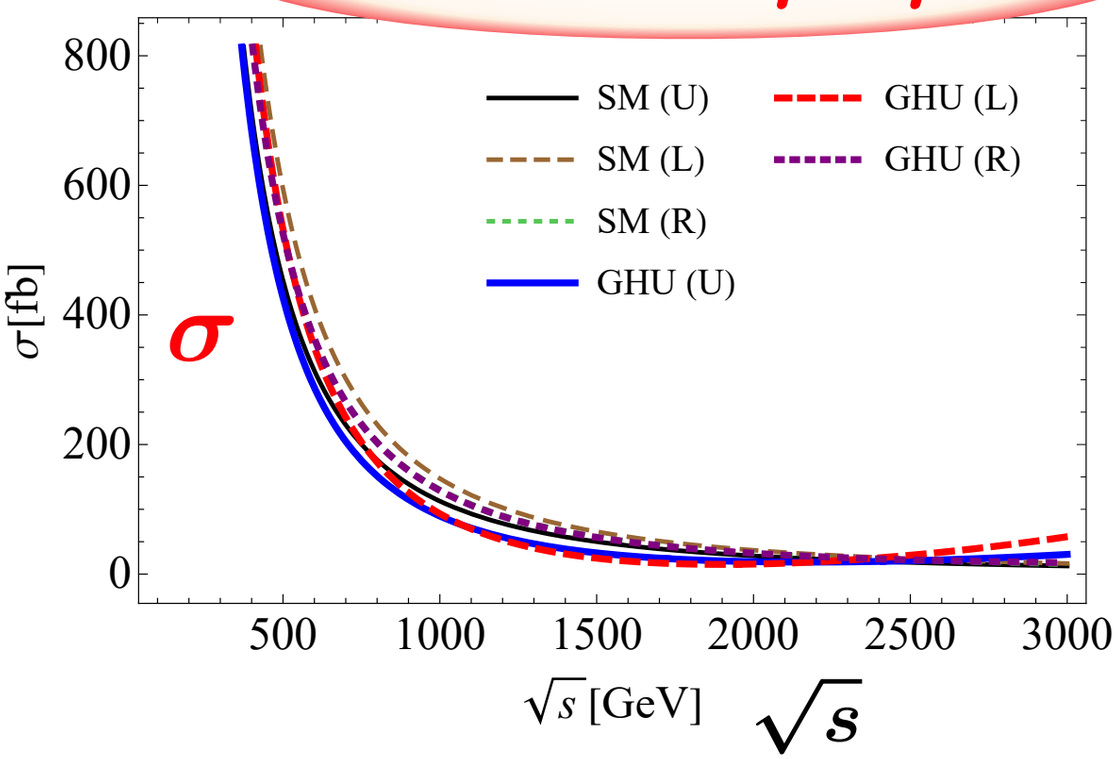
$$(250\,\mathrm{GeV})^2 \sim (1\,\mathrm{TeV})^2$$

interference effects

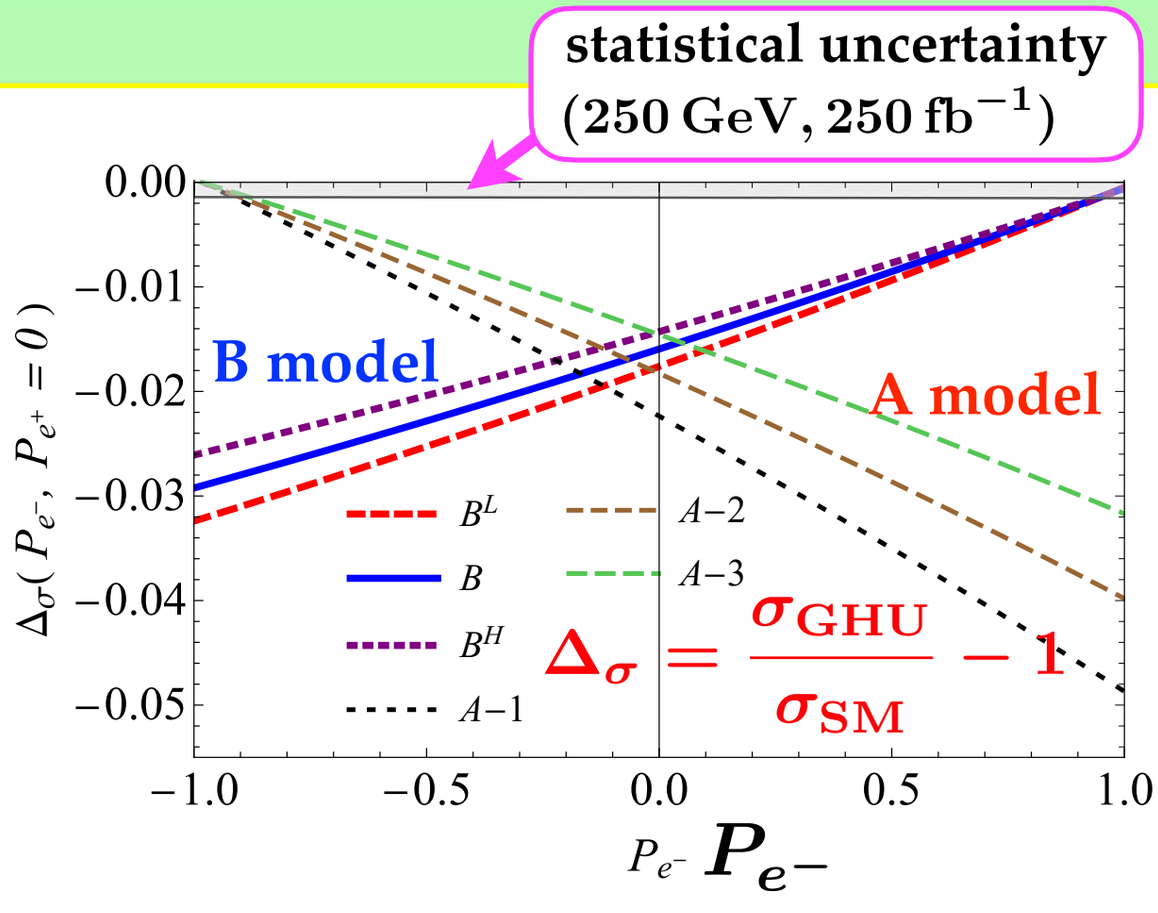
$$\frac{\mathcal{M}_0 \mathcal{M}_{Z'}^*}{|\mathcal{M}_0|^2} \sim -15\,\frac{s}{m_{Z'}^2}$$

$$\sim -0.02 \quad \text{at } \sqrt{s} = 250\,\mathrm{GeV}$$

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



$\theta_H = 0.1\ ,\ m_{\rm KK} = 13\,{\rm TeV}$



$\sqrt{s} = 250\,{\rm GeV}$

	(P_{e^-}, P_{e^+})
U	$(0, 0)$
L	$(-0.8, +0.3)$
R	$(+0.8, -0.3)$

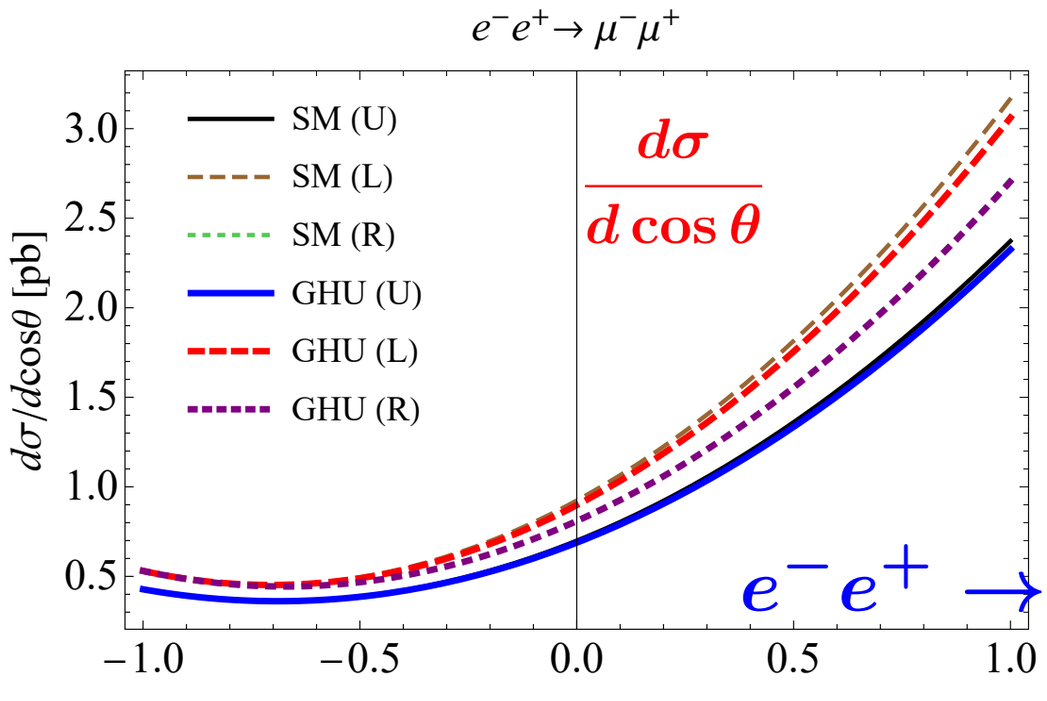
B model	θ_H	$m_{\rm KK}$
B^L	0.10	11 TeV
B	0.10	13 TeV
B^H	0.10	15 TeV

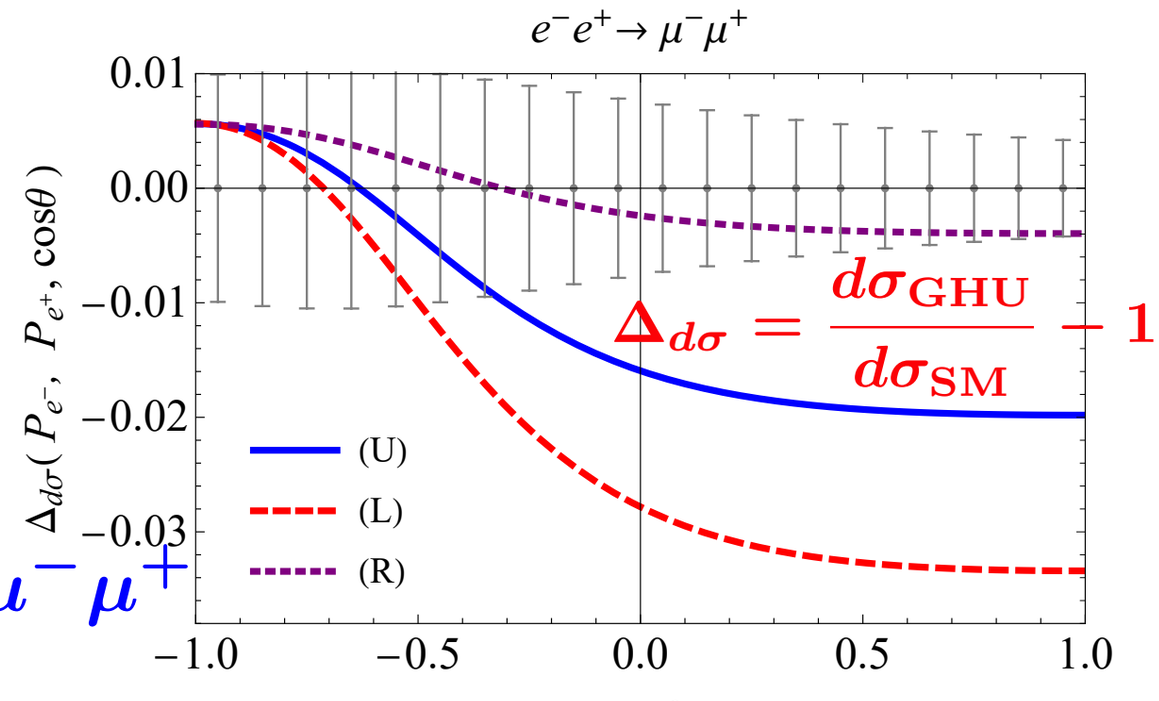
A model	θ_H	$m_{\rm KK}$
A_1	0.10	8.1 TeV
A_2	0.09	8.7 TeV
A_3	0.08	9.5 TeV

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

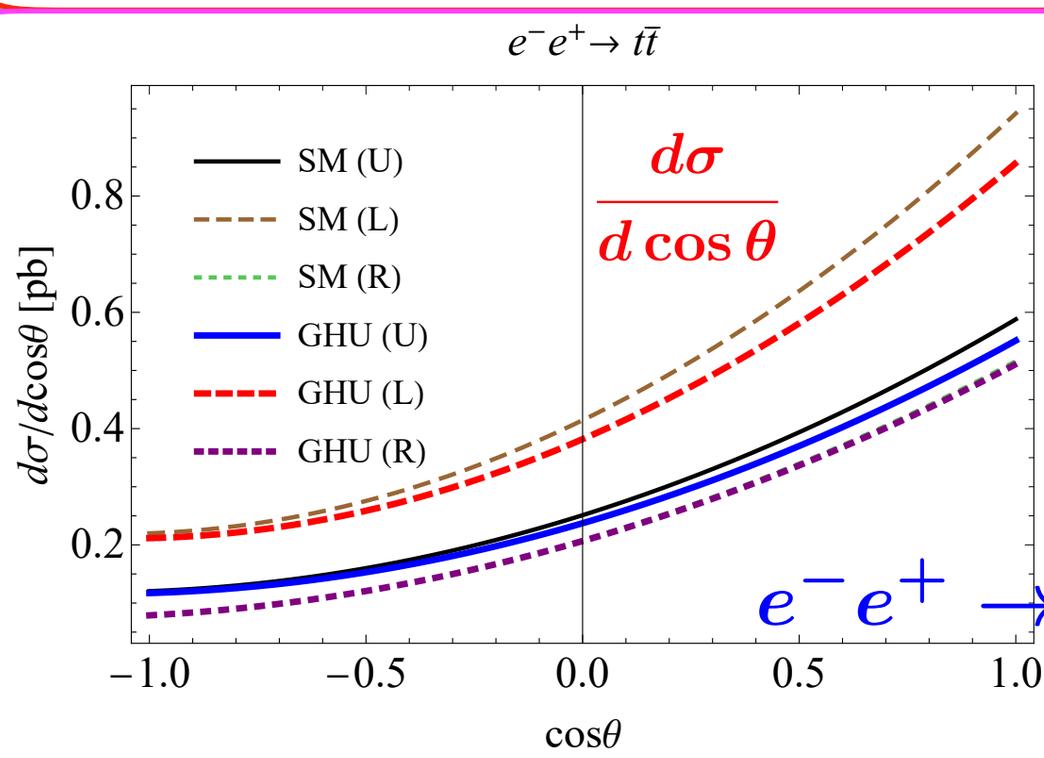
Physics OSAKA UNIVERSITY

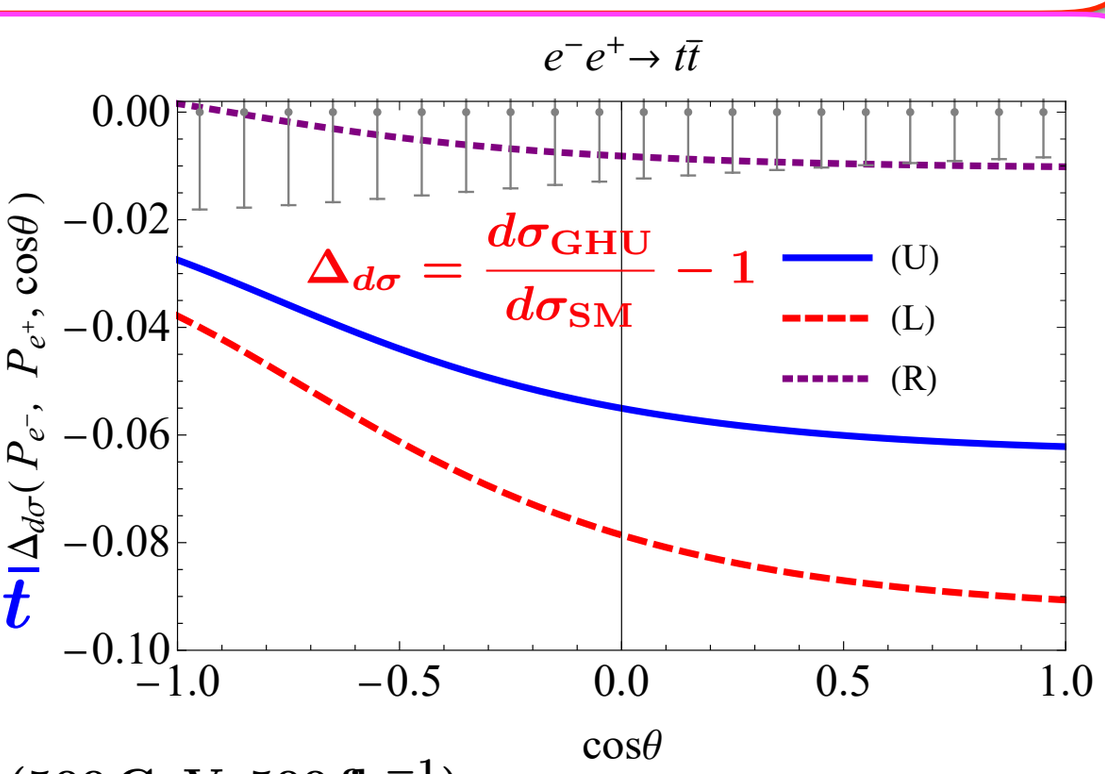
Angular distribution





$\theta_H = 0.1\ ,\ m_{\rm KK} = 13\,{\rm TeV}\quad (250\,{\rm GeV}, 250\,{\rm fb}^{-1})$

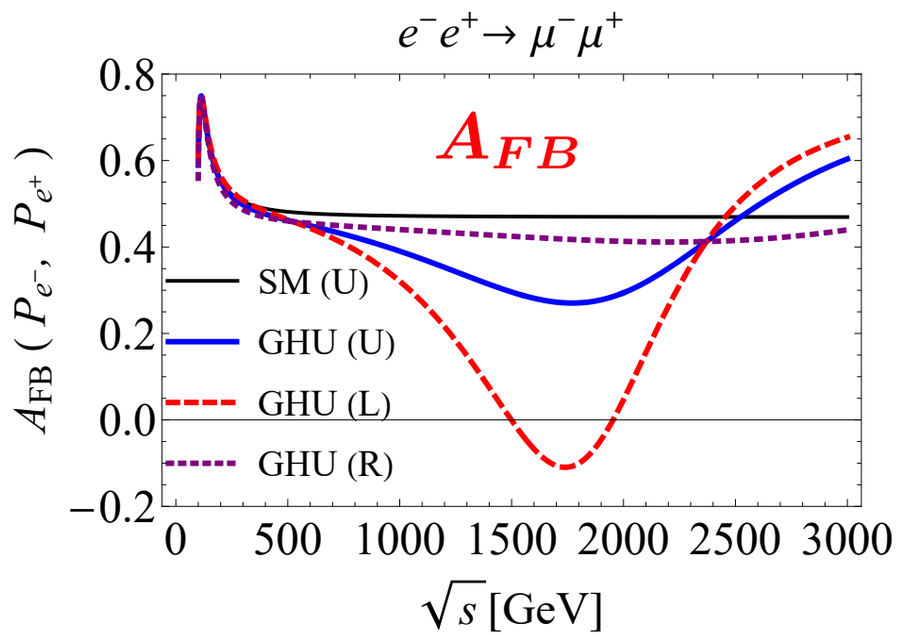


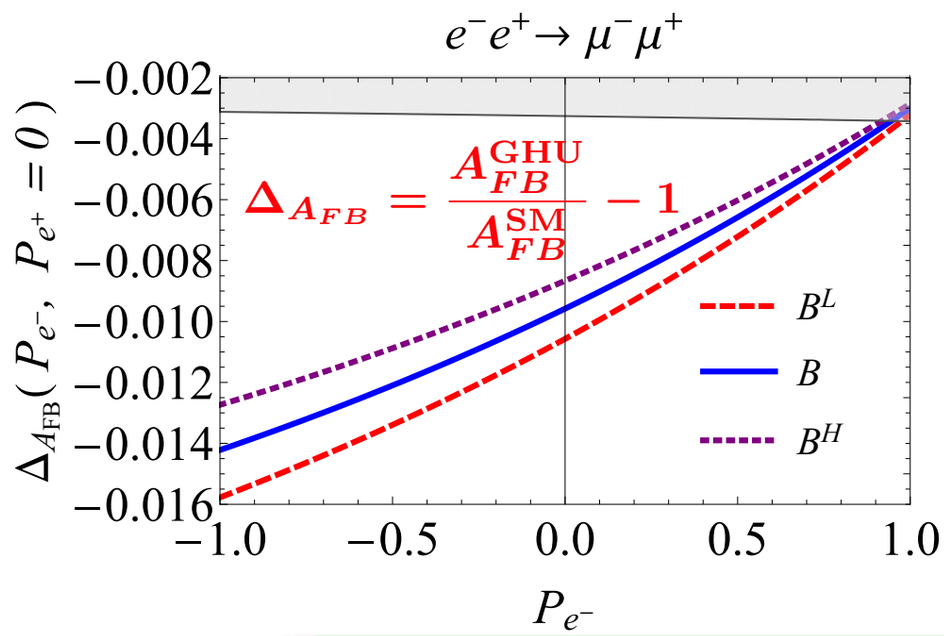


$\theta_H = 0.1\ ,\ m_{\rm KK} = 13\,{\rm TeV}\quad (500\,{\rm GeV}, 500\,{\rm fb}^{-1})$

Forward-backward asymmetry

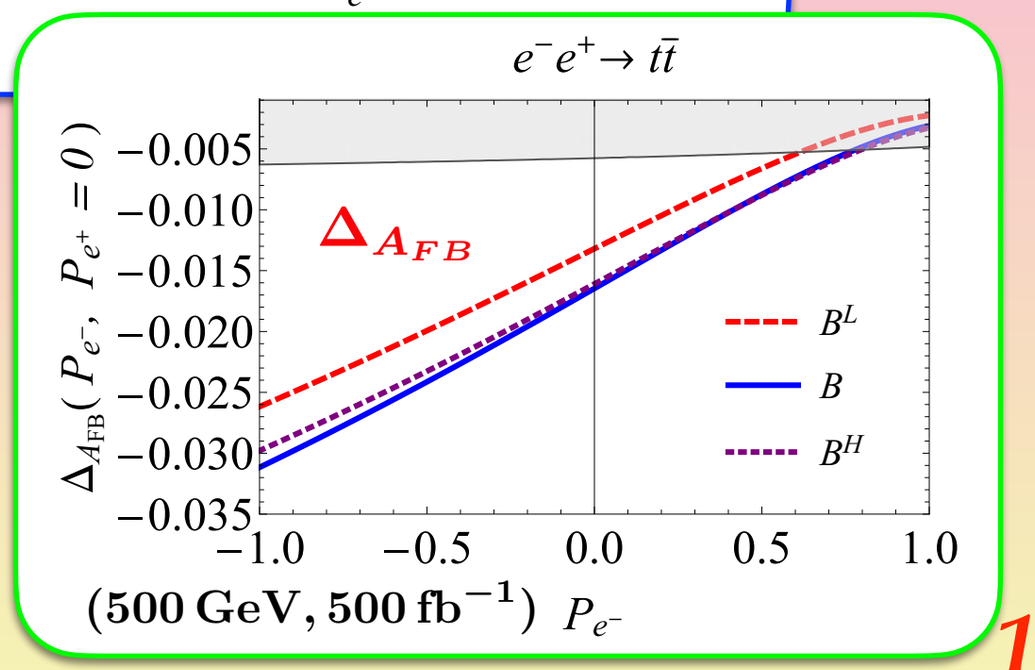
$$A_{FB} = \frac{\sigma_{\text{forward}} - \sigma_{\text{backward}}}{\sigma_{\text{forward}} + \sigma_{\text{backward}}}$$





$\theta_H = 0.1$, $m_{\rm KK} = 13$ TeV $\quad (250\ \text{GeV}, 250\ \text{fb}^{-1})$

	(P_{e^-}, P_{e^+})
U	$(0, 0)$
L	$(-0.8, +0.3)$
R	$(+0.8, -0.3)$

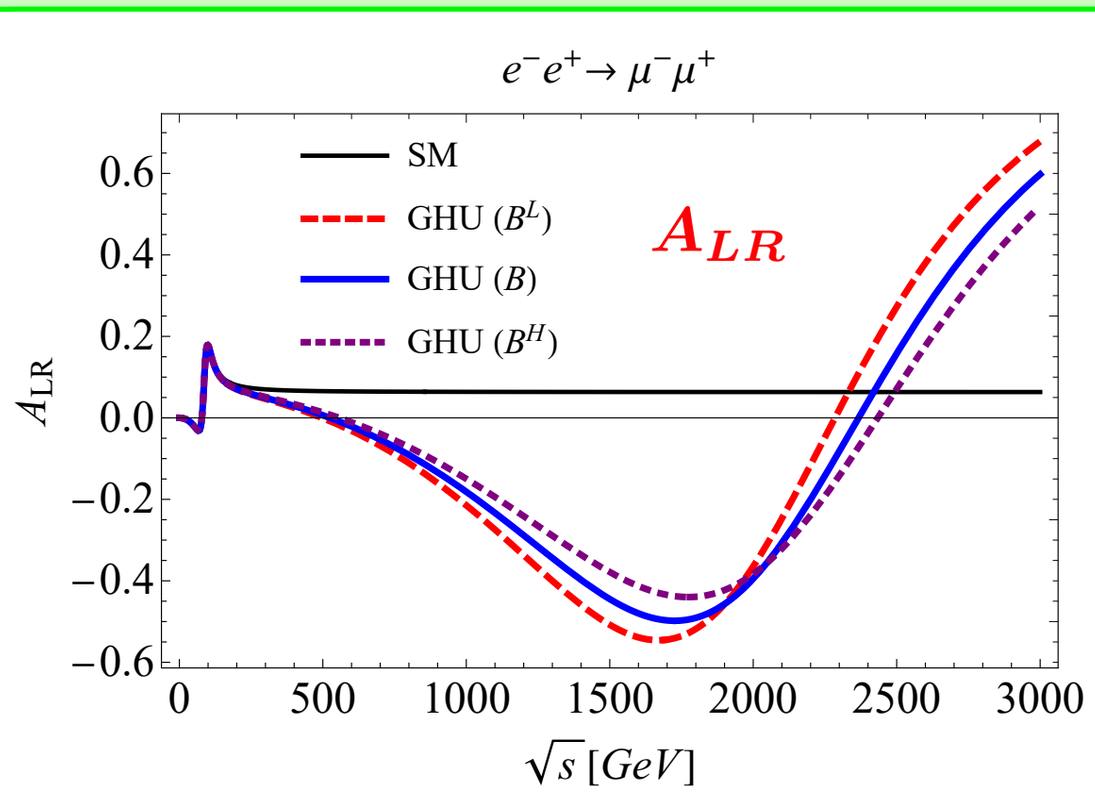


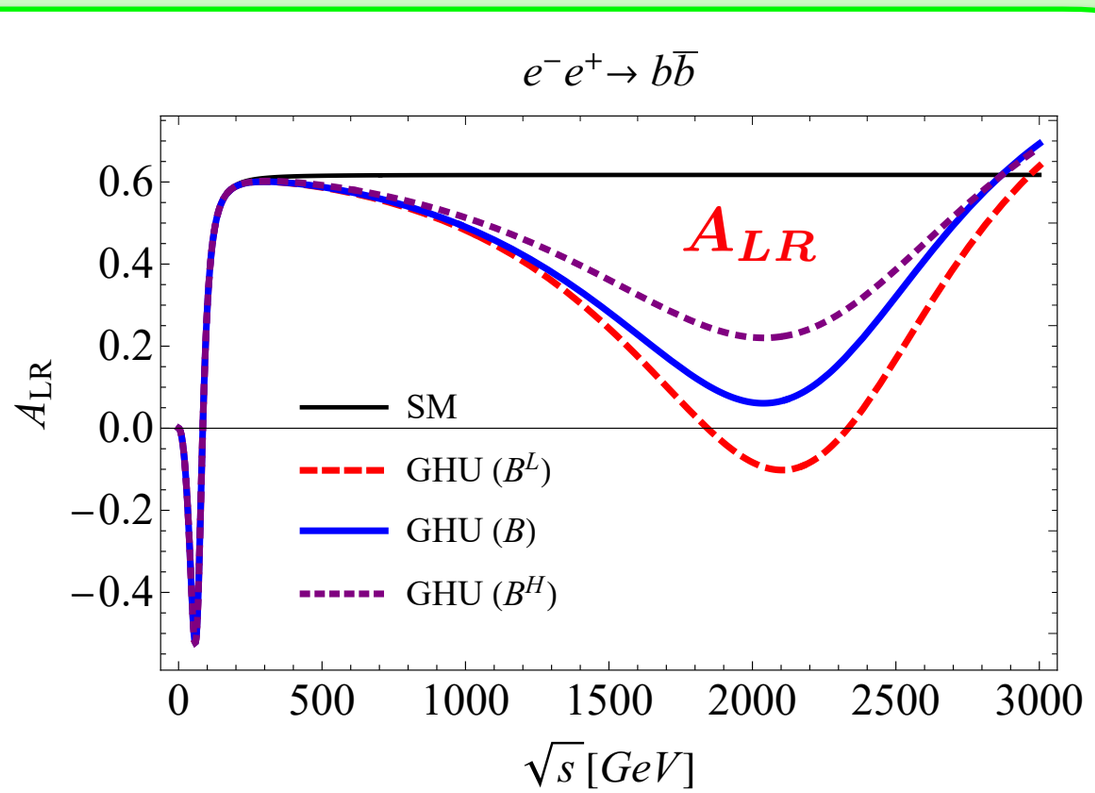
Physics
OSAKA UNIVERSITY

Left-right asymmetry

$$A_{LR} = \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}}$$

$$= \frac{1}{P_{\text{eff}}} \frac{\sigma(P_{e^-}, P_{e^+}) - \sigma(-P_{e^-}, -P_{e^+})}{\sigma(P_{e^-}, P_{e^+}) + \sigma(-P_{e^-}, -P_{e^+})}$$



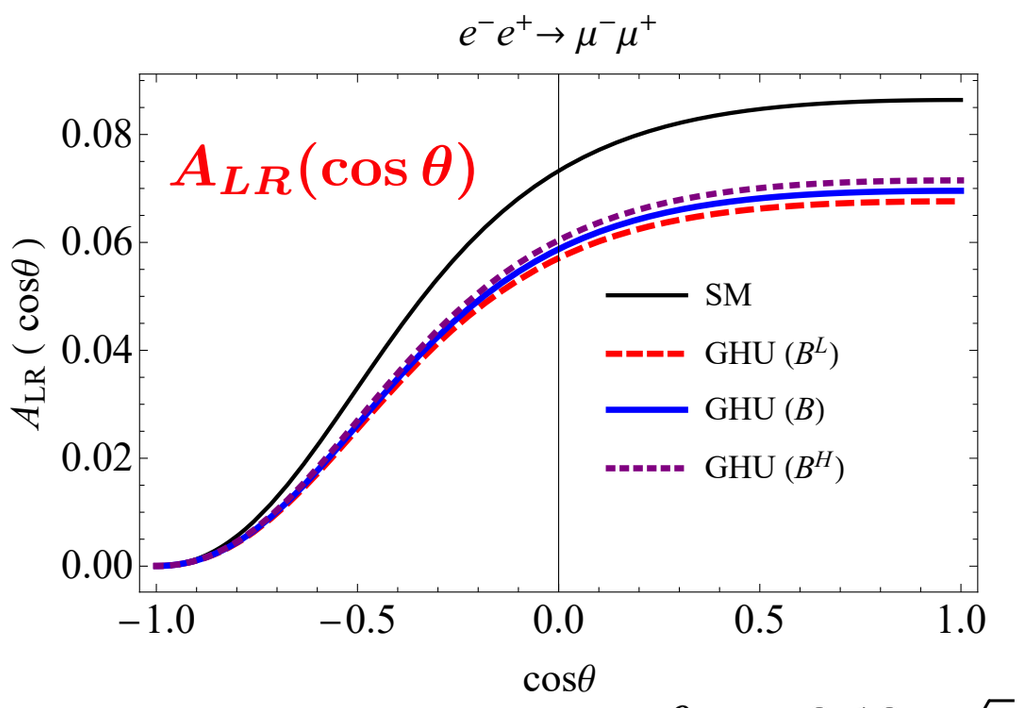


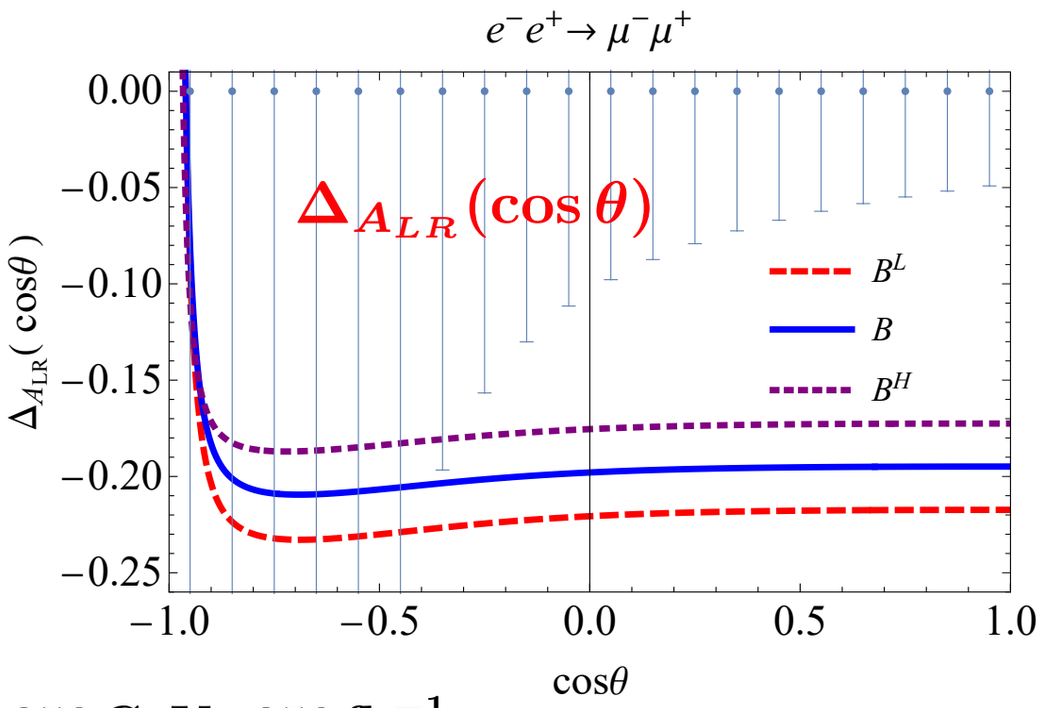
Physics
OSAKA UNIVERSITY

Differential left-right asymmetry

$$A_{LR}(\cos\theta) = \frac{d\sigma_{LR} - d\sigma_{RL}}{d\sigma_{LR} + d\sigma_{RL}} \quad \Leftarrow \quad d\sigma_{LR} \equiv \frac{d\sigma_{LR}}{d\cos\theta}$$

$$= \frac{1}{P_{\rm eff}} \frac{d\sigma(P_{e^-}, P_{e^+}) - d\sigma(-P_{e^-}, -P_{e^+})}{d\sigma(P_{e^-}, P_{e^+}) + d\sigma(-P_{e^-}, -P_{e^+})} \quad \Leftarrow \quad d\sigma(P_{e^-}, P_{e^+}) \equiv \frac{d\sigma(P_{e^-}, P_{e^+})}{d\cos\theta}$$





$$\theta_H = 0.10,\ \sqrt{s} = 250\,\text{GeV},\ 250\,\text{fb}^{-1}$$

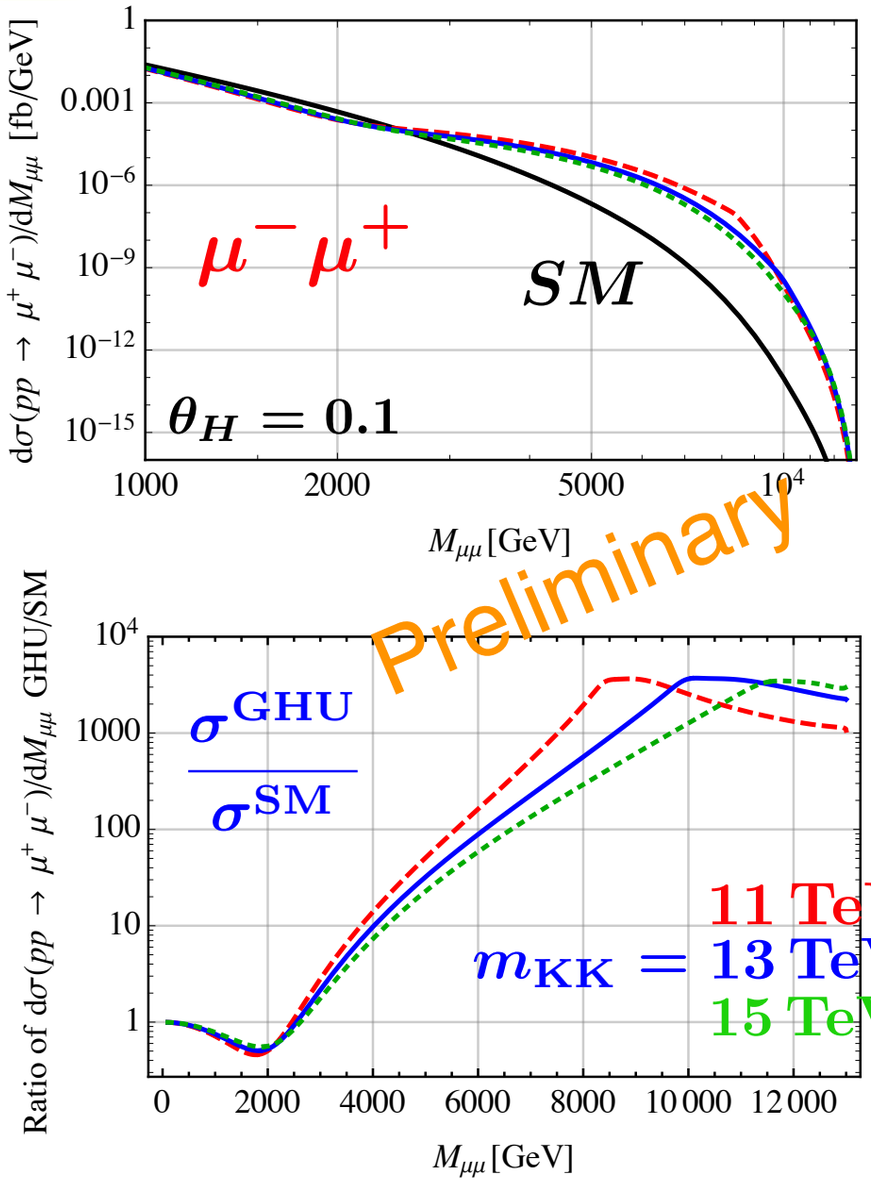
Physics
OSAKA UNIVERSITY

LHC signals

$$p\,p \xrightarrow{Z'} e^-e^+\ ,\ \mu^-\mu^+$$

$$p\,p \xrightarrow{g^{(1)}} t\,\bar{t}$$

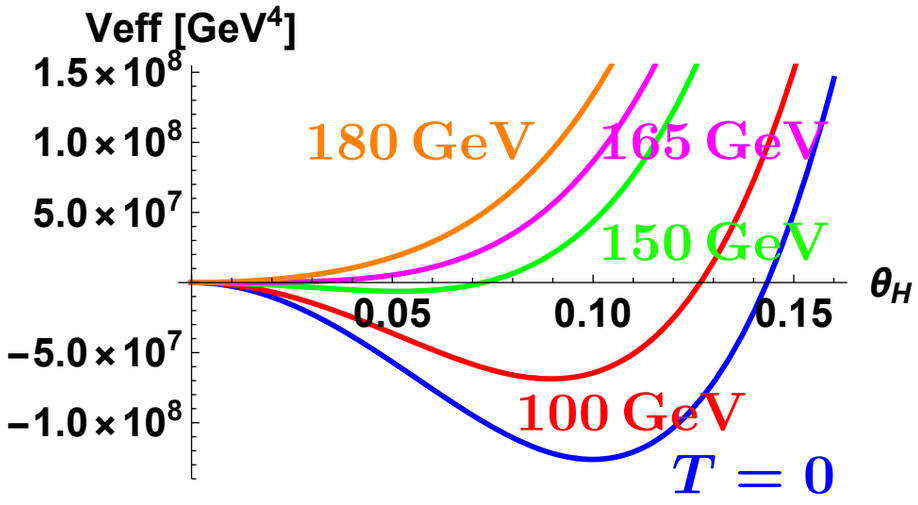
$$p\,p \xrightarrow{W'} t\,\bar{b}$$

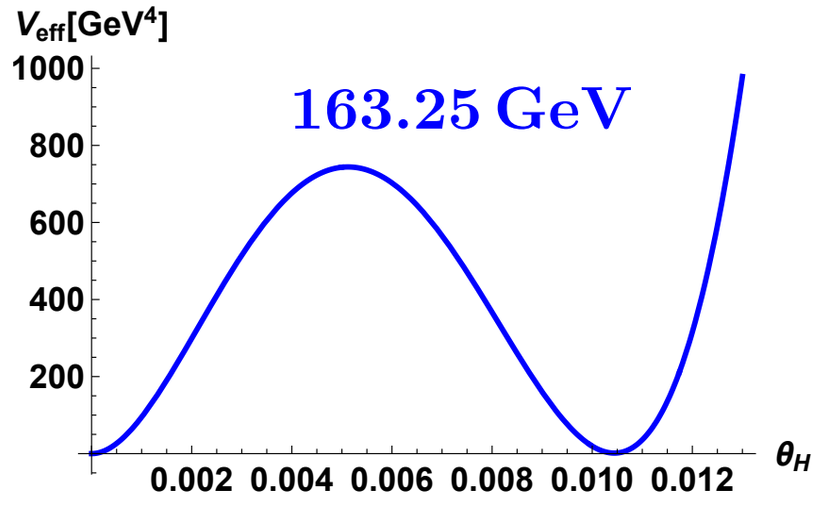


Phase transitions

[arXiv: 2103.16320]

Electroweak transition: similar to SM

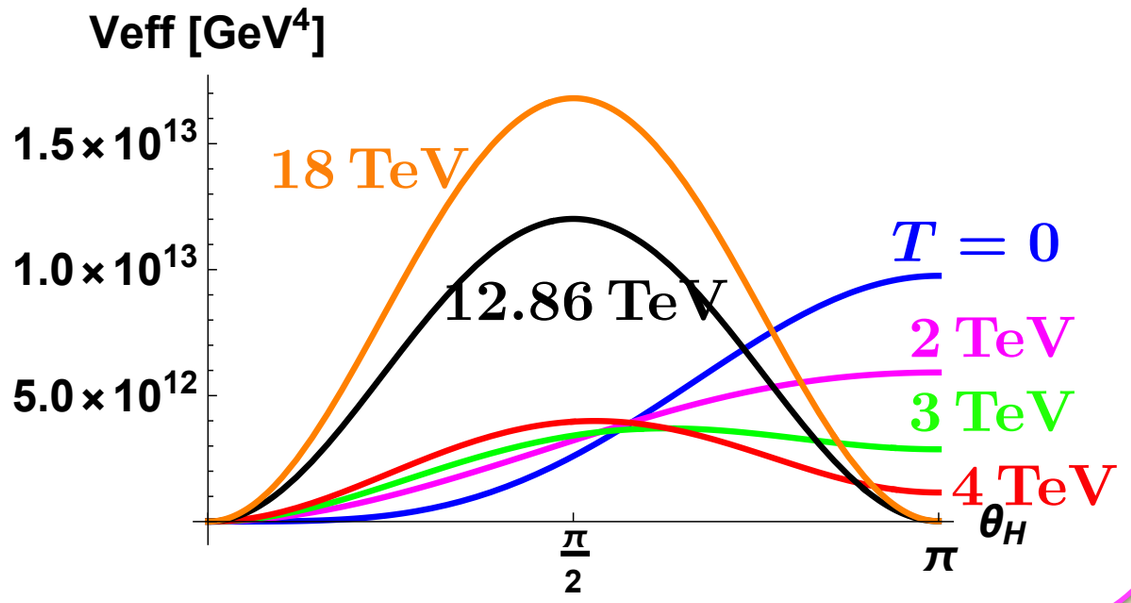




Left-right transition:

$SU(2)_L \times U(1)_Y$
$\theta_H = 0$

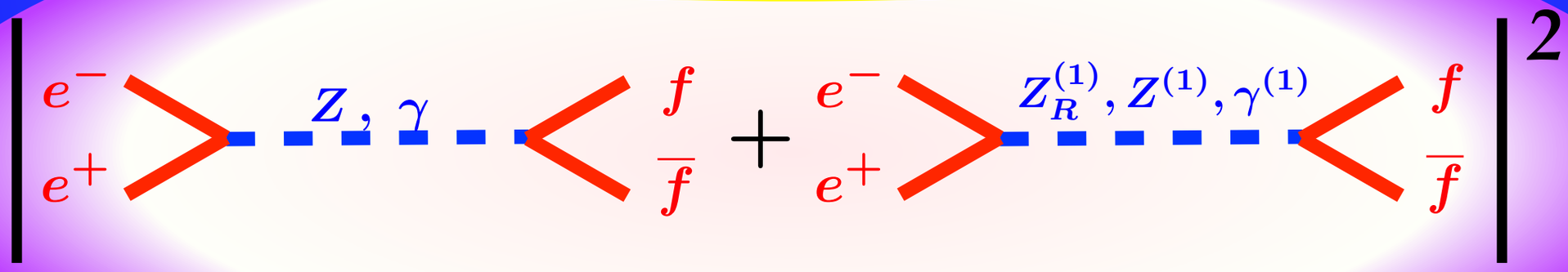
$SU(2)_R \times U(1)_{Y'}$
$\theta_H = \pi$



Summary

GUT inspired gauge-Higgs unification

New particles Z' & extra dimensions can be explored



in the early stage of ILC 250

Physics
OSAKA UNIVERSITY