Study of photon-associated Higgs production at the ILC

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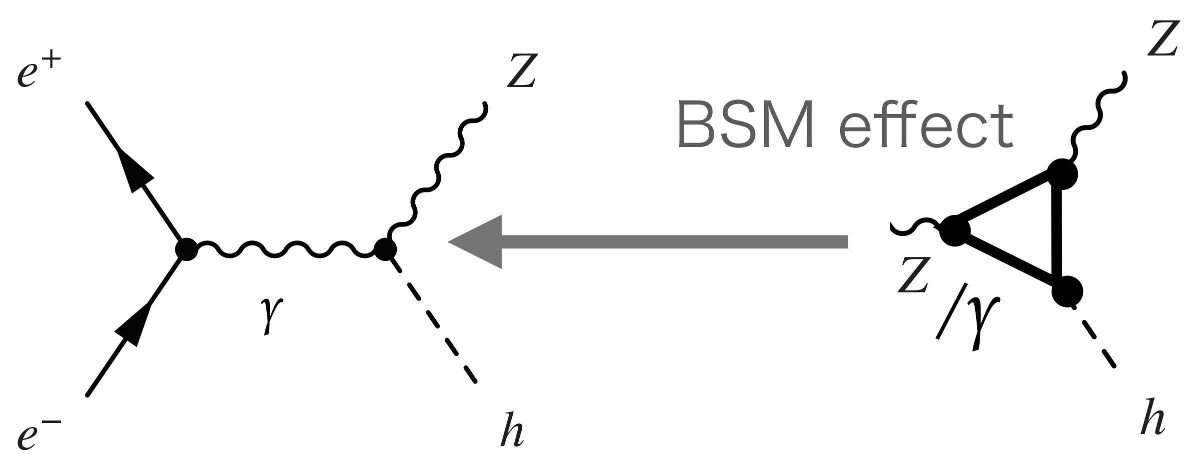
1.Motivation

Find new physics via hγγ and hγZ couplings

hγZ coupling in the Standard Model (SM) is a loop induced coupling.
→We expect BSM amplitude can be larger than SM amplitude.

We are the first to study the hγZ coupling bond using $e^+e^- \to h\gamma$



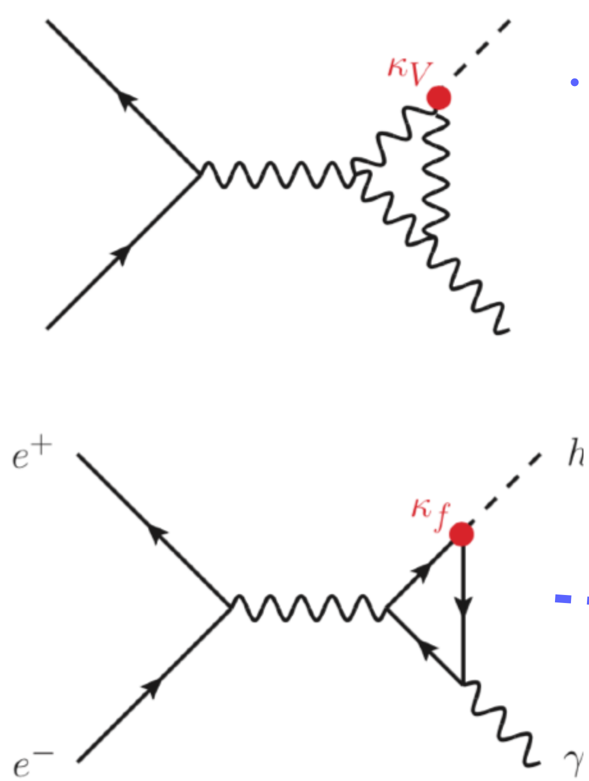
Any deviation of the coupling constants from SM signals new physics.

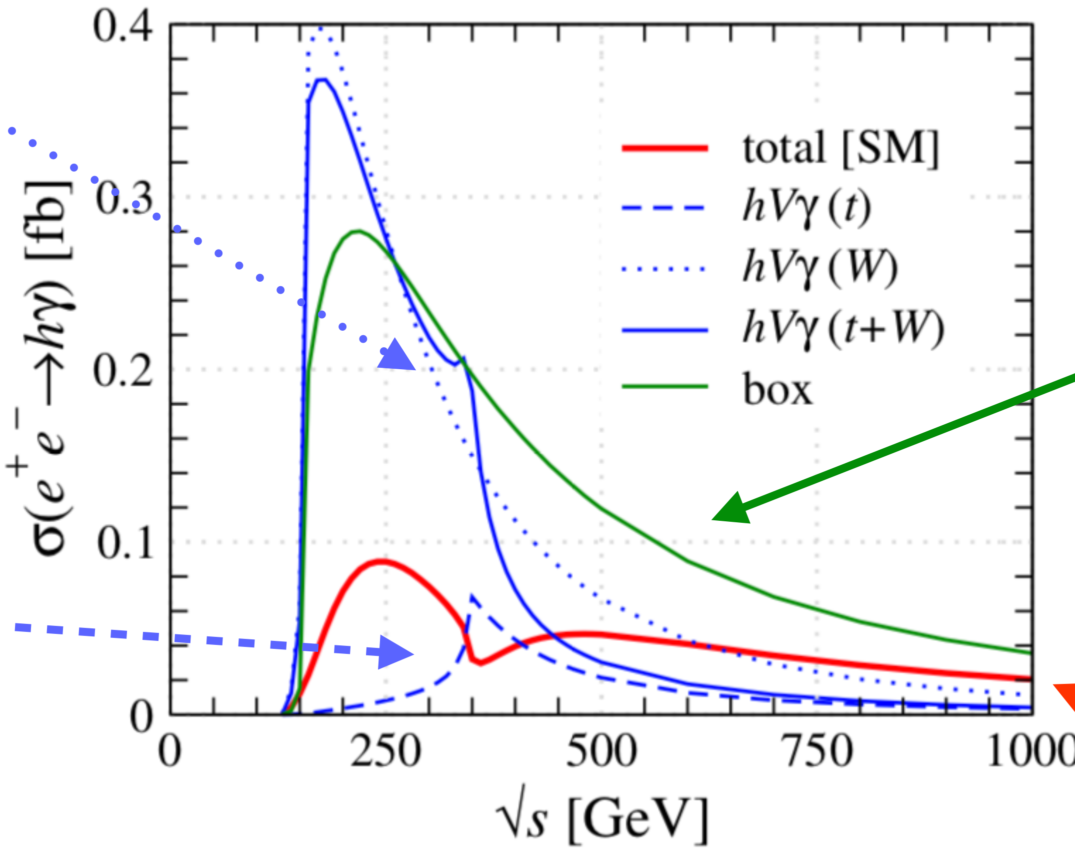
In this talk, we will report the simulation results of cross-section at ILC and the constraints such as model independent and hγz coupling constant.

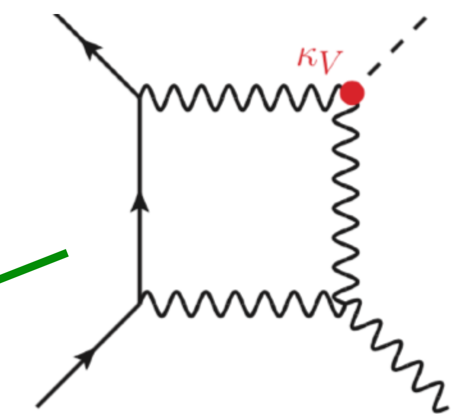
2. Theoretical framework for our analysis

SM one-loop predictions

※For unpolarized beam







Kanemura, et al, arXiv:1808.10268

Destructive interference

SM cross sections by one loop calculation: $\sqrt{s}$ = 250 GeV

e^- e^+

σ^L_{SM}=0.35 fb for (-100%,+100%)

σ^R_{SM}=0.016 fb for (+100%,-100%)

This analysis is very challenging.

σ_{SM}^-=**0.20 fb** for (-80%,+30%) σ_{SM}^+=**0.021 fb** for (+80%,-30%)

3.Experimental Method

The effective field theory (EFT) Lagrangian (model-independent)

effective hγZ coupling   effective hγγ coupling

$$L_{\gamma H} = L_{\rm SM} + \frac{\zeta_{AZ}}{v} A_{\mu\nu} Z^{\mu\nu} H + \frac{\zeta_A}{2v} A_{\mu\nu} A^{\mu\nu} H$$

$A_{\mu\nu}$, $Z_{\mu\nu}$: field strength tensors   v: vacuum expectation value

Phys.Rev. D94 (2016) 095015

cross section of e+e- —> γH

$$\frac{\sigma_{\gamma H}}{\sigma_{SM}} = 1 - 273\zeta_A - 201\zeta_{AZ} \quad \text{(eLpR)}$$

$$\frac{\sigma_{\gamma H}}{\sigma_{SM}} = 1 + 492\zeta_A - 311\zeta_{AZ} \quad \text{(eRpL)}$$

Since ζ_A is already constrained by measurement of h→ γγ branching ratio at LHC, we can extract ζ_{AZ} parameter by just measuring cross section for a single beam polarization.

4. Simulation framework

Event generation

- $\sqrt{s}$=250 GeV
  Integrated Luminosity: 2000 fb^{-1}
  (900 fb^{-1} each for Left / Right handed pol.)
- background : 2f,4f (DBD sample)
- ISR and Beamstrahlung effects are included

Detector simulation

- ILD full simulation (Mokka)
- Geant4 based, realistic detailed detector model

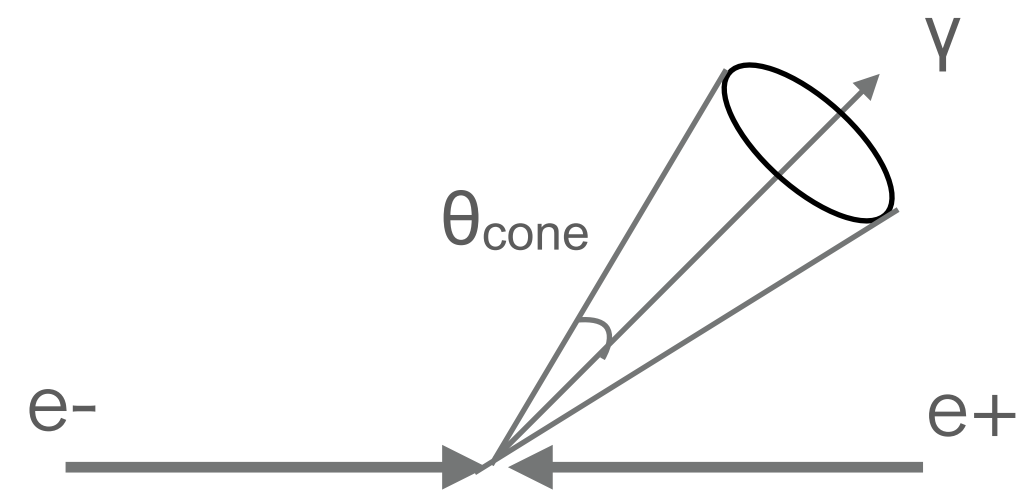
Event reconstruction

- Full reconstruction chain from detector signals to 4-vectors
  (iLCSoft v01-16-02/ MarlinReco, PandoraPFA, LCFI+, Isolated photon finder, jet clustering)

Event selection

- h→bb
- h→WW* fully hadronic
- h→WW* semi leptonic

5. Pre-Event selection



Isolated photon

- Photon ID
- $E_\gamma > 50$ GeV

※The split photon clusters within a small cone are recovered

- ($\cos\theta_{cone}$=0.998)

Remaining particles other than photon

- Jet clustering (Durham)
- Flavor tagged（LCFI+）

For h→WW* semi-leptonic : number of decay w to qq=1

For h→WW* fully-hadronic : number of decay w to qq=2

5. Event selection

Signal	Cut	Backgrounds
$e^+e^- \to \gamma h \to \gamma(b\bar{b})$		
2 b jets	b likeliness1>0.77	$e^+e^- \to \gamma Z \to \gamma qq$
	missing energy<35 GeV	Background with ν
m(bb)= Higgs mass	The Higgs hypothesis mass	$e^+e^- \to \gamma Z \to \gamma qq$
Isolated photon with energy 93 GeV	Energy of photon	
	angle between 2jets	
	angle between a jet and photon	

The Higgs hypothesis mass, Energy of photon, angle between 2jets and angle between a jet and photon → Input to TMVA

5. Signal Significance

$$significance \quad \frac{N_s}{\sqrt{N_s + N_B}}$$

N_S: # of signal

N_B: # of bg

Left	2f	4f	total bg	Signal	Significance
Expected	1.0×10^8	3.7×10^7	1.4×10^8	1.1×10^2	9.0×10^{-3}
Pre selection	2.8×10^7	1.6×10^6	2.9×10^7	9.9×10^1	1.8×10^{-2}
b likeliness>0.77	2.2×10^6	2.1×10^4	2.2×10^6	9.0×10^1	6.0×10^{-2}
Emis<35	1.9×10^6	1.6×10^4	1.9×10^6	8.2×10^1	5.9×10^{-2}
mvabdt >0.025	1.9×10^4	3.2×10^2	2.0×10^4	3.4×10^1	2.4×10^{-1}
$-0.92< cos\theta_\gamma <0.92$	1.2×10^4	1.3×10^2	1.2×10^4	2.9×10^1	2.6×10^{-1}

Right	2f	4f	total bg	Signal	Significance
Expected	7.3×10^7	4.6×10^6	7.8×10^7	1.1×10^1	1.3×10^{-3}
Pre selection	2.3×10^7	4.7×10^5	2.3×10^7	1.0×10^1	2.1×10^{-3}
b likeliness>0.77	1.4×10^6	9.3×10^3	1.5×10^6	9.4×10^0	7.8×10^{-3}
Emis<35	1.3×10^6	7.7×10^3	1.3×10^6	8.4×10^0	7.5×10^{-3}
mvabdt > 0.025	1.0×10^4	2.1×10^2	1.0×10^4	3.4×10^0	3.4×10^{-2}
$-0.92 < cos\theta_\gamma <0.92$	5.9×10^3	5.7×10^1	5.9×10^3	3.0×10^0	3.9×10^{-2}

5. Event selection

Signal

Backgrounds

W1 W2

$$e^+e^- \to \gamma h \to \gamma(WW^*) \to \gamma(2j)(l\nu)$$

# of charged particle in jets >3 — e^+e^- -> 2l

W1 or W2 is on-shell — |mw1-80.4|<10 GeV or |mw2-80.4|<9.4 GeV

No b-quark jets — b likeliness<0.77

Momenta of 2jets+l+ν ~Higgs hypothesis, Isolated photon with energy 93 GeV

- The Higgs invariant mass
- Energy of photon
- Mass of γqq
- Missing Energy

→ Input to TMVA

5. Signal Significance

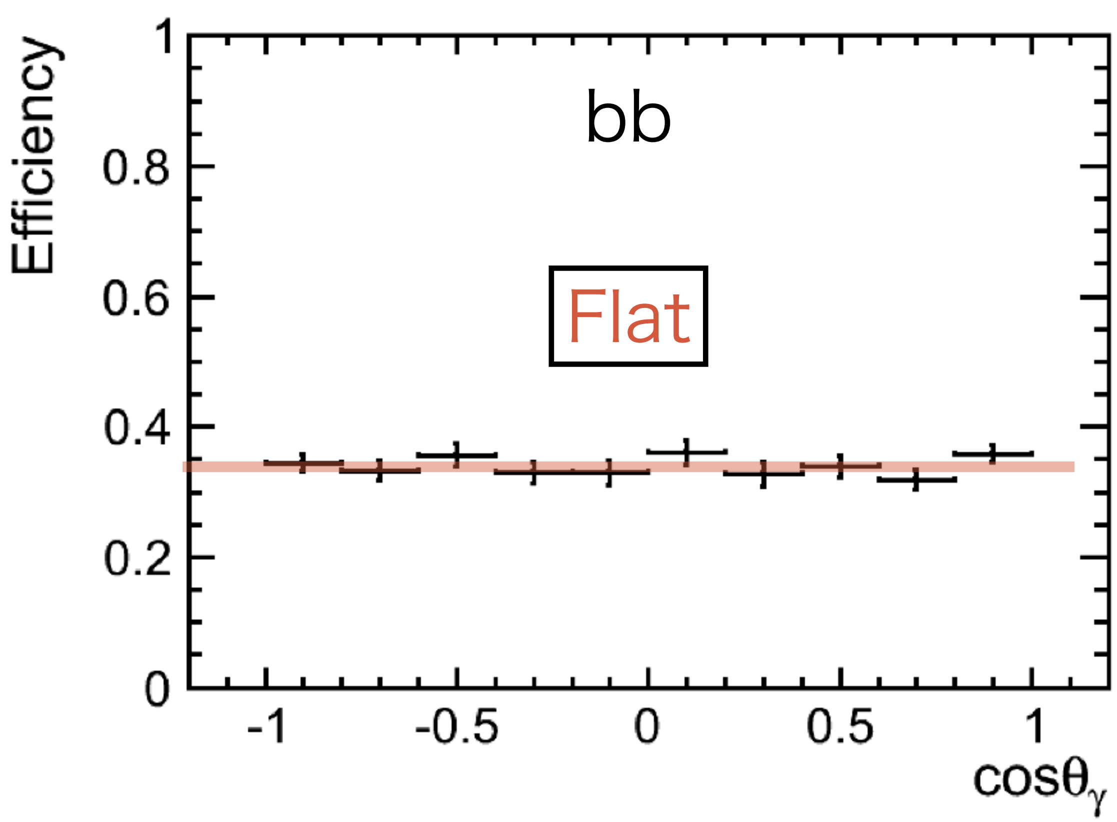
Left	2f	4f	total bg	Signal	Significance
Expected	1.0×10^8	3.7×10^7	1.4×10^8	1.8×10^1	3.4×10^{-3}
Pre selection	1.3×10^7	7.5×10^5	1.3×10^7	1.0×10^1	3.6×10^{-3}
of charged particle>3	7.8×10^4	2.3×10^5	3.1×105	5.4	9.8×10^{-3}
$\lvert m_{W1}-80.4\rvert < 10\ GeV$ $\lvert m_{W2}-80.4\rvert < 9.4\ GeV$	2.5×10^4	1.6×10^5	1.9×10^5	3.7	8.6×10^{-3}
b likeliness<0.77	1.7×10^4	1.6×10^5	1.8×10^5	3.7	8.7×10^{-3}
mvabdt > 0.1	3.1	3.8×10^1	4.1×10^1	1.0	1.6×10^{-1}
-0.93< $cos\theta_\gamma$ <0.93	0.0	8.4	8.4	9.5×10^{-1}	3.1×10^{-1}

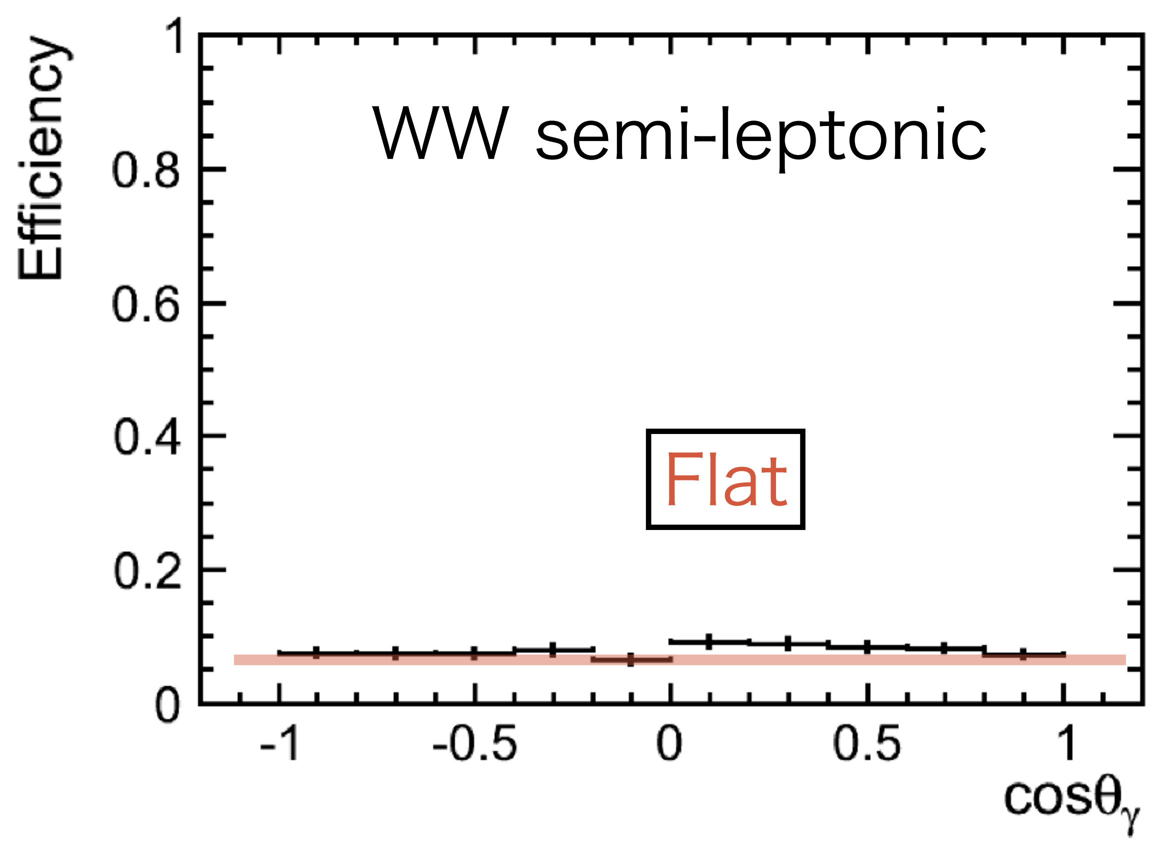
Right	2f	4f	total bg	Signal	Significance
Expected	7.3×10^7	4.6×10^6	7.8×10^7	1.9	4.8×10^{-4}
Pre selection	1.2×10^7	3.1×10^5	1.2×10^7	2.0	3.9×10^{-4}
of charged particle > 3	5.0×10^4	3.6×10^4	8.6×10^4	1.5×10^0	1.9×10^{-3}
$\lvert m_{W1}-80.4\rvert < 10\ GeV$ $\lvert m_{W2}-80.4\rvert < 9.4\ GeV$	1.7×10^4	1.5×10^4	3.2×10^4	3.8×10^{-1}	2.1×10^{-3}
b likeliness<0.77	1.2×10^4	1.4×10^4	2.6×10^5	3.7×10^{-1}	2.3×10^{-3}
mvabdt > 0.1	5.3×10^1	2.1×10^1	7.4×10^1	1.0×10^{-1}	1.2×10^{-2}
-0.93< $cos\theta_\gamma$ < 0.93	0.0	4.7	4.7	9.3×10^{-2}	4.2×10^{-2}

6. cosθγ Distribution

We assume no difference between SM and BSM $\cos\theta_\gamma$ distribution
→Is this assumption reasonable?

$$\frac{d\sigma}{d\cos\theta} = \frac{d\sigma_{SM}}{d\cos\theta} + \zeta_A \frac{d\sigma_{BSM}}{d\cos\theta}(\zeta_A = 1, \zeta_{AZ} = 0) + \zeta_{AZ} \frac{d\sigma_{BSM}}{d\cos\theta}(\zeta_A = 0, \zeta_{AZ} = 1)$$





$$\text{Efficiency} = \frac{\text{\# of signal after cut}}{\text{\# of signal before cut}}$$

There are no $\cos\theta$ dependence

7. Combined result - Each polarization

95% C.L upper limit

$$\sigma_{h\gamma} = \sigma_{SM} + \frac{1.64}{\text{significance}}\sigma_{SM}$$

(Pe, Pp)=(-80%, +30%)

$H \to bb$	Significance = 0.26 for SM
$H \to WW$ (Semi-leptonic)	Significance = 0.31 for SM
Combined	Significance = 0.40 for SM

σ_{SM}^{-}=**0.20 fb** $\quad \frac{\sigma_{h\gamma}^{-}}{\sigma_{SM}^{-}} < 5.1 \quad$ $\sigma_{h\gamma}^{-} < 1.0$ fb (95% C.L upper limit)

(+80%, -30%)

$H \to bb$	Significance = 0.039 for SM
$H \to WW$ (Semi-leptonic)	Significance = 0.042 for SM
Combined	Significance = 0.06 for SM

σ_{SM}^{+}=**0.021 fb** $\quad \frac{\sigma_{h\gamma}^{+}}{\sigma_{SM}^{+}} < 28.3 \quad$ $\sigma_{h\gamma}^{+} < 0.6$ fb (95% C.L upper limit)

7. Combined result - Each polarization

95% C.L upper limit

$$\sigma_{h\gamma} = \sigma_{SM} + \frac{1.64}{\text{significance}}\sigma_{SM}$$

(Pe, Pp)=(-100%, +100%)

Combined

Significance = 0.41 for SM

σ^L_{SM}=0.35 fb for (-100%,+100%)

$\frac{\sigma_{h\gamma}^L}{\sigma_{SM}^L} < 5.0$ $\sigma_{h\gamma}^L < 1.8$ fb (95% C.L upper limit)

(Pe, Pp)=(+100%, -100%)

Combined

Significance = 0.027 for SM

σ^R_{SM}=0.016 fb for (+100%,-100%)

$\frac{\sigma_{h\gamma}^R}{\sigma_{SM}^R} < 61.7$ $\sigma_{h\gamma}^R < 0.99$ fb (95% C.L upper limit)

8. Constraints from sigma

σ limit from experiment

$\sigma_{h\gamma}^{L} < 1.8$ fb

$\sigma_{h\gamma}^{R} < 0.99$ fb

Constraint on ζ_{AZ} coupling

Model Independent

Constraint on concrete models

Inert Triplet Model

Under construction

Constraint on electron Yukawa coupling

8. Constraint on ζ_{AZ} coupling

$$L_{\gamma H} = L_{\rm SM} + \frac{\zeta_{AZ}}{v} A_{\mu\nu} Z^{\mu\nu} H + \frac{\zeta_A}{2v} A_{\mu\nu} A^{\mu\nu} H$$

Left handed **Combined** Significance = 0.41 for SM

5.0 > $\dfrac{\sigma_{\gamma H}}{\sigma_{SM}} = 1 - 273\zeta_A - 201\zeta_{AZ}$ >0 asume ζ_A =0

-0.020< ζ_{AZ} <0.005

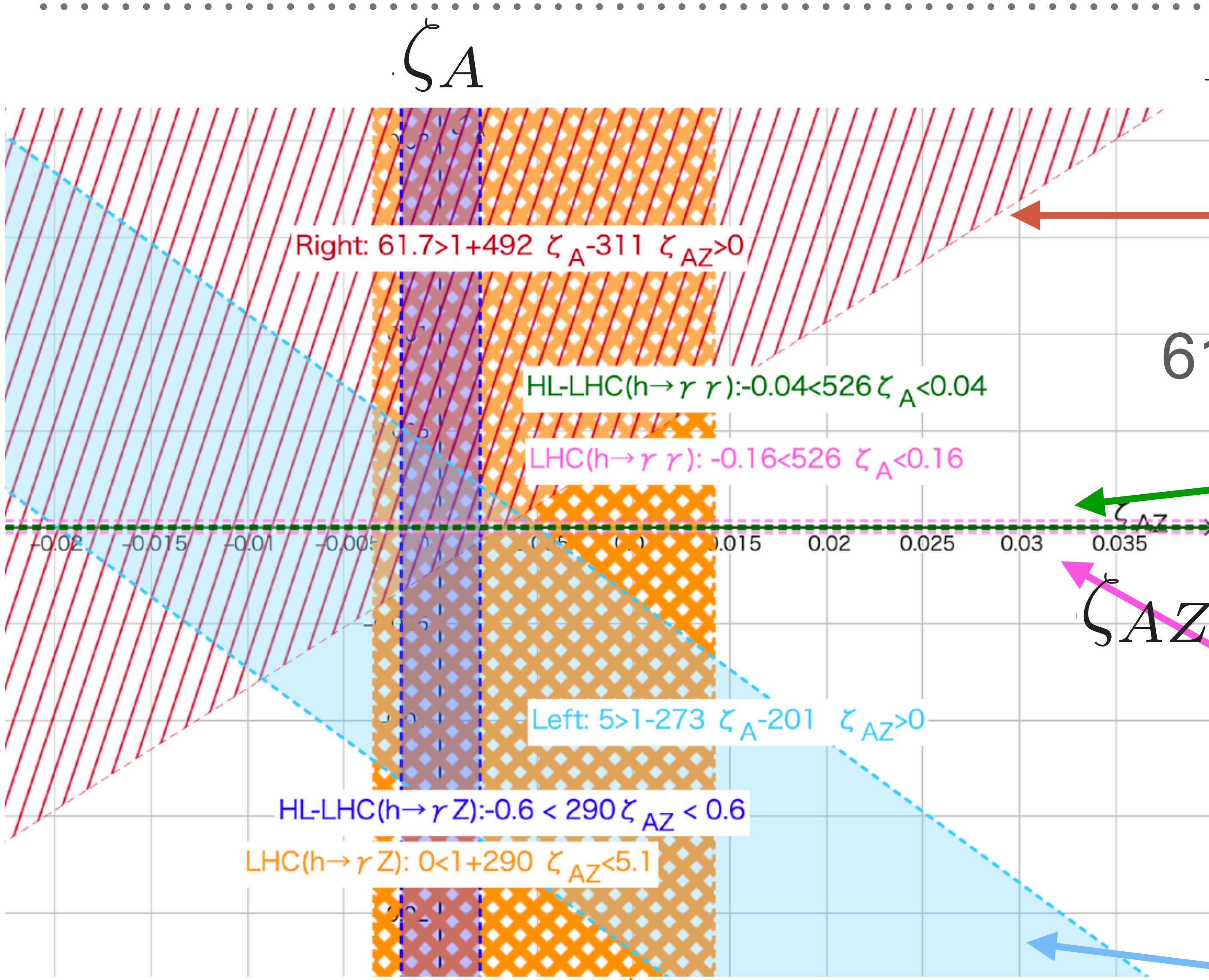
Right handed **Combined** Significance = 0.027 for SM

61.7 > $\dfrac{\sigma_{\gamma H}}{\sigma_{SM}} = 1 + 492\zeta_A - 311\zeta_{AZ}$ >0 asume ζ_A =0

-0.195< ζ_{AZ} <0.0032

8. Comparison with LHC

$$L_{\gamma H} = L_{\rm SM} + \frac{\zeta_{AZ}}{v} A_{\mu\nu} Z^{\mu\nu} H + \frac{\zeta_A}{2v} A_{\mu\nu} A^{\mu\nu} H$$



Right handed limit

61.7 > $1 + 492\zeta_A - 311\zeta_{AZ}$ >0

HL-LHC limit (h→γγ) (Expected)

-0.04< $\delta\Gamma(h \to \gamma\gamma) = 526\zeta_A$ <0.04

ATL-PHYS-PUB-2018-054

https://arxiv.org/abs/1708.09079

LHC limit (h→γγ) (Measured)

ATLAS-CONF-2020-026.pdf

Left handed limit

5.0 > $1 - 273\zeta_A - 201\zeta_{AZ}$ >0

LHC limit (h→γZ) (Measured)

0 < $1 + \delta\Gamma(h \to Z\gamma) = 1 + 290\zeta_{AZ}$ < 5.1

CMS-PAS-HIG-19-014 PhysRevD.97.053004

HL-LHC limit (h→γZ) (Expected) $-0.6 < \delta\Gamma(h \to Z\gamma) = 290\zeta_{AZ} < 0.6$

8. Constraint on concrete models

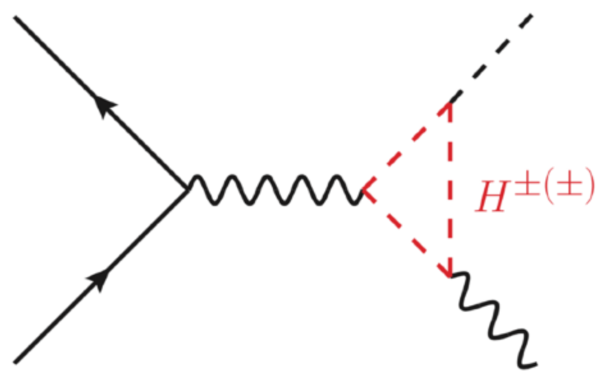
$$\frac{\sigma_{h\gamma}^{L}}{\sigma_{SM}^{L}} < 5.0$$

$$\frac{\sigma_{h\gamma}^{R}}{\sigma_{SM}^{R}} < 61.7$$

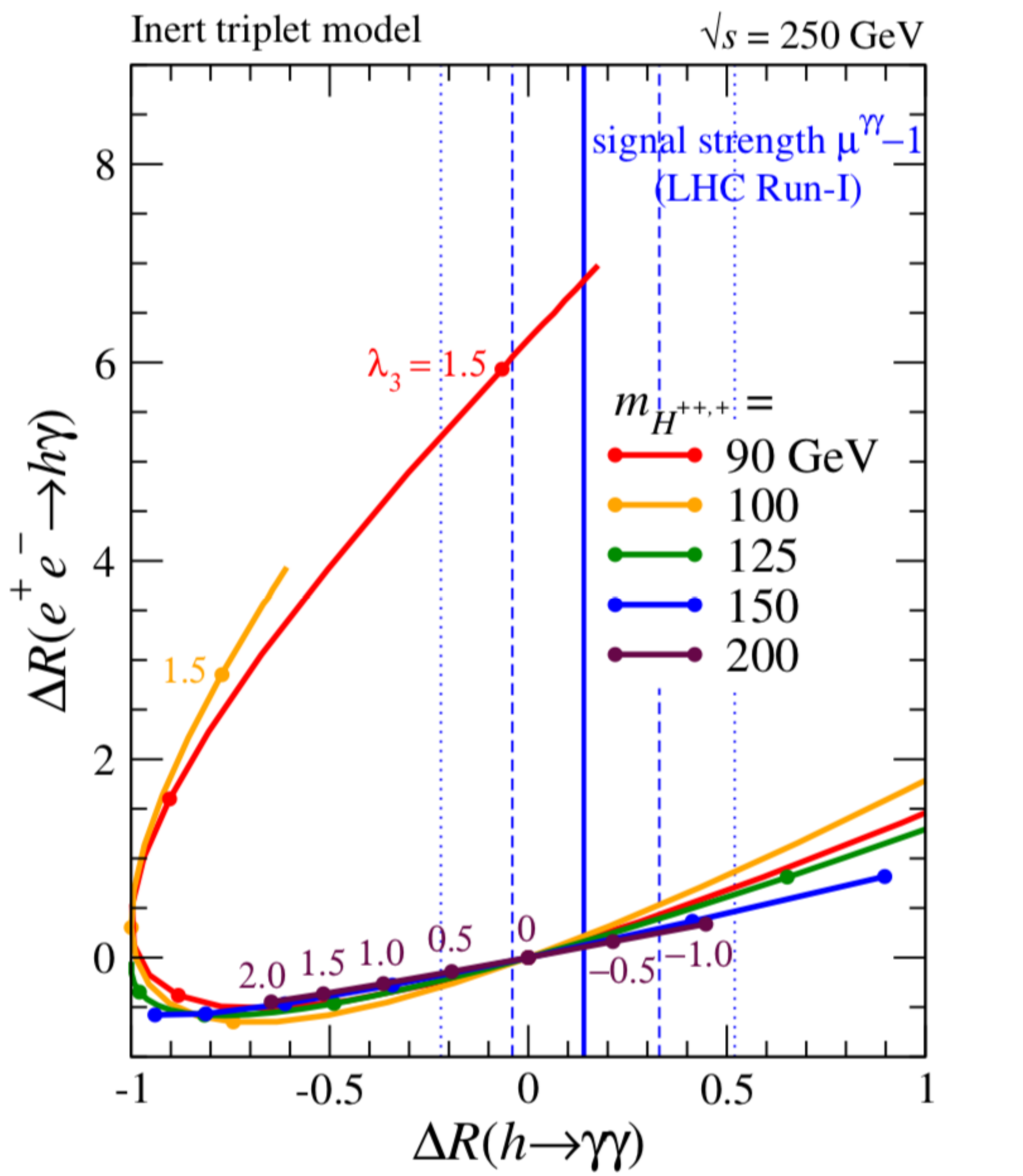
(95% C.L upper limit)

$$\Delta R(e^+e^- \to h\gamma) = \frac{\sigma(e^+e^- \to h\gamma)}{\sigma_{SM}(e^+e^- \to h\gamma)} - 1$$

Inert Triplet Model



Kanemura, et al, arXiv:1808.10268



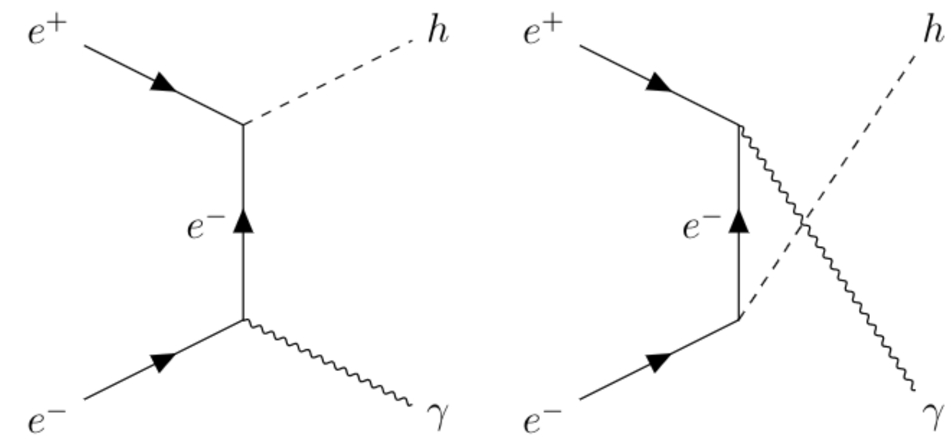
This is the unpolarization plot→

Kanemura, et al, arXiv:1808.10268

I asked theorist to provide new version of HCOUP, which can calculate cross-section to prepare similar plot for each polarization.

8. Constraint on electron Yukawa coupling

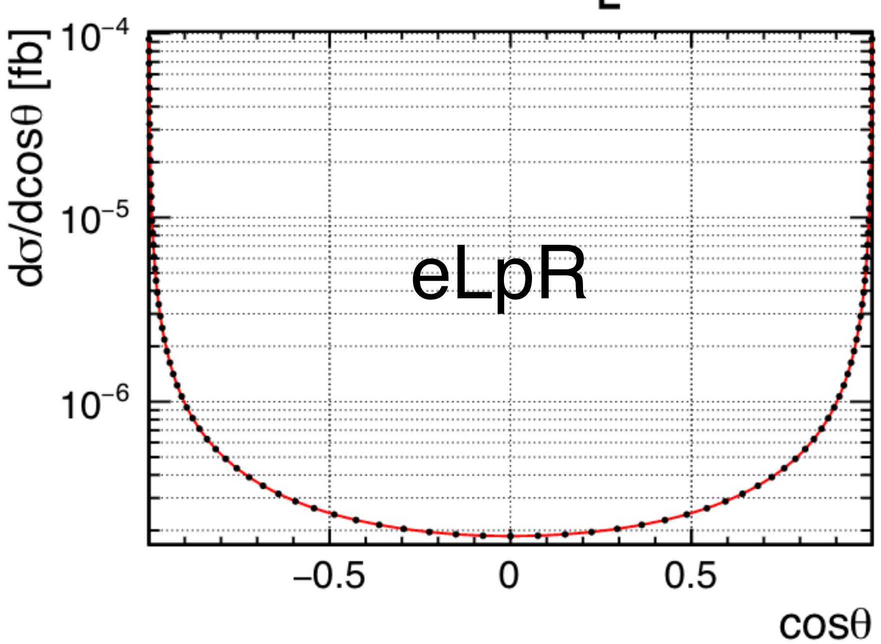
The the differential cross section is calculated as :



$$\frac{d\sigma_{LL}}{d\cos\theta} = \frac{d\sigma_{RR}}{d\cos\theta} =$$

$$\frac{1}{2s\beta_e} 2e^2 \left(\frac{m_e}{v}\right)^2 D_t D_u s^2 \left[\left(1 - \frac{m_h^2}{s}\right)^2 tuD_tD_u + 2\left(\frac{m_h^2}{s}\right)\right] \frac{\bar{\beta}}{16\pi}$$

$$\frac{1}{q^2 - m_e^2} = D_t, \frac{1}{r^2 - m_e^2} = D_u$$



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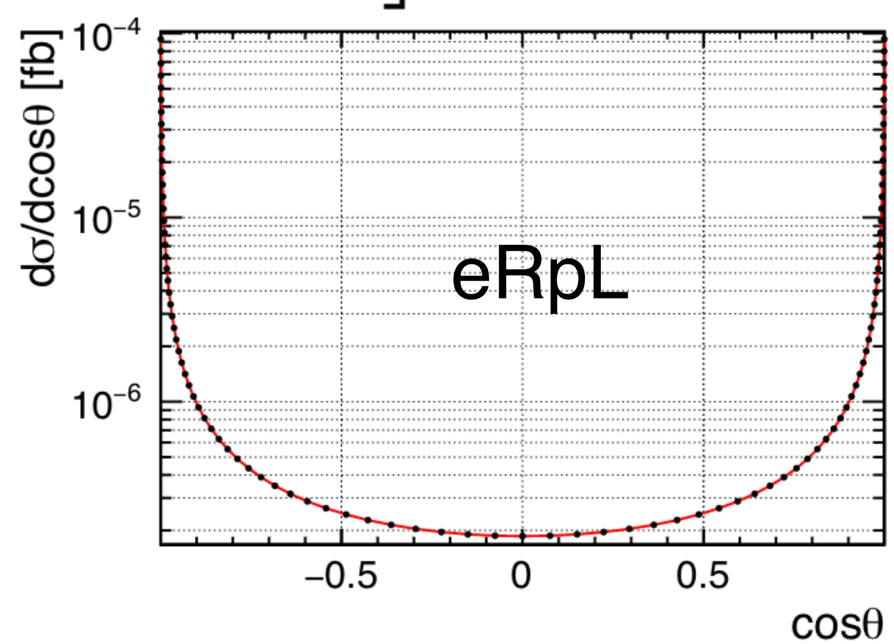


The cross-section is small in the small |cosθ| region.
→It is very difficult to capture the photon and h in this region because it is the pipeline of the detector.

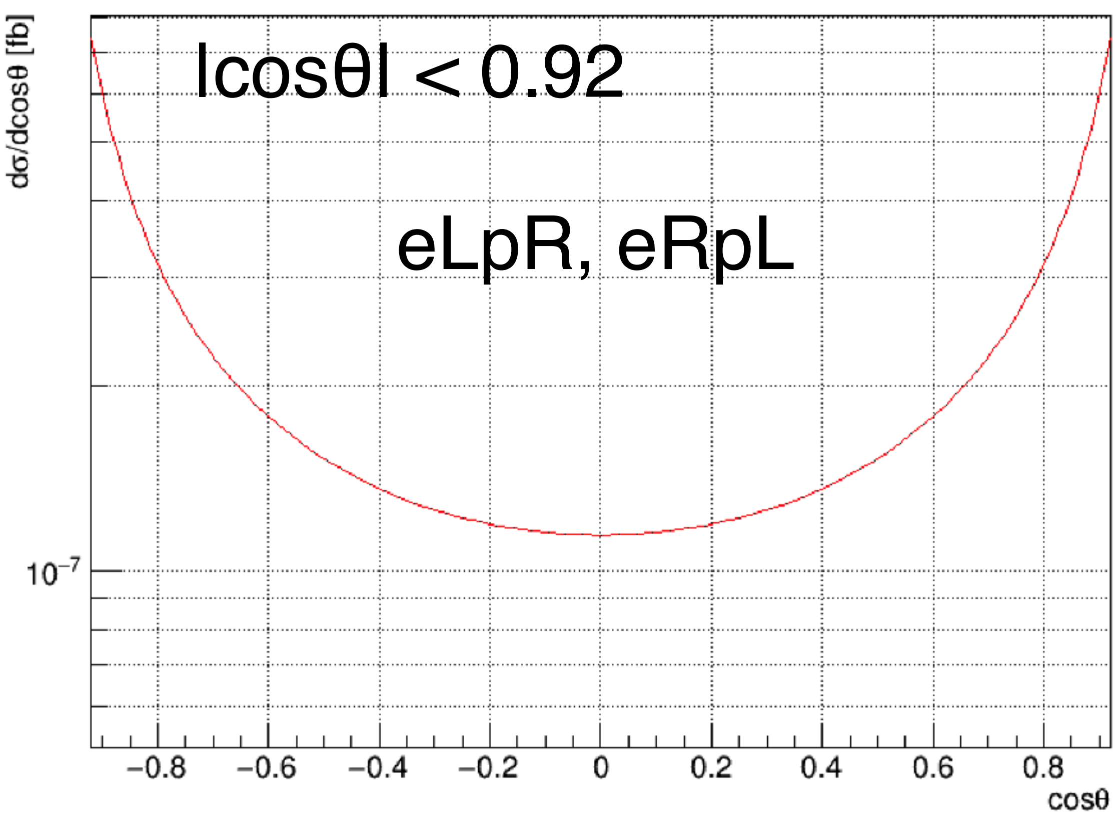
8. cosθ Integration

95% C.L upper limit

σ_{SM}^{-}=**0.20 fb** σ_{SM}^{+}=**0.021 fb**

Significance (-80, +30)= 0.40 for SM

Significance (+80, -30)= 0.06 for SM



$$\Delta\sigma^{-} = \frac{\sigma^{-}}{n_{sig}^{-}} = \frac{0.20}{0.40} = 0.50 \text{ fb}$$

$$\Delta\sigma^{+} = \frac{\sigma^{+}}{n_{sig}^{+}} = \frac{0.021}{0.0.60} = 0.35 \text{ fb}$$

$$\frac{1}{(\Delta\sigma)^2} = \frac{1}{(\Delta\sigma^{+})^2} + \frac{1}{(\Delta\sigma^{-})^2} = \frac{1}{(0.29\text{fb})^2}$$

$$\Delta\sigma_y = 0.29 \text{ fb}$$

95% C.L upper limit : $\sigma_y^{95} = 1.64 \times 0.29\text{fb}$

$\sigma_{h\gamma}^{LR/RL}$ (Electron-Yukawa) = 3.6×10^{-7} [fb]

$$\frac{\sigma_y^{95}}{\sigma_y^{SM}} = \frac{1.64 \times 0.29}{3.6 \times 10^{-7}} = \left(\frac{y_e^{95}}{y_e^{SM}}\right)^2$$

$$\frac{y_e^{95}}{y_e^{SM}} = 1.1 \times 10^{3}$$ (Combined)

9. Summary

We have performed a full simulation study of $e^+e^-\to h\gamma$ at 250 GeV ILC, using ILD detector and full 1-loop SM amplitudes.

Upper limit of $e^+e^- \to \gamma h$ at $\sqrt{s}$=250 GeV, 900 fb^{-1}

(-80%, +30%) **$\sigma_{h\gamma}^- < 1.0$ fb (95% C.L upper limit)**

(+80%, -30%) **$\sigma_{h\gamma}^+ < 0.6$ fb (95% C.L upper limit)**

Constraint on ζ_{AZ} coupling

(Left handed) $-0.020 < \zeta_{AZ} < 0.005$

(Right handed) $-0.195 < \zeta_{AZ} < 0.0032$

Constraint on electron-Yukawa coupling

$$\frac{y_e}{y_e^{SM}} < 1.1 \times 10^3$$ (Combined 95% C.L upper limit)

Future work

Constraint on concrete models (ITM)