# Anomalous VVH couplings at the ILC

**2017/02/04**

**Not so many updates  from last LCWS**

# Lagrangian and parametrization

- Effective field theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \sum_{n\geq} \frac{g_i}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

W. Buchmüller and D. Wyler, Nucl. Phys. **B268**, 621 (1986);
K. Hagiwara, R. Szalapski, and D. Zeppenfeld, Phys. Lett. B **318**, 155 (1993).

- In dim-6, there are operators which interact with Higgs boson and vector boson fields

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi \, G^a_{\mu\nu} G^{a\mu\nu} \ , \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \ , \qquad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \ ,$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \ , \qquad \mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \ , \qquad \mathcal{O}_{B} = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi) \ ,$$

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \, \Phi^\dagger \Phi \, (D^\mu \Phi) \ , \ \mathcal{O}_{\Phi,2} = \tfrac{1}{2} \partial^\mu \left( \Phi^\dagger \Phi \right) \partial_\mu \left( \Phi^\dagger \Phi \right) \ ,$$

- Extract relevant structures which couple a scalar field to two vector bosons

Require operators to be P and C even — Require operators to be P and C odd

$$\mathcal{L}_{dim6} = \frac{g^2}{2\Lambda^2} V_{\mu\nu} V^{\mu\nu} (\Phi^\dagger \Phi) + \frac{g^2}{2\Lambda^2} V_{\mu\nu} \widetilde{V}^{\mu\nu} (\Phi^\dagger \Phi)$$

$$1/\Lambda = g^2 v / \Lambda^2$$

$$\mathcal{L}_{dim5} = \frac{1}{2\Lambda} V_{\mu\nu} V^{\mu\nu} H + \frac{1}{2\Lambda} V_{\mu\nu} \widetilde{V}^{\mu\nu} H$$

- Including SM coupling, we construct effective Lagrangians for ZZH and WWH interaction

$$\mathcal{L}_{ZZH} = 2M_Z^2 \left( \frac{1}{v} + \frac{a}{\Lambda} \right) Z_\mu Z^\mu H + \frac{b}{2\Lambda} Z_{\mu\nu} Z^{\mu\nu} H + \frac{\widetilde{b}}{2\Lambda} Z_{\mu\nu} \widetilde{Z}^{\mu\nu} H \qquad (4)$$

$$\mathcal{L}_{WWH} = 2M_W^2 \left( \frac{1}{v} + \frac{a}{\Lambda} \right) W_\mu^+ W^{-\mu} H + \frac{b}{\Lambda} W^+_{\mu\nu} W^{-\mu\nu} H + \frac{\widetilde{b}}{\Lambda} W^+_{\mu\nu} \widetilde{W}^{-\mu\nu} H \qquad (5)$$

# Lagrangian and parametrization

- Including SM coupling, we construct effective Lagrangians for ZZH and WWH interaction

$$\mathcal{L}_{ZZH} = 2M_Z^2\Big(\frac{1}{v}+\frac{a}{\Lambda}\Big)Z_\mu Z^\mu H + \frac{b}{2\Lambda}Z_{\mu\nu}Z^{\mu\nu}H + \frac{\widetilde{b}}{2\Lambda}Z_{\mu\nu}\widetilde{Z}^{\mu\nu}H \quad (4)$$

$$\mathcal{L}_{WWH} = 2M_W^2\Big(\frac{1}{v}+\frac{a}{\Lambda}\Big)W_\mu^+ W^{-\mu} H + \frac{b}{\Lambda}W_{\mu\nu}^+ W^{-\mu\nu}H + \frac{\widetilde{b}}{\Lambda}W_{\mu\nu}^+\widetilde{W}^{-\mu\nu}H \quad (5)$$

- How much is the ILC sensitive anomalous parameters?

- **All major processes for ZZH and WWH vertices have been used**
- **Analysis based on angular asymmetries is almost done. => lcws16**
- [ZZH] ZH process at 250 GeV, ee → eeH / μμH / qqH(H→bb)
- [ZZH] ZH process at 500GeV, ee → eeH / μμH / qqH(H→bb)
- [ZZH] ZZ-f process at 500GeV, ee → eeH

- [WWH] ZH process at 250GeV, ee → ZH → vvWW (WW →cxcx/qqqq)
- ee → ZH → qqWW (WW →lvqq)
- [WWH] WW-f process at 500GeV, ee → vvH (H→bb)
- [WWH] WW-f process at 500GeV, ee → vvH (WW →cxcx/qqqq)

# Constraints on ZZH with nominal luminosity

$$\mathcal{L}_{ZZH} \quad = \quad 2M_Z^2\left(\frac{1}{v}+\frac{a}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b}{2\Lambda}Z_{\mu\nu}Z^{\mu\nu}H + \frac{\widetilde{b}}{2\Lambda}Z_{\mu\nu}\widetilde{Z}^{\mu\nu}H \qquad (4)$$

- **Constraints with nominal luminosity:**
- **Only ZH process is used, Three parameters are free.**

**250GeV L0.8 R0.3 + R0.8 L0.3 250fb-1 + 250fb-1**

PARAMETER CORRELATION COEFFICIENTS

| NO. | GLOBAL | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | 0.99015 | 1.000 | -0.990 | 0.031 |
| 2 | 0.99015 | -0.990 | 1.000 | -0.031 |
| 3 | 0.03150 | 0.031 | -0.031 | 1.000 |

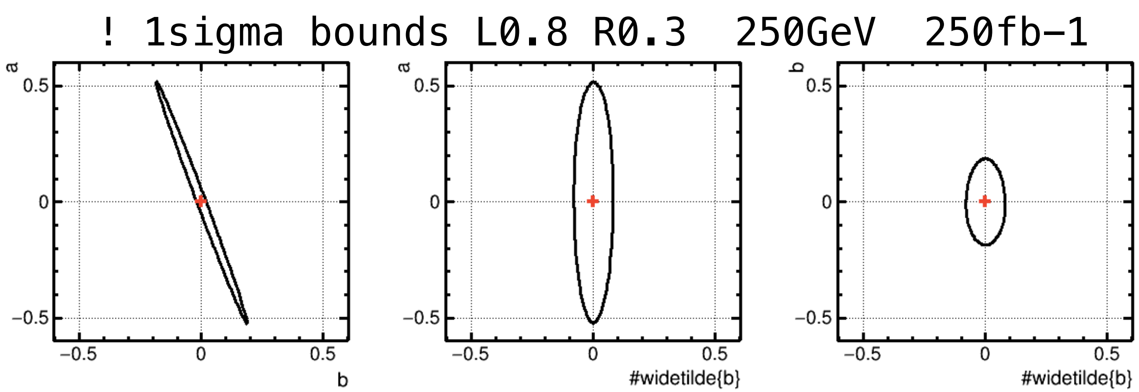
**a parameter: 0 +/- 0.383384**
**b parameter: 0 +/- 0.137872**
**bt parameter: 0 +/- 0.0793514**

**500GeV L0.8 R0.3 + R0.8 L0.3 500fb-1 + 500fb-1**

PARAMETER CORRELATION COEFFICIENTS

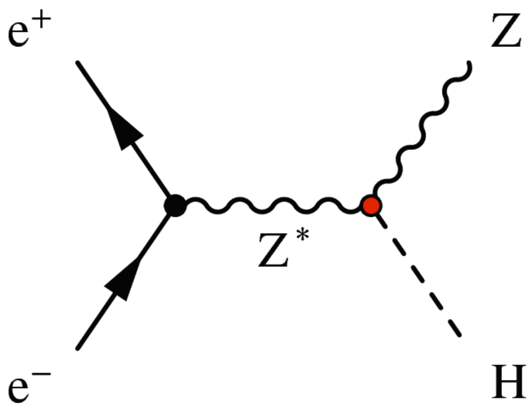
| NO. | GLOBAL | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | 0.76265 | 1.000 | -0.763 | -0.001 |
| 2 | 0.76265 | -0.763 | 1.000 | 0.000 |
| 3 | 0.00208 | -0.001 | 0.000 | 1.000 |

**a parameter: 0 +/- 0.125133**
**b parameter: 0 +/- 0.0220664**
**bt parameter: 0 +/- 0.0279172**



# Anomalous AZH on ZH process

$$\mathcal{L}_{ZZH} \;=\; 2M_Z^2\left(\frac{1}{v}+\frac{a}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b}{2\Lambda}Z_{\mu\nu}Z^{\mu\nu}H + \frac{\widetilde{b}}{2\Lambda}Z_{\mu\nu}\widetilde{Z}^{\mu\nu}H \qquad (4)$$

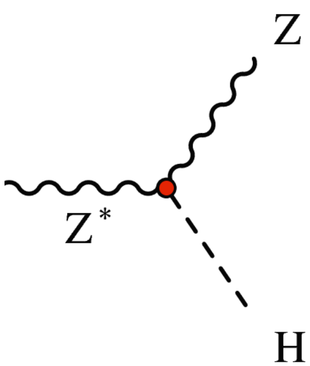


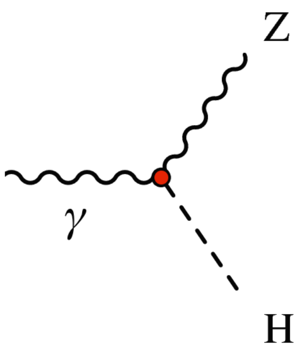

- **Replace the previous parameters with**
- **dimensionless $\zeta_{ZZ}$, $\zeta t_{ZZ}$**
- **and introduce additional parameter $\zeta_{AZ}$, $\zeta t_{AZ}$**

$$b = \frac{\Lambda}{v}\,\zeta_{ZZ}, \qquad \zeta_{AZ}$$

$$\widetilde{b} = \frac{\Lambda}{v}\,\widetilde{\zeta}_{ZZ} \qquad \widetilde{\zeta}_{AZ}$$

**In reality**




$$\mathcal{L}_{ZZH} \;=\; 2M_Z^2\frac{1}{\Lambda}\left(\frac{\Lambda}{v}+a\right)Z_\mu Z^\mu H$$

$$+\frac{1}{2v}\left(\,\zeta_{ZZ}Z_{\mu\nu}Z^{\mu\nu}+\zeta_{AZ}A_{\mu\nu}Z^{\mu\nu}\,\right)H$$

- **original b term**

$$+\frac{1}{2v}\left(\,\widetilde{\zeta}_{ZZ}Z_{\mu\nu}\widetilde{Z}^{\mu\nu}+\widetilde{\zeta}_{AZ}A_{\mu\nu}\widetilde{Z}^{\mu\nu}\,\right)H$$

- **original bt term**

# b term at 250GeV (Trial)

- **We calculated relative difference for both cases in order to connect two notation.**

My calculation for the parameter $b$ at 250 GeV is below: The center relation corresponds to the new definition including the effect of mixing of $\gamma$. The left relation is our previous definition where only $Z^*$ is considered.

**(New relation)** **(original)**

$$eLpR: \quad \frac{\sigma_{BSM}}{\sigma_{SM}} = 1 + 5.70\,\zeta_{ZZ} + 7.70\,\zeta_{AZ} = 1 + 5.70\,b_{LR}$$

$$eRpL: \quad \frac{\sigma_{BSM}}{\sigma_{SM}} = 1 + 5.70\,\zeta_{ZZ} - 9.05\,\zeta_{AZ} = 1 + 5.70\,b_{RL}$$

$$\begin{cases} \zeta_{ZZ} + 1.355\,\zeta_{AZ} = b_{LR} \\ \zeta_{ZZ} - 1.588\,\zeta_{AZ} = b_{RL} \end{cases}$$

- **Fitting results for parameters**

**<u>250GeV L0.8 R0.3 + R0.8 L0.3 250fb-1 + 250fb-1</u>**

| | | |
|---|---|---|
| a parameter: | 0 +/- | 0.383384 |
| b parameter: | 0 +/- | 0.137872 |
| bt parameter: | 0 +/- | 0.0793514 |

```
PARAMETER  CORRELATION COEFFICIENTS
      NO.  GLOBAL      1      2      3      4
        1  0.99016   1.000 -0.990 -0.026  0.032
        2  0.99017  -0.990  1.000  0.036 -0.032
        3  0.08345  -0.026  0.036  1.000 -0.008
        4  0.03259   0.032 -0.032 -0.008  1.000
```

| | | |
|---|---|---|
| a parameter: | 0 +/- | 0.383509 |
| zZZ parameter: | 0 +/- | 0.137963 |
| zAZ parameter: | 0 +/- | 0.0131591 |
| bt parameter: | 0 +/- | 0.0793541 |

# bt term at 250GeV (Trial)

- **We calculated relative difference for both cases in order to connect two notation.**

My calculation for the parameter $\widetilde{b}$ at 250 GeV is below:

$$eLpR: \quad \frac{\sigma_{BSM}}{\sigma_{SM}} = 1 - 1.14\times10^{-3}\,\widetilde{\zeta}_{ZZ} - 1.80\times10^{-3}\,\widetilde{\zeta}_{AZ} = 1 - 1.14\times10^{-3}\,\widetilde{b}_{LR}$$

$$eRpL: \quad \frac{\sigma_{BSM}}{\sigma_{SM}} = 1 + 2.40\times10^{-3}\,\widetilde{\zeta}_{ZZ} + 1.18\times10^{-3}\,\widetilde{\zeta}_{AZ} = 1 + 2.40\times10^{-3}\,\widetilde{b}_{RL}$$

$$\begin{cases} \widetilde{\zeta}_{ZZ} + 1.575\,\widetilde{\zeta}_{AZ} = \widetilde{b}_{LR} \\ \widetilde{\zeta}_{ZZ} + 0.494\,\widetilde{\zeta}_{AZ} = \widetilde{b}_{RL} \end{cases}$$

- **Fitting results for parameters**

**<u>250GeV L0.8 R0.3 + R0.8 L0.3 250fb-1 + 250fb-1</u>**

| | | |
|---|---|---|
| a parameter: | 0 +/- | 0.383509 |
| zZZ parameter: | 0 +/- | 0.137963 |
| zAZ parameter: | 0 +/- | 0.0131591 |
| bt parameter: | 0 +/- | 0.0793541 |

PARAMETER CORRELATION COEFFICIENTS

| NO. | GLOBAL | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | 0.99037 | 1.000 | -0.990 | 0.040 | 0.144 | -0.146 |
| 2 | 0.99037 | -0.990 | 1.000 | -0.028 | -0.143 | 0.145 |
| 3 | 0.09301 | 0.040 | -0.028 | 1.000 | 0.032 | -0.029 |
| 4 | 0.89371 | 0.144 | -0.143 | 0.032 | 1.000 | -0.894 |
| 5 | 0.89374 | -0.146 | 0.145 | -0.029 | -0.894 | 1.000 |

| | | |
|---|---|---|
| a parameter: | 0 +/- | 0.38773 |
| zZZ parameter: | 0 +/- | 0.139376 |
| zAZ parameter: | 0 +/- | 0.0131555 |
| zZZt parameter: | 0 +/- | 0.176666 |
| zAZt parameter: | 0 +/- | 0.150106 |

# Summary

Based on the effective field theory, we tried to constrain anomalous couplings on ZZH and WWH vertices. We got several values for constraint of theses couplings based on analysis that angular asymmetries were used.

- Now I'm writing a paper.

This time we tried to get constraint on new parameters $\zeta_{AZ}, \zeta t_{AZ}$ in order to consider the effect of A.

The b term seems to be good? The bt term need to be improved?

Several discussion will be needed, but it will be an easy task.

# Scale to H20 Senario

- Three parameters are completely free
- Scale to H20 senario
- Considering processes are only ZZH

| | (-,+) | (+,-) |
|---|---|---|
| $\sqrt{s}$ | [$\mathrm{fb}^{-1}$] | [$\mathrm{fb}^{-1}$] |
| 250 GeV | 1350 | 450 |
| ~~350 GeV~~ | ~~135~~ | ~~45~~ |
| 500 GeV | 1600 | 1600 |

$$\mathcal{L}_{VVH} = 2M_V^2\frac{1}{\Lambda}\left(\frac{\Lambda}{v}+a\right)HV_\mu^+V^{-\mu} + C_V\frac{b}{\Lambda}HV_{\mu\nu}^+V^{-\mu\nu} + C_V\frac{\tilde{b}}{\Lambda}H\epsilon^{\mu\nu\rho\sigma}V_{\mu\nu}^+\tilde{V}_{\rho\sigma}^-$$

$$(\Lambda = 1\ \mathrm{TeV},\quad \mathrm{C_V} = \frac{1}{2}, 1\ \ \mathrm{for\ V = Z, W})$$

**Preliminary**

$$a = 0 \pm 0.021$$
$$b = 0 \pm 0.0050$$
$$\tilde{b} = 0 \pm 0.0057$$

$$\begin{pmatrix} 1 & -0.8 & 0.01 \\ -0.8 & 1 & 0.02 \\ 0.01 & 0.02 & 1 \end{pmatrix}$$

correlation matrix

- WWH will be available.

# Constraints on ZZH

$$\mathcal{L}_{ZZH} = 2M_Z^2\left(\frac{1}{v}+\frac{a}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b}{2\Lambda}Z_{\mu\nu}Z^{\mu\nu}H + \frac{\widetilde{b}}{2\Lambda}Z_{\mu\nu}\widetilde{Z}^{\mu\nu}H \quad (4)$$

- **With nominal luminosity:**

**<u>250GeV L0.8 R0.3 250fb-1</u>**

PARAMETER CORRELATION COEFFICIENTS

| NO. | GLOBAL | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | 0.98433 | 1.000 | -0.984 | 0.047 |
| 2 | 0.98433 | -0.984 | 1.000 | -0.046 |
| 3 | 0.04733 | 0.047 | -0.046 | 1.000 |

a parameter: 0 +/- 0.526508
b parameter: 0 +/- 0.192201
bt parameter: 0 +/- 0.109208

**<u>250GeV R0.8L0.3 250fb-1</u>**

PARAMETER CORRELATION COEFFICIENTS

| NO. | GLOBAL | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | 0.98719 | 1.000 | -0.987 | 0.058 |
| 2 | 0.98719 | -0.987 | 1.000 | -0.058 |
| 3 | 0.05809 | 0.058 | -0.058 | 1.000 |

a parameter: 0 +/- 0.578343
b parameter: 0 +/- 0.213362
bt parameter: 0 +/- 0.160497

L0.8 R0.3 500GeV 500fb-1

PARAMETER CORRELATION COEFFICIENTS

| NO. | GLOBAL | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | 0.76777 | 1.000 | -0.768 | 0.015 |
| 2 | 0.76775 | -0.768 | 1.000 | -0.012 |
| 3 | 0.01478 | 0.015 | -0.012 | 1.000 |

! parameter: 0 +/- 0.17626
! parameter: 0 +/- 0.030942
! parameter: 0 +/- 0.0385972

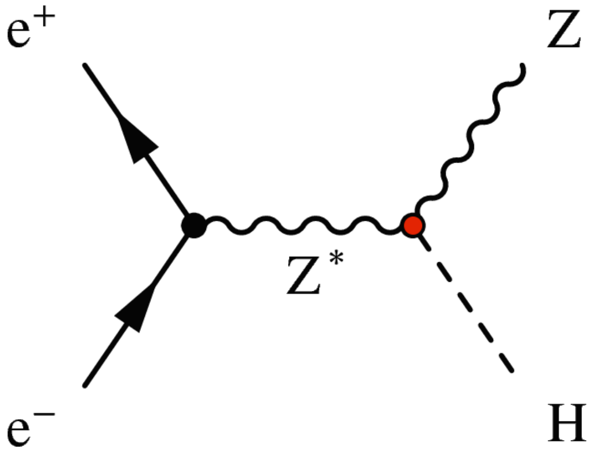
R0.8 L0.3 500GeV 500fb-1

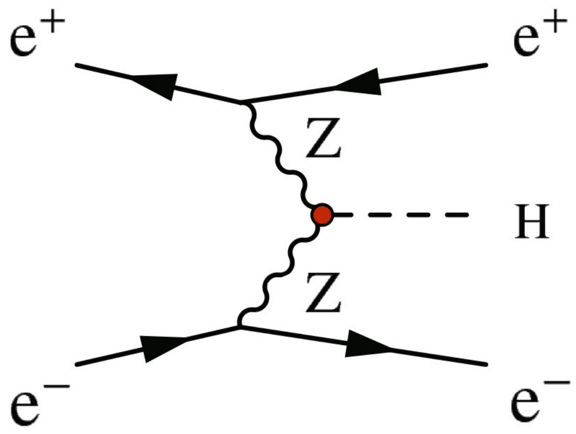
PARAMETER CORRELATION COEFFICIENTS

| NO. | GLOBAL | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | 0.84693 | 1.000 | -0.847 | -0.019 |
| 2 | 0.84694 | -0.847 | 1.000 | 0.021 |
| 3 | 0.02124 | -0.019 | 0.021 | 1.000 |

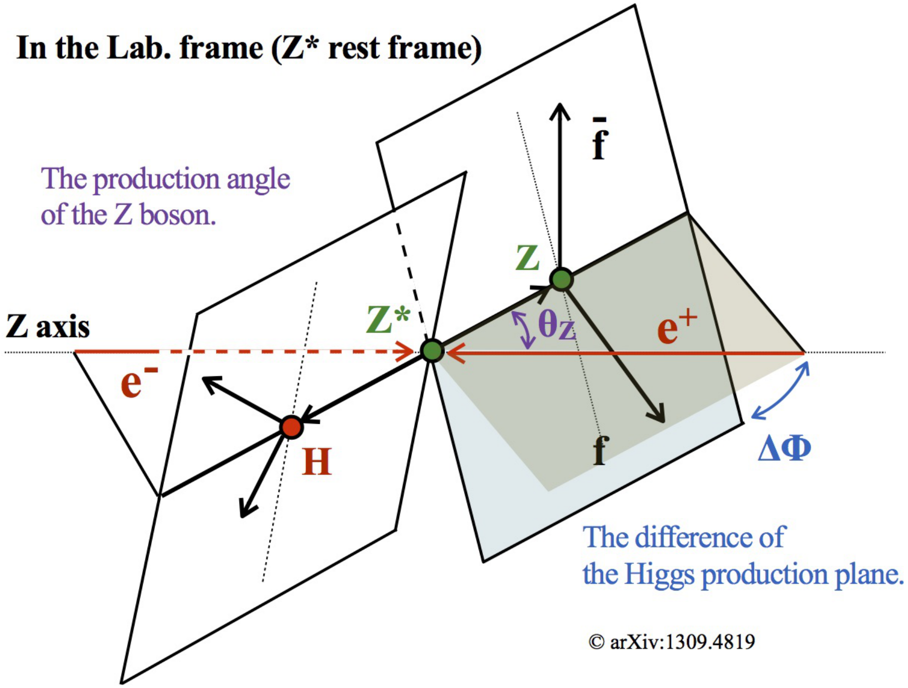
! parameter: 0 +/- 0.214624
! parameter: 0 +/- 0.04104
! parameter: 0 +/- 0.0537379

# ZZH vertices

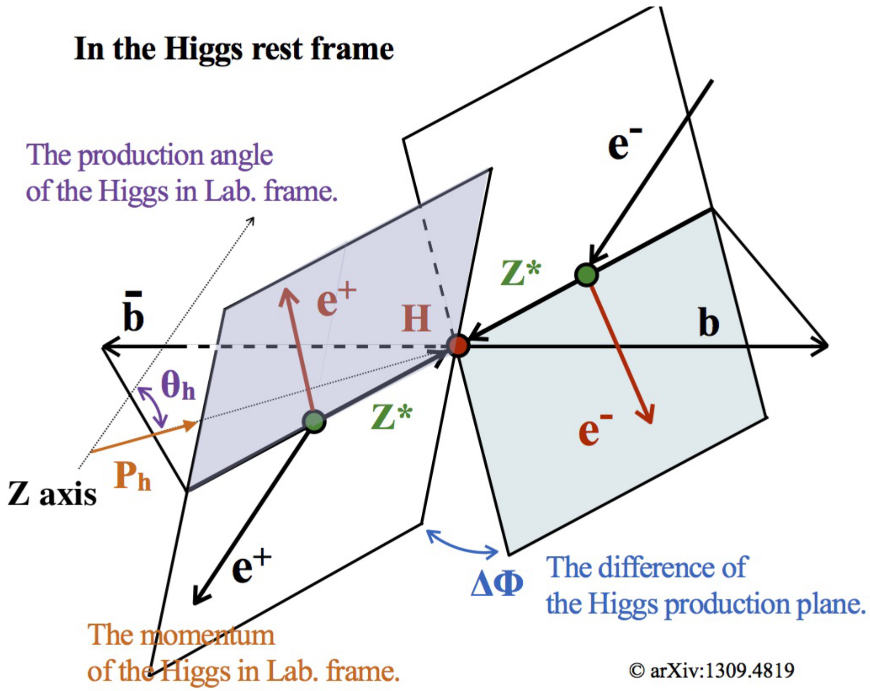



**In the Lab. frame (Z* rest frame)**




**In the Higgs rest frame**



# Angular asymmetries 250GeV ee→llH

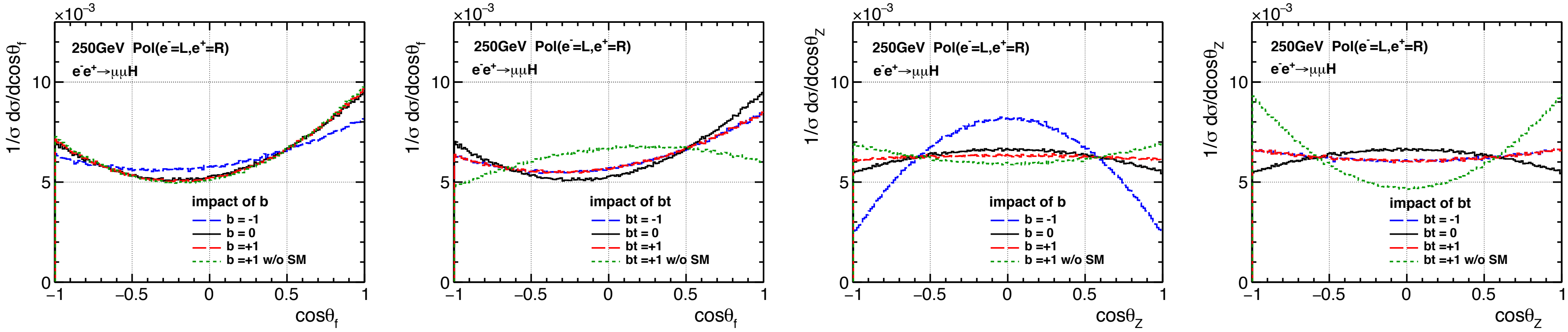
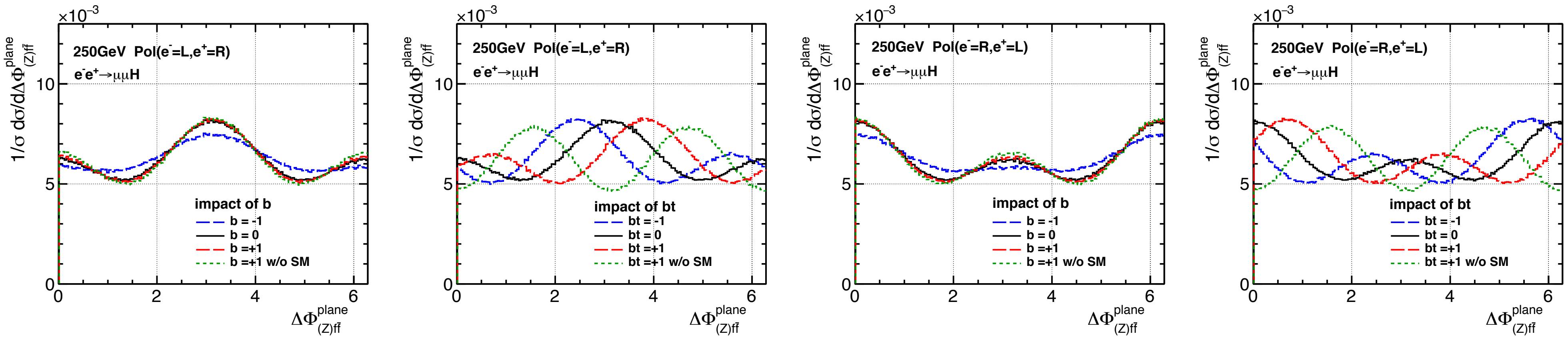



**Figure 4:** The Higgs-strahlung process,



# Angular asymmetries 500GeV ee→llH

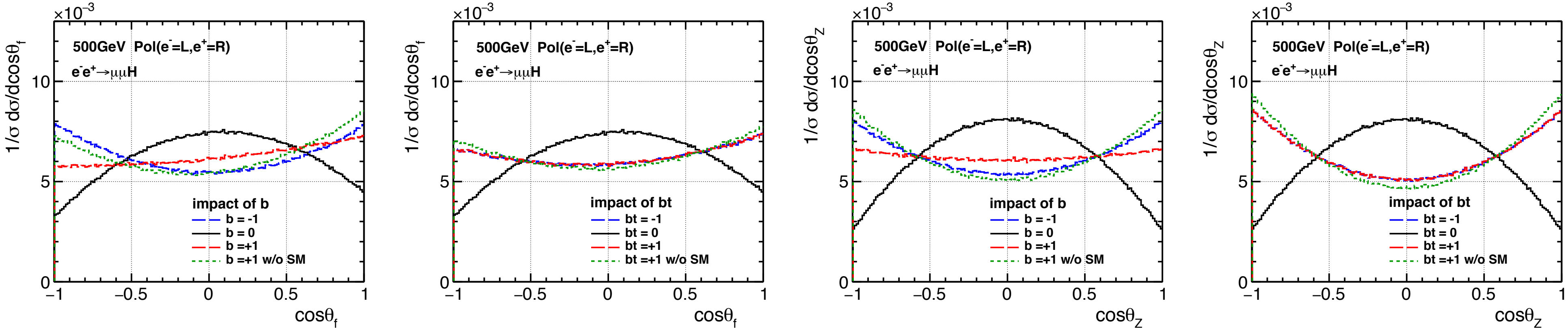
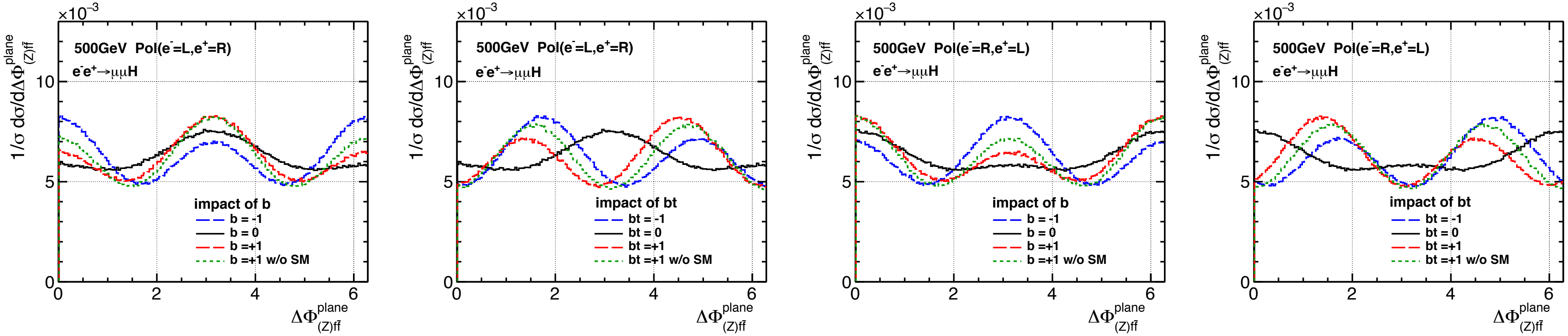



**Figure 6:** The Higgs-strahlung process,



# Angular asymmetries 250GeV ee→qqH

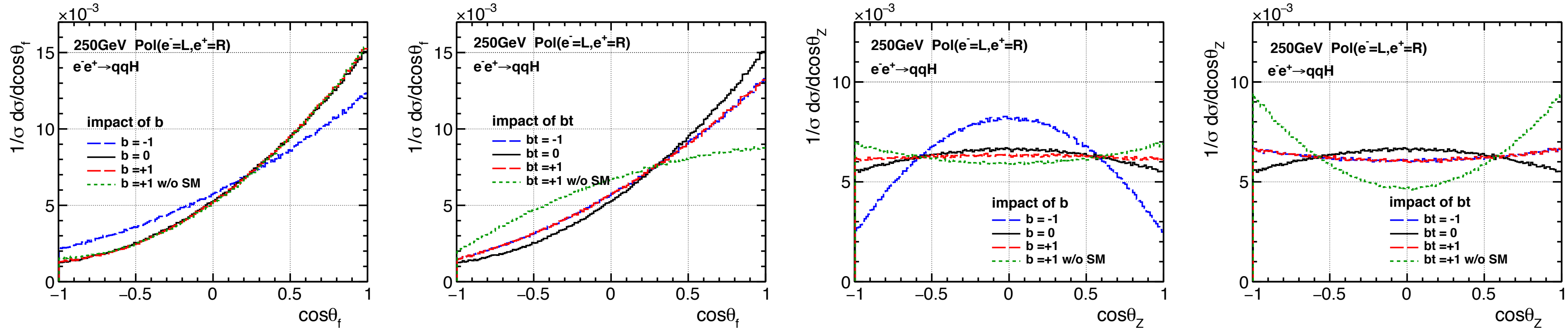
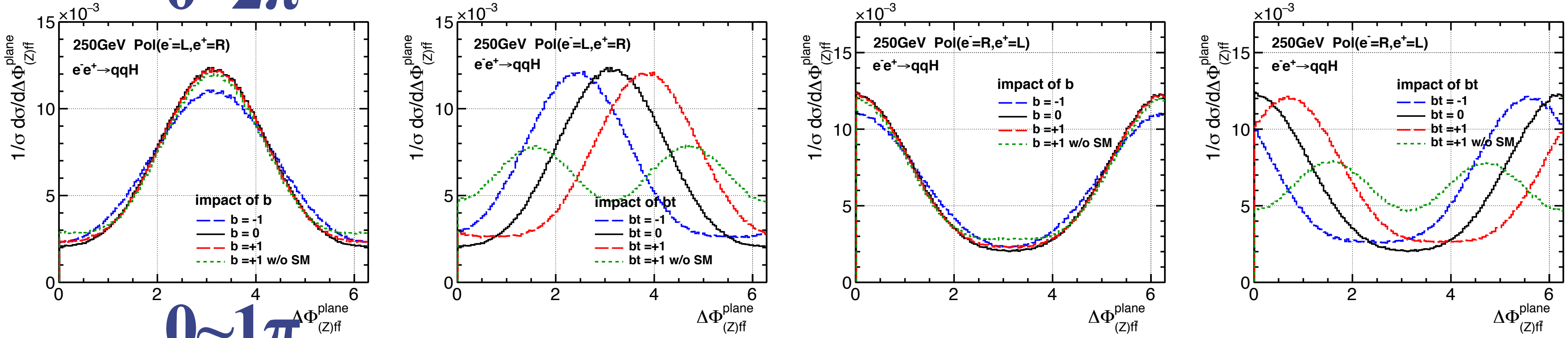
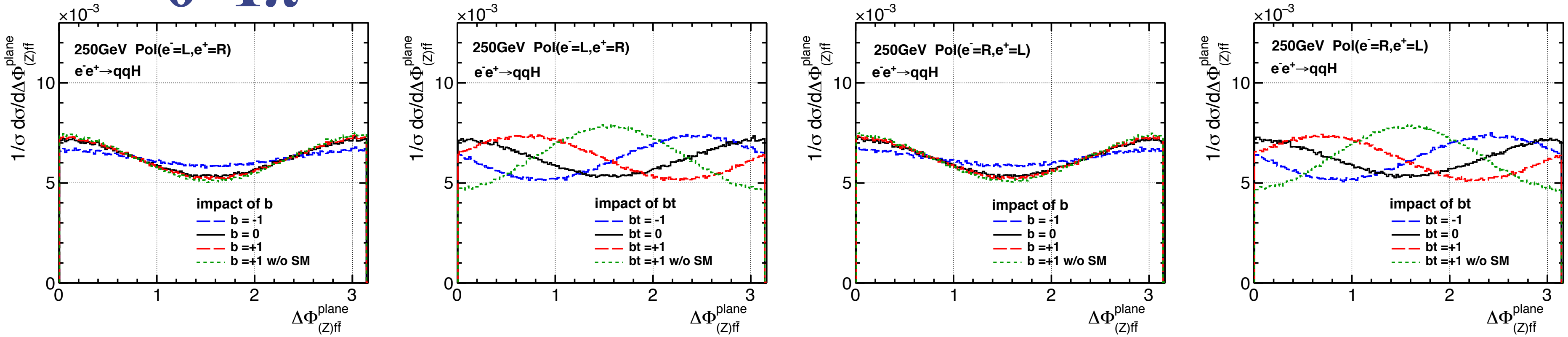



**Figure 8:** The Higgs-strahlung process,

0~2π




0~1π



# Angular asymmetries 500GeV ee→qqH

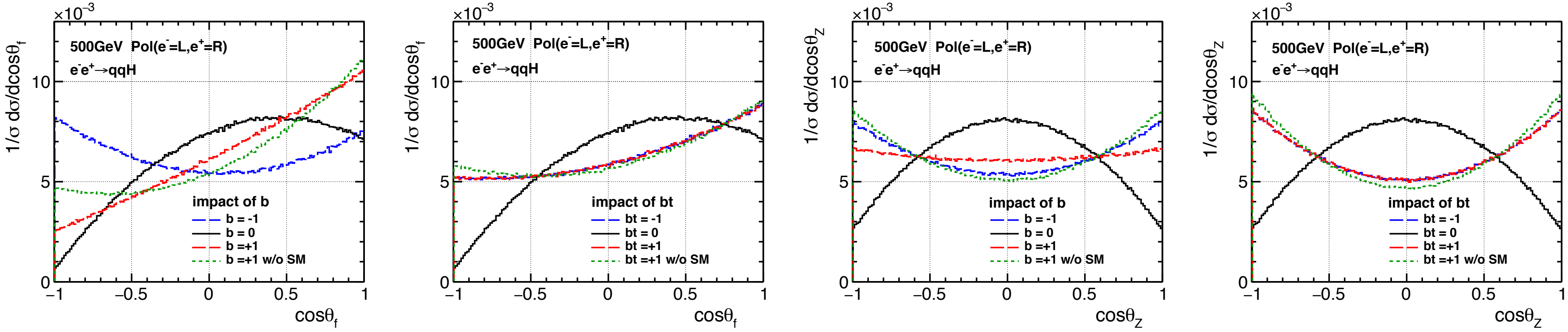



**Figure 10:** The Higgs-strahlung process,