EPS Conference on High Energy Physics
Venice, Italy 5-12 July 2017

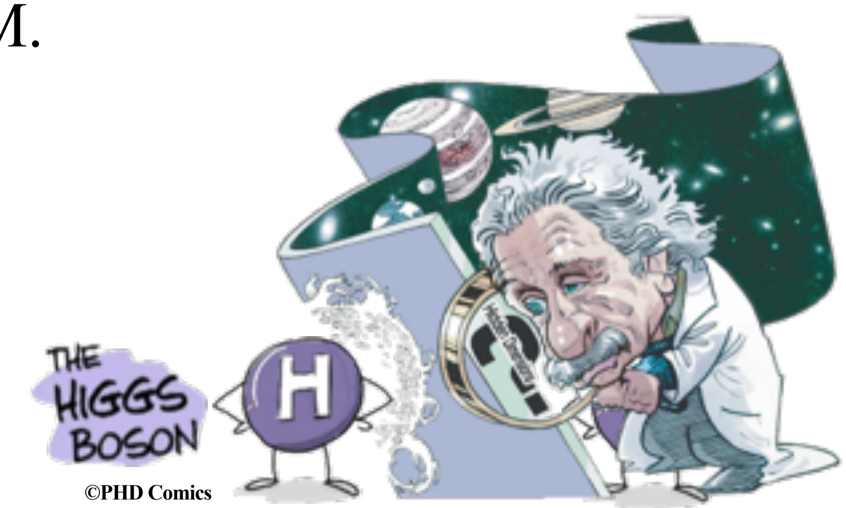
Study of sensitivity to anomalous VVH couplings at the ILC

T. Ogawa (SOKENDAI)
J. Tian (U-Tokyo)
K. Fujii (KEK)

Introduction

The SM has been successful to describe nature.
However, there are phenomena we can't explain only with the SM.
(Dark matter, baryon asymmetry in our universe, …)

The Higgs is the key particle connecting to New Physics.
The Higgs is a tool to identify the theory of nature.



The Lorentz structure of the VVH (V=Z/W/γ) couplings
plays an important role to probe the new physics beyond the SM.
(Higgs CP, the electroweak symmetry breaking mechanism)

In the framework of effective field theory, an effective Lagrangian containing **ZZH couplings** can be written:

Tim Barklow et al.
https://agenda.linearcollider.org/event/7371/contributions/37884/

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H$$

Expected deviations from the SM are small.
(~ a few % or less James E. Brau et al., , arXiv:1210.0202 [hep-ex])

Precise measurement is necessary,
and the ILC is suitable for this purpose.

Verification of the Lorentz structures

- "a_z" : a normalization parameter affecting the overall cross section. (rescales the SM-coupling)

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda} \hat{Z}_{\mu\nu} \hat{Z}^{\mu\nu} H + \frac{\tilde{b}_Z}{2\Lambda} \hat{Z}_{\mu\nu} \tilde{\hat{Z}}^{\mu\nu} H$$

- "b_z" : a different CP-even tensor structure affecting **momentum and changes angular distribution.**

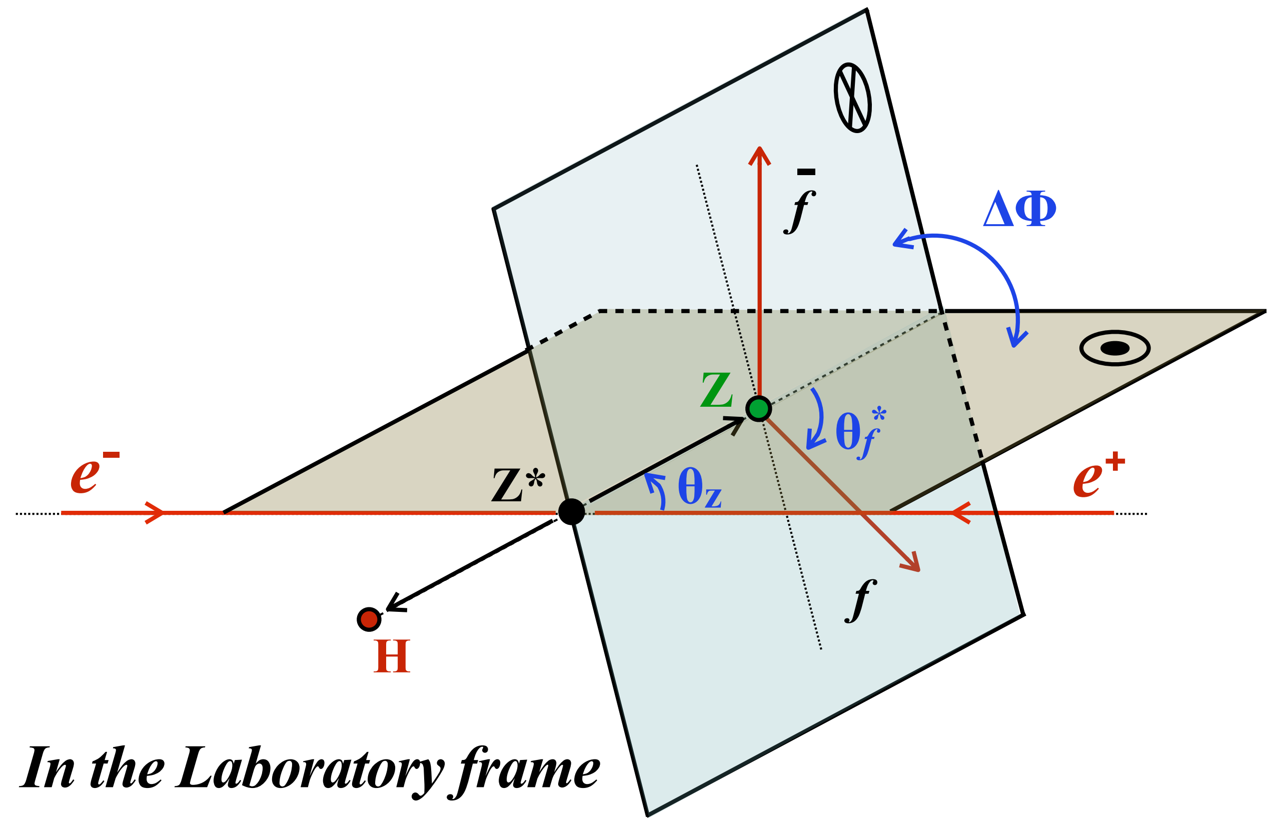
- "$\tilde{b}_z$" : a CP-violating parameter affecting **angular/spin correlations.**

$$e^+e^- \rightarrow ZH \rightarrow l^+l^- H$$

$\cos\theta_z$: a production angle of the Z.

$\cos\theta_f^*$: a helicity angle of a Z's daughter.

$\Delta\Phi$: an angle between two production plane.

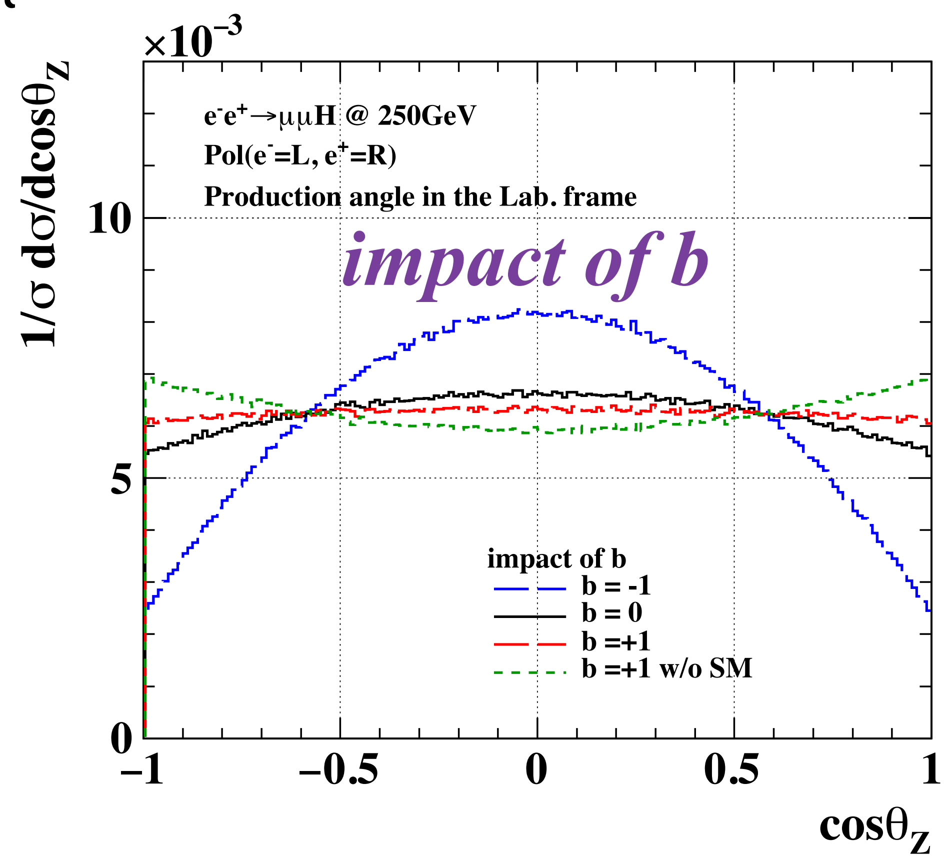


In the Laboratory frame

Verification of the Lorentz structures

$ZH \rightarrow l^+l^- H$, $\sqrt{s} = 250GeV$

- “a_Z” : a
  affecti
  (resca
- “b_Z” :
  affec
  chan
- “$\tilde{b}_Z$” :
  angu



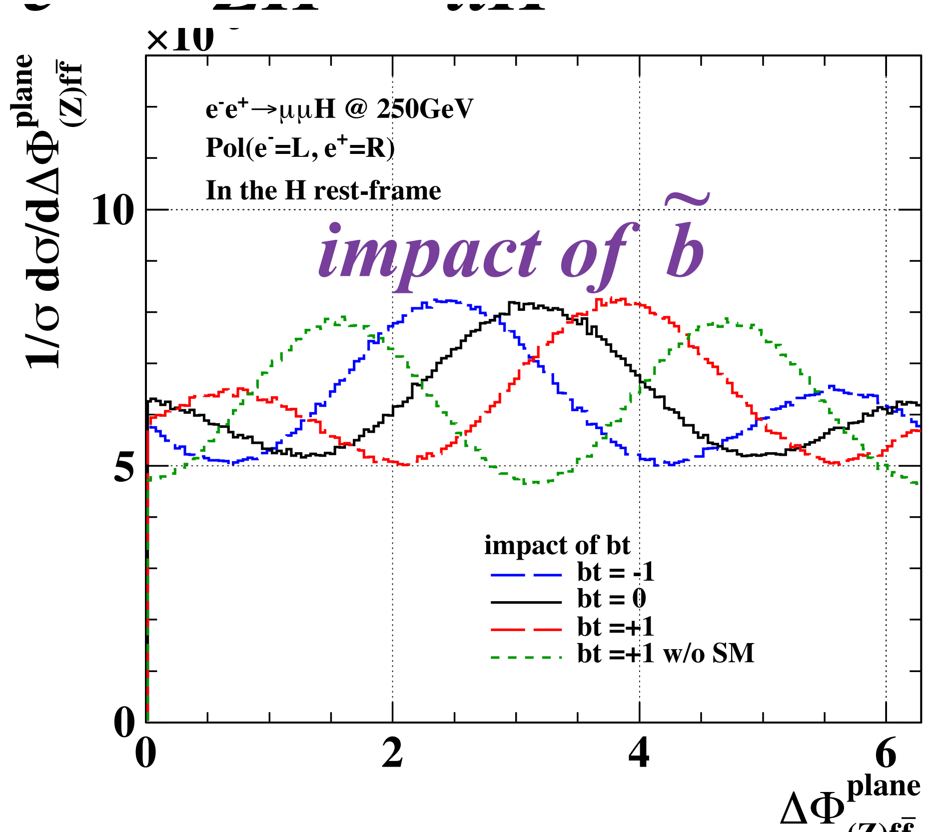
$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H$$

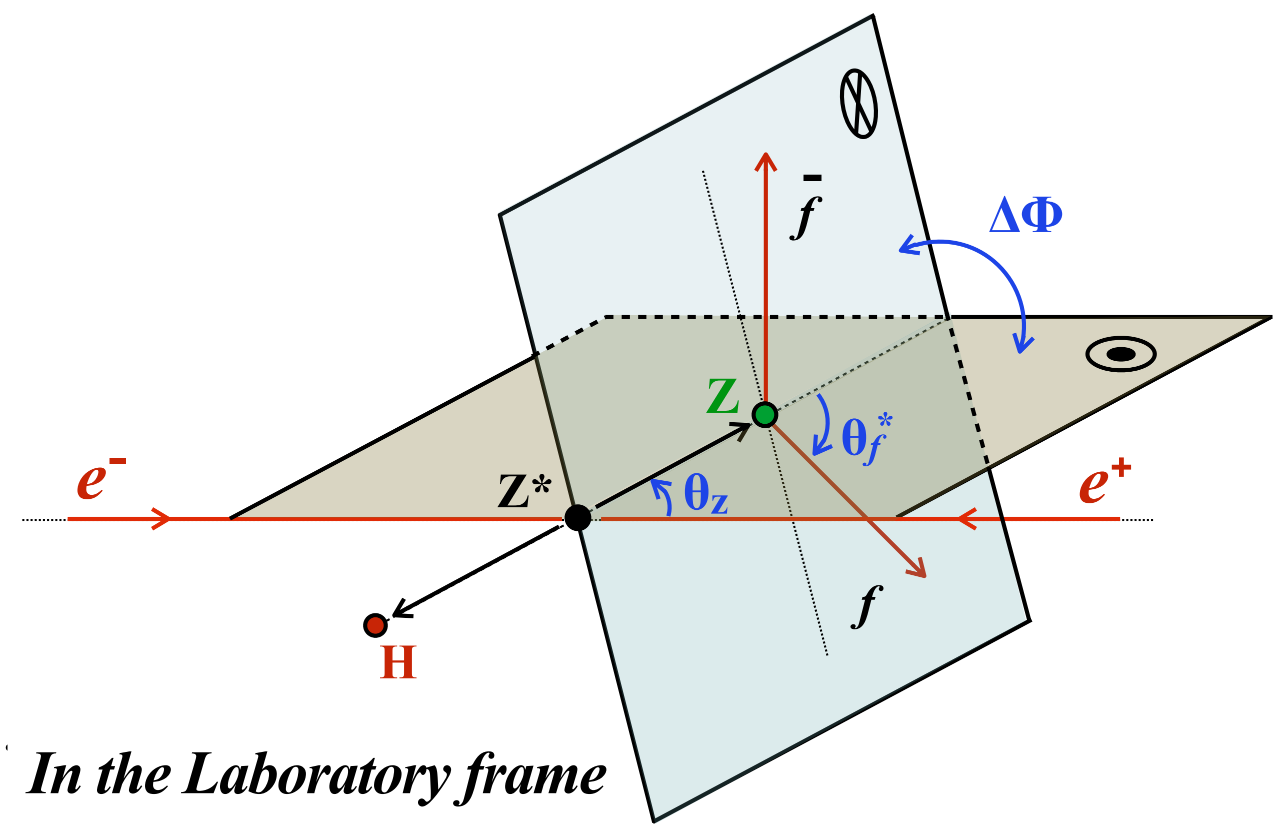
cosθz :

cosθf*:

ΔΦ :

ane.



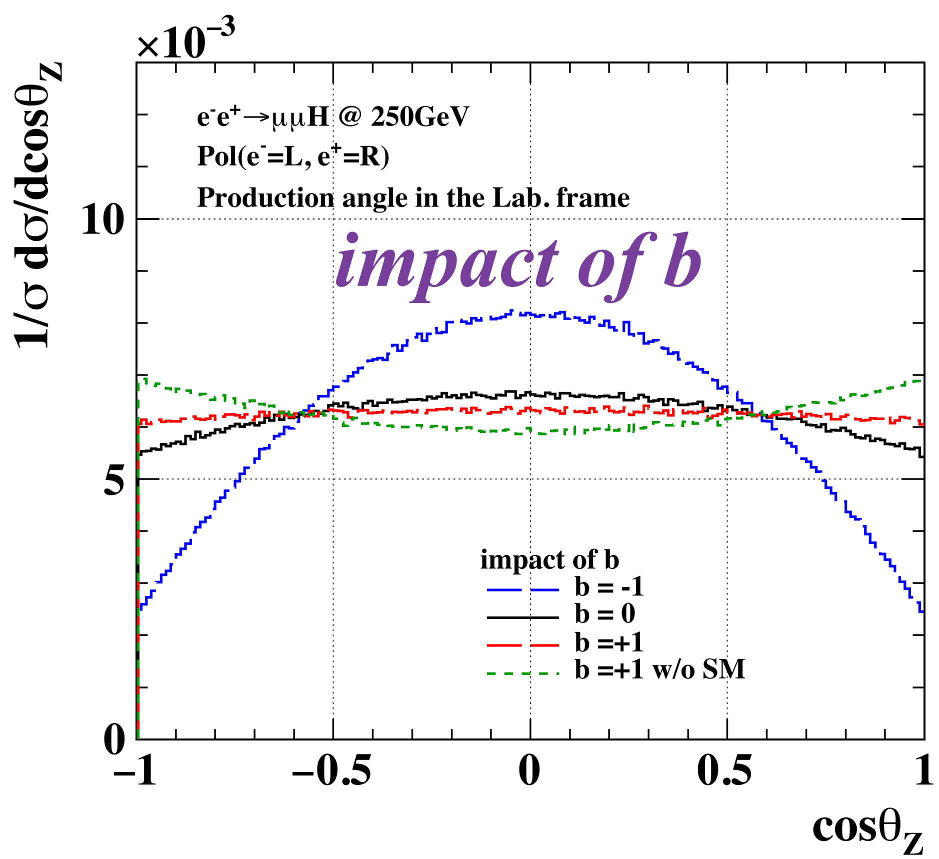


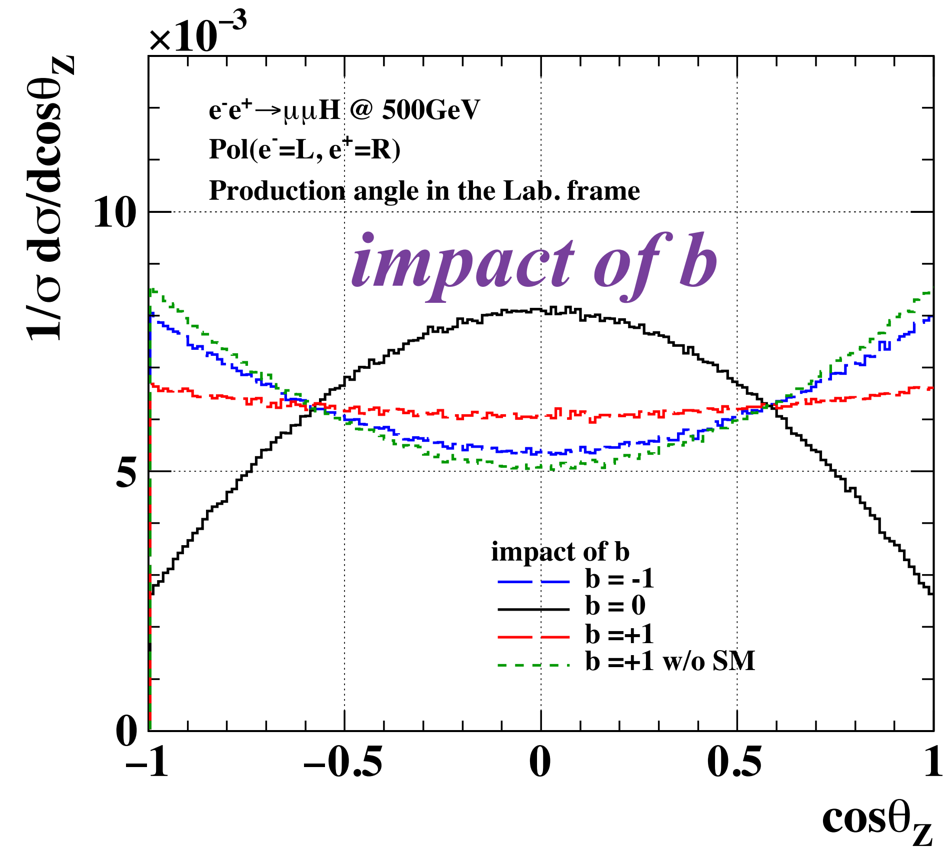
In the Laboratory frame

Verification of the Lorentz structures

$ZH \rightarrow l^+l^-H$, $\sqrt{s} = 250GeV$ $\sqrt{s} = 500GeV$

- “a_Z” : affect (resca
- “b_Z” : affec **chan**
- “$\tilde{b}_Z$” : **angu**



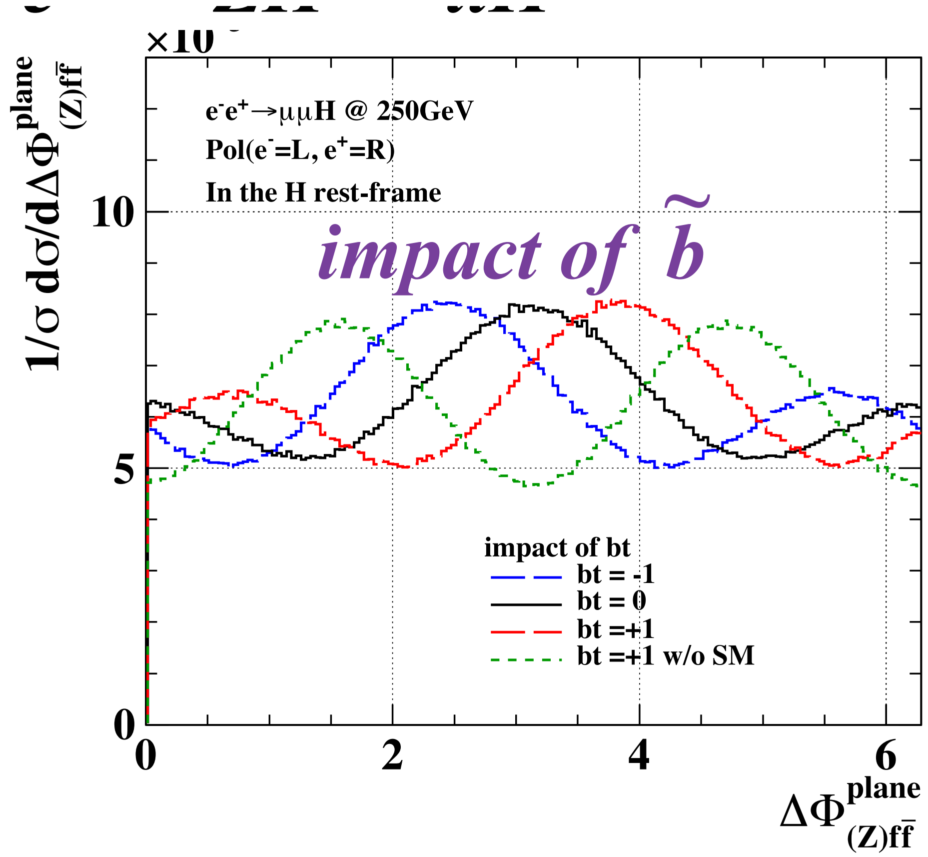


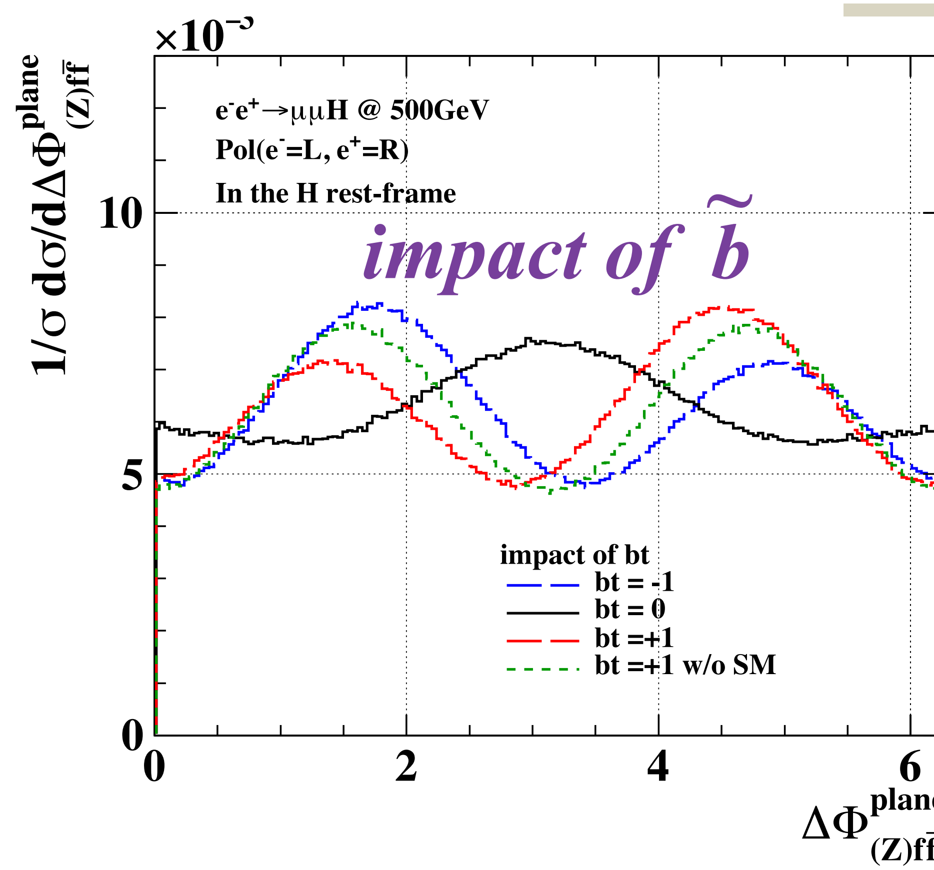
$\tilde{Z}^{\mu\nu}$ H

cosθz :

cosθf*:

ΔΦ   :   an

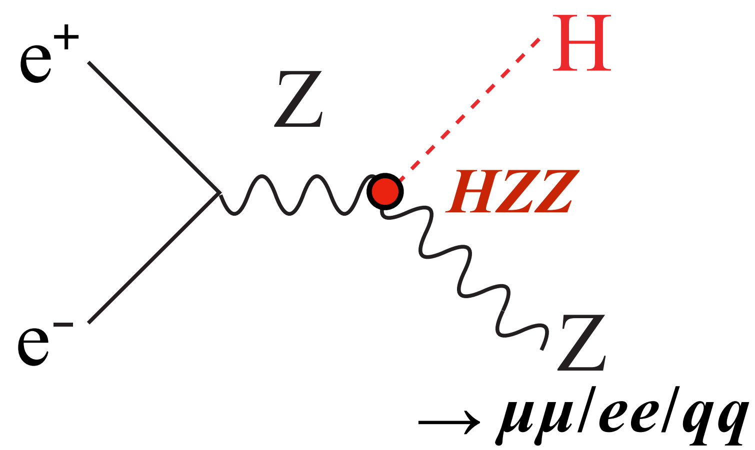




Analysis Strategy on ZZH

Available processes

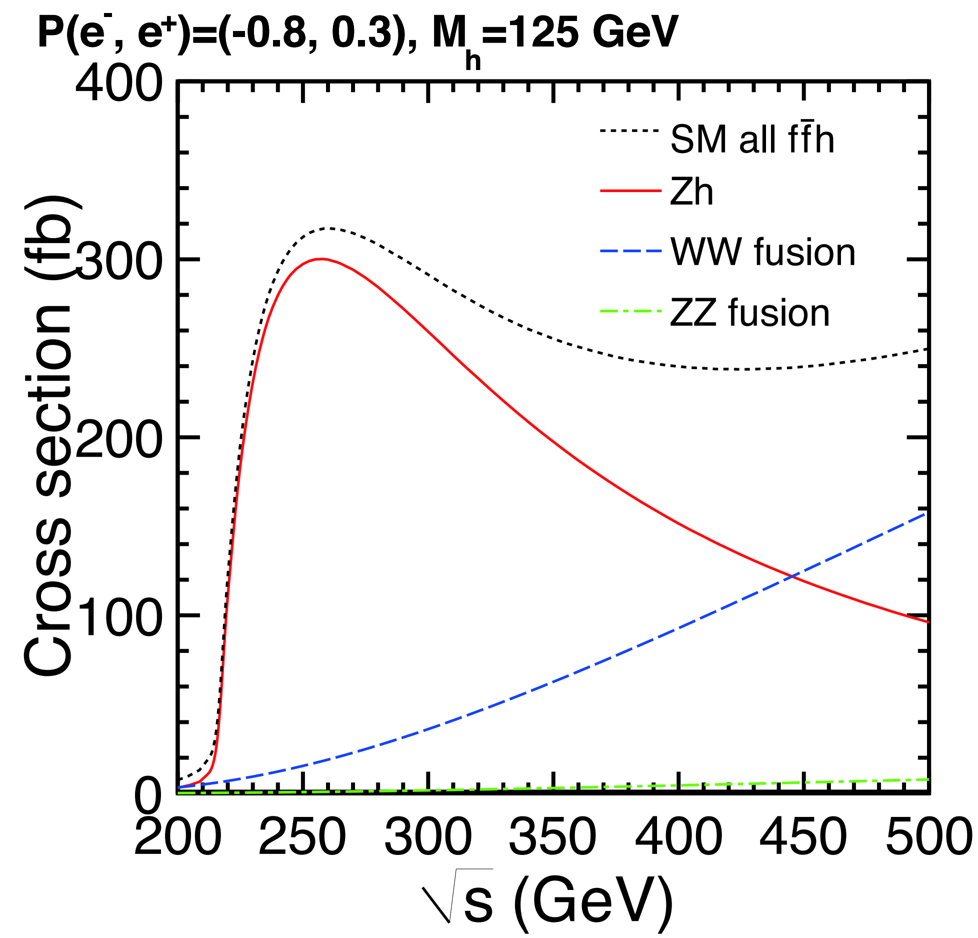
Higgsstrahlung
@250, 500GeV



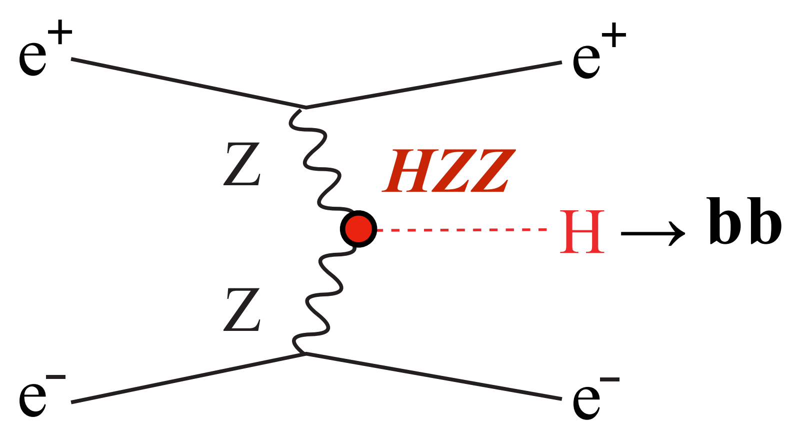
σ_{zh} is close to maximum @250GeV

main obs. ΔΦ, cosθz, $\cos\theta_f$*

arXiv:1306.6352 OLC-TDR2
Howard Baer



ZZ-fusion
@250, 500GeV



@500GeV σ_{eeh} is similar to lepton channels of the *Higgsstrahlung*.

main obs. ΔΦ, cosθh, P_h

→ **All analysis is done based on the full simulation of the ILD**

Analysis Strategy : χ^2 definition

Our approach to evaluate the sensitivity to the anomalous couplings
based on a combined chi2.

- Kinematical/Shape information

"Generator level" distribution
Calculated dσ/dX with explicit parameters.

$$\chi_s^2 = \sum_{i=1}^{n} \left[\frac{\frac{N_{SM}}{\sigma} \frac{d\sigma}{dX}(x_i) \cdot f_i - \frac{N_{SM}}{\sigma} \frac{d\sigma}{dX}(x_i; a_Z, b_Z, \tilde{b}_Z) \cdot f_i}{\delta N_{SM}(x_i)} \right]^2$$

i is Nth-bin

Detector response function
→ Transfer to **"Detector level" distribution**

Poisson error on each bin
(SM Bkgs are taken into account)

- Normalization information

Expected #events
with different models

$$\chi_c^2 = \left[\frac{N_{SM} \cdot \epsilon - N_{BSM} \cdot \epsilon}{\delta\sigma \cdot N_{SM} \cdot \epsilon} \right]^2$$

Erros on σ

δσ(ZH) = 2.0 % and 3.0 %
for 250 and 500 GeV

δσ(ZZf) = 28.0 % and 5.0 %
for 250 and 500 GeV

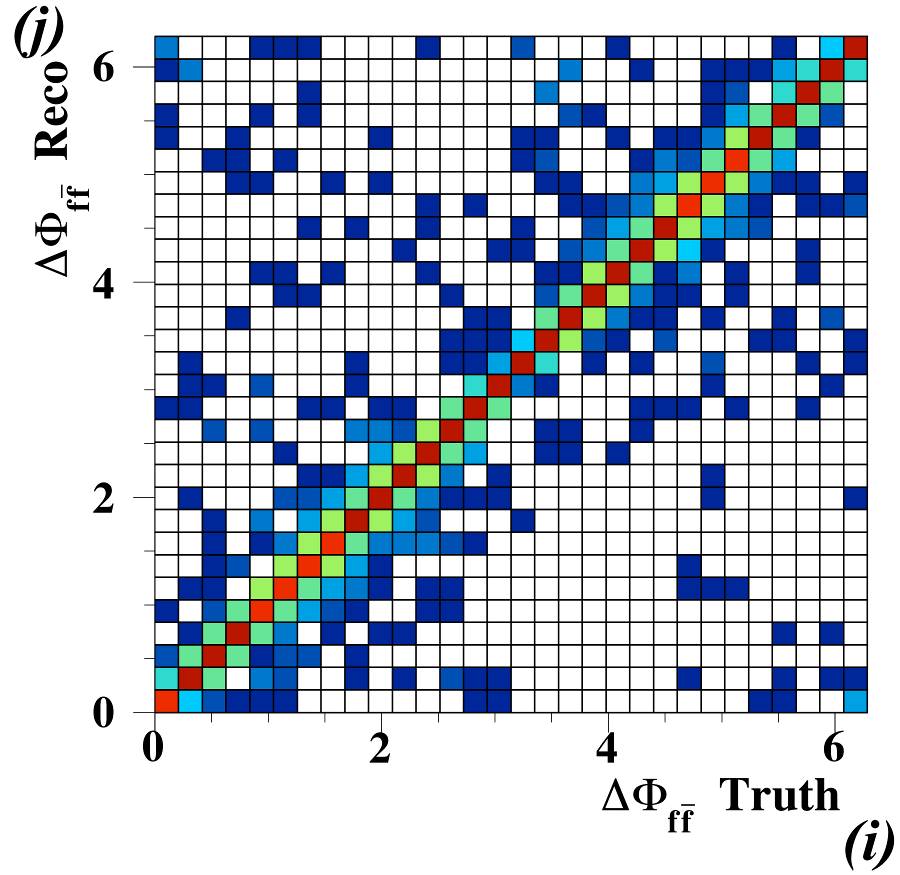
full simulation, T. Barklow et al.,
"ILC Operating Scenarios", arXiv:1506.07830 [hep-ex]

Analysis Strategy : Migration effect

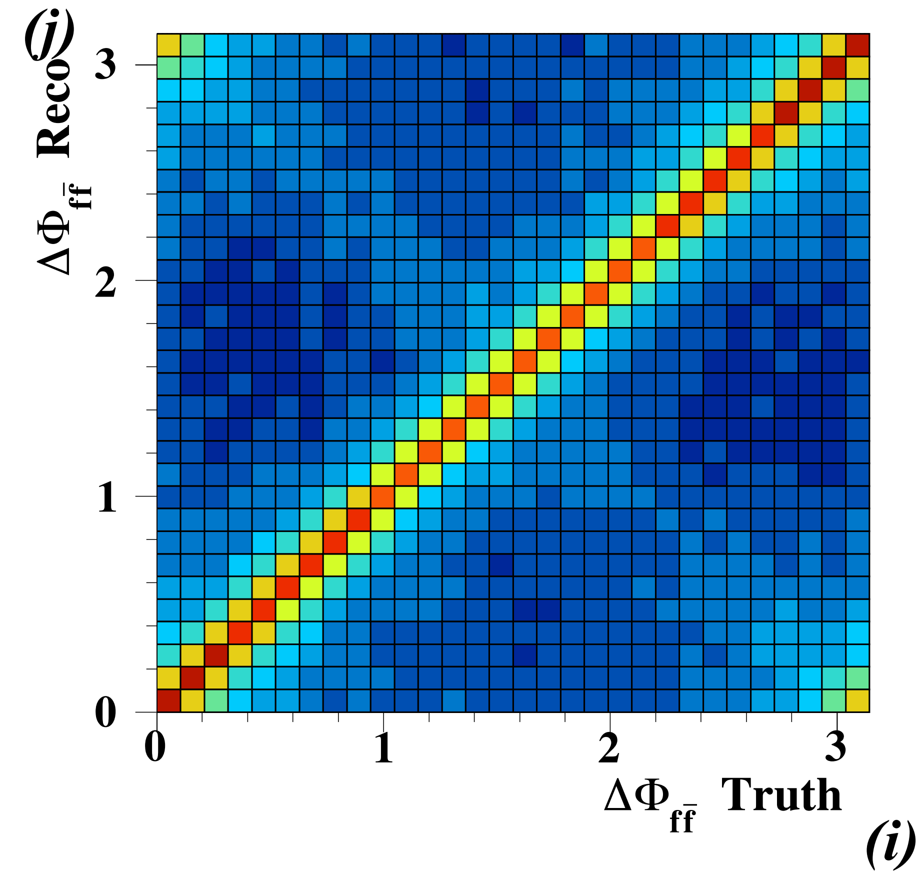
Distributions are subject to migration effects due to

- finite detector resolution
- jet clustering,
- missing particles
- …

ΔΦ on ZH→ l^+l^-H @250GeV



ΔΦ on ZH→ qqbb @250GeV



→ detector response *f*

$$N^{Rec}(x_j^{Rec}) = \sum_i \underbrace{f(x_j^{Rec}, x_i^{Gen})}_{\text{detector response}} \cdot N^{Gen}(x_i^{Gen})$$

$$N^{Rec}(x_j^{Rec}) = \sum_i f_{ji} \cdot N_i^{Gen} = \sum_i \bar{f}_{ji} \cdot \eta_i \cdot N_i^{Gen}$$

Normalized to 1

$$\eta_i \equiv \frac{N_i^{Accept}}{N_i^{Gene}} \quad (\text{Event Acceptance})$$

$$\bar{f}_{ji} \equiv \frac{N_{ji}^{Accept}}{N_i^{Accept}} \quad (\text{Migration Matrix})$$

For a binned in N distribution,

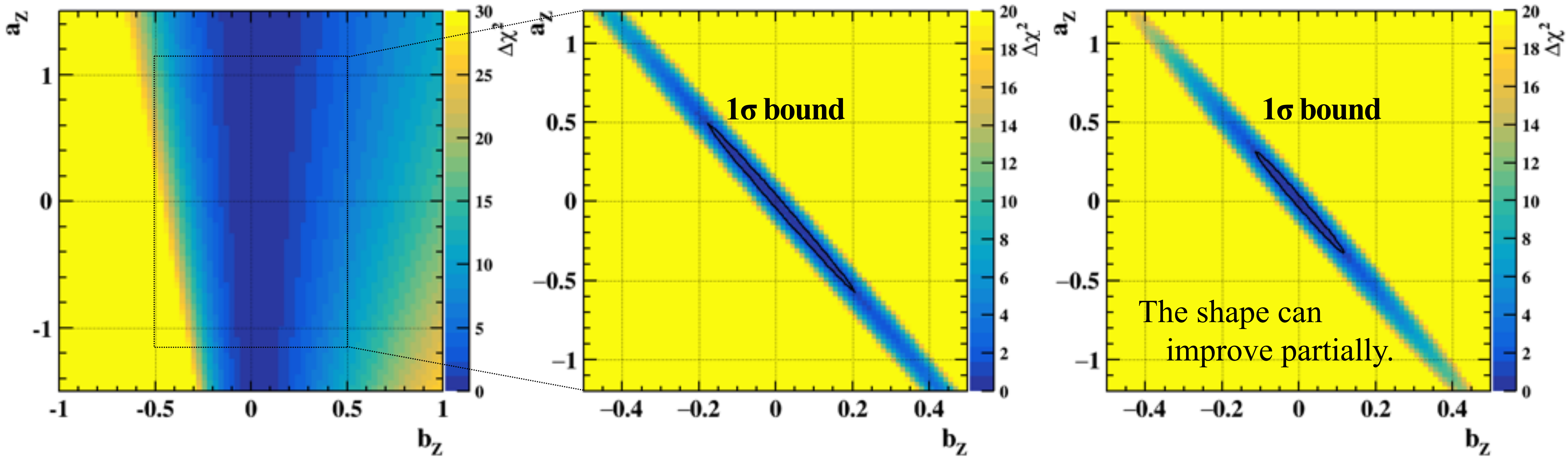
an NxN migration matrix is necessary to transfer the "generator" level to the "detector" level.

Sensitivity to ZZH couplings @ 250 GeV

$\Delta\chi^2$ distribution in the two-parameter space. : a_Z vs b_Z

Higgsstrahlung and *ZZ-fusion* are combined.

$\sqrt{s}$=250GeV and $\int Ldt$=250fb^{-1} are assumed.



Shape information ***Normalization information*** ***Both information***

There is no shape info. along the parameter "a_Z", the sensitivity is coming from normalization info.

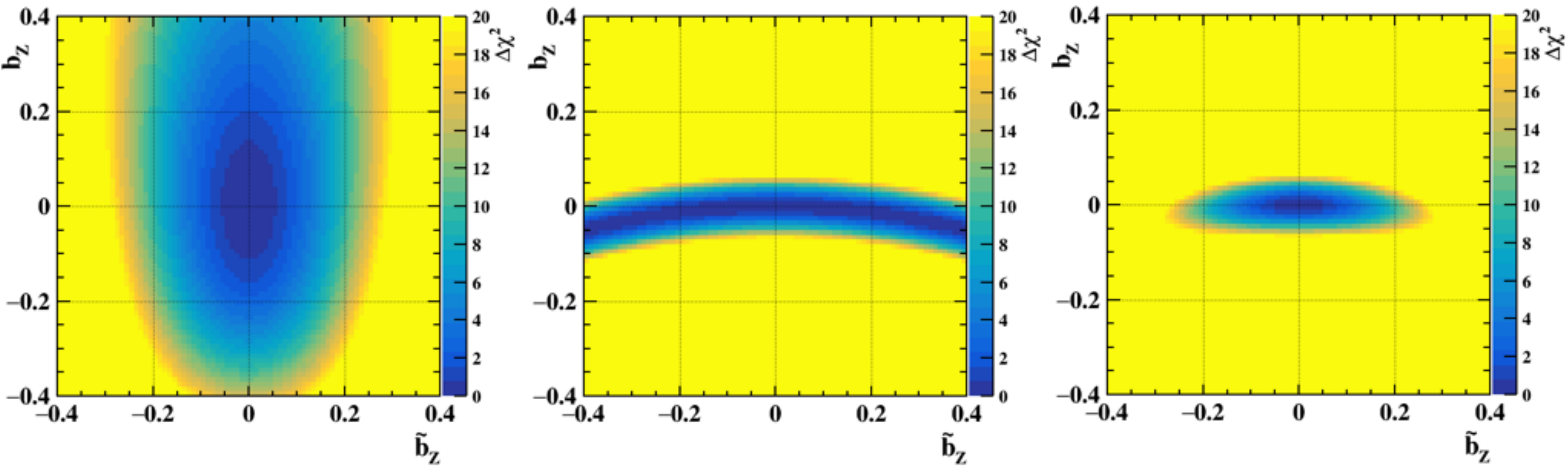
Correlation between the parameters "a_Z" and "b_Z" is strong and coming from normalization change.

Sensitivity to ZZH couplings @ 250 GeV

$\Delta\chi^2$ distribution in the two-parameter space. : b_Z vs $\tilde{b}_Z$

Higgsstrahlung and *ZZ-fusion* are combined.

$\sqrt{s}$=250GeV and $\int Ldt$=250fb^{-1} are assumed.



Shape information *Normalization information* *Both information*

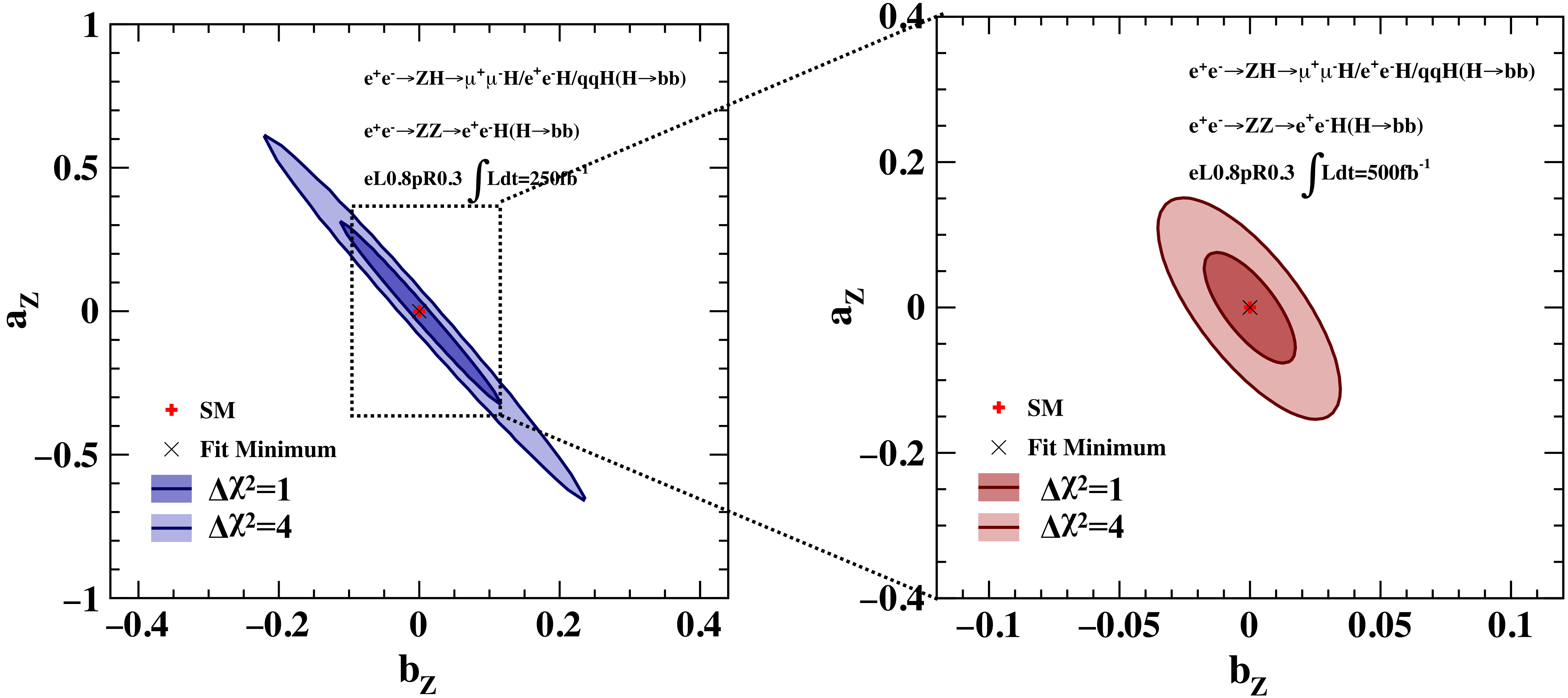
With only normalization info, the sensitivity to "$\tilde{b}_Z$" is limited.

The Shape info. is very useful to squeeze the sensitive parameter space.

Sensitivity to ZZH couplings 250 GeV vs 500 GeV

Simultaneous fitting is performed in three-parameter space.

$\sqrt{s}$=250GeV and $\int Ldt$=250fb^{-1} $\sqrt{s}$=500GeV and $\int Ldt$=500fb^{-1}



The shape distributions quickly change at 500GeV
the correlation between "a_Z" and "b_Z" can be disentangled.

Sensitivity to ZZH couplings 250 GeV + 500 GeV

A realistic ILC full operation is assumed

T. Barklow and J. Brau et al., "ILC Operating Scenarios", arXiv:1506.07830 [hep-ex]

H20 scenario :

Total luminosities of 2000 f b^{-1} and 4000 f b^{-1} are planned to be accumulated at $\sqrt{s}$ =250 and 500 GeV, respectively.

New physics scale Λ is assumed to be 1 TeV.

A table showing sensitivity to ZZH at 250 + 500 GeV.

1σ bounds		a_Z	b_Z	$\tilde{b}_Z$
ZH				
with shape	total	-	± 0.0080	± 0.0070
ZH				
with shape+σ	total	± 0.0307	± 0.0074	± 0.0070
ZH+ZZ-fusion				
with shape	total	-	± 0.0079	± 0.0067
ZH+ZZ-fusion				
with shape+σ	total	± 0.0218	± 0.0058	± 0.0067

For the parameter "a" (SM-like couplings) **precision is a_z few %.**

For new tensor structures **precision of less than 1% or better is possible to achieve.**

Precision on $\tilde{b}_z$ **is decided by angular info.**

Sensitivity to ZZH and γZH couplings

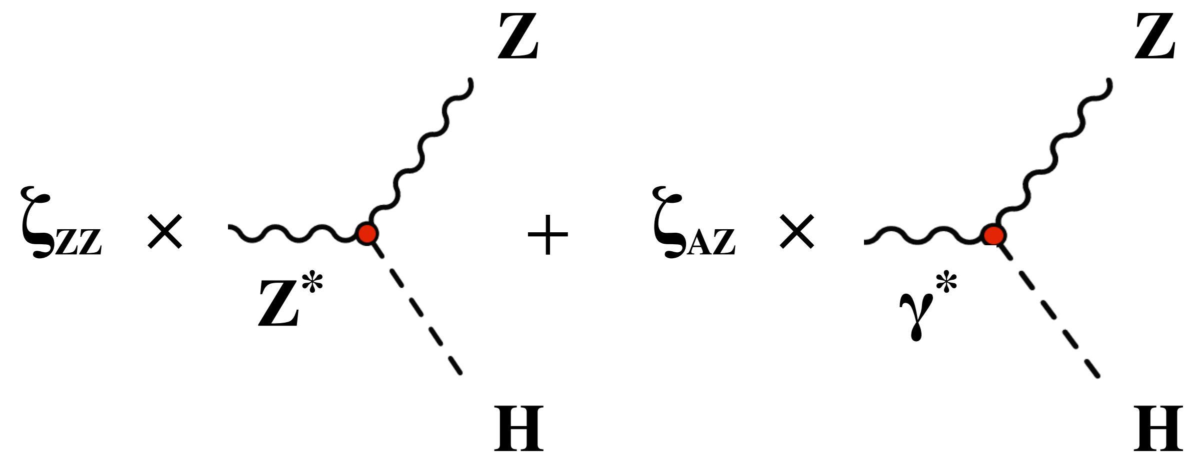
Once ZZH couplings are assumed, γZH couplings should be considered because of the electroweak mixing.

$$B_\mu = \cos\theta_W\, A_\mu - \sin\theta_W\, Z_\mu\,,$$

$$W_\mu{}^3 = \cos\theta_W\, Z_\mu + \sin\theta_W\, A_\mu\,.$$

B couples to **both e_L and e_R** in the same way.

W^3 couples to **e_L only.**



By employing beam polarization (Left- and Right-state) it is possible to disentangle **the ZZH and the γZH couplings.**

Sensitivity to ZZH and γZH couplings

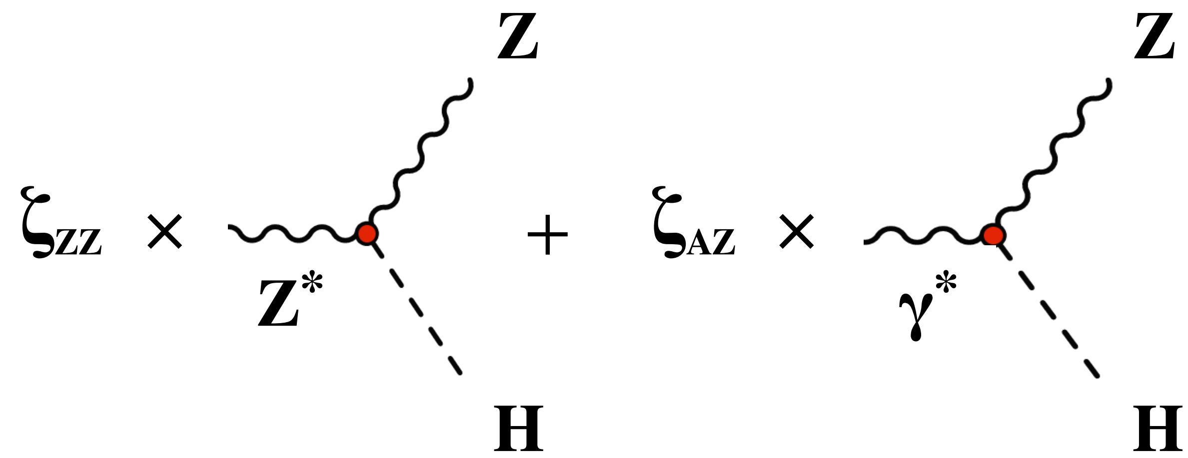
Once ZZH couplings are assumed, γZH couplings should be considered because of the electroweak mixing.

$$B_\mu = \cos\theta_{\rm W}\, A_\mu - \sin\theta_{\rm W}\, Z_\mu\,,$$

$$W_\mu{}^3 = \cos\theta_{\rm W}\, Z_\mu + \sin\theta_{\rm W}\, A_\mu\,.$$

B couples to **both e_L and e_R** in the same way.

W^3 couples to **e_L only.**



By employing beam polarization (Left- and Right-state)
it is possible to disentangle **the ZZH and the γZH couplings.**

Modification of the Lagrangian

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu} H$$

$$\zeta_{ZZ} = \frac{v}{\Lambda} b_Z, \qquad \tilde{\zeta}_{ZZ} = \frac{v}{\Lambda}\tilde{b}_Z$$

$$\begin{aligned}\mathcal{L}_{VVH} =& M_Z^2\left(\frac{1}{v} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H \\ &+ \frac{1}{2v}\left(\zeta_{ZZ}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} + \zeta_{AZ}\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\right) H \\ &+ \frac{1}{2v}\left(\tilde{\zeta}_{ZZ}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu} + \tilde{\zeta}_{AZ}\hat{A}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu}\right) H\end{aligned}$$

Full formula is given by Tim Barklow et al.
https://agenda.linearcollider.org/event/7371/contributions/37884/

Sensitivity to ZZH and γZH couplings and general EFT coefficients

Through the sensitivity of ZZH and γZH couplings,
sensitivity to general EFT coefficients
describing the effective Lagrangian is given.

Detailed description of the Higgs couplings in the EFT will be given in Tim Barklow's talk (tomorrow).

$$\begin{cases} a_Z = 1 - C_T - \frac{1}{2} C_H - C'_{HL} \\ \zeta_{ZZ} = 8(c_0^2 C_{WW} + 2 s_0^2 C_{WB} + \frac{s_0^4}{c_0^2} C_{BB}) \\ \zeta_{AZ} = 8 s_0^2 (C_{WW} - 2 C_{WB} + C_{BB}) \\ + \text{CP violating terms} \end{cases}$$

CH, Cww, Cwwt can be evaluated under the assumption that other params. are strongly restricted ~ 0. by Triple Gauge Couplings (TGCs) and $\Gamma(H \to \gamma\gamma)$ from LHC and ILC

John Ellis, 10.1007/JHEP03(2016)089
John Ellis, 10.1007/JHEP07(2014)036

Under the assumption of the ILC full operation,

New physics scale Λ is assumed to be 1 TeV.

1σ bounds	a_Z	ζ_{ZZ}	ζ_{AZ}	$\tilde{\zeta}_{ZZ}$	$\tilde{\zeta}_{AZ}$	C_H	C_{WW}	$\tilde{C}_{WW}$
ZH+ZZ-fusion with shape+σ	±0.022	±0.0057	±0.0028	±0.00825	±0.00049	±0.0112	±0.00081	±0.000240

The anomalous ZZH and γZH couplings can be measured to 1% or better.

Summary

The Higgs boson is the key particle to new physics.
The new physics could be imprinted in the Lorentz structure of the VVH coupling.

Based on full simulation, the sensitivity to the anomalous ZZH couplings is evaluated, where backgrounds and detector response are taken into account.

Shape information is important to verify the new tensor structures and higher $\sqrt{s}$ is useful to disentangle the correlation of the parameters.

Beam polarization has power to disentangle the ZZH and γZH couplings and makes it possible to evaluate sensitivity to the γZH couplings.

The different Lorentz structures originating from the ZZH and γZH couplings can be measured to 1% or better with the ILC full operation.

back up slides

A preprint of our ZZH study
has been prepared …

Study of sensitivity to anomalous ZZH couplings at the International Linear Collider

T. Ogawa,[1] J. Tian,[2] and K. Fujii[3]

[1] *The Graduate University for Advanced Studies (SOKENDAI), Tsukuba 305-0801, Japan*
[2] *International Center for Elementary Particle Physics (ICEPP), Tsukuba 305-0801, Japan*
[3] *High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
(Dated: July 3, 2017)

In this report, we present prospective sensitivity to the anomalous couplings between the Higgs boson and the Z boson at the future International Linear Collider (ILC) experiment. The analysis is performed by employing a framework of the Effective Field Theory (EFT) where general Lorentz tensor structures of the ZZH couplings including both CP-even and -odd contributions of the Higgs boson is assumed with dimension-5 operators and a new physics scale Λ. The evaluation of the sensitivity is carried out based on full detector simulation in which background contributions are taken into account. Kinematical distributions of leading channels of main Higgs production processes $e^+e^- \to ZH \to f\bar{f}H$ and $e^+e^- \to ZZ \to e^+e^-H$ and information of cross sections are used for finding out deviations from the SM. Results are given with assumption of benchmark integrated luminosities and certain realistic running scenario of the ILC experiment for both center-of-mass energies $\sqrt{s}$=250 and 500 GeV with two different beam polarization states. Sensitivity to the anomalous γZH couplings are also given based on the framework of EFT by utilizing two beam polarizations. A discussion on sensitivity to general parameters describing the new Lorentz tensor structures related to the Higgs and the vector bosons is given at the end.

A complete set of an effective Lagrangian with dim-6 operators

Tim Barklow et al.

"Model-Independent Determination of the Triple Higgs Coupling at e+e- Colliders"

https://agenda.linearcollider.org/event/7371/contributions/37884/

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

$$\left.\begin{aligned} &+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\ &+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \end{aligned}\right\} + \text{CP violating terms}$$

$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$

$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

After electro weak symmetry breaking, Lorentz tensor structures between the Higgs and gauge bosons,

$$\Delta\mathcal{L}_h = -\eta_h\lambda_0 v_0 h^3 + \frac{\theta_h}{v_0}h\partial_\mu h\partial^\mu h + \eta_Z\frac{m_Z^2}{v_0}Z_\mu Z^\mu h + \frac{1}{2}\eta_{2Z}\frac{m_Z^2}{v_0^2}Z_\mu Z^\mu h^2$$

$$+\eta_W\frac{2m_W^2}{v_0}W^+_\mu W^{-\mu}h + \eta_{2W}\frac{m_W^2}{v_0^2}W^+_\mu W^{-\mu}h^2$$

$$\left.\begin{aligned} &+\frac{1}{2}\left(\zeta_Z\frac{h}{v_0} + \frac{1}{2}\zeta_{2Z}\frac{h^2}{v_0^2}\right)\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} + \left(\zeta_W\frac{h}{v_0} + \frac{1}{2}\zeta_{2W}\frac{h^2}{v_0^2}\right)\hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu} \\ &+\frac{1}{2}\left(\zeta_A\frac{h}{v_0} + \frac{1}{2}\zeta_{2A}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{A}^{\mu\nu} + \left(\zeta_{AZ}\frac{h}{v_0} + \zeta_{2AZ}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\ . \end{aligned}\right\} + \text{CP violating terms}$$

Sensitivities to the a, b and bt with only the *Higgsstrahlung*

Nominal energies and luminosities

√s=250GeV and ∫Ldt=250fb^{-1}

TABLE V. The sensitivity to the anomalous ZZH couplings at $\sqrt{s}$ =250 GeV assuming the benchmark integrated luminosity of 250 fb^{-1} with both beam polarizations. The values correspond to one sigma bounds. The words, with shape and $+\sigma$, in the table indicate that the only shape information is used for the evaluation, and the shape information together with the cross section information are used.

		a_Z	b_Z	$\tilde{b}_Z$
ZH	$e^-_L e^+_R$	-	±0.110	±0.051
with shape	$e^-_R e^+_L$	-	±0.129	±0.061
ZH	$e^-_L e^+_R$	±0.309	±0.109	±0.051
with shape+σ	$e^-_R e^+_L$	±0.356	±0.125	±0.061

correlation matrix (w/ shape+σ P(LR))

$$\rho = \begin{pmatrix} 1 & -0.9917 & 0.0064 \\ & 1 & -0.0051 \\ & & 1 \end{pmatrix}$$

√s=500GeV and ∫Ldt=500fb^{-1}

TABLE VI. The sensitivity to the anomalous ZZH couplings at $\sqrt{s}$ =500 GeV assuming the benchmark integrated luminosity of 500 fb^{-1} with both beam polarizations. The values correspond to one sigma bounds. The words in the table, with shape and $+\sigma$, indicate that the only shape information is used, and the shape information together with the cross section information are used for the evaluation of the sensitivity.

		a_Z	b_Z	$\tilde{b}_Z$
ZH	$e^-_L e^+_R$	-	±0.0199	±0.0183
with shape	$e^-_R e^+_L$	-	±0.0215	±0.0198
ZH	$e^-_L e^+_R$	±0.116	±0.0201	±0.0183
with shape+σ	$e^-_R e^+_L$	±0.130	±0.0217	±0.0198

correlation matrix (w/ shape+σ P(LR))

$$\rho = \begin{pmatrix} 1 & -0.848 & 0.0136 \\ & 1 & -0.0124 \\ & & 1 \end{pmatrix}$$

Angular Asymmetry derived from the new structures

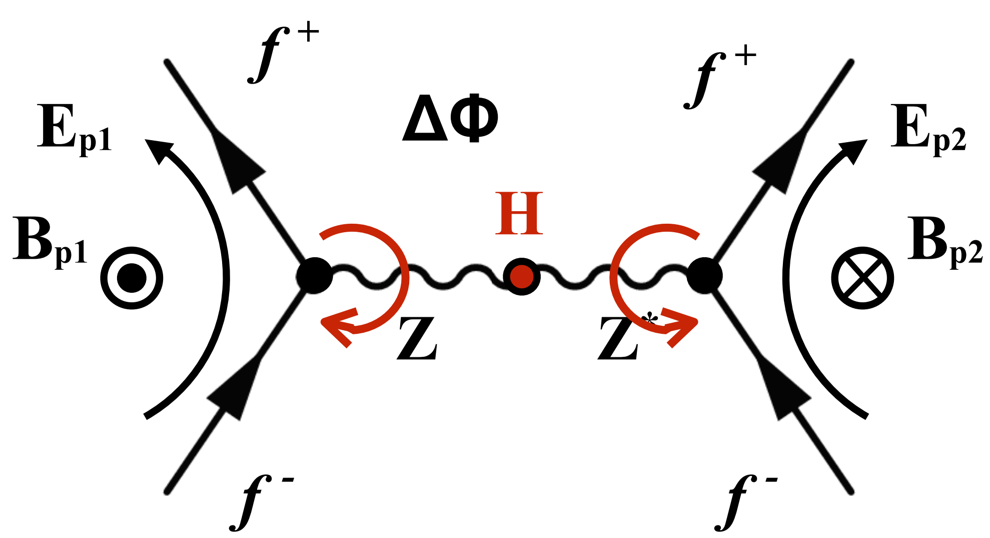
The Lorentz structure

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu}H$$

$$\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} \propto \mathbf{B_{p1}}\cdot\mathbf{B_{p2}} - \mathbf{E_{p1}}\cdot\mathbf{E_{p2}}$$

$$\hat{F}_{\mu\nu}\widetilde{\hat{F}}^{\mu\nu} \propto \mathbf{E_{p1}}\cdot\mathbf{B_{p2}}$$

in the Higgs rest frame



current is running

- "a_z" : a normalization parameter affecting the overall cross section. (rescales the SM-coupling)
- "b_z" : a different CP-even tensor structure affecting **momentum and changes angular distribution.**
- "$\tilde{b}_z$" : a CP-violating parameter affecting **angular/spin correlations.**

The new tensor structures can be resulted in a simple field strength of the EM field.

ΔΦ which is defined by two different planes can be the useful observable.

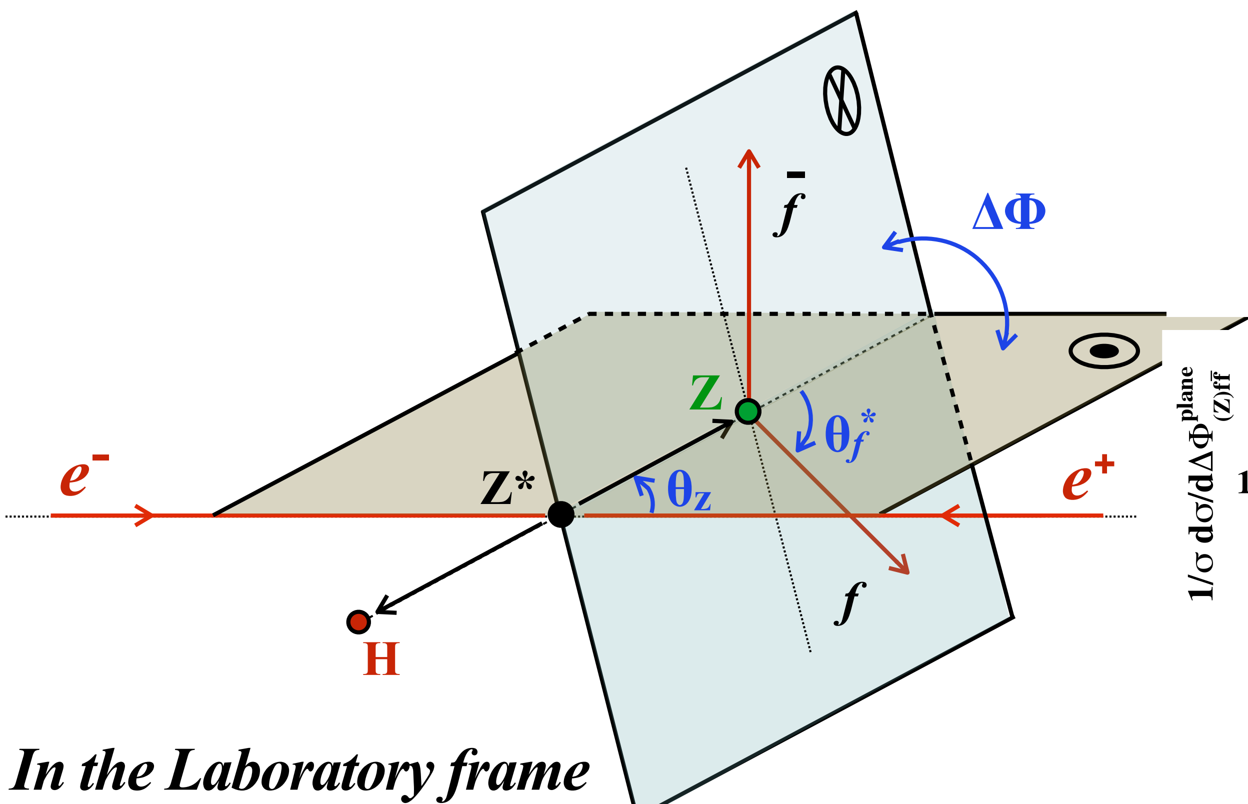
ΔΦ tends to be parallel / perpendicular .

4 processes for different √s are available.
ZH → ee/μμH and qqH(H→bb)
ZZf → eeH(H→bb)

Angular Asymmetry : 250GeV

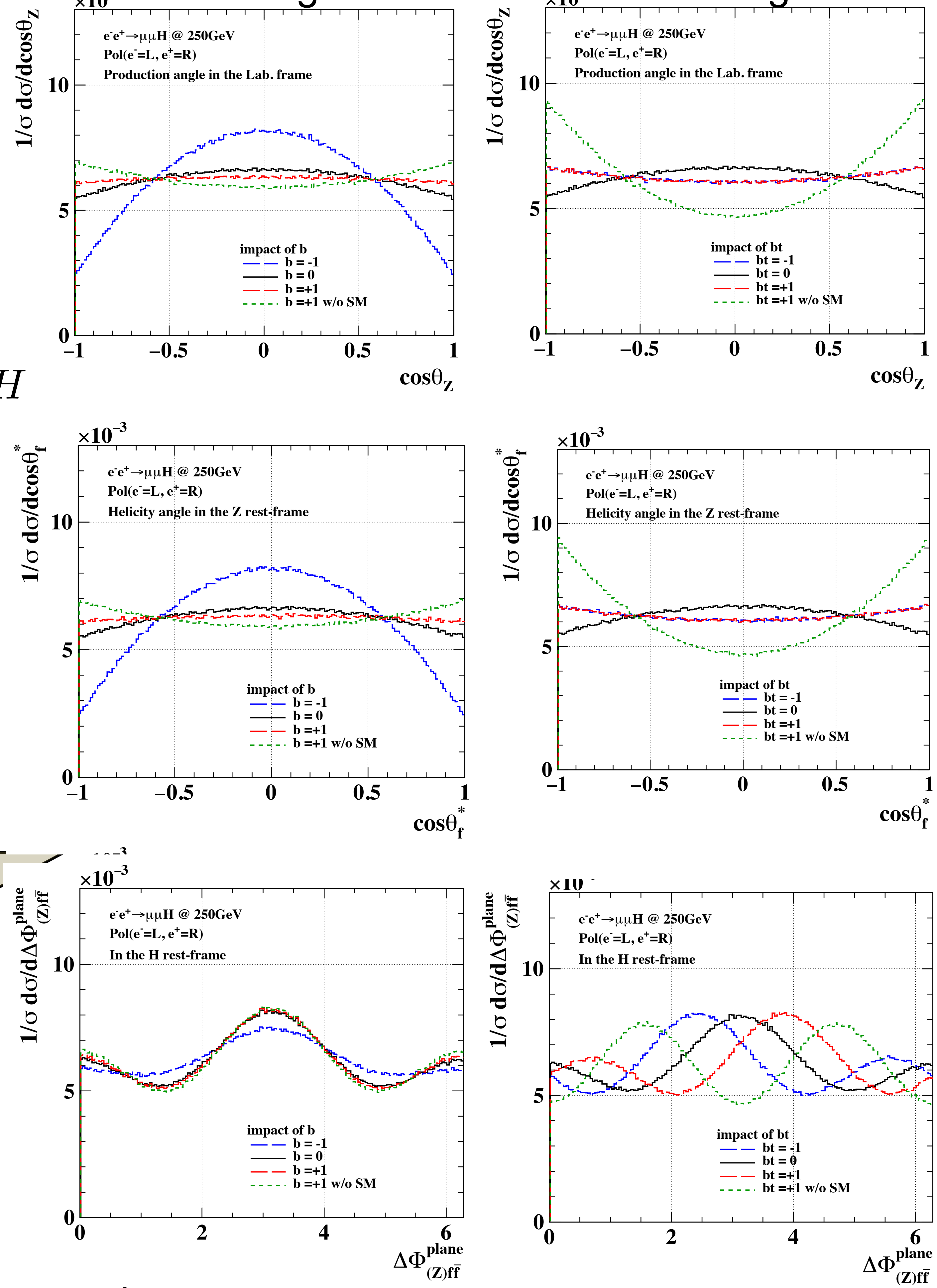
The Lorentz structure

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu}H$$



In the Laboratory frame

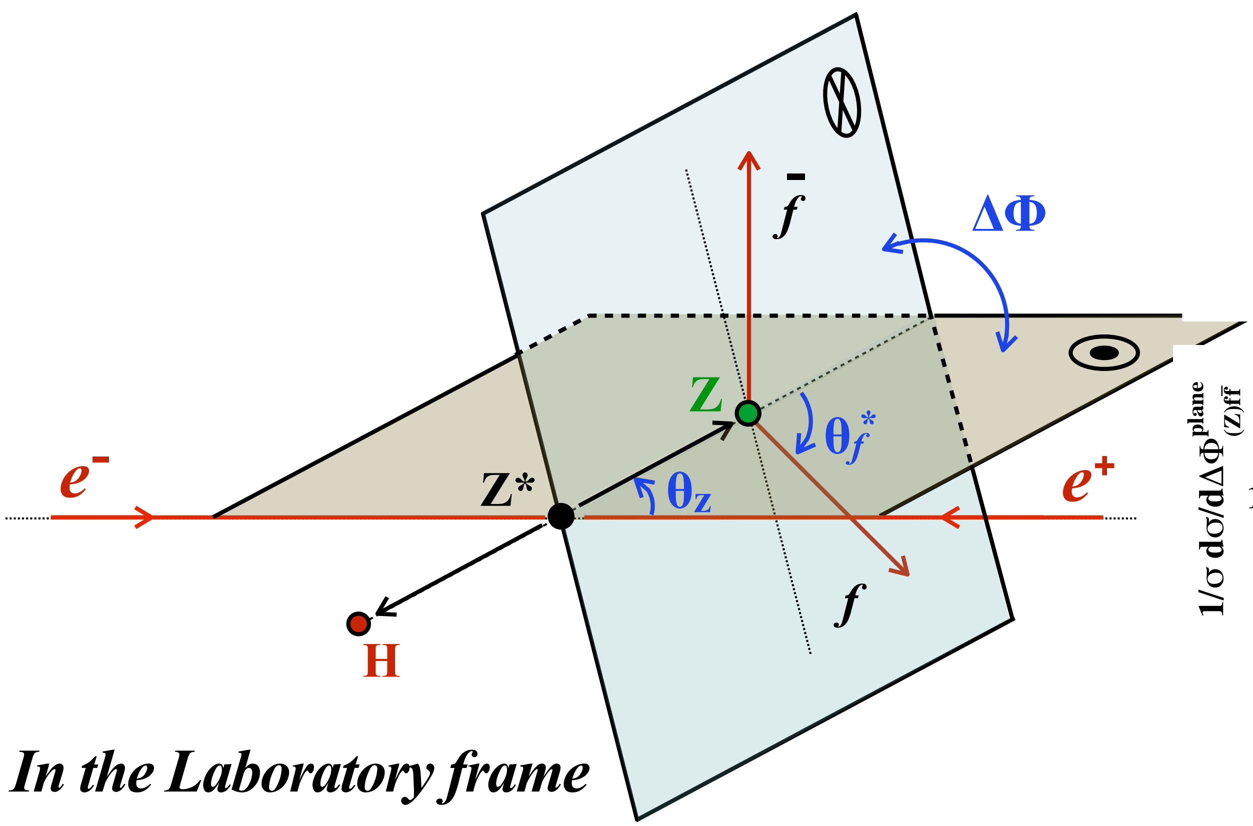
Change b | Change bt

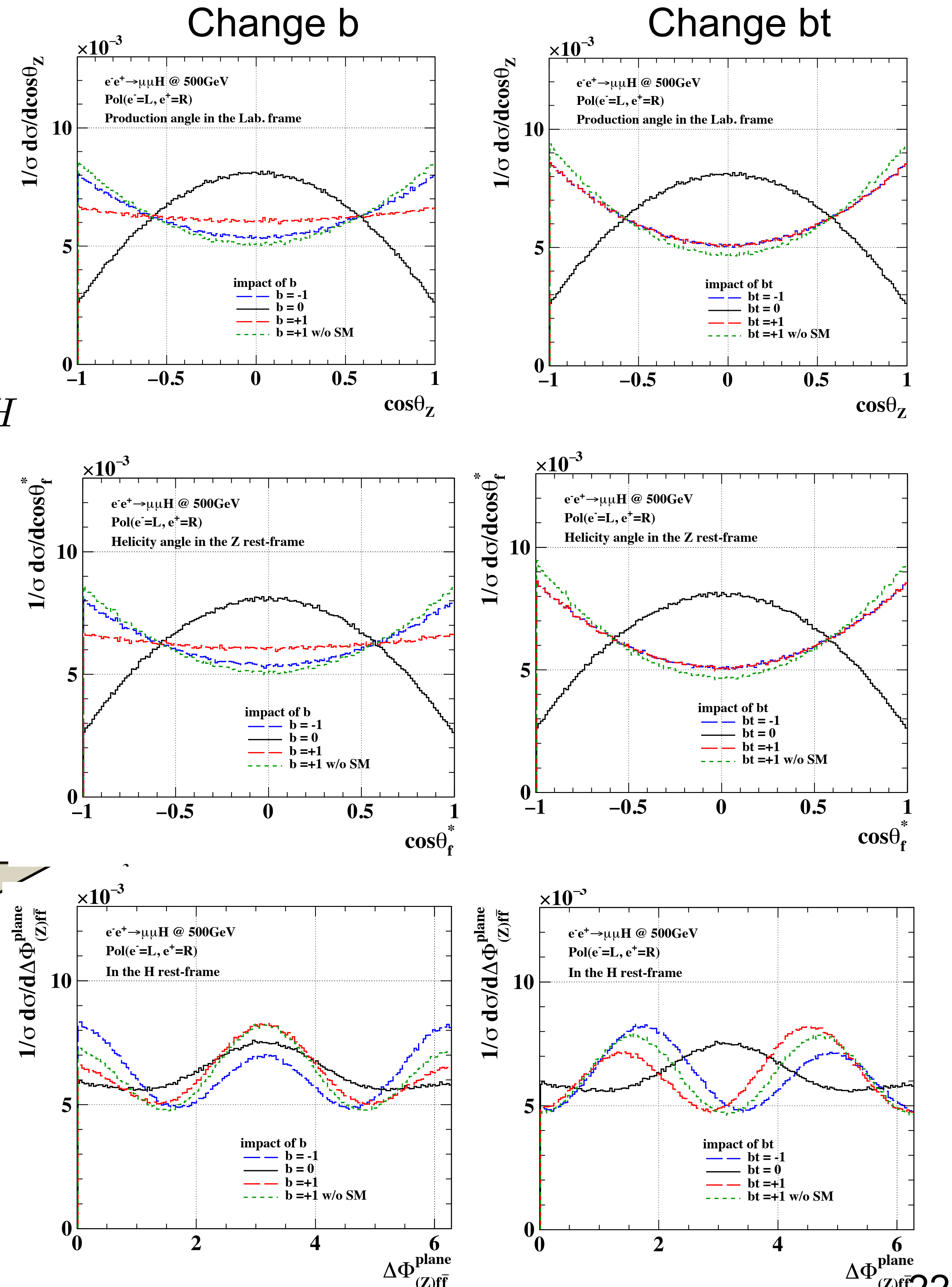


Angular Asymmetry : 500GeV

The Lorentz structure

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu} H$$

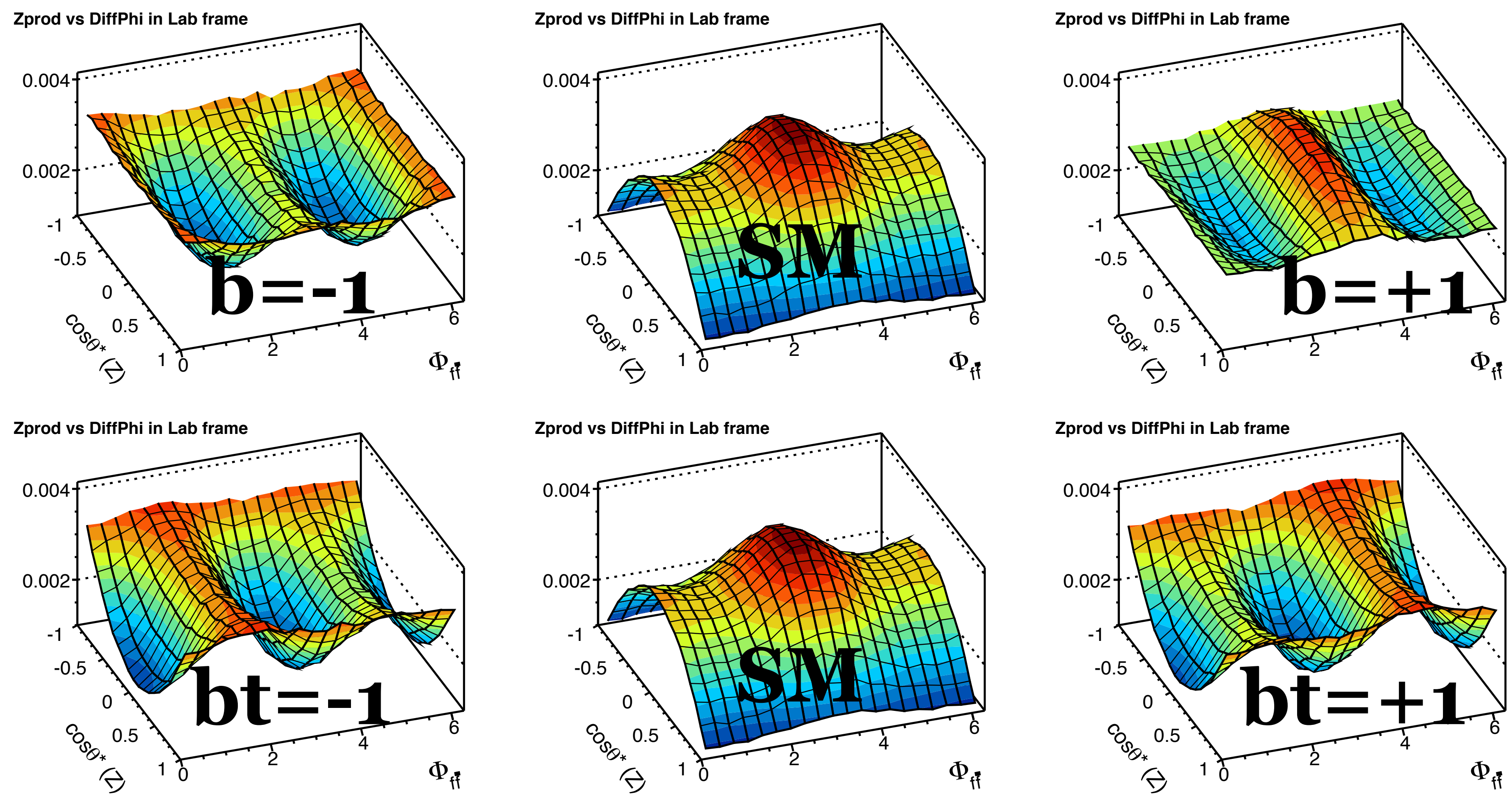




Kinematical distribution with the ZH : 2-dimensional @ 500GeV

ee→Zh→llh

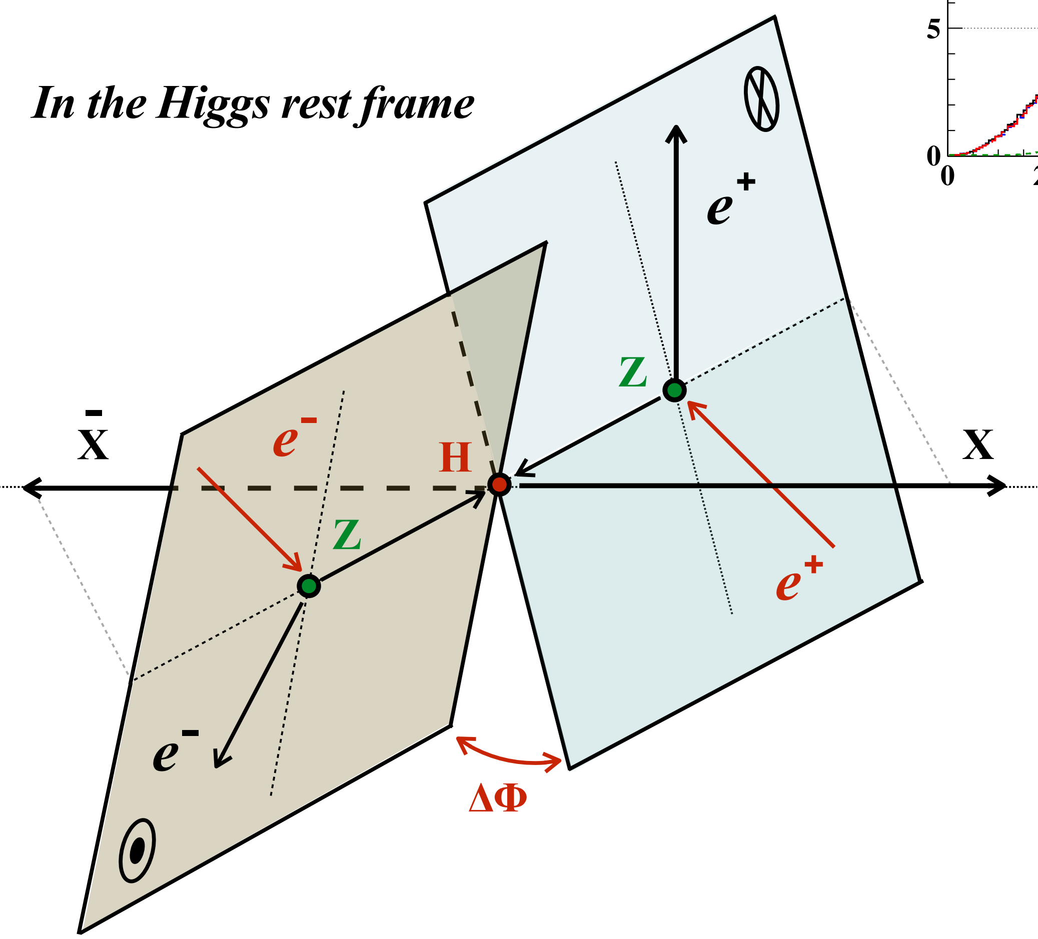
ΔΦ vs cosθz
Φ [0~2π]

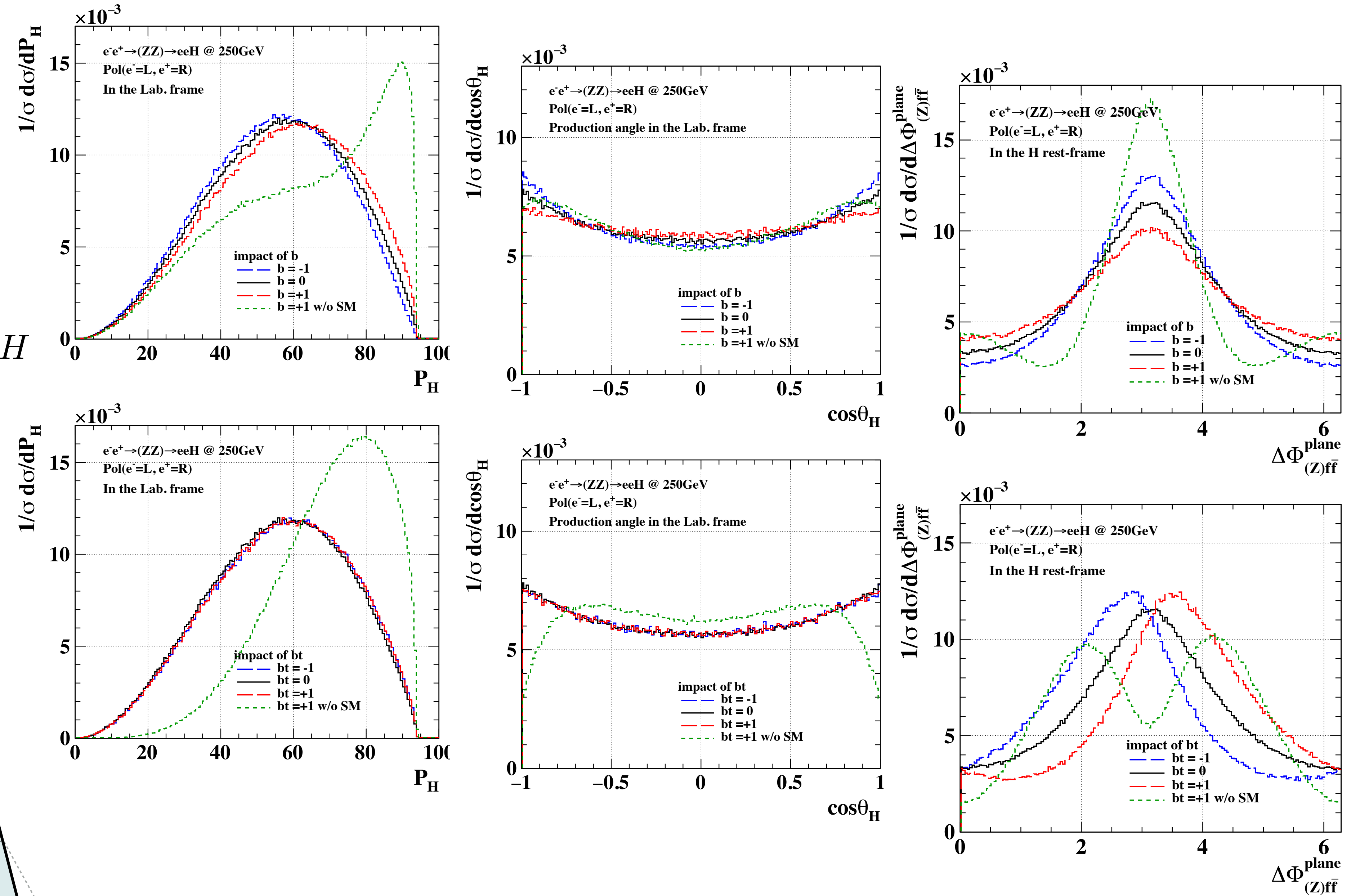


Kinematical distribution with the ZZ-fusion : 250GeV

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu} H$$

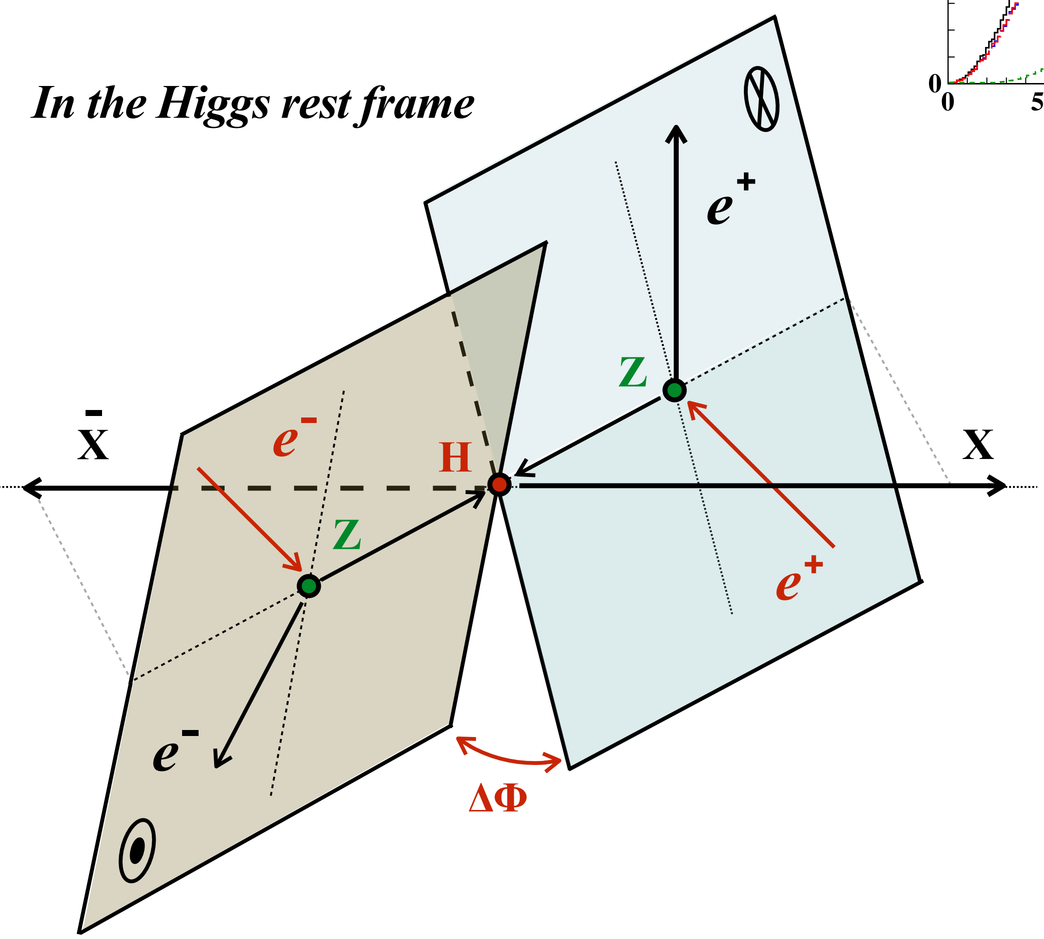
In the Higgs rest frame

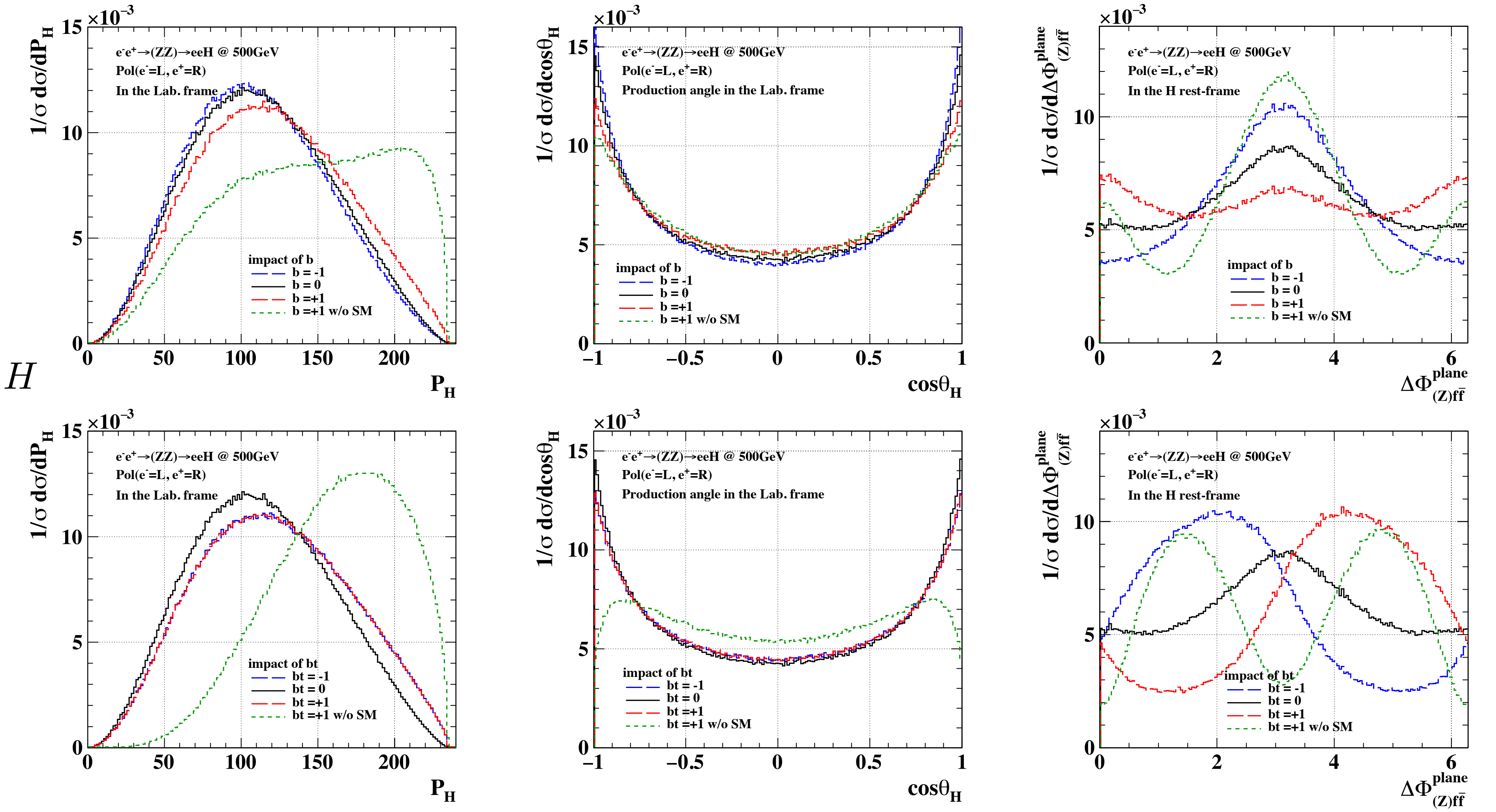


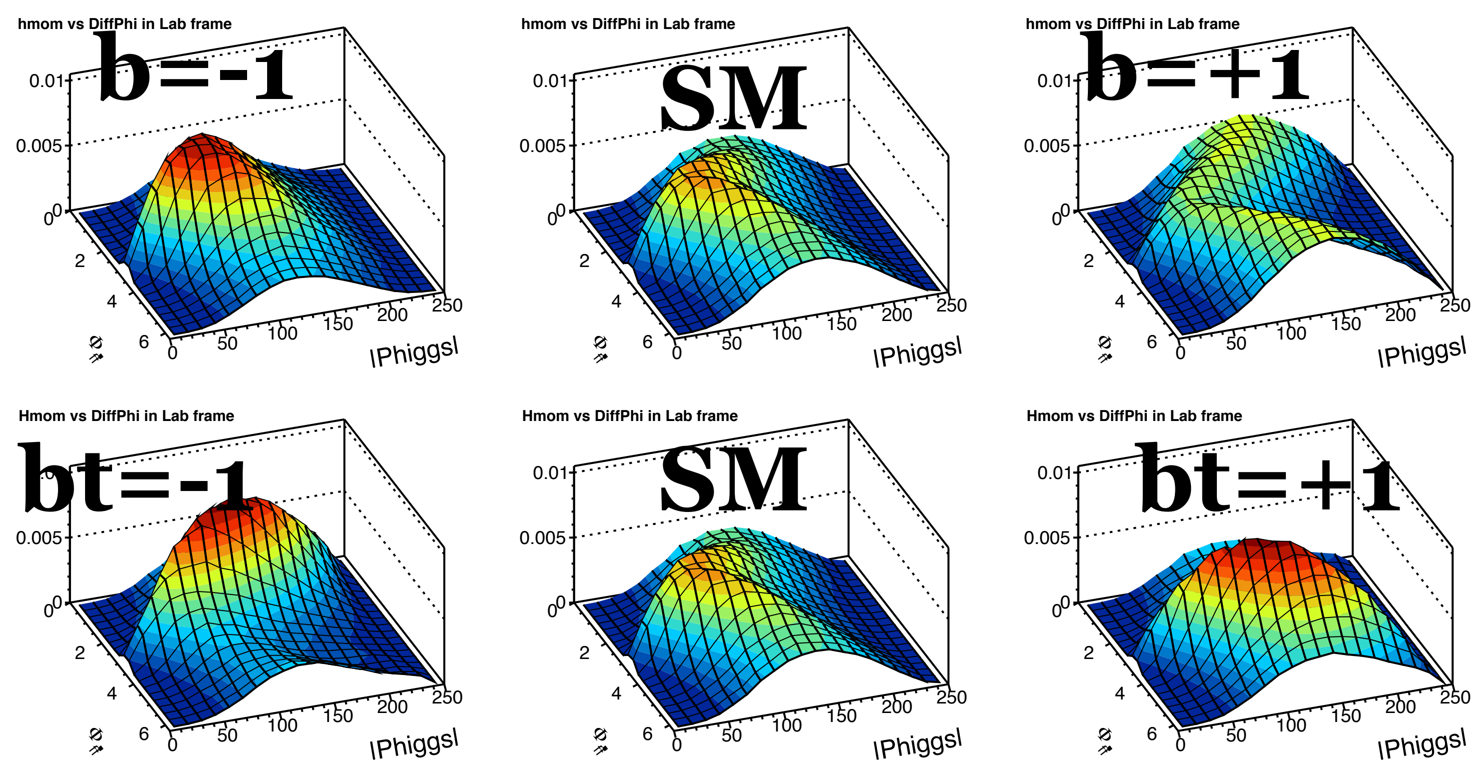


Kinematical distribution with the ZZ-fusion : 500GeV

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu}H$$







Analysis Strategy : χ^2 test

Our approach to evaluate the sensitivity to the anomalous couplings **is a binned analysis.**

- Kinematical/Shape information (for an 1-dimensional distribution)

$$\chi_s^2 = \sum_{i=1}^{n} \left[\frac{\frac{N_{SM}}{\sigma}\frac{d\sigma}{dX}(x_i) \cdot f_i - \frac{N_{SM}}{\sigma}\frac{d\sigma}{dX}(x_i; a_Z, b_Z, \tilde{b}_Z) \cdot f_i}{\delta N_{SM}(x_i)} \right]^2$$

i is Nth-bin

Computed differential cross section with SM parameters and BSM parameters
→ **"Generator level" distribution**
Normalized to #event expected with the SM for extracting impact of the shape.

Detector acceptance function evaluated with full detector simulation
(event acceptance and detector migration is considered)
→ Transfer to **"Detector level" distribution**

Poisson error on each bin (full simulation, SM Bkgs are taken into account)

- Cross section information

$$\chi_c^2 = \left[\frac{N_{SM} \cdot \epsilon - N_{BSM} \cdot \epsilon}{\delta\sigma \cdot N_{SM} \cdot \epsilon} \right]^2$$

Expected #events
Selection efficiency

Deviation of cross section of corresponding processes is also important information.

δσ(ZH) = 2% and 3% for 250 and 500GeV
δσ(ZZf) = 28% and 5% for 250 and 500GeV

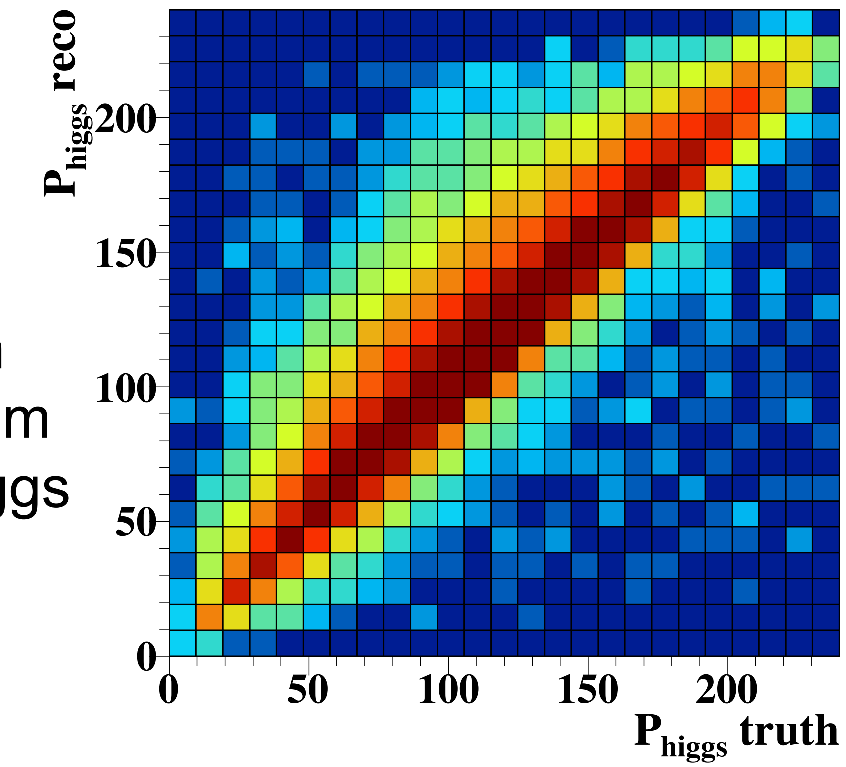
full simulation, T. Barklow et al., "ILC Operating Scenarios", arXiv:1506.07830 [hep-ex]

Analysis Strategy : Migration Matrix for Detector acceptance f

A reconstructed distribution receives a migration effect due to

Detector finite resolution
Jet clustering, missing particles etc…

500GeV
ZZ-fusion
Momentum
of the Higgs

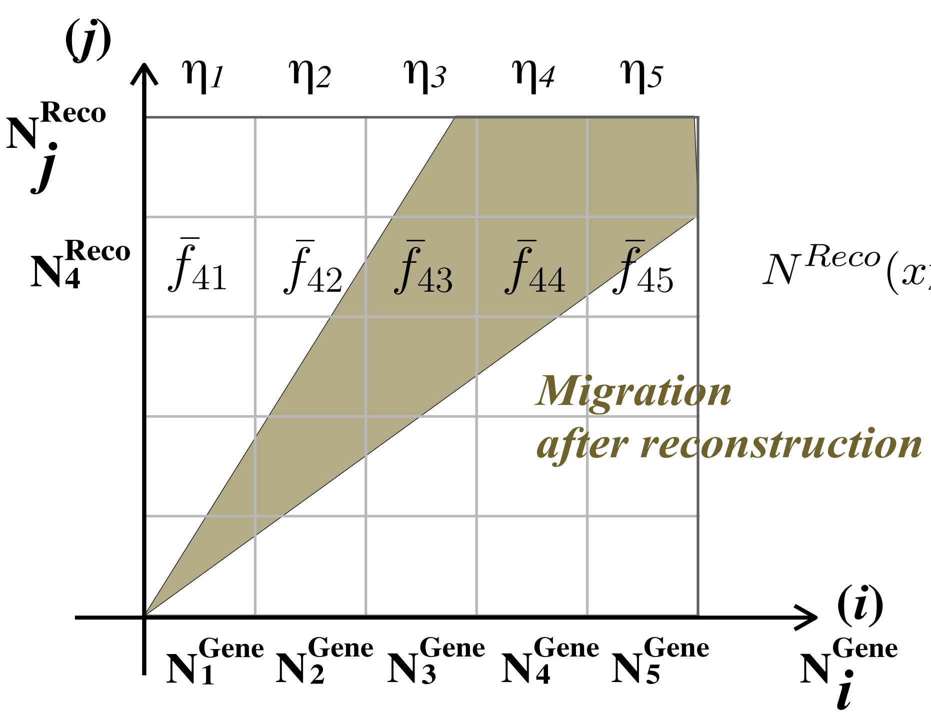


$$N^{Rec}(x_j^{Rec}) = \sum_i f(x_j^{Rec}, x_i^{Gen}) \cdot N^{Gen}(x_i^{Gen})$$

acceptance

$$N^{Rec}(x_j^{Rec}) = \sum_i f_{ji} \cdot N_i^{Gen} = \sum_i \bar{f}_{ji} \cdot \eta_i \cdot N_i^{Gen}$$

$$\left.\begin{aligned} \eta_i &\equiv \frac{N_i^{Accept}}{N_i^{Gene}} \quad (\text{Event Acceptance}) \\ \bar{f}_{ji} &\equiv \frac{N_{ji}^{Accept}}{N_i^{Accept}} \quad (\text{Migration Matrix}) \end{aligned}\right\} \text{Normalized to 1}$$



$$\begin{aligned} N^{Reco}(x_4^{Reco}) &= \sum_i \bar{f}_{4i} \cdot \eta_i \cdot N_i^{Gene} \\ &= \eta_1 \bar{f}_{41} \cdot N_1^{Gene} + \eta_2 \bar{f}_{42} \cdot N_2^{Gene} + \eta_3 \bar{f}_{43} \cdot N_3^{Gene} \\ &\quad + \eta_4 \bar{f}_{44} \cdot N_4^{Gene} + \eta_5 \bar{f}_{45} \cdot N_5^{Gene} \end{aligned}$$

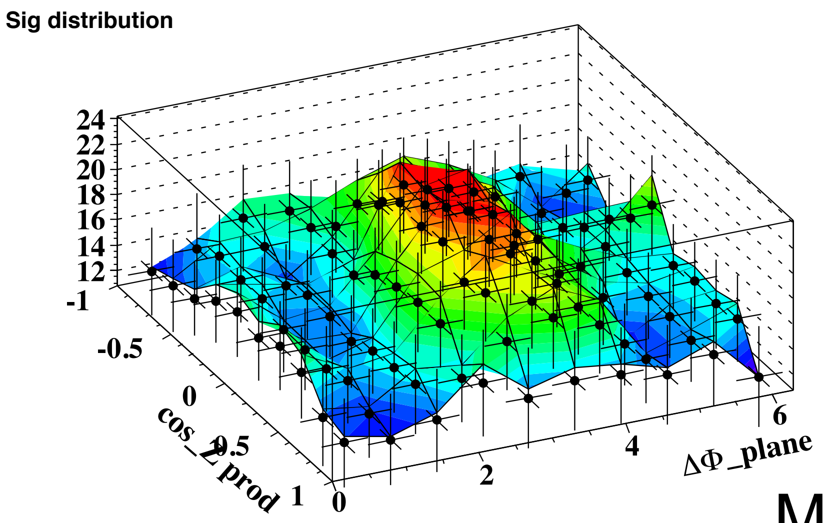
In order to transfer the generator distribution (binned in N) to the detector level distribution, a NxN matrix is needed.

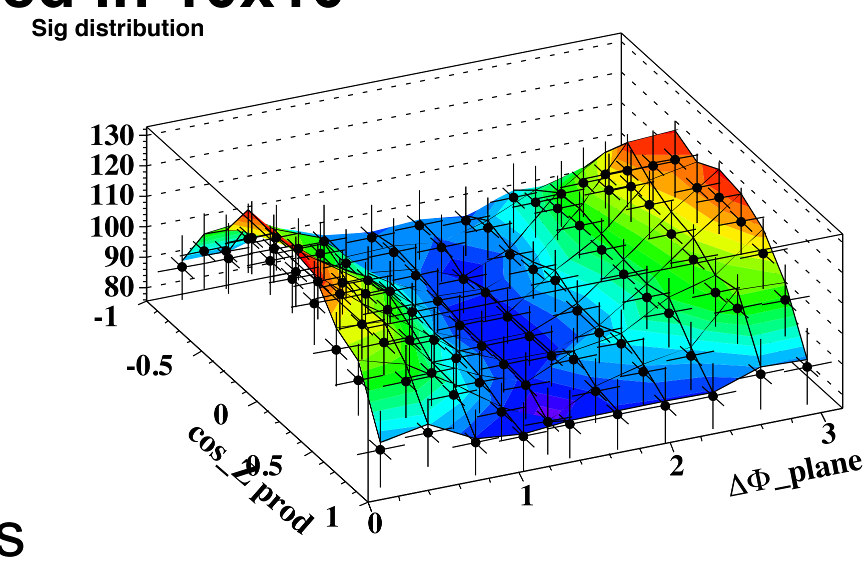
Examples : Reconstructed angular distribution & Migration matrix

ZH → μμH @ 250GeV

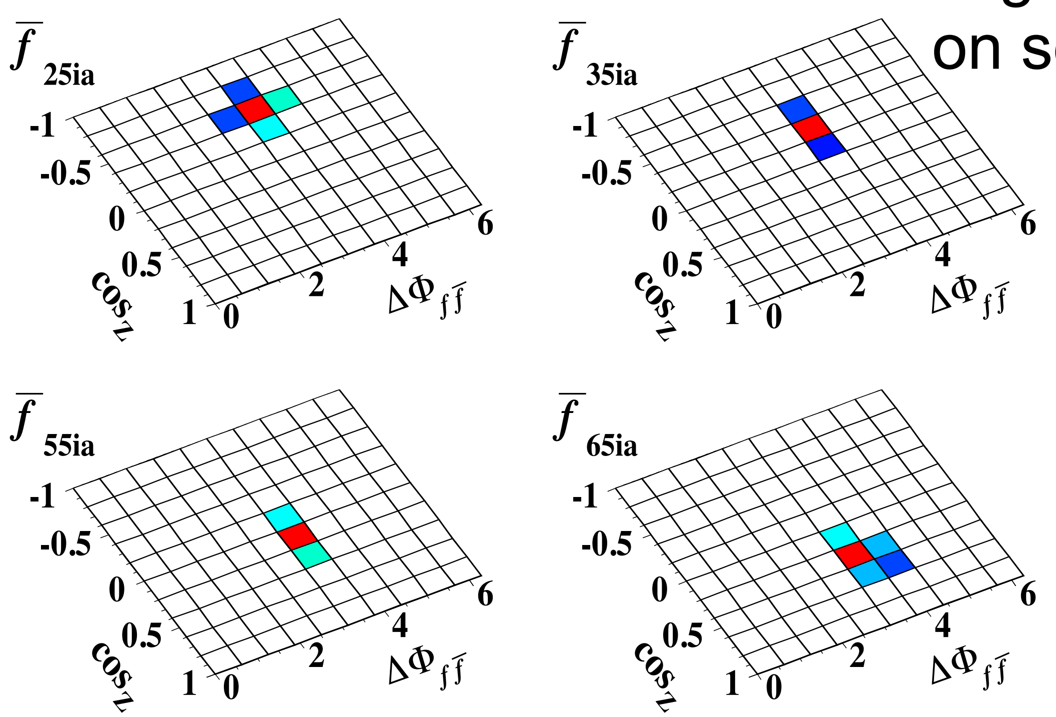
ZH → qqH(H→bb) @ 250GeV

Reconstructed distribution of **ΔΦ vs cosθz binned in 10x10**

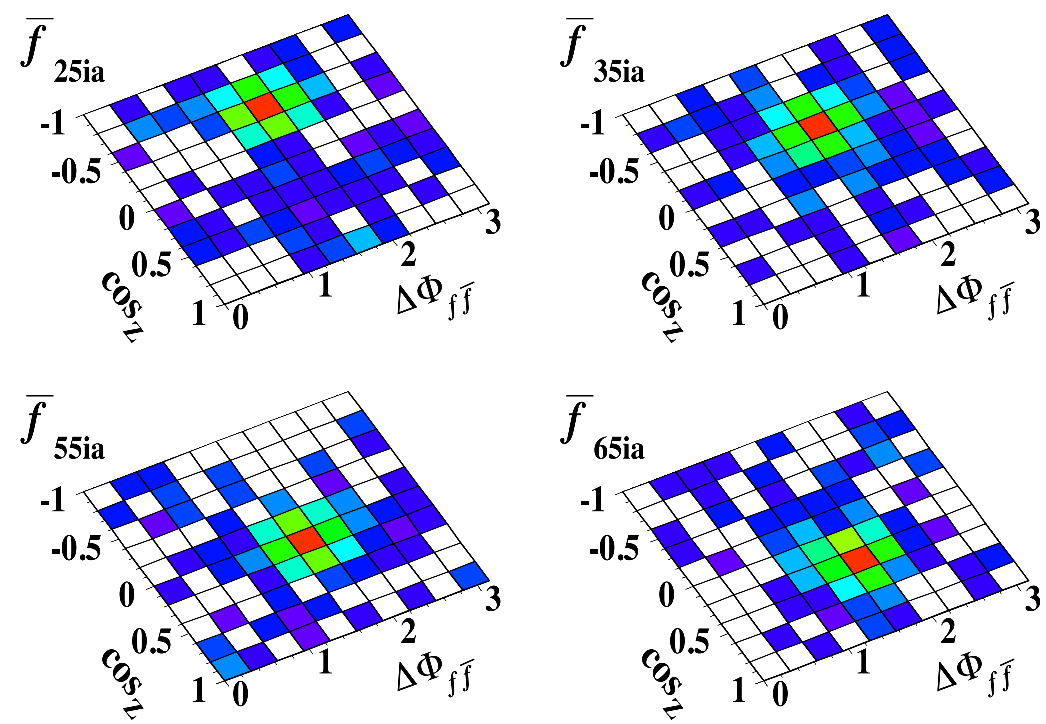




Migration matrices on several bins



Matrix element [0~1]



Lepton channel is very clean signature.
Hadron channel has relatively large migration.

2d detector acceptance

$$N^{Reco}(x^{Reco}_{j\beta}) = \sum_i \sum_\alpha f(x^{Reco}_{j\beta}, x^{Gene}_{i\alpha}) \cdot N^{Gene}(x^{Gene}_{i\alpha}) = \sum_i \sum_\alpha f_{j\beta i\alpha} \cdot N^{Gene}_{i\alpha}$$

$$N^{Reco}(x^{Reco}_{j\beta}) = \sum_i \sum_\alpha \bar{f}_{j\beta i\alpha} \cdot \eta_{i\alpha} \cdot N^{Gene}_{i\alpha}$$

$$\eta_{i\alpha} \equiv \frac{N^{Accept}_{i\alpha}}{N^{Gene}_{i\alpha}} \quad \text{(Event Acceptance)}$$

2d Migration matrix

$$\bar{f}_{j\beta i\alpha} \equiv \frac{N^{Accept}_{j\beta i\alpha}}{N^{Accept}_{i\alpha}} \quad \text{(Migration Matrix)}$$

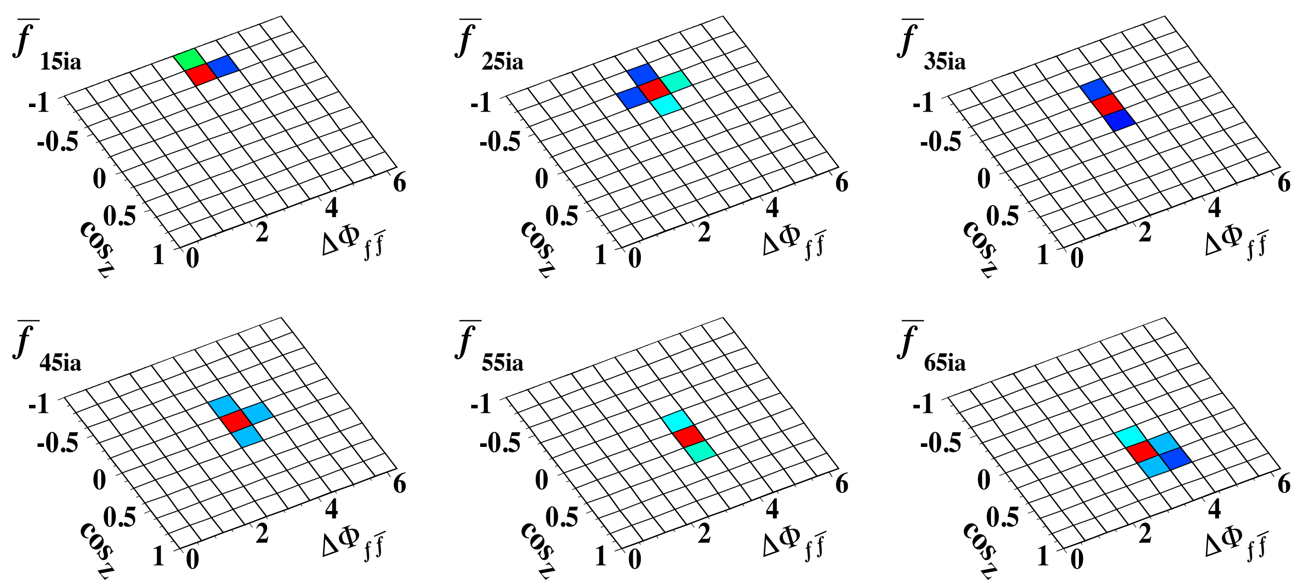


FIG. 7. Distributions showing the migration matrix on several bins when the two-dimensional distribution $X(\cos\theta_Z, \Delta\Phi_{f\bar{f}})$ binned in 10×10 is used. Compared with the channel $q\bar{q}b\bar{b}(H)$ showing in the next section, the migration is almost nothing because of the clear signature of the signal process. ($\bar{f}_{jbia}$: the index jb denotes certain reconstructed bin in the two-dimensional distribution, and the index ia corresponds to the other axises defining MC truth directions which are shown in the distributions. The range of the Z axis is [0, 1] and the normalization of each distribution is $\sum_{j,\,b} \bar{f}_{jbia} = 1$.)

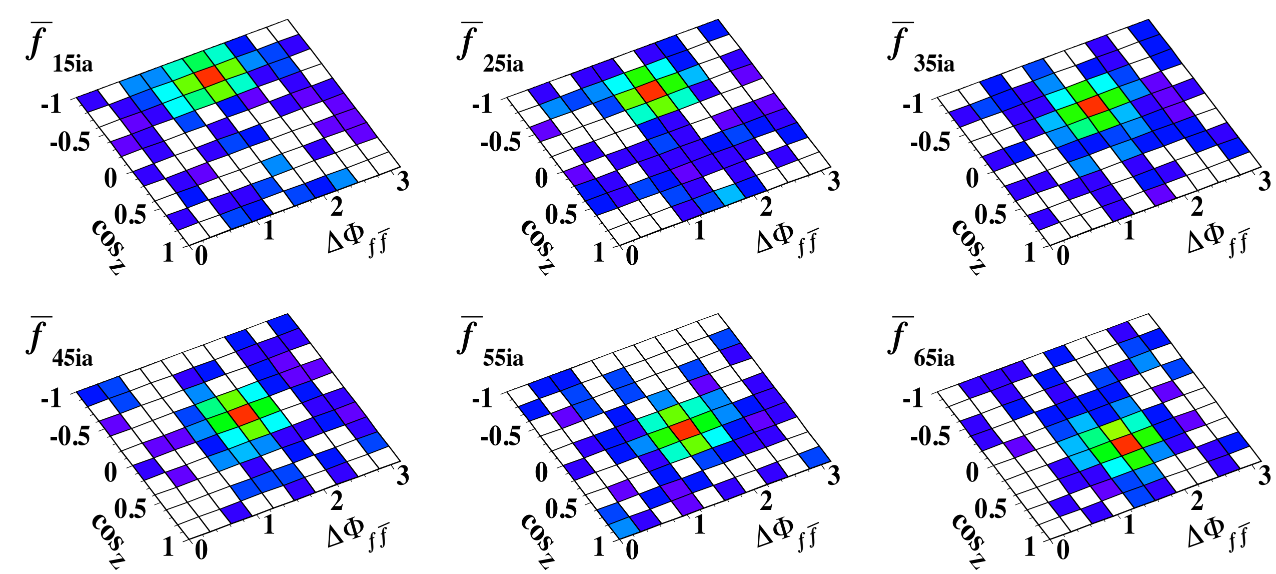
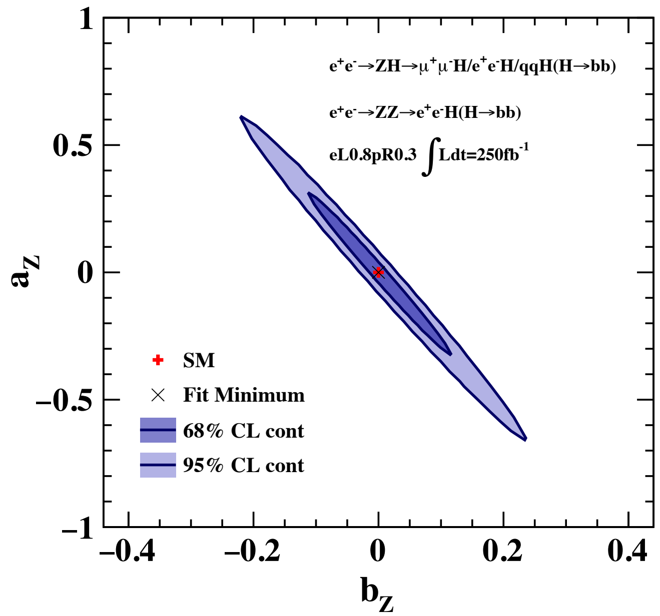


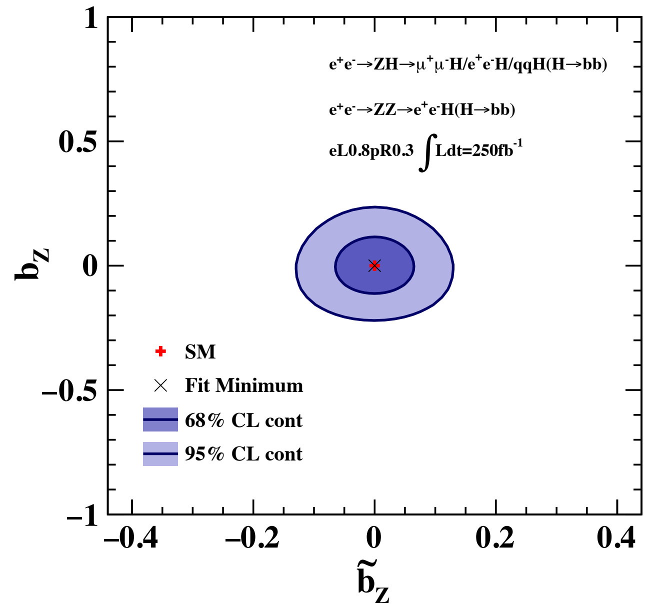
FIG. 8. Distributions showing the migration matrix on several bins in which the two-dimensional distribution $X(\cos\theta_Z, \Delta\Phi_{f\bar{f}})$ binned in 10×10 is used. Compared with the channel $\mu\mu H$, clear the bin-by-bin migration can be seen, which is originating from the multiple jet environment.

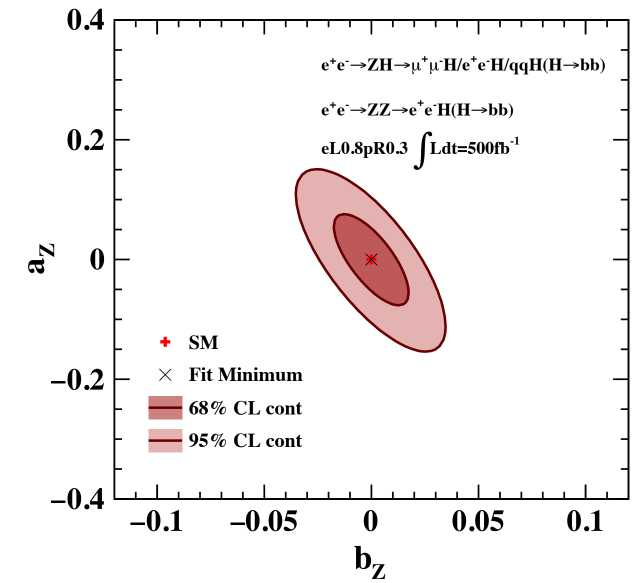
Sensitivity to ZZH couplings

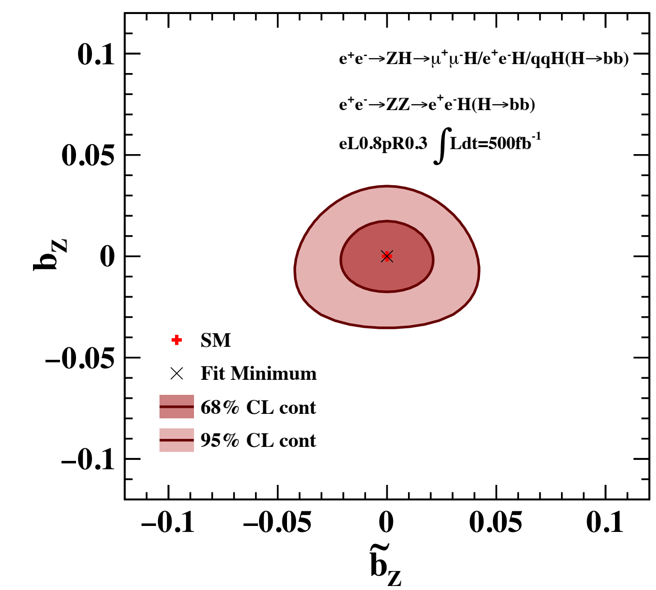
Contours showing sensitivities with three parameter space.

250fb^{-1} and 500fb^{-1} are assumed as the integrated luminosity for 250 and 500GeV.









		a_Z	b_Z	$\tilde{b}_Z$
ZH	$e_L^- e_R^+$	-	± 0.110	± 0.051
with shape	$e_R^- e_L^+$	-	± 0.129	± 0.061
ZH	$e_L^- e_R^+$	± 0.309	± 0.109	± 0.051
with shape+σ	$e_R^- e_L^+$	± 0.356	± 0.125	± 0.061
ZH+ZZ-fusion	$e_L^- e_R^+$	-	± 0.110	± 0.051
with shape	$e_R^- e_L^+$	-	± 0.129	± 0.061
ZH+ZZ-fusion	$e_L^- e_R^+$	± 0.238	± 0.084	± 0.050
with shape+σ	$e_R^- e_L^+$	± 0.278	± 0.098	± 0.060

		a_Z	b_Z	$\tilde{b}_Z$
ZH	$e_L^- e_R^+$	-	± 0.0199	± 0.0183
with shape	$e_R^- e_L^+$	-	± 0.0215	± 0.0198
ZH	$e_L^- e_R^+$	± 0.116	± 0.0201	± 0.0183
with shape+σ	$e_R^- e_L^+$	± 0.130	± 0.0217	± 0.0198
ZH+ZZ-fusion	$e_L^- e_R^+$	-	± 0.0200	± 0.0174
with shape	$e_R^- e_L^+$	-	± 0.0214	± 0.0190
ZH+ZZ-fusion	$e_L^- e_R^+$	± 0.061	± 0.0134	± 0.0174
with shape+σ	$e_R^- e_L^+$	± 0.071	± 0.0156	± 0.0188

bt can be evaluated through
only shape information @ 250 and 500GeV

Correlation a and b is strong
because σ info. is much stronger than that of the shape

@ 500GeV the shape quickly changes
the correlation can be disentangled.

Power of each process for the anomalous couplings

ZH : leptonic(e/μ) / hadronic (q)
ZZ : H → bb

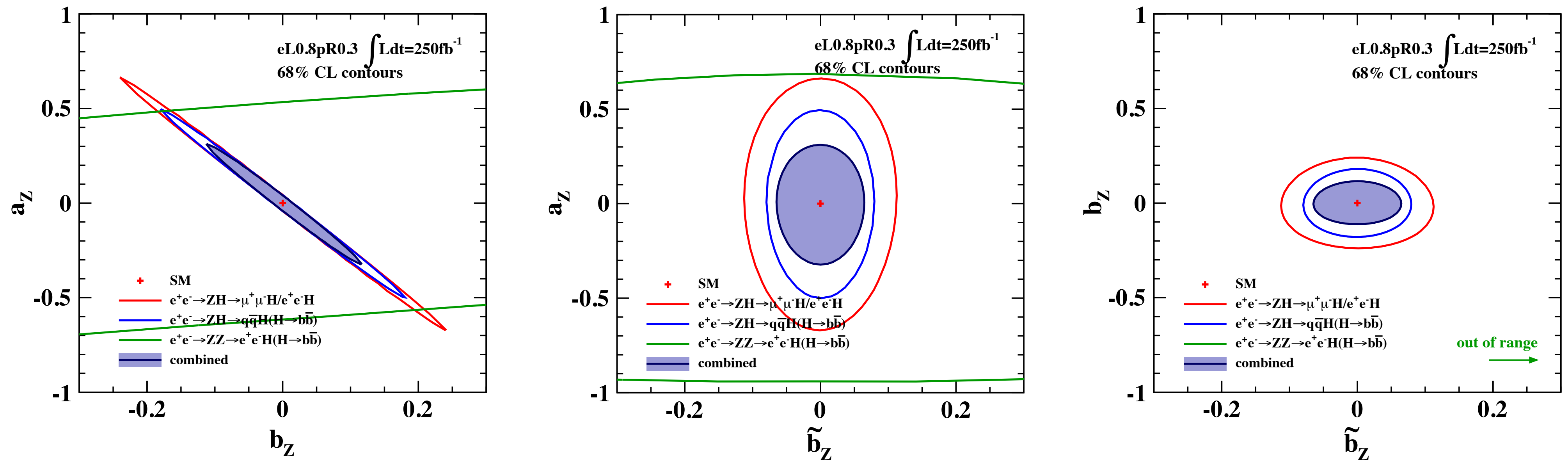


FIG. 25. A plot shows the sensitivity to the anomalous ZZH couplings. Fitting is performed with simultaneous fitting in three free parameter space, and each contour showing impact of each channel are projected into the a_Z-b_Z parameter space. The integrated luminosity is assumed to be 250 fb^{-1} with left-handed polarization $e^-_L e^+_R$.

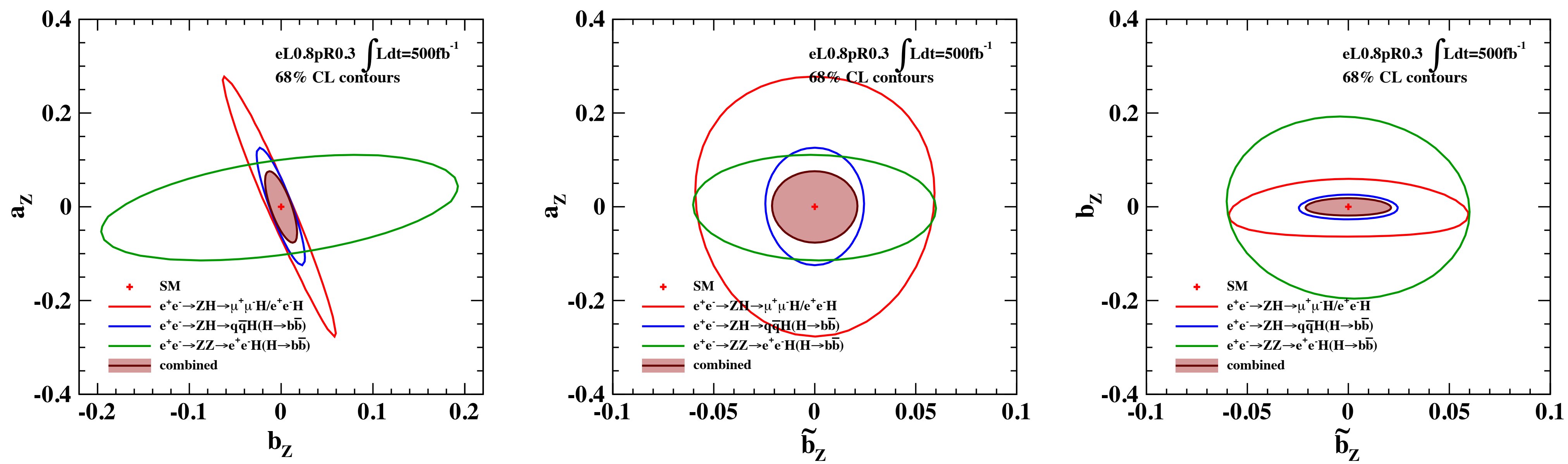
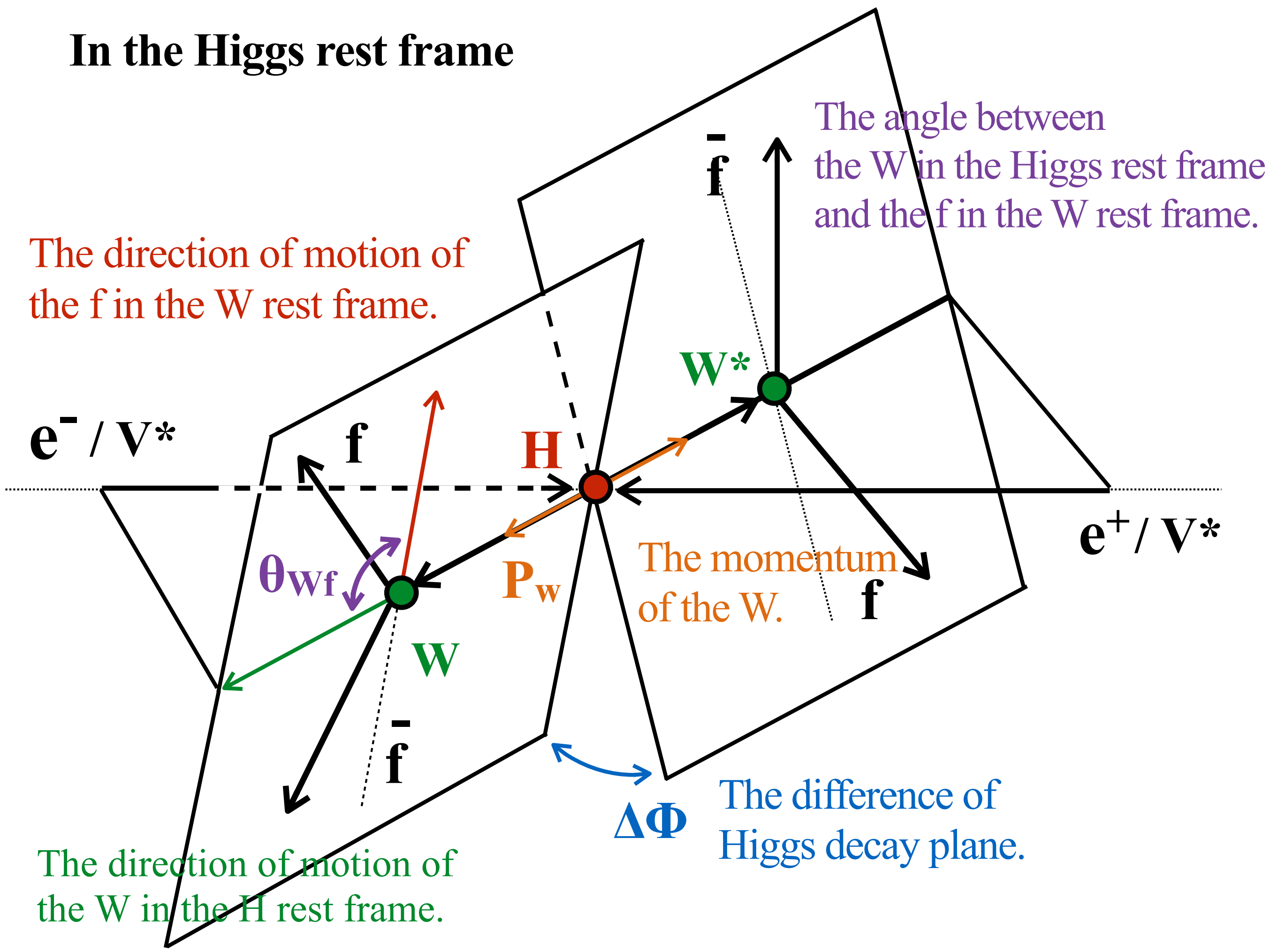
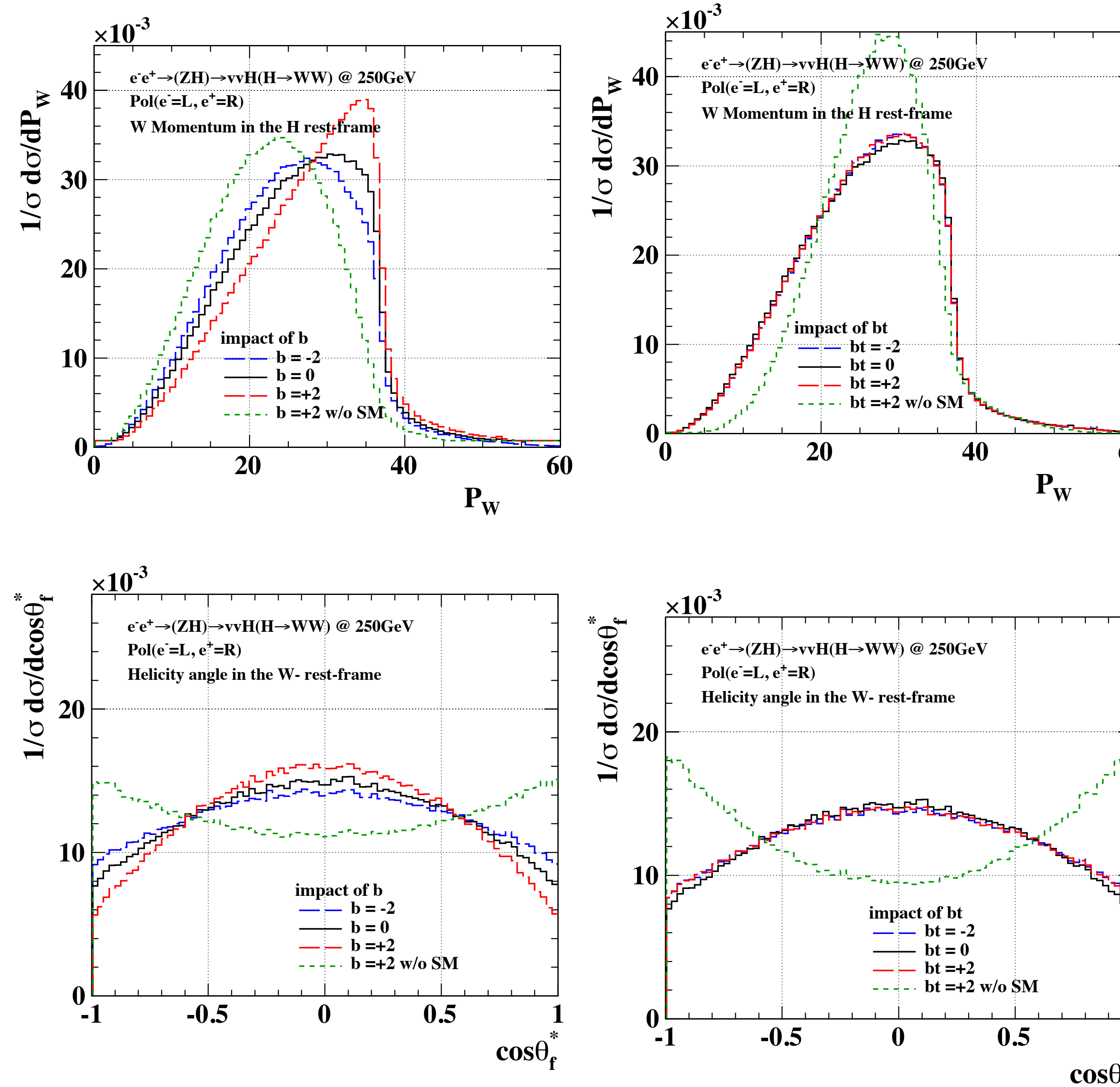


FIG. 26. A plot shows the sensitivity to the anomalous ZZH couplings. Fitting is performed with simultaneous fitting in three free parameter space, and each contour showing impact of each channel are projected into the a_Z-b_Z parameter space. The integrated luminosity is assumed to be 500 fb^{-1} with left-handed polarization $e^-_L e^+_R$.

anomalous WWH couplings

The Lorentz tensor structures described by the anomalous parameters b and bt affect angular and momentum distributions of the W boson and helicity angle of a daughter particle.

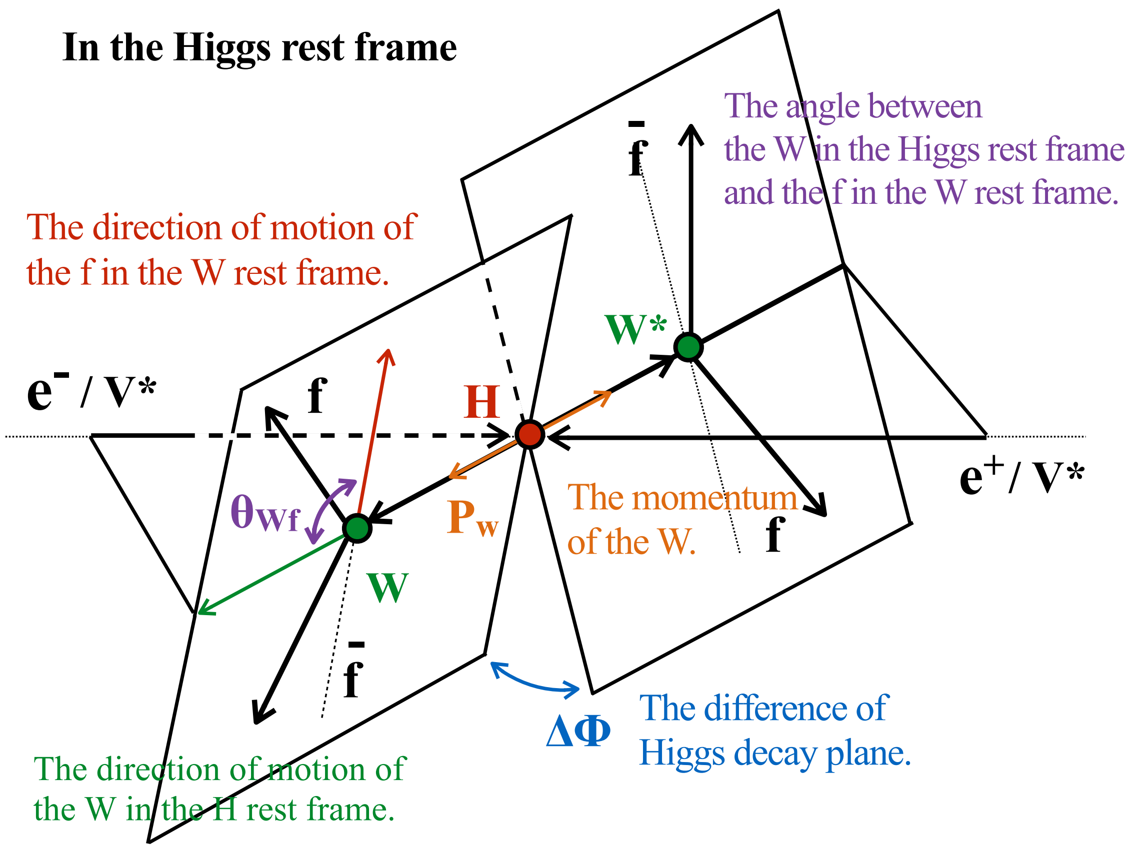


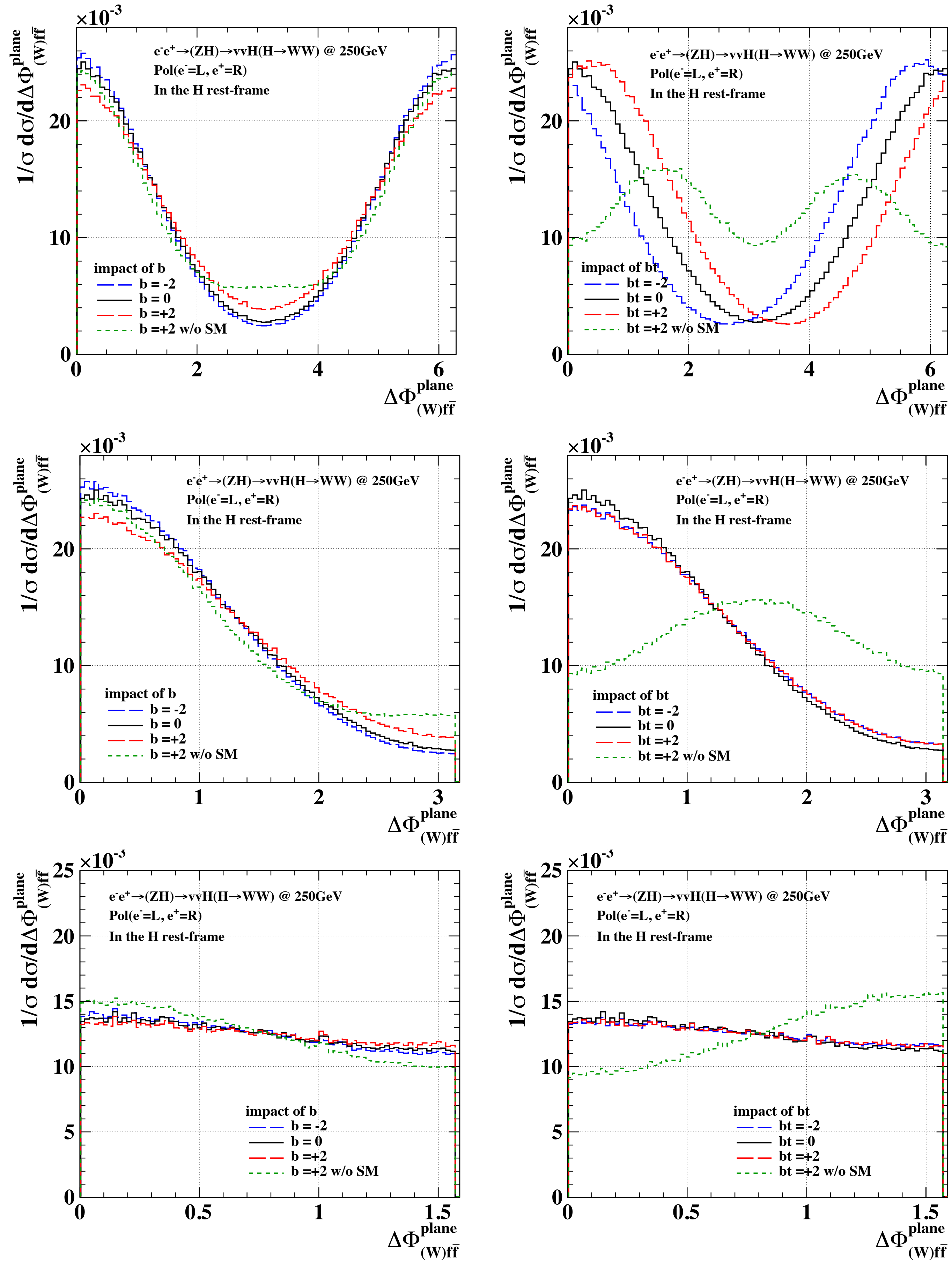


anomalous WWH couplings

The Lorentz tensor structures described by th
b and bt affect angular and momentum disti
and helicity angle of a daughter particle.

In the Higgs rest frame





The most effective observable to catch bt is ΔΦ.

ZH → νvH (H→WW → qqqq)
The final state is multi-jet state.

An original idea to keep sensitivity of ΔΦ
is to use Jets deriving from Cs in the W bosons.

two c-jets : sensitivity become harf
No id : sensitivity become quarter.