Sensitivity to Anomalous VVH Couplings at the ILC

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on behalf of the ILD Concept Group

This study was done mostly by **Tomohisa Ogawa** of KEK.

November 29, 2018: HC2018

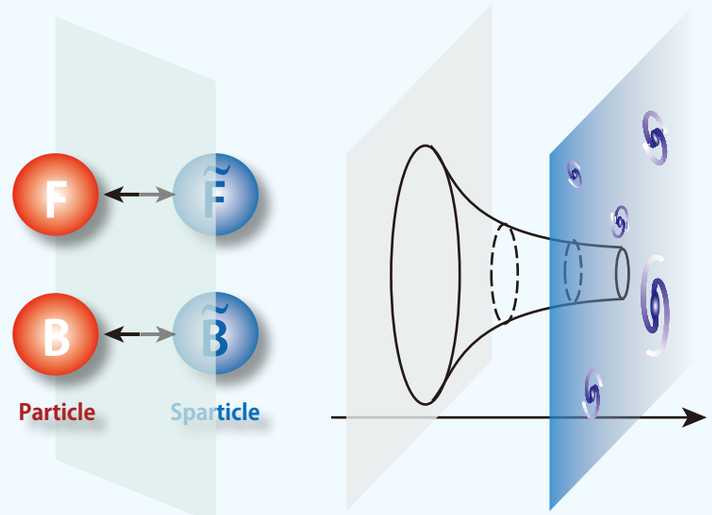
We are at a big fork

Extension of Space-Time
SUSY / Extra-dimensions

Key = Precision Higgs and Top couplings
SUSY particle discovery

Fermionic Extra -dim. = SUSY

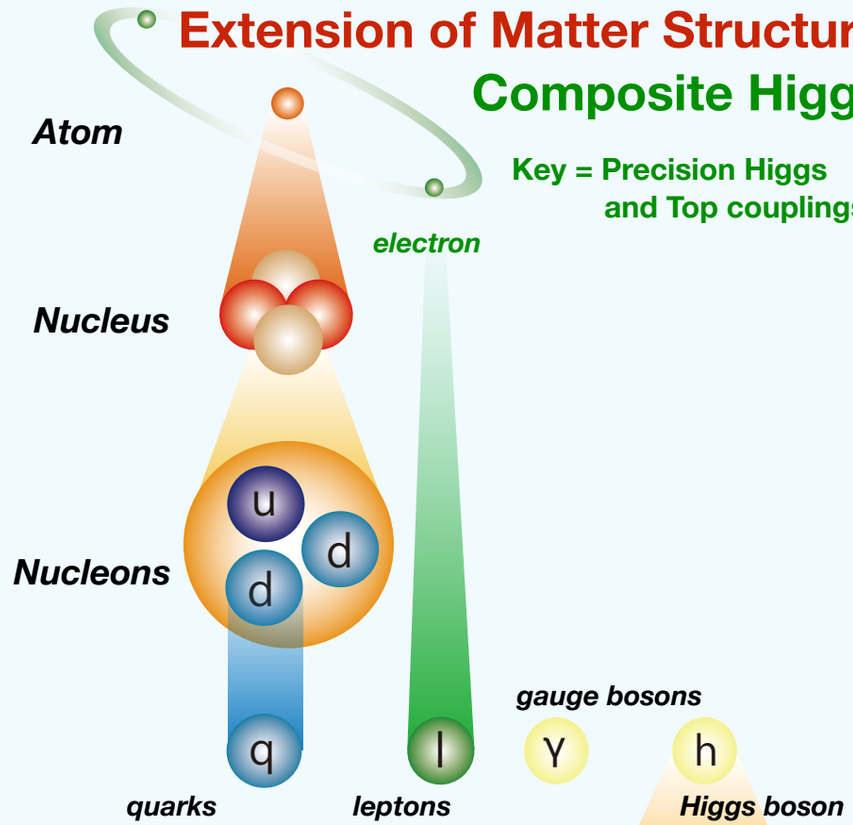
Bosonic Extra -dim. = RS (ADD)



Big step towards ultimate unification

Extension of Matter Structure
Composite Higgs

Key = Precision Higgs and Top couplings

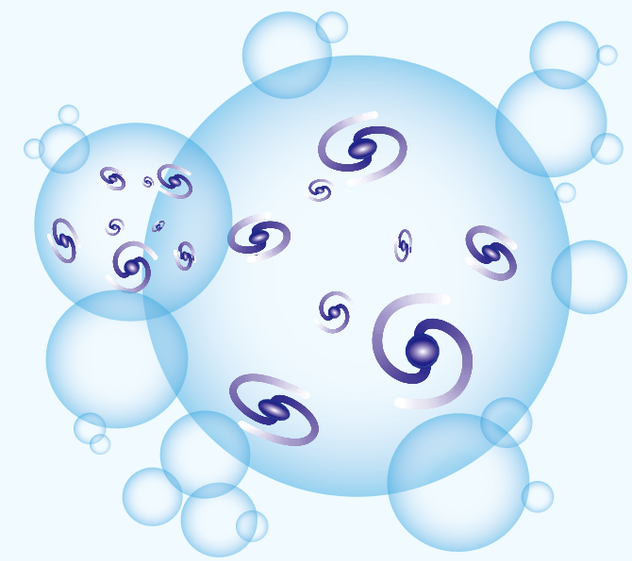


Jungle of new heavy composite particles in the TeV+ scale

New Strong Force

Completely New Principle
Multiverse + Anthropic Principle ?

Key = precision m_t and m_h measurements



No deviation from SM

The 1st Road: Existence of another dimension

The 2nd Road: Existence of a new stratum of Nature

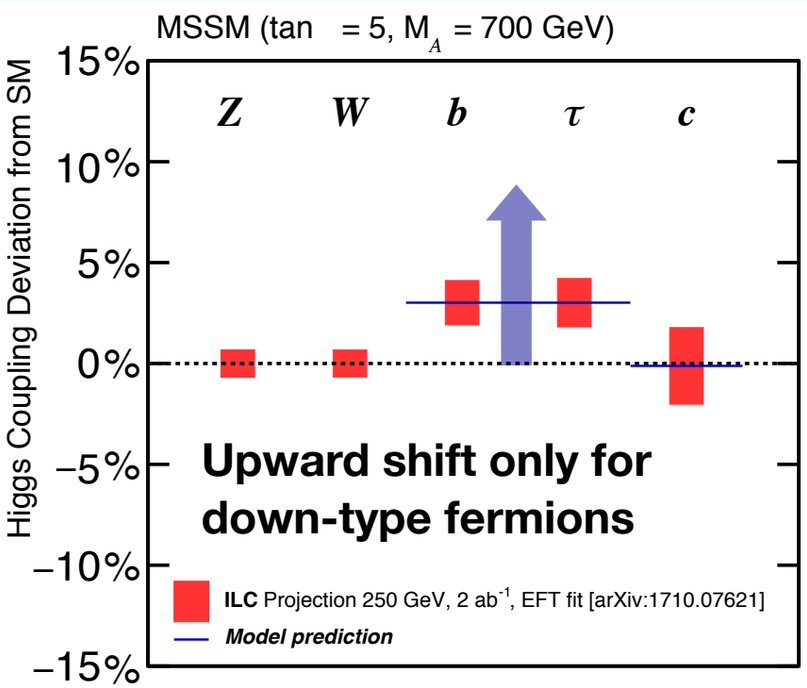
The 3rd Road: Existence of a myriad of universes ?

We are ***here***

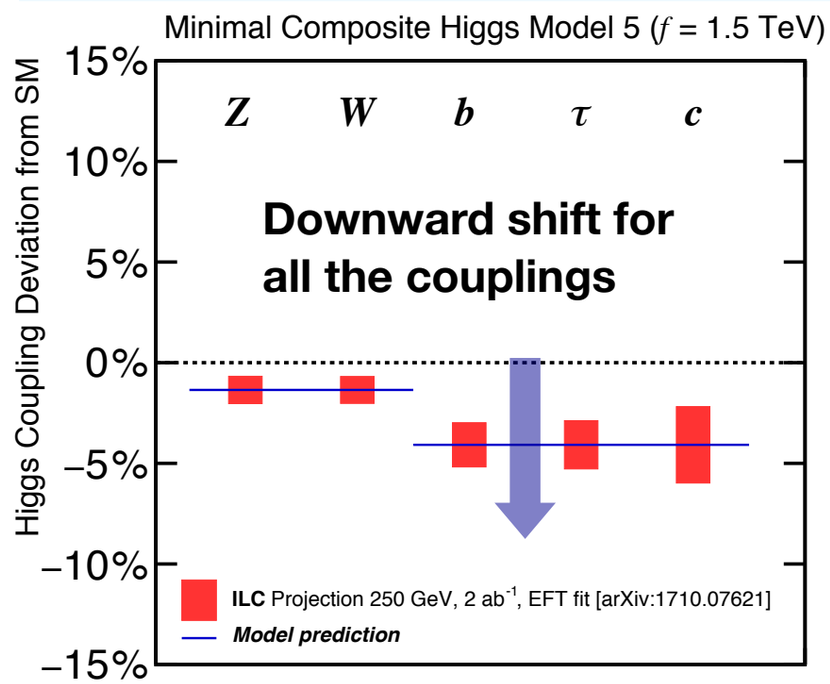
Which way to go?

Decide the way by fingerprinting models with Precision Higgs Measurements

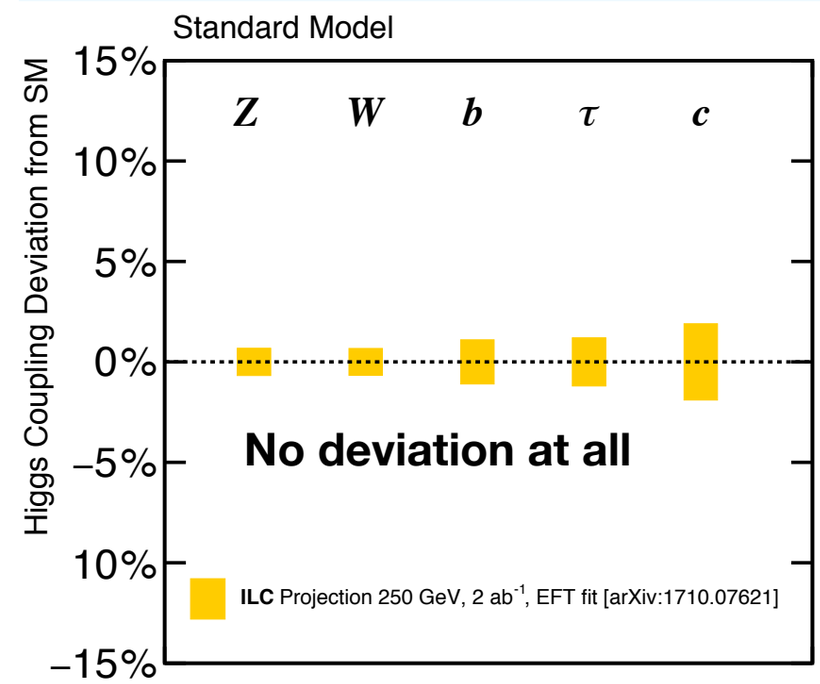
Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



Multi-verse?
(Standard Model)



Different models predict different deviation patterns
→ Deviation pattern tells us which way to go.

Complementary to direct searches at LHC: Depending on parameters, ILC's sensitivity goes beyond that of LHC.

Precision Higgs coupling

study *is* ***a torch***

to shine our way ahead.

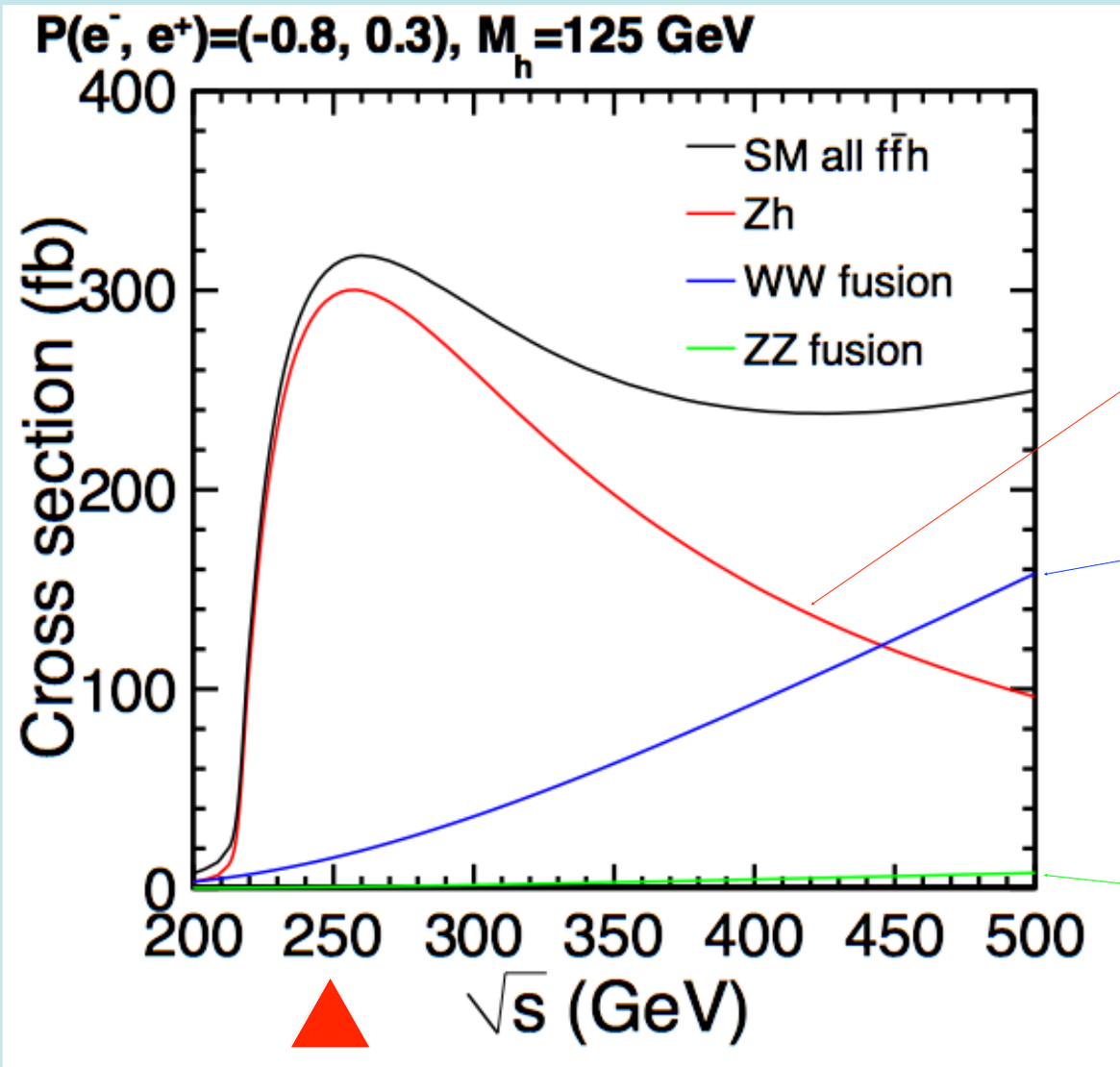
Mass-produce Higgs bosons and study them in detail

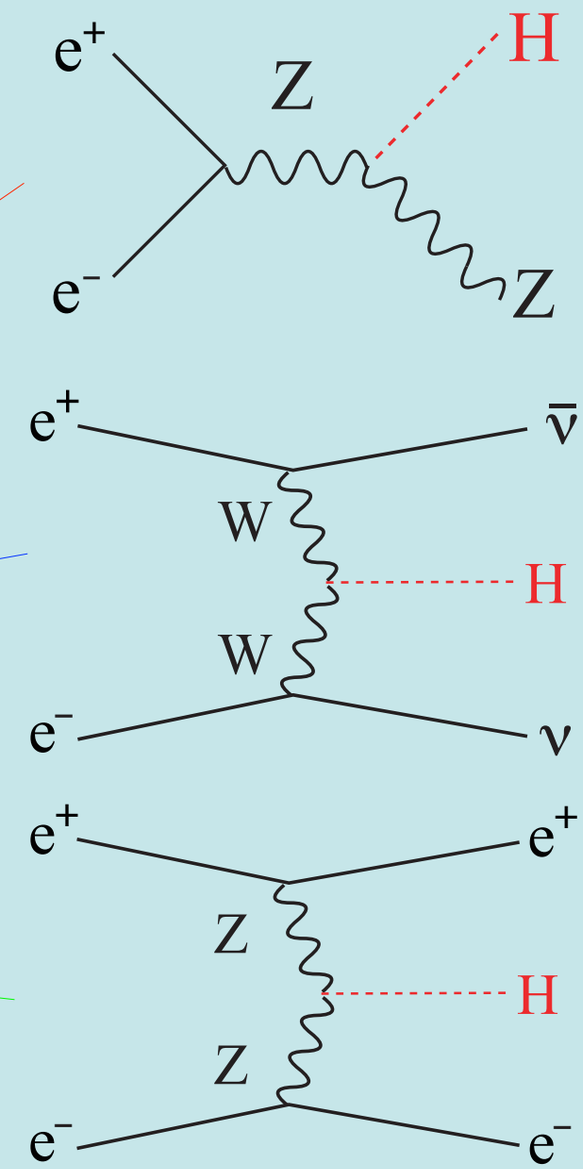
250 GeV ILC as a Higgs Factory

250 GeV is a Special Energy

Single Higgs production cross section maximum

Production Cross Section as a fun. of E_{cm}





250 GeV: cross section maximum (~0.5 Million events for 2 ab^{-1})

Mass-produce Higgs bosons and study them in detail!

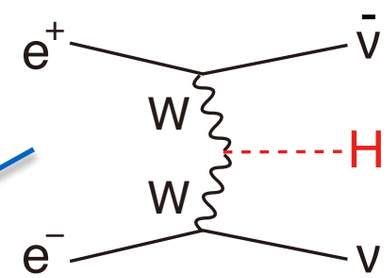
Recent Development: EFT Analysis

Potential drawback:

It has been said that Γ_h (Higgs total width) necessary for absolute coupling normalization requires >350GeV.

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$

$$\Gamma(h \to WW^*) \propto \sigma(\nu\bar{\nu}h)$$



cross section: small@250GeV

Solution: ***EFT (Effective Field Theory)*** to relate **hZZ** and **hWW** couplings

LHC Run II results suggest that **250 GeV** is likely **in the validity range of the EFT**

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

SU(2)xU(1) inv. dim.6 operators

EFT coefficients to decide:

17 @ ILC

This ILC number is quite tractable:

W_L and Z_L are NGBs from the Higgs sector. can use All the SM processes with W and Z to constrain EFT coefficients.

(The importance of the σ_{Zh} measurement by recoil mass technique remains the same!)

Beam polarization essentially doubles the number of usable observables.
→ ***can test the validity of the EFT***

Absolute and model-independent Higgs coupling measurements possible with the 250 GeV data alone!

EFT Lagrangian Before EW Symmetry Breaking

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

Manifestly SU(2)xU(1) gauge invariant

$$\begin{aligned}\Delta\mathcal{L} = & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\ & + \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\ & + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\ & + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\ & + i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .\end{aligned}$$

CP conserving

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

CP violating

Phys. Rev. D 97 (2018) 053004

EFT Lagrangian After EW Symmetry Breaking

$$
\begin{aligned}
\Delta\mathcal{L}_h \quad = \quad & -\eta_h \lambda_0 v_0 h^3 + \frac{\theta_h}{v_0} h \partial_\mu h\, \partial^\mu h + \eta_z \frac{m_Z^2}{v_0} Z_\mu Z^\mu h + \frac{1}{2}\eta_{2z} \frac{m_Z^2}{v_0^2} Z_\mu Z^\mu h^2 \\
& + \eta_W \frac{2m_W^2}{v_0} W_\mu^+ W^{-\mu} h + \eta_{2W} \frac{m_W^2}{v_0^2} W_\mu^+ W^{-\mu} h^2 \\
& + \frac{1}{2}\left(\zeta_Z \frac{h}{v_0} + \frac{1}{2}\zeta_{2Z}\frac{h^2}{v_0^2}\right) \hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} + \left(\zeta_W \frac{h}{v_0} + \frac{1}{2}\zeta_{2W}\frac{h^2}{v_0^2}\right) \hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu} \\
& + \frac{1}{2}\left(\zeta_A \frac{h}{v_0} + \frac{1}{2}\zeta_{2A}\frac{h^2}{v_0^2}\right) \hat{A}_{\mu\nu}\hat{A}^{\mu\nu} + \left(\zeta_{AZ} \frac{h}{v_0} + \frac{1}{2}\zeta_{2AZ}\frac{h^2}{v_0^2}\right) \hat{A}_{\mu\nu}\hat{Z}^{\mu\nu} \\
& + \frac{1}{2}\left(\tilde{\zeta}_Z \frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2Z}\frac{h^2}{v_0^2}\right) \hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu} + \left(\tilde{\zeta}_W \frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2W}\frac{h^2}{v_0^2}\right) \hat{W}^+_{\mu\nu}\tilde{\hat{W}}^{-\mu\nu} \\
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\end{aligned}
$$

CP conserving

CP violating

Coefficients, η's and ζ's are given in terms of C's and hence interrelated, for instance

$$
\begin{aligned}
\eta_W &= -\frac{1}{2} C_H \\
\eta_Z &= -\frac{1}{2} C_H - \boxed{C_T}
\end{aligned}
$$

Nonzero C_T breaks custodial SU(2) Symmetry

Precision observables can determine C_T

which come to our rescue in Γ_h determination at 250 GeV where the WW-fusion cross section is small.

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& + \frac{1}{2}\left(\tilde{\zeta}_Z \frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2Z}\frac{h^2}{v_0^2}\right) \hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu} + \left(\tilde{\zeta}_W \frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2W}\frac{h^2}{v_0^2}\right) \hat{W}^+_{\mu\nu}\tilde{\hat{W}}^{-\mu\nu} \\
& + \frac{1}{2}\left(\tilde{\zeta}_A \frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2A}\frac{h^2}{v_0^2}\right) \hat{A}_{\mu\nu}\tilde{\hat{A}}^{\mu\nu} + \left(\tilde{\zeta}_{AZ} \frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2AZ}\frac{h^2}{v_0^2}\right) \hat{A}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}
\end{aligned}
$$

VVH

CP conserving

CP violating

Coefficients, η's and ζ's are given in terms of C's and hence interrelated, for instance

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Search for

Anomalous VVH

Couplings

is an essential part of

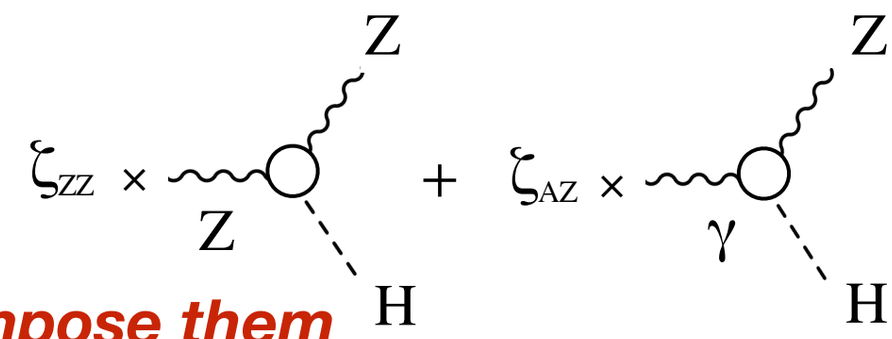
the SM EFT Analysis

Anomalous ZZH/γZH couplings

A and *Z* are mixtures of *B* and *W*

B couples to e_L **and** e_R in the same way.
W^3 couples to e_L ***only.***

⇨ ***Beam polarization is essential to decompose them***



Redefinition of coefficients

$$\mathcal{L}_{VVH} = \frac{m_Z^2}{v}(1+\eta_Z)\, Z_\mu Z^\mu h + \frac{1}{2v}\left(\zeta_Z \hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} + \zeta_{AZ}\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\right) h + \frac{1}{2v}\left(\tilde{\zeta}_Z \hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu} + \tilde{\zeta}_{AZ}\hat{A}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}\right) h$$

⇨

$$\boxed{\begin{aligned}\eta_Z &= \frac{v}{\Lambda}a_Z \\ \zeta_Z &= \frac{v}{\Lambda}b_Z \\ \tilde{\zeta}_Z &= \frac{v}{\Lambda}\tilde{b}_Z\end{aligned}}$$

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

Different $b_Z, \tilde{b}_Z$ for different beam polarizations

$(\Lambda = 1\,\mathrm{TeV})$

(v/Λ≃1/4)

$$\begin{cases} e_L^- e_R^+ : 1 + 5.70\,\zeta_{ZZ} + 7.70\,\zeta_{AZ} = 1 + 5.70\, b_Z^{e_L^- e_R^+} \\ e_R^- e_L^+ : 1 + 5.70\,\zeta_{ZZ} - 9.05\,\zeta_{AZ} = 1 + 5.70\, b_Z^{e_R^- e_L^+} \end{cases}$$

Analysis strategy

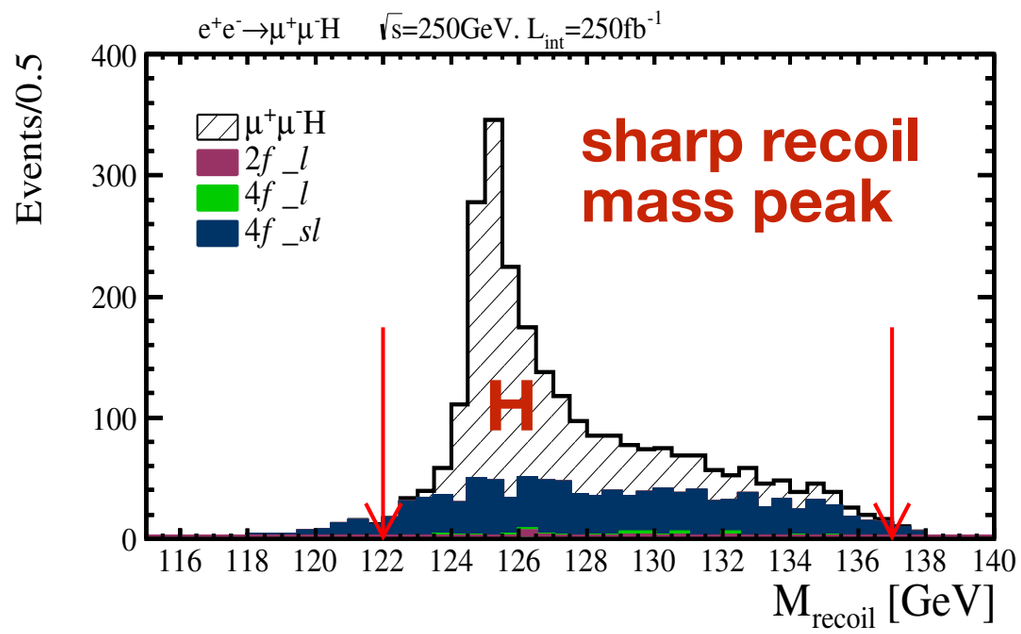
With **full detector simulation**, decide **acceptance *η*** and **migration matrix *f̄***
and use them to translate **theory to reconstructed distributions.**

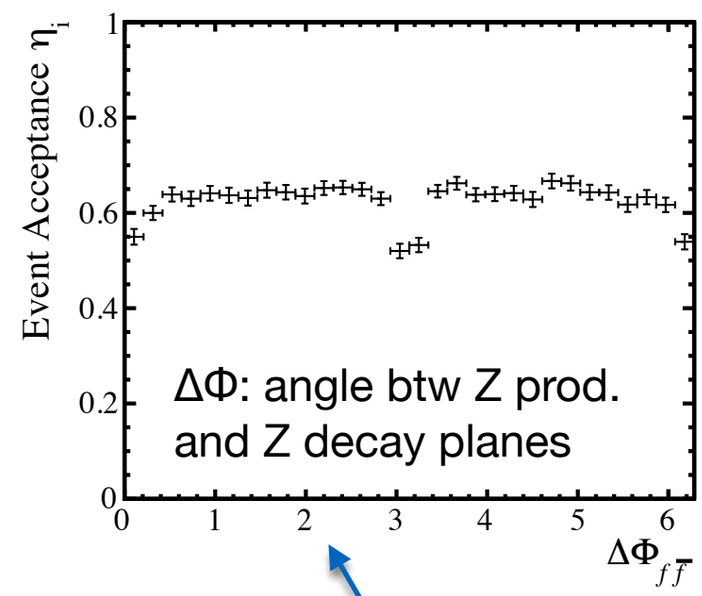
Then **fit the translated theory distributions to the toy MC for SM** to estimate **ILC's sensitivity to anomalous couplings**.

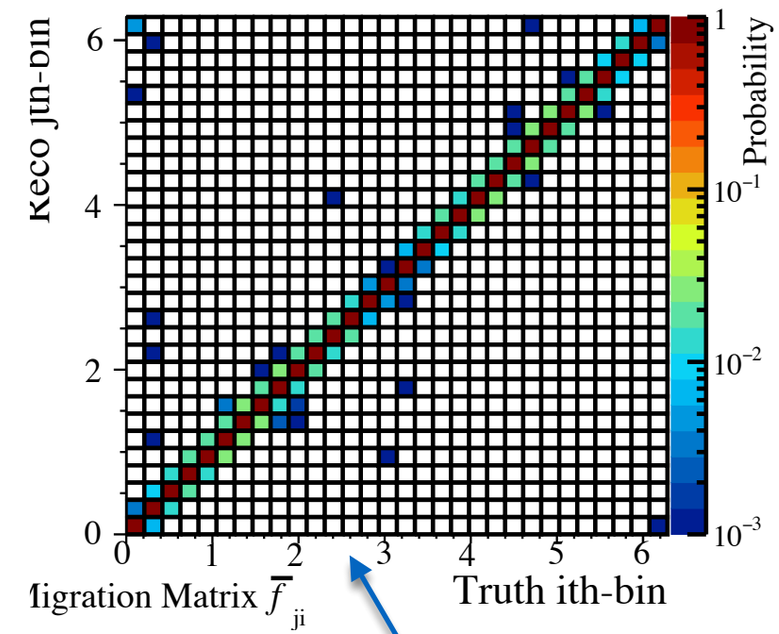
ZH→ μμH / qqH(bb)

μμH

ILD full simulation







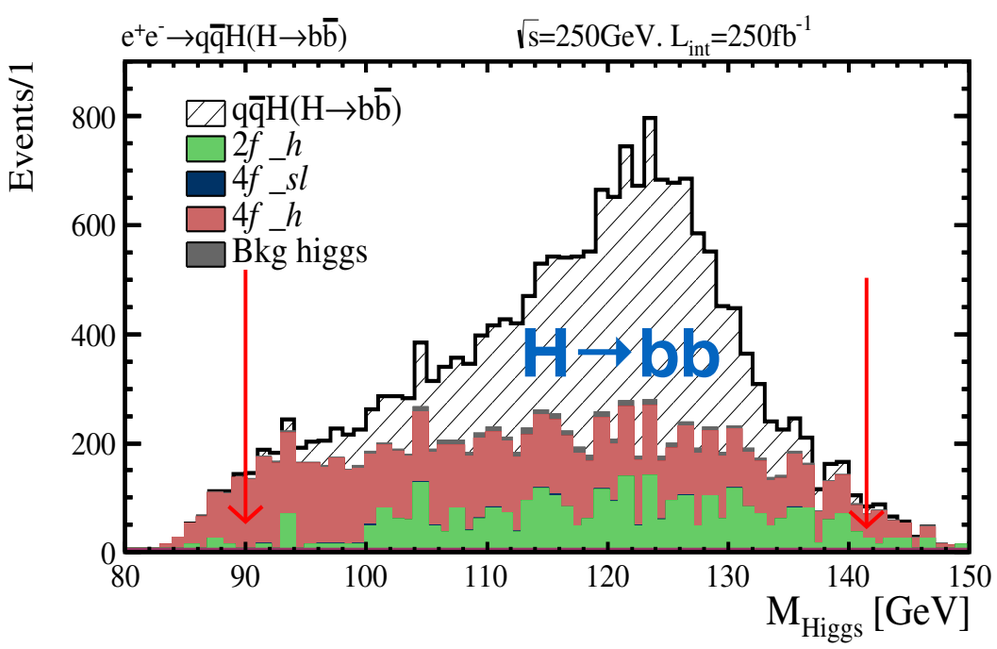
Observables: Z prod. & decay angles

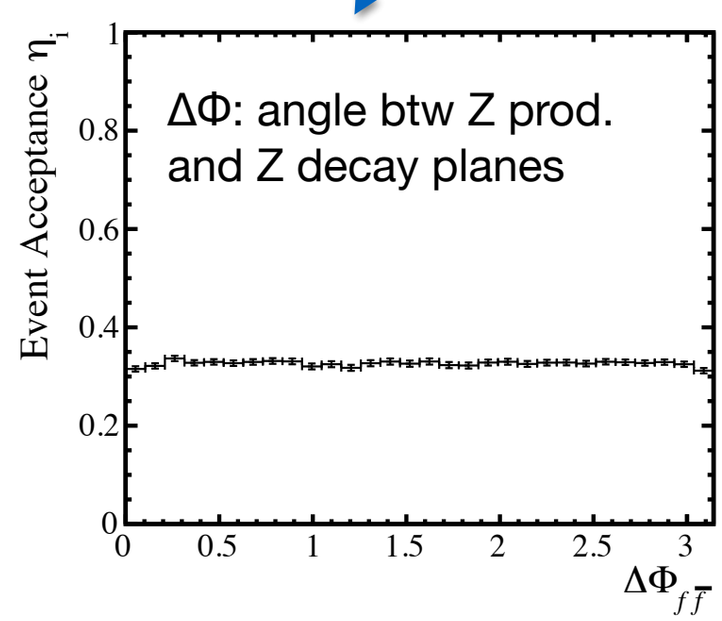
acceptance *η*

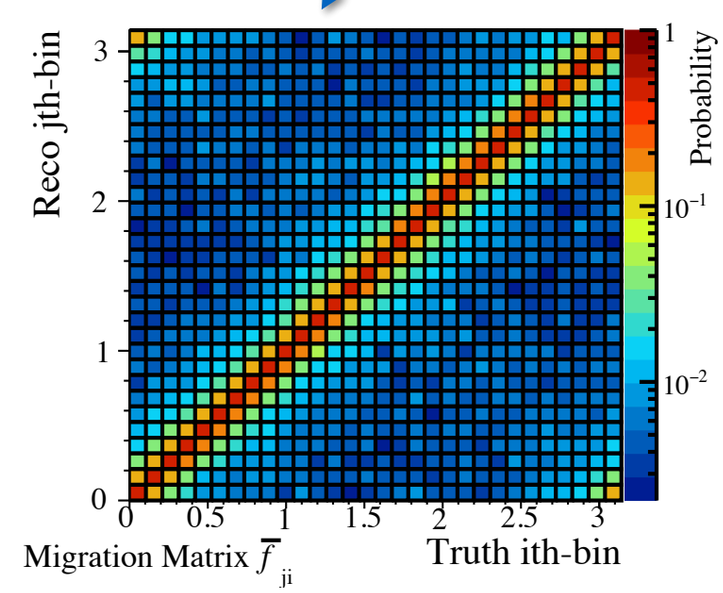
migration matrix *f*

qqH

high stat. signal sample





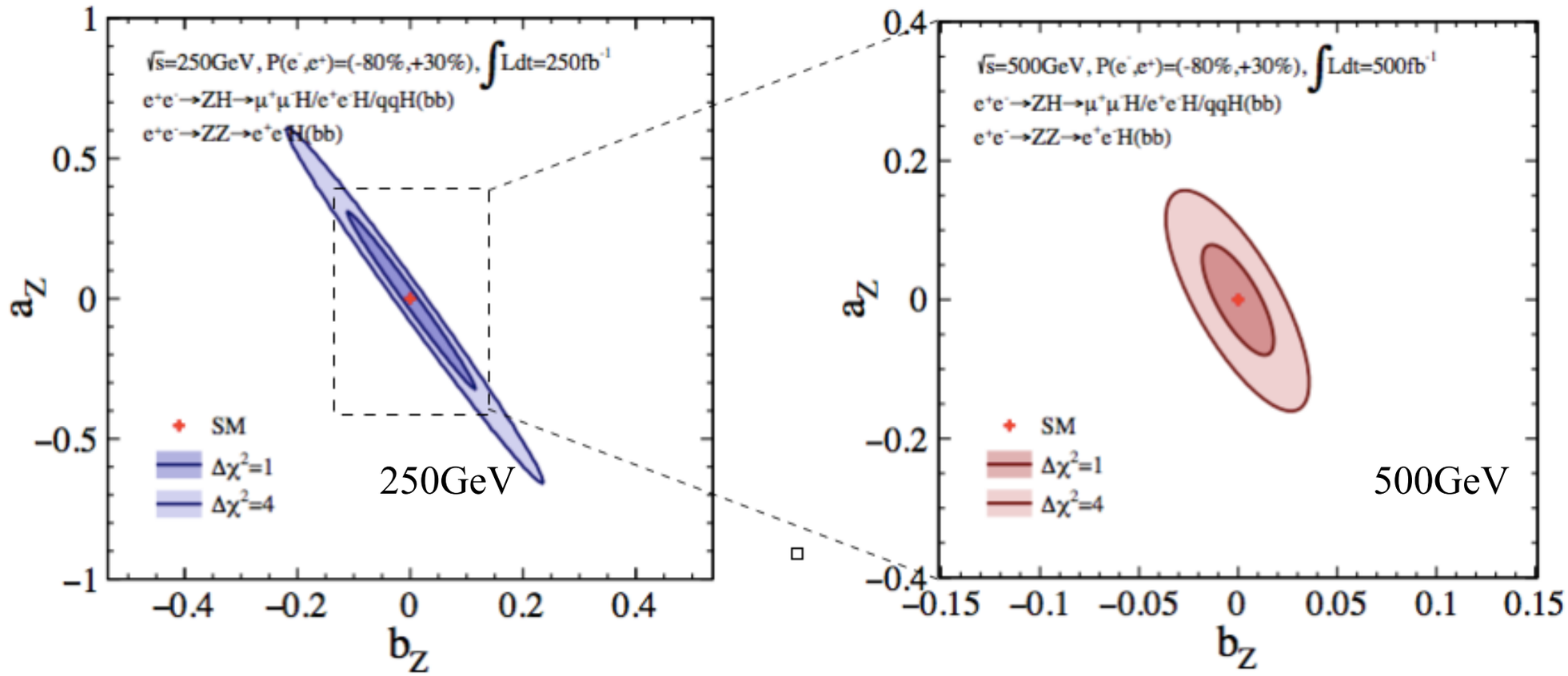


Anomalous ZZH/γZH couplings

3-parameter fit

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

(Λ=1TeV)



5-parameter fit

$ZH + ZZ$ at $250 + 500$ GeV with $H20$

https://arxiv.org/abs/1506.07830

1σ bounds
including 500 GeV operation

$$\begin{cases} a_Z = \pm 0.0223 \\ \zeta_{ZZ} = \pm 0.0067 \\ \zeta_{AZ} = \pm 0.0024 \\ \tilde{\zeta}_{ZZ} = \pm 0.0109 \\ \tilde{\zeta}_{AZ} = \pm 0.0006 \end{cases}, \quad \rho = \begin{pmatrix} 1 & -.837 & -.134 & -.009 & -.010 \\ - & 1 & .040 & .008 & .013 \\ - & - & 1 & .006 & -.0012 \\ - & - & - & 1 & .600 \\ - & - & - & - & 1 \end{pmatrix}$$

(η_Z =±0.5%)

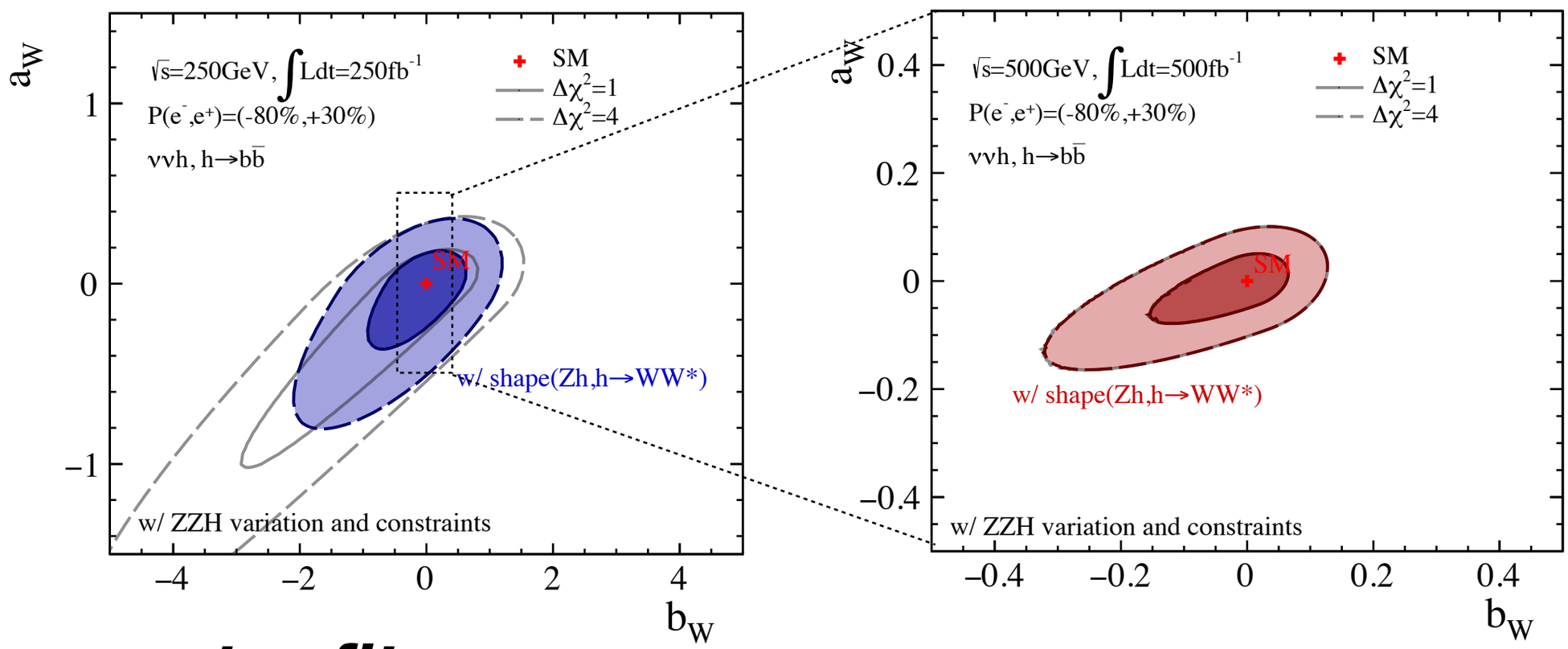
ZZH / γZH structures can be measured to ~0.5% or much better

Anomalous WWH couplings

3-parameter fit

$$\mathcal{L}_{WWH} = 2M_W^2\left(\frac{1}{v}+\frac{a_W}{\Lambda}\right)W^+_\mu W^{-\mu}H + \frac{b_W}{\Lambda}\hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu}H + \frac{\tilde{b}_W}{\Lambda}\hat{W}^+_{\mu\nu}\widetilde{\hat{W}}^{-\mu\nu}H$$

(Λ=1TeV)



6-parameter fit

1σ bounds
including 500GeV operation

SM-like structure can be measured to ~0.5 %

New structures to a few % or better

ΔΦ(decay planes H→WW) need to be reconstructed for bt*

$\sqrt{s} = 250 + 500$ GeV with L_{int} = H20 and $P(e^-, e^+)$ = Both

w/ ZZH contributions

w/ the shape $\nu\bar{\nu}h$ + w/ the shape $Zh, h \to WW^*$

https://arxiv.org/abs/1506.07830

$$\begin{cases} a_W = [-0.024,\ \ 0.019] \\ b_W = [-0.070,\ \ 0.036] \\ \tilde{b}_W = [-0.175,\ \ 0.179] \\ a_Z = [-0.031,\ \ 0.031] \\ b_Z = [-0.0090,\ \ 0.0090] \\ \tilde{b}_Z = [-0.0093,\ \ 0.0093] \end{cases}, \quad \rho = \begin{pmatrix} 1 & .3907 & -.0534 & -.0445 & -.0064 & .0003 \\ - & 1 & -.0856 & -.0128 & .0059 & 5.7\text{E-}5 \\ - & - & 1 & .0045 & -.0032 & 3.6\text{E-}5 \\ - & - & - & 1 & -.9186 & -.0018 \\ - & - & - & - & 1 & .0009 \\ - & - & - & - & - & 1 \end{pmatrix}$$

$\eta_W = (v/\Lambda)a_W$, etc.

Sensitivity to Anomalous VVH Couplings

ILC full operation (=H20 including 500 GeV data)

For conversion to common *notation*

$$\eta_Z = \frac{v}{\Lambda} a_Z, \text{ etc.}$$

divide a, b, and b-tilde, by a factor of 4.07

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

$\sim$ **0.5%** ($a_Z \sim$ **2%**)

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

$\sim$ **0.5%** ($a_W \sim$ **2%**)

$$+\frac{1}{2}\left(\zeta_Z \frac{h}{v_0} + \frac{1}{2}\zeta_{2Z}\frac{h^2}{v_0^2}\right)\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} + \left(\zeta_W \frac{h}{v_0} + \frac{1}{2}\zeta_{2W}\frac{h^2}{v_0^2}\right)\hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu}$$

$<$ **0.3%** ($b_Z \sim$ **1%**) $\sim$ **1-2%** ($b_W \sim$ **3-7%**)

$$+\frac{1}{2}\left(\zeta_A \frac{h}{v_0} + \frac{1}{2}\zeta_{2A}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{A}^{\mu\nu} + \left(\zeta_{AZ} \frac{h}{v_0} + \zeta_{2AZ}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}$$

. $<$ **0.3%**

$$+\frac{1}{2}\left(\tilde{\zeta}_Z \frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2Z}\frac{h^2}{v_0^2}\right)\hat{Z}_{\mu\nu}\hat{\tilde{Z}}^{\mu\nu} + \left(\tilde{\zeta}_W \frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2W}\frac{h^2}{v_0^2}\right)\hat{W}^+_{\mu\nu}\hat{\tilde{W}}^{-\mu\nu}$$

$<$ **0.3%** ($\tilde{b}_Z \sim$ **1%**) $\sim$ **5%** ($\tilde{b}_W \sim$ **17%**)

$$+\frac{1}{2}\left(\tilde{\zeta}_A \frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2A}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{\tilde{A}}^{\mu\nu} + \left(\tilde{\zeta}_{AZ} \frac{h}{v_0} + \tilde{\zeta}_{2AZ}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{\tilde{Z}}^{\mu\nu}$$

$<$ **0.3%**

heavy flavor ID, jet charge ID can improve more for especially WWH

The values given above are from direct measurements just using the three single Higgs production processes.

A global fit including other SM processes with no Higgs in the final state such as $e^+e^- \rightarrow W^+W^-$, Zγ, etc. can further improve the sensitivity.

Summary

- **Precision Higgs coupling study is a torch** to shine our way ahead.
- **250 GeV ILC is an ideal torch,** which allows us **precision model-independent** measurements of various **absolutely normalized Higgs couplings** in the framework of dim-6 SM EFT.
- **One of the key elements** of the SM EFT analysis is **search for anomalous VVH couplings.**
- With full ILC program including 500 GeV operation, we can measure
  - **SM-like ZZH/WWH couplings to ~0.5%**
  - **New ZZH/γZH couplings to ~0.3%**
  - **New WWH couplings to ~1-2 % (CPC) and ~5% (CPV)**

Backup

EFT Lagrangian Before EW Symmetry Breaking

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

$$\begin{aligned}
\Delta\mathcal{L} = {} & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\
& + \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\
& + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\
& + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\
& + i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ . \\
& + \frac{g^2\tilde{c}_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + \frac{4gg'\tilde{c}_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g'^2\tilde{c}_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\tilde{B}^{\mu\nu}
\end{aligned}$$

Manifestly SU(2)xU(1) gauge invariant

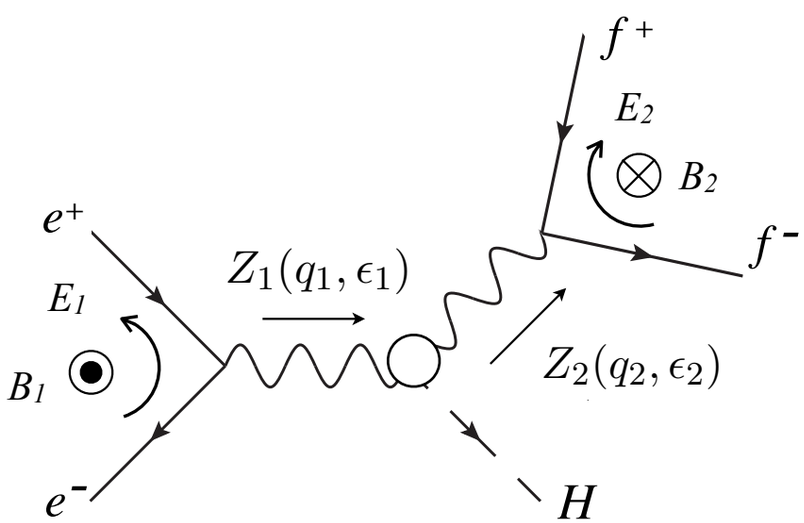
10 parameters of which C_6 only affects Higgs self-coupling analysis.
5 parameters to account for Higgs coupling to b, c, τ, μ, g.
\+ **2** parameters to account for invisible and exotic Higgs decays.
\+ **4** parameters to account for the shifts of g, g', v, and λ
\+ **2** parameters (CHL-type) to shift W, Z widths.

Observables (Shape of the Zh process)

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

SM-like coupling CP-conserving CP-violating

Matrix Element

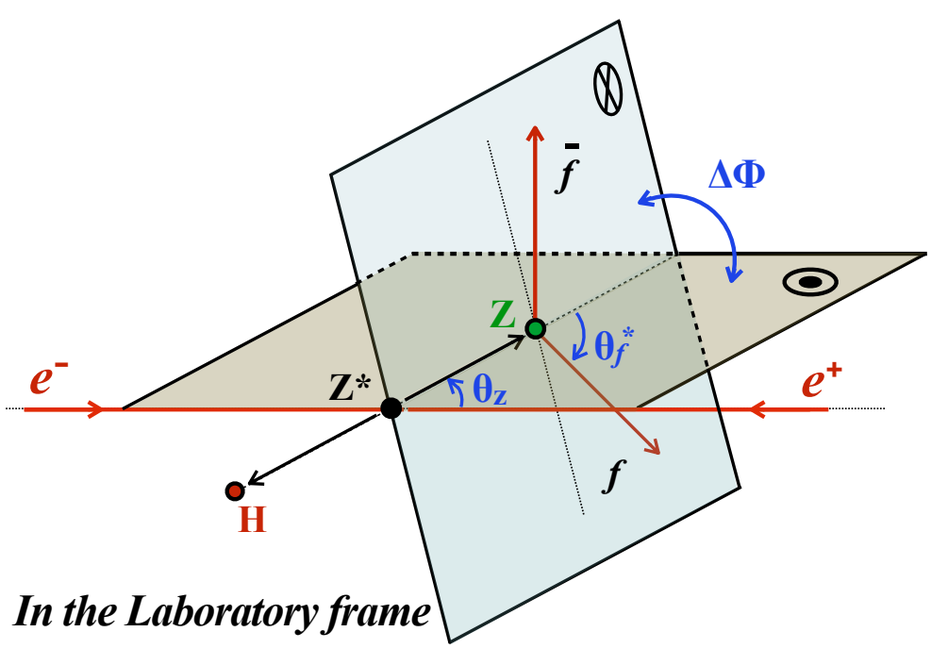


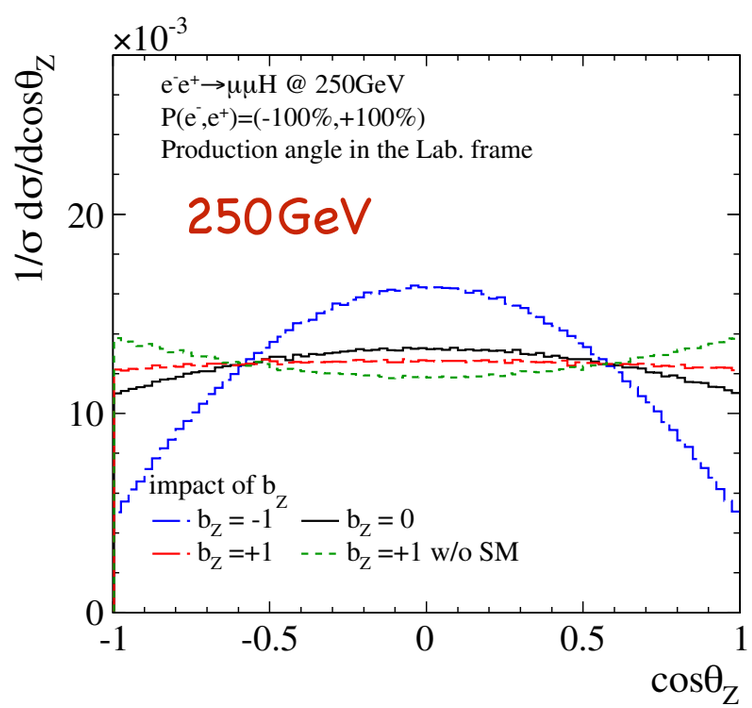
$\mathcal{M}^{Zh}_{a_Z}$ does not change shape $= \quad -\epsilon_1\cdot\epsilon_2$

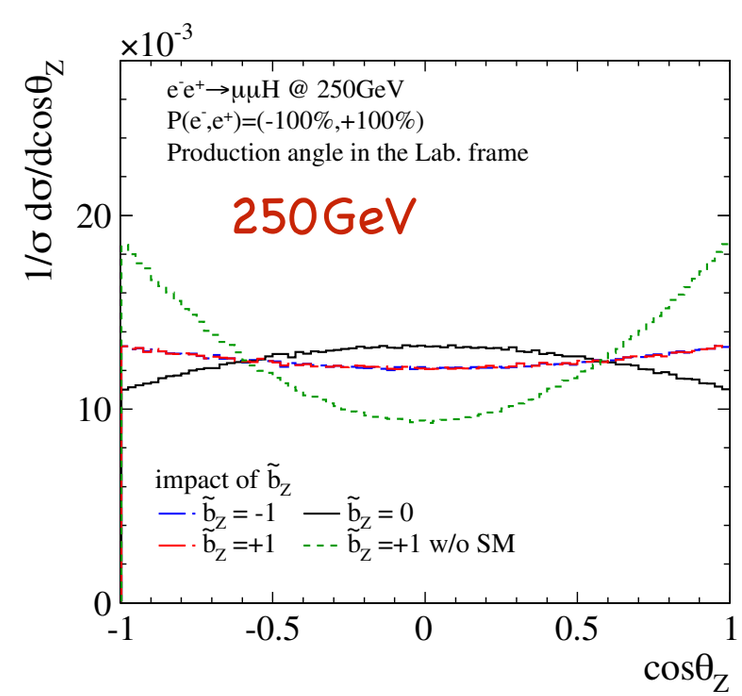
$$\mathcal{M}^{Zh}_{b_Z} = Z_{1\mu\nu}Z_2{}^{\mu\nu} = (\partial_{1\mu}Z_{1\nu}-\partial_{1\nu}Z_{1\mu})(\partial_2{}^\mu Z_2{}^\nu - \partial_2{}^\nu Z_2{}^\mu)$$

$$= -2\big[-E_2\sqrt{s}(-\boldsymbol{\epsilon}_1\cdot\boldsymbol{\epsilon}_2)-0\big] = -2E_2\sqrt{s}(\boldsymbol{\epsilon}_1\cdot\boldsymbol{\epsilon}_2)$$

=> The larger E, the larger effect







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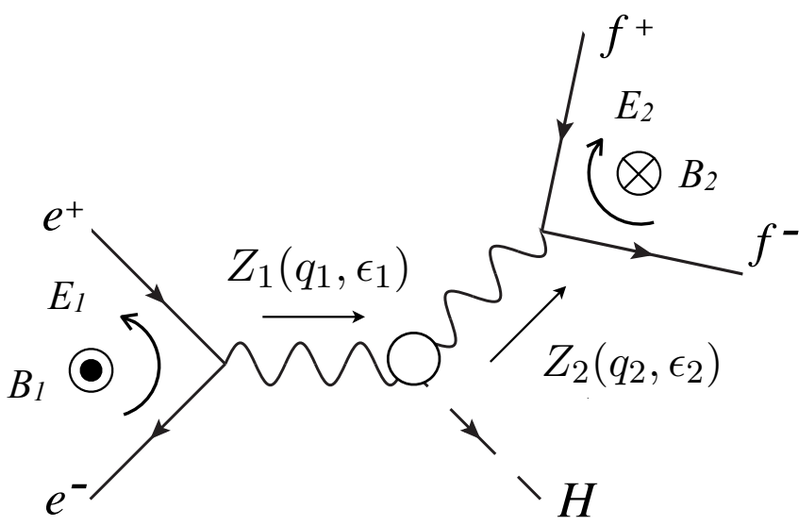
SM-like coupling CP-conserving CP-violating

Matrix Element

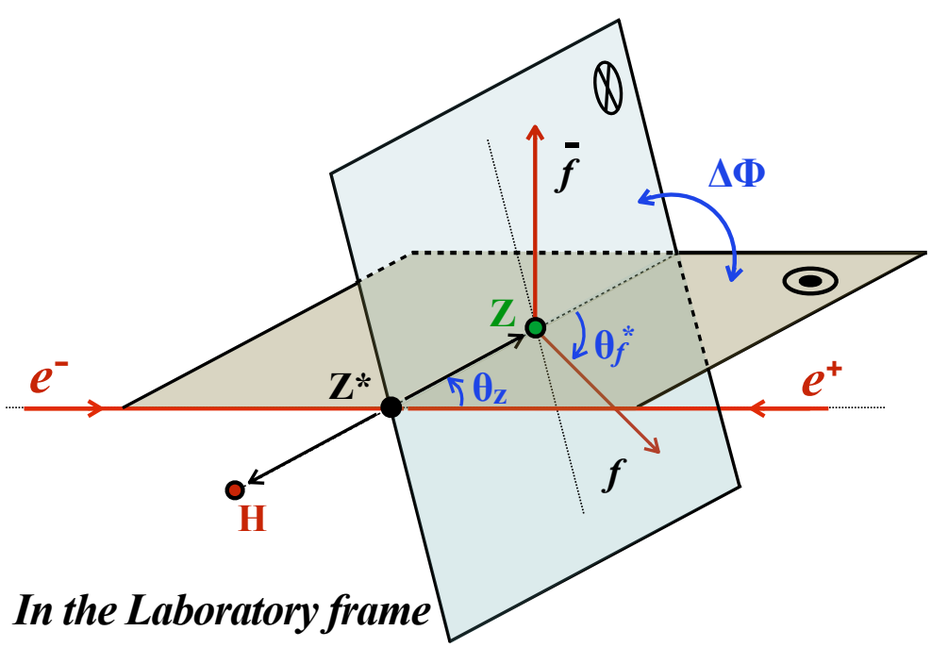


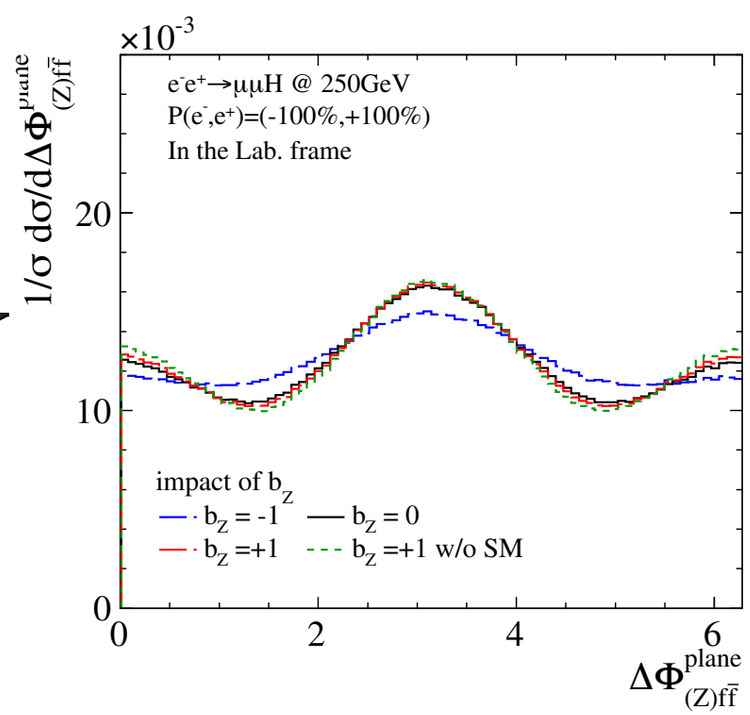
running hyper/weak charge

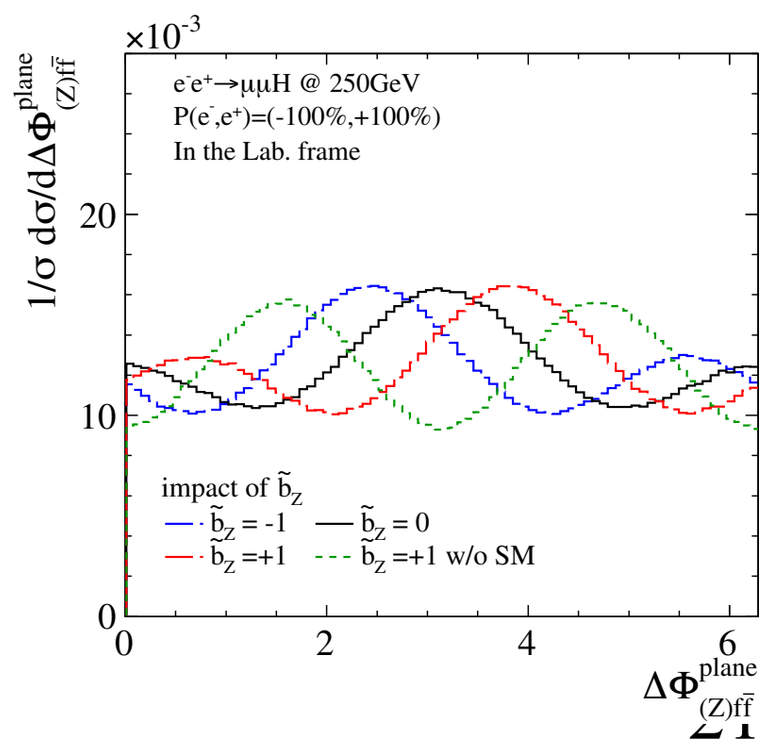
field strengths

$\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} \propto \boldsymbol{B}_1\cdot\boldsymbol{B}_2 - \boldsymbol{E}_1\cdot\boldsymbol{E}_2$ => tends to be parallel

$\hat{F}_{\mu\nu}\tilde{\hat{F}}^{\mu\nu} \propto \boldsymbol{E}_1\cdot\boldsymbol{B}_2$ => tends to be perpendicular







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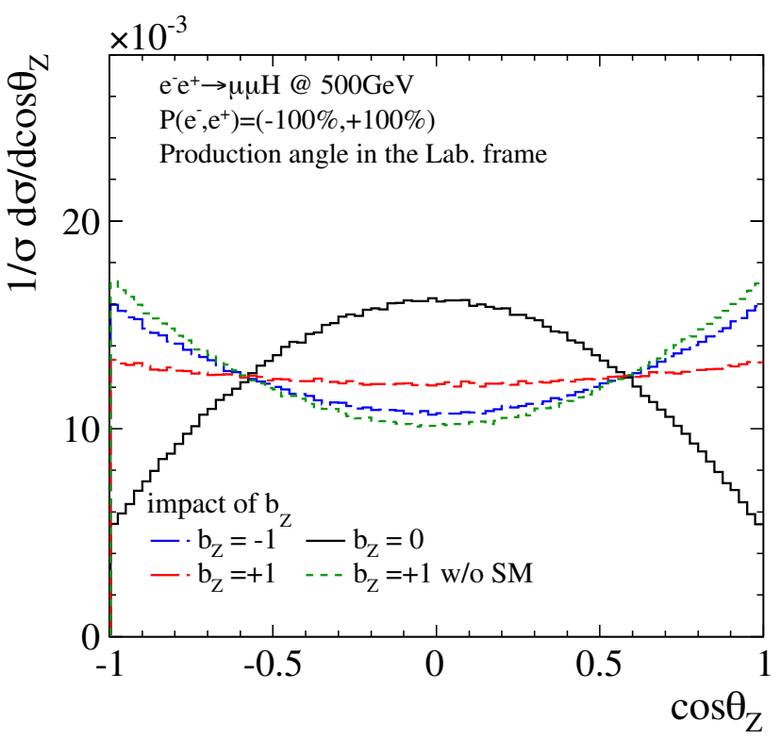
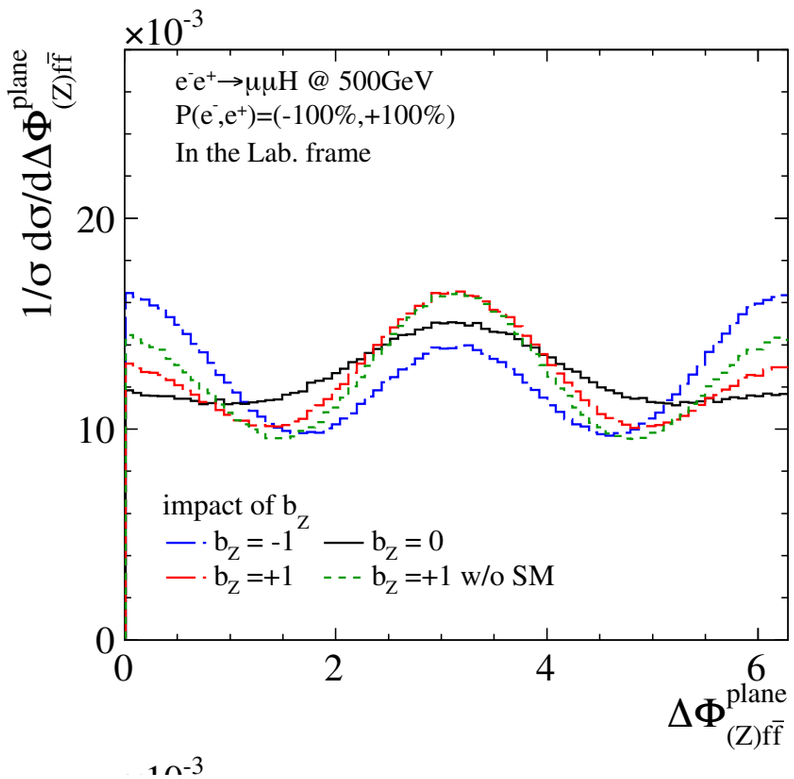
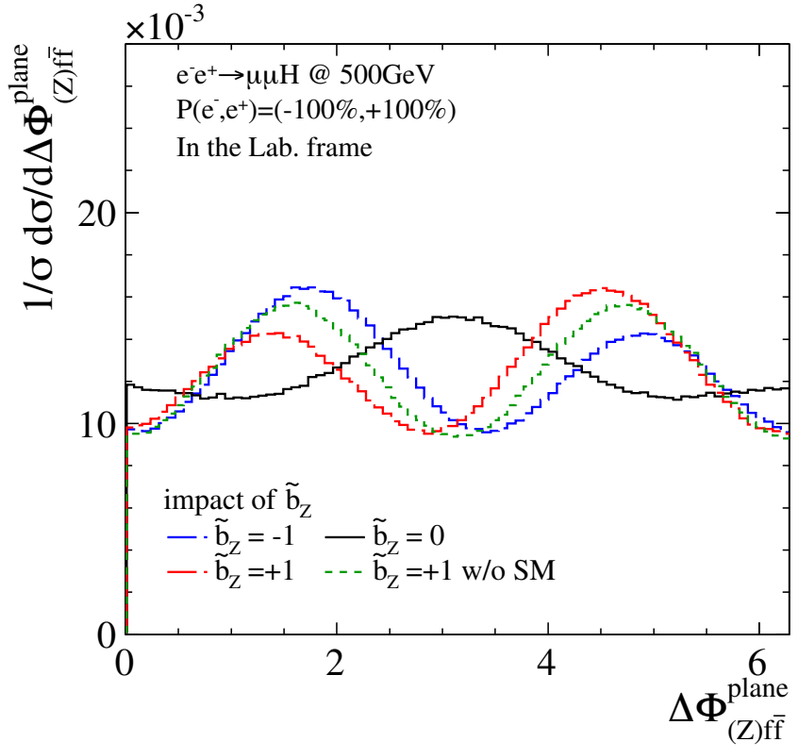
SM-like coupling CP-conserving CP-violating

Since the Field strengths have momentum dependence the effect increases with the energy

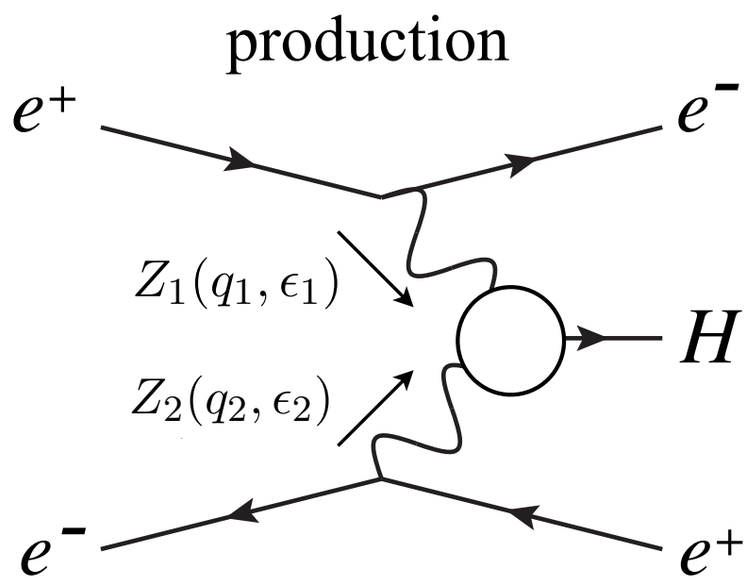
250GeV => 500GeV

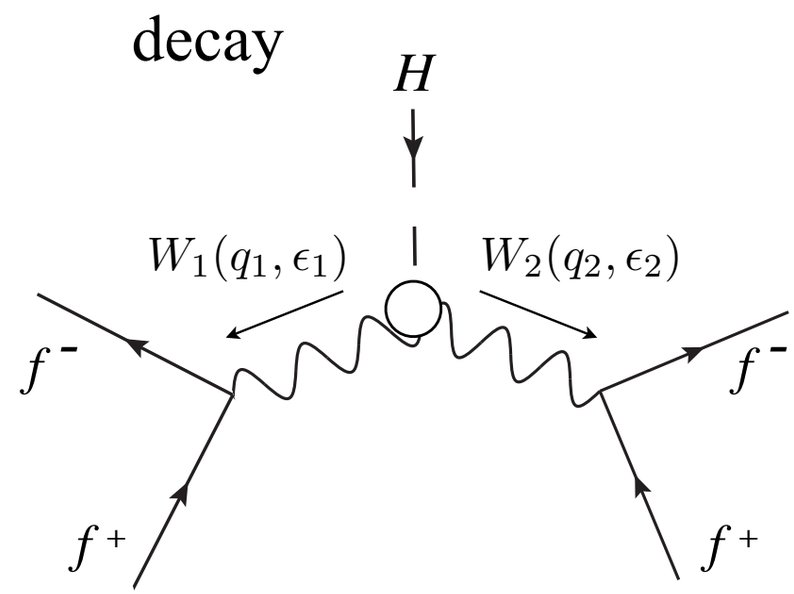


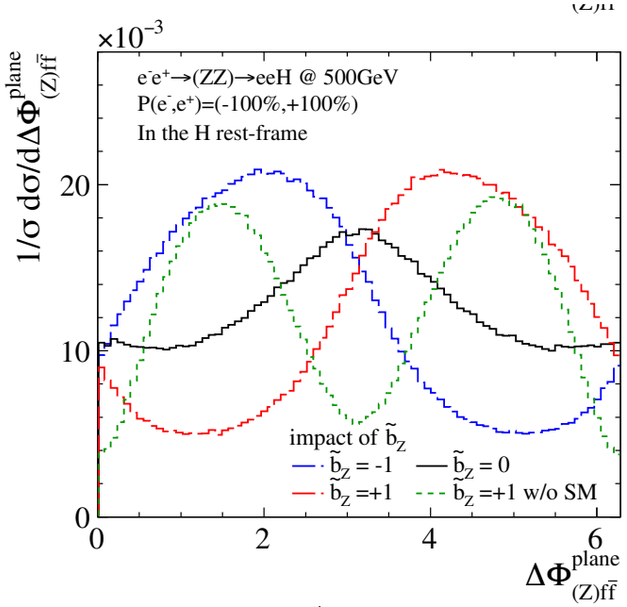


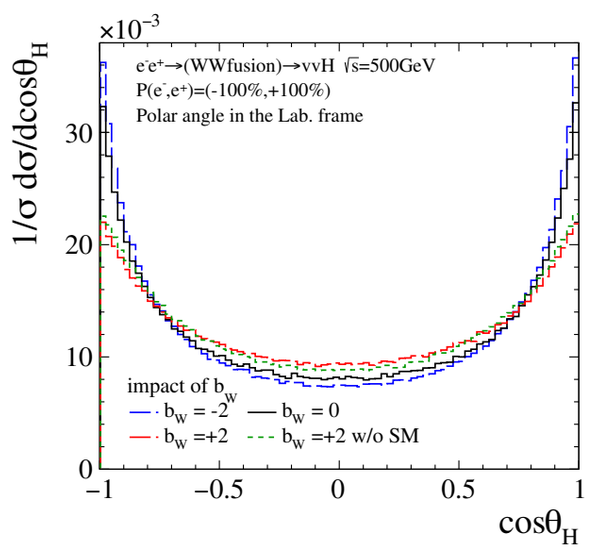


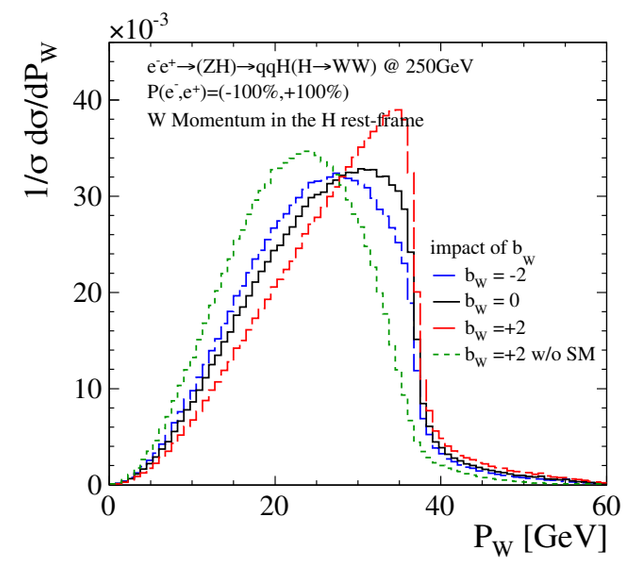
Observables (Shape of the VV-fusion process)

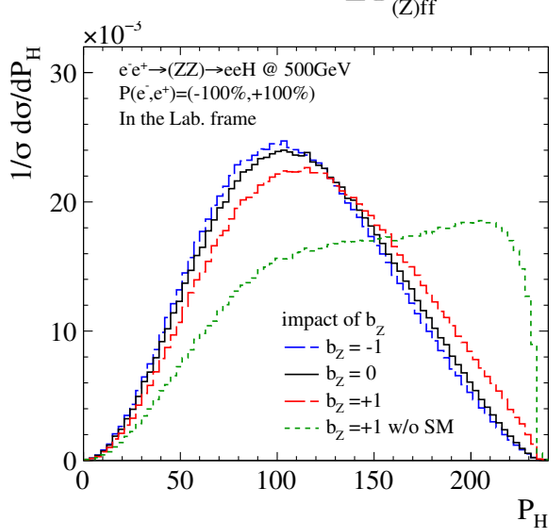


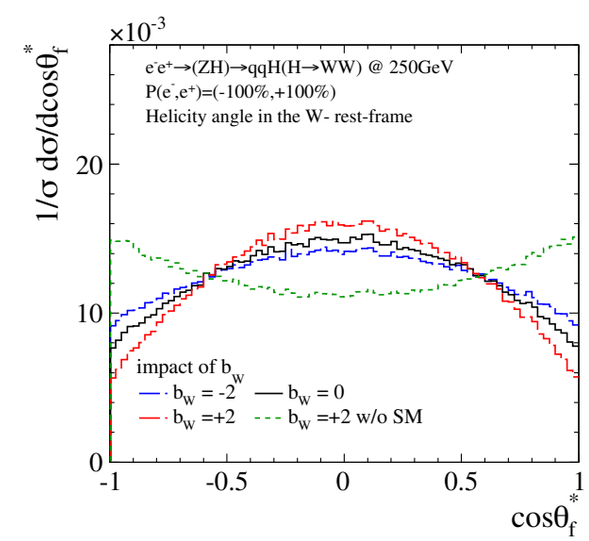






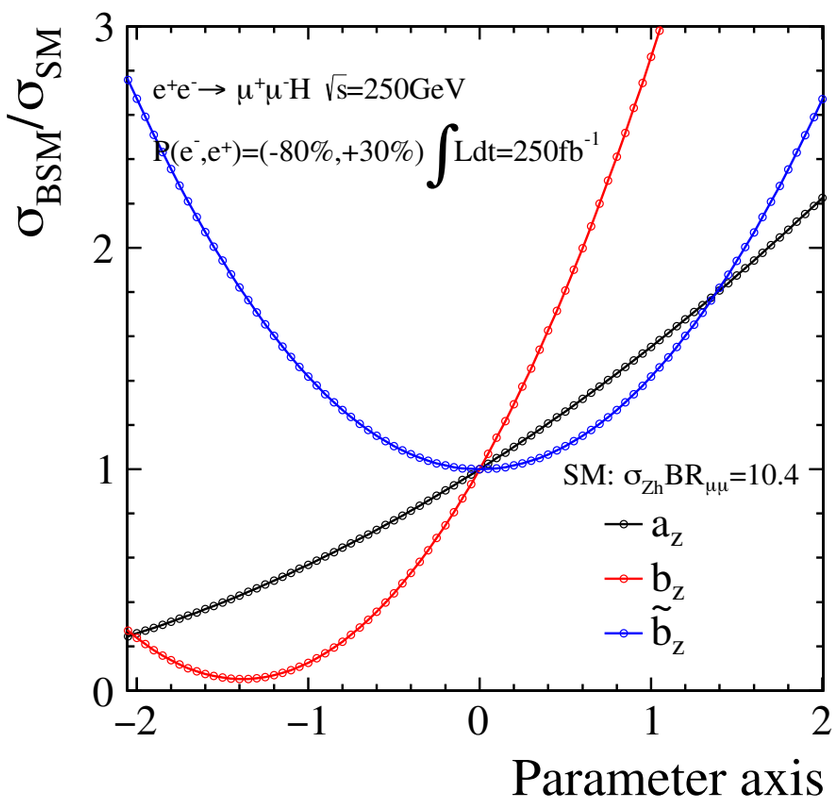


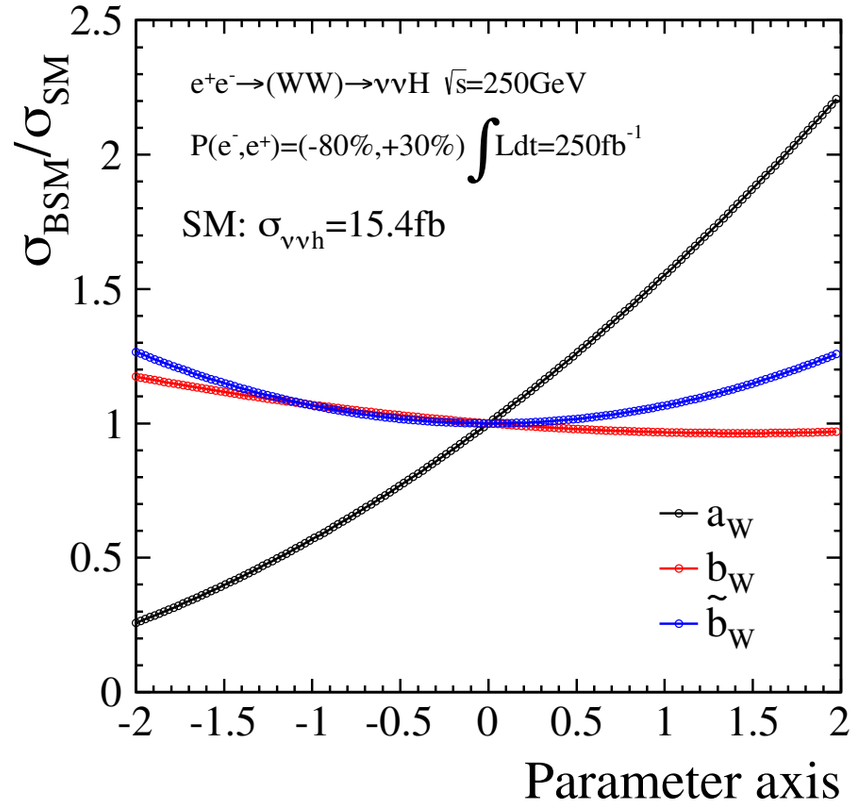




Observables (Cross-section)

Strong effect on the total cross section





b: Asymmetric variation, $(F_{\mu\nu}F^{\mu\nu})^2$ gives diff. terms with diff. signs

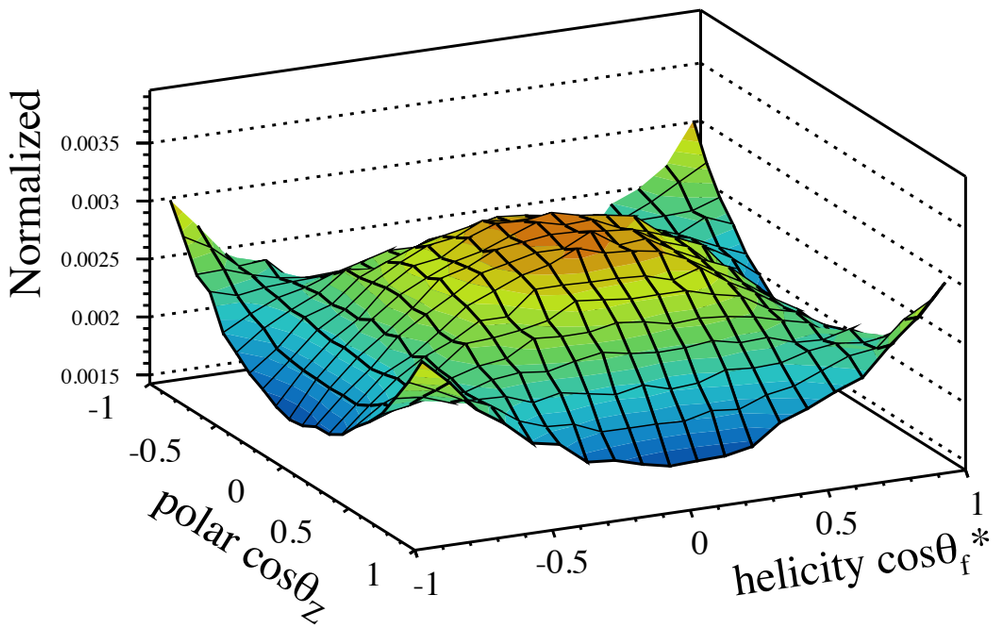
bt: Symmetric variation, $(F_{\mu\nu}\tilde{F}^{\mu\nu})^2$ gives one term. or just imagine CP-even obs.

The Energy dependence also appears

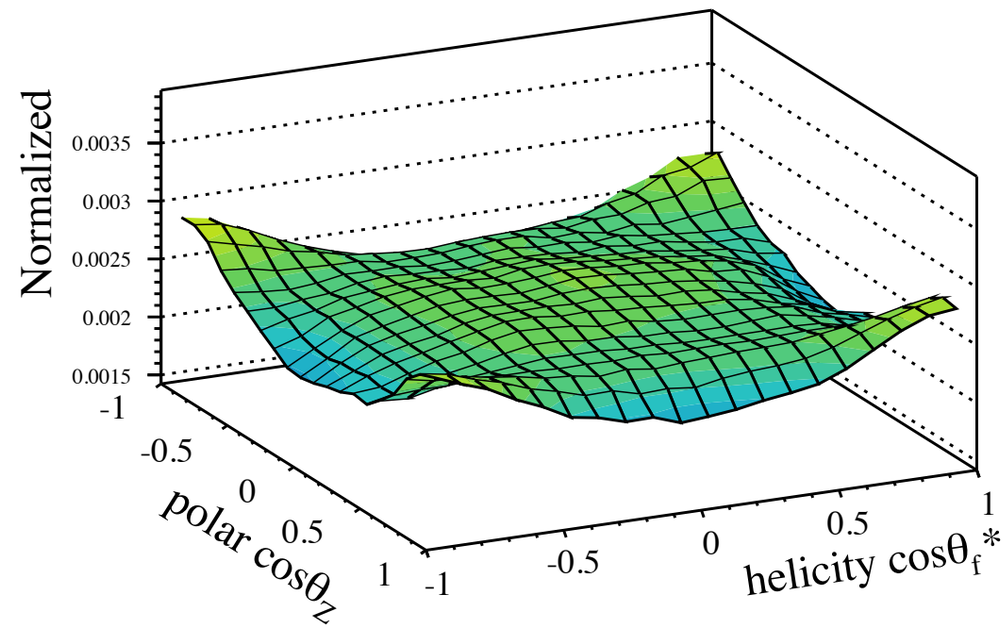
Detector Effects

Take detector effects into account with acceptance and migration functions

e.g.) $e^+e^- \rightarrow ZH \rightarrow qqH(bb)$ @ 250GeV



($\cos\theta z$, $\cos\theta f^*$) : helicity angle



detector response function

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

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

2 functions

Event acceptance: η and migration matrix: $\bar{f}$

to take into account migration due to finite detector resolution

Theoretical distributions => observed distributions with detector acceptance and resolution

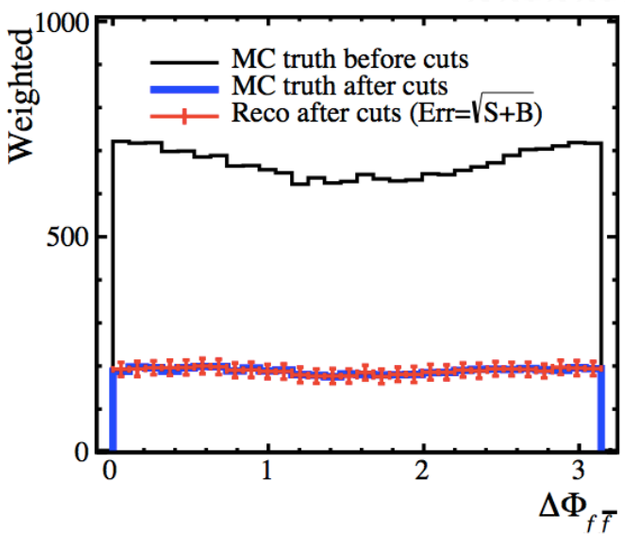
Detector Effects

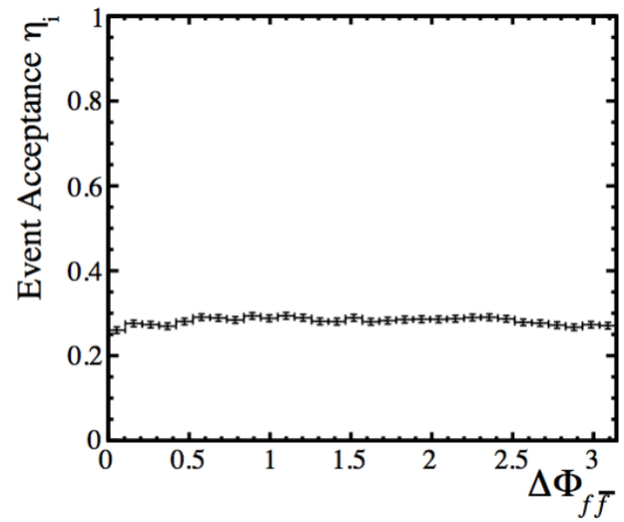
ILD full simulation

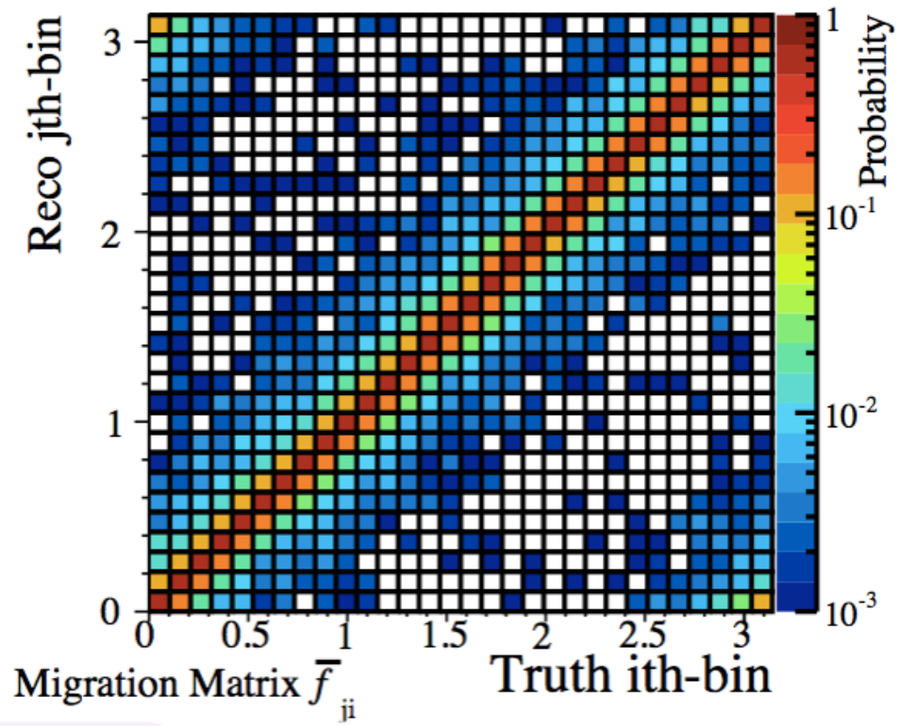
Take detector effects into account with acceptance and migration functions

Theoretical distributions => observed distributions
with detector acceptance and resolution

1-dim observable $\Delta\Phi$







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

generated

Observed

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

Two functions:

$$\begin{cases} \eta_i \equiv \dfrac{N_i^{Accept}}{N_i^{Gene}} & \text{(Event acceptance)} \\ \bar{f}_{ji} \equiv \dfrac{N_{ji}^{Accept}}{N_i^{Accept}} & \text{(Migration matrix)} \end{cases}$$

Shape Analysis

Kinematical "shape" information to test the deviation.

Normalized to N_{SM}

"Generator level" distribution
from dσ/dX with and without anomalous couplings

$$\chi^2_{shape} = \sum_{j=1}^{\overset{\#\text{bins}}{n}} \left[\frac{N_{SM} \sum_{i=1}^{n} \left(\frac{1}{\sigma}\frac{d\sigma}{dx}(x_i) \cdot f_{ji} - \frac{1}{\sigma}\frac{d\sigma}{dx}(x_i; a_V, b_V, \tilde{b}_V) \cdot f_{ji} \right)}{\Delta n^{obs}_{SM}(x_j)} \right]^2$$

Poisson error for each bin
(including SM Bkgs)

=> full simulation information

Detector response function
→ Translate theory to
"Detector level" distribution

=> full simulation information

Addition of Normalization Information

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

"Cross-section" information to test the deviation.

$$\chi^2_{norm} = \left[\frac{\overset{\#\text{expected}}{N_{SM}} - N_{BSM}(a_V, b_V, \tilde{b}_V)}{\delta\sigma_{Zh/eeh} \cdot N_{SM}} \right]^2$$

Relative errors of cross-section measurement
(SM Bkgs are taken into account)

=> full simulation information

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

As for δσ(**fusion**)

=> Partial widths will vary due to anom-VVH
=> need to have some assumptions
=> keep model-independence by using BR measured model-independently

$\delta(\sigma_{eeh} \cdot BR_{hbb})$ = 27.0 % and 4.0 % for 250 and 500 GeV

δBR_{hbb} = 2.9 % and 3.5 % for 250 and 500 GeV

by propagating error of δBR_{hbb}

250 GeV 250 fb-1 for both Pol.
500 GeV 500 fb-1 for both Pol.

$\delta\sigma_{eeh}$ are 27.16 % and 5.32 % for 250 and 500 GeV

$\delta\sigma_{\nu\nu h}$ 8.1% and 1.0% for 250 and 500 GeV