Determination of anomalous VVH couplings at the ILC

1). An overview of the anomalous VVH study
ZZH/γZH and WWH induced with dim-6 operators

2). An application of a Matrix Element method
toward further improvement of the sensitivity

Asian Linear Collider Workshop
@ Fukuoka. Japan

Tomohisa Ogawa
Junping Tian
Keisuke Fujii

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2). An application of a Matrix Element method
toward further improvement of the sensitivity

Effective Field Theory

General definition $$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i^{(5)}}{\Lambda^1}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots .$$

W. Buchmuller, D. Wyler, Nucl. Phys. B268 (1986) 621–653.

possible to describe dynamics below Λ,

dim-5 ($L^\dagger \Phi \Phi^\dagger L$) gives majonara neutrino mass

can reflect symmetries of an underlying theory.

by introducing general operators based on the gauge symmetry.

The number of relevant dim-6 operators @ ILC = 17 operators

Warsaw bases

Grządkowski et al. arXiv:arXiv: 1008.4884,

General structures
before symmetry breaking

makes all SM Higgs couplings shift

Combination w/ Φ

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu} + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g^2 \tilde{c}_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} + \frac{4gg' \tilde{c}_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}\widetilde{B}^{\mu\nu} + \frac{g'^2 \tilde{c}_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde{B}^{\mu\nu}$$

T. Barklow et al., Phys. Rev. D 97 (2018) 053003.

Combination w/ V, Φ

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General structures
After symmetry breaking

Focusing on VVH structures

T. Barklow et al.,
Phys. Rev. D 97 (2018) 053003.

→ Complete formula is given

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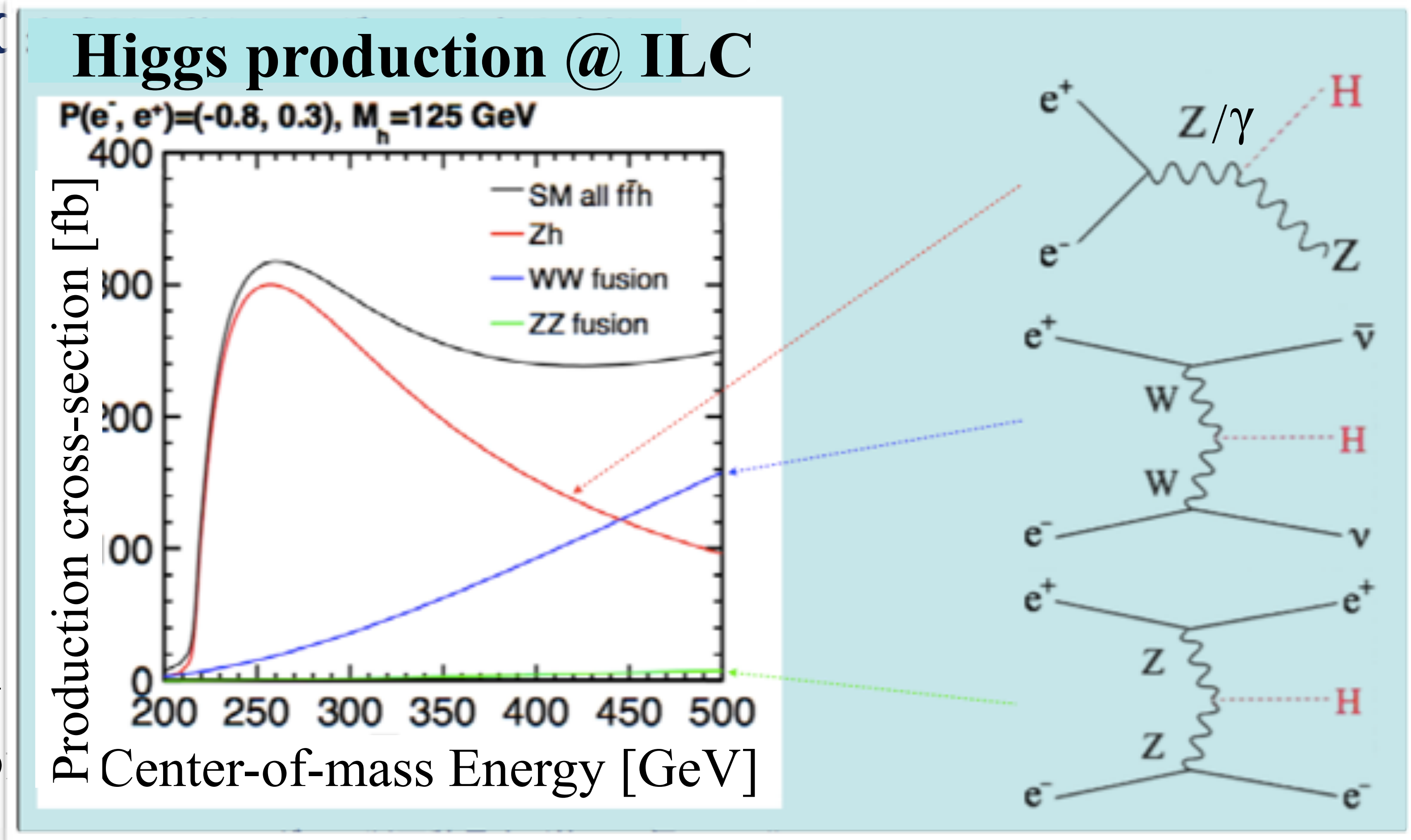
Effective Fiel

General definition



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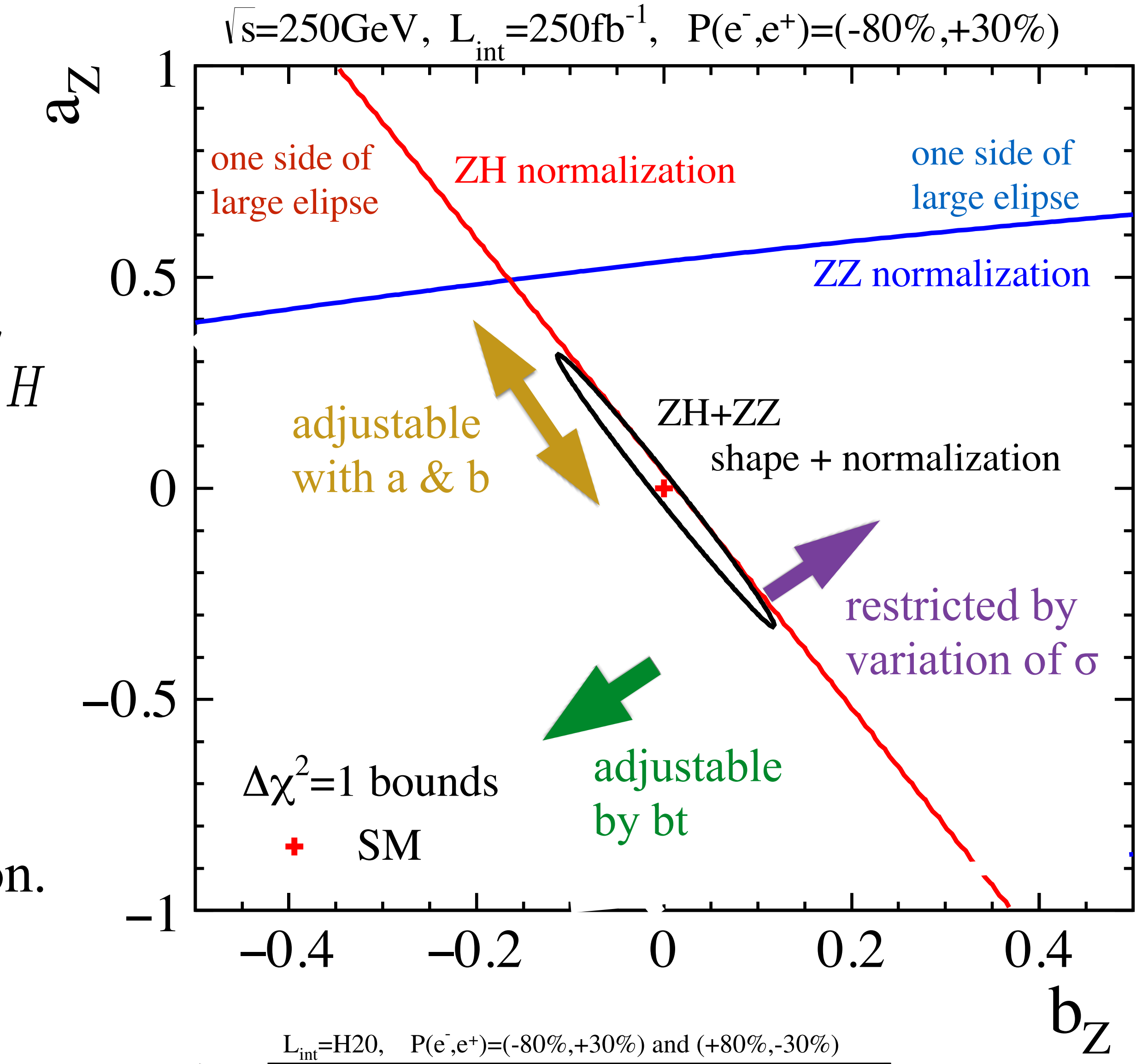
→ Complete formula is given

anomalous ZZH : 3 parameters fit

Notation on ZZH ⇨ az, bz, btz parameters
assuming beam Pol. left/right

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

(Λ=1TeV)

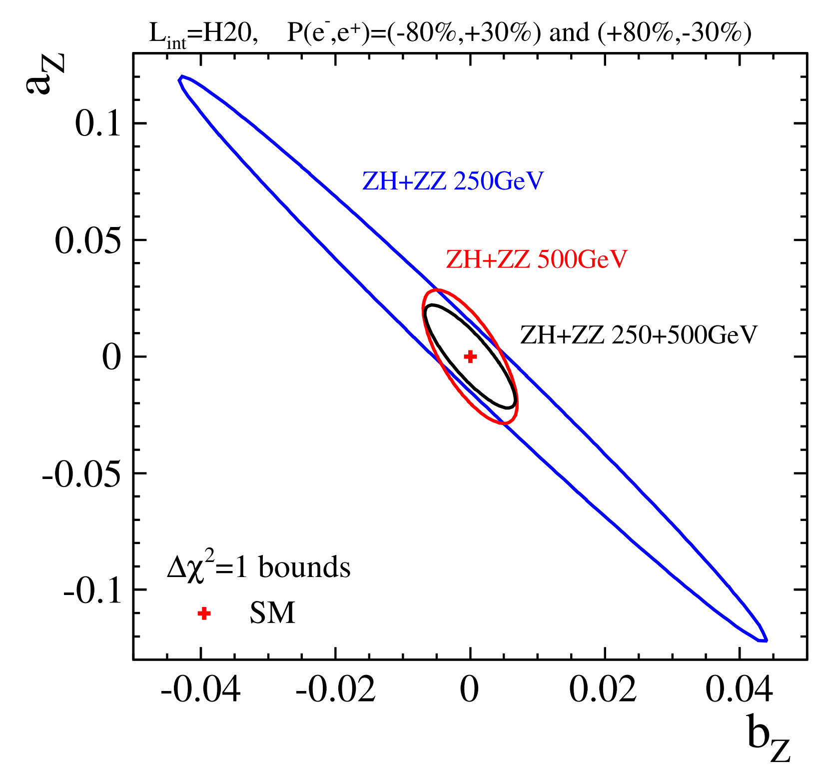


All SM bkgs are considered
Detector response is considered.

The sensitivity can not be given with norm. only.
The shape information is critical for the determination.

EPS17 talk
https://indico.cern.ch/event/466934/contributions/2588482/

Annual ILC physics and detector meeting
https://agenda.linearcollider.org/event/7837/contributions/40946/attachments/32854/49991/annualMeeting18.pdf



Energy is also can improve the sensitivity

H20 operation (250GeV 2ab^{-1})
including 500GeV

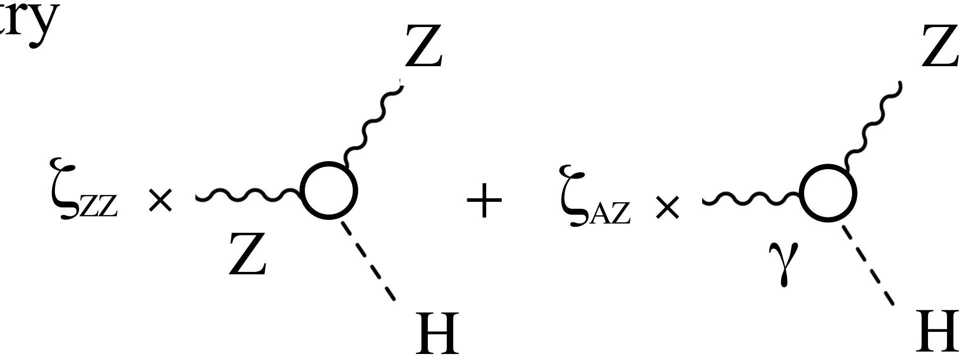
H20 operation
https://arxiv.org/abs/1506.07830

anomalous ZZH/γZH : 3 parameters fit

- *A* and *Z* are mixing through SU2xU1 gauge symmetry

  B couples to $\mathbf{e_L}$ **and** $\mathbf{e_R}$ in the same way.
  ***W*^{3}** couples to $\mathbf{e_L}$ **only.**

  ⇨ Beam polarization can disentangle them



- The Lagrangian is replaced

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

⇨

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

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

Five parameters fit

1σ bounds
including 500GeV operation

ZZH / γZH structures can be measured ~2% or much better

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

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

anomalous WWH : 3 parameters fit

LCWS17
https://agenda.linearcollider.org/event/7645/contributions/40062/attachments/32273/49230/LCWS17_Ogawa_v171025.pdf

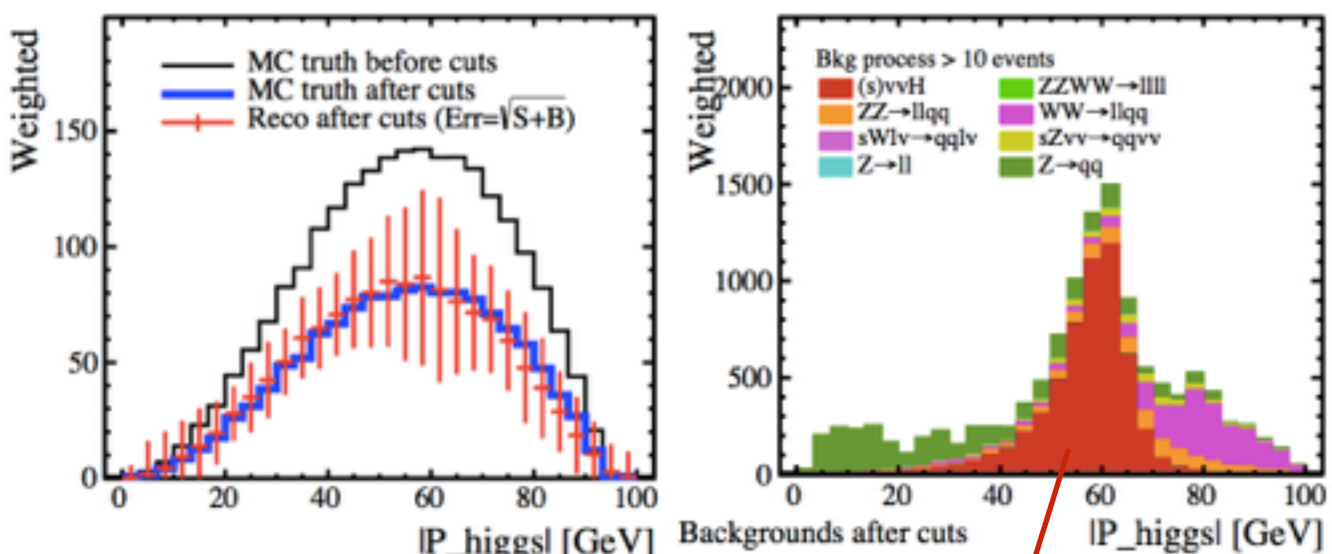
Annual ILC physics and detector meeting
https://agenda.linearcollider.org/event/7837/contributions/40946/attachments/32854/49991/annualMeeting18.pdf

Notation on ZZH ⇨ aw, bw, btw parameters

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

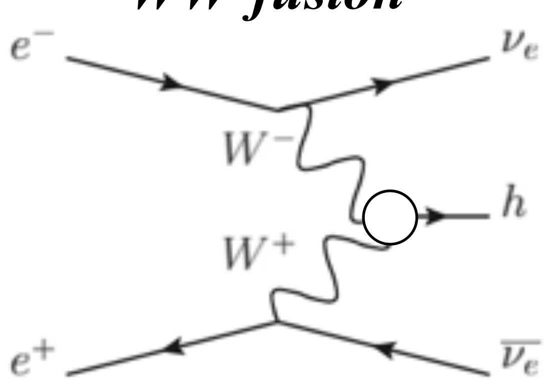
(Λ=1TeV)

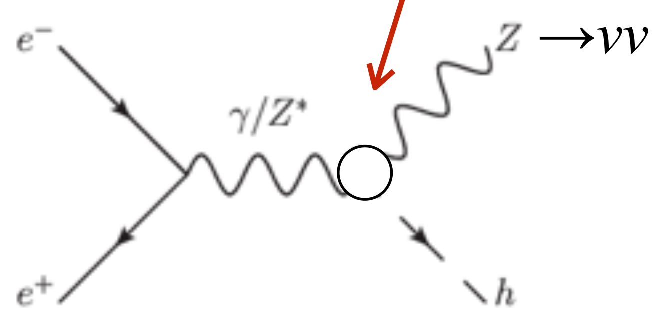
Ex. WW-fusion 250GeV, h→ bb : sig & bkgs distributions



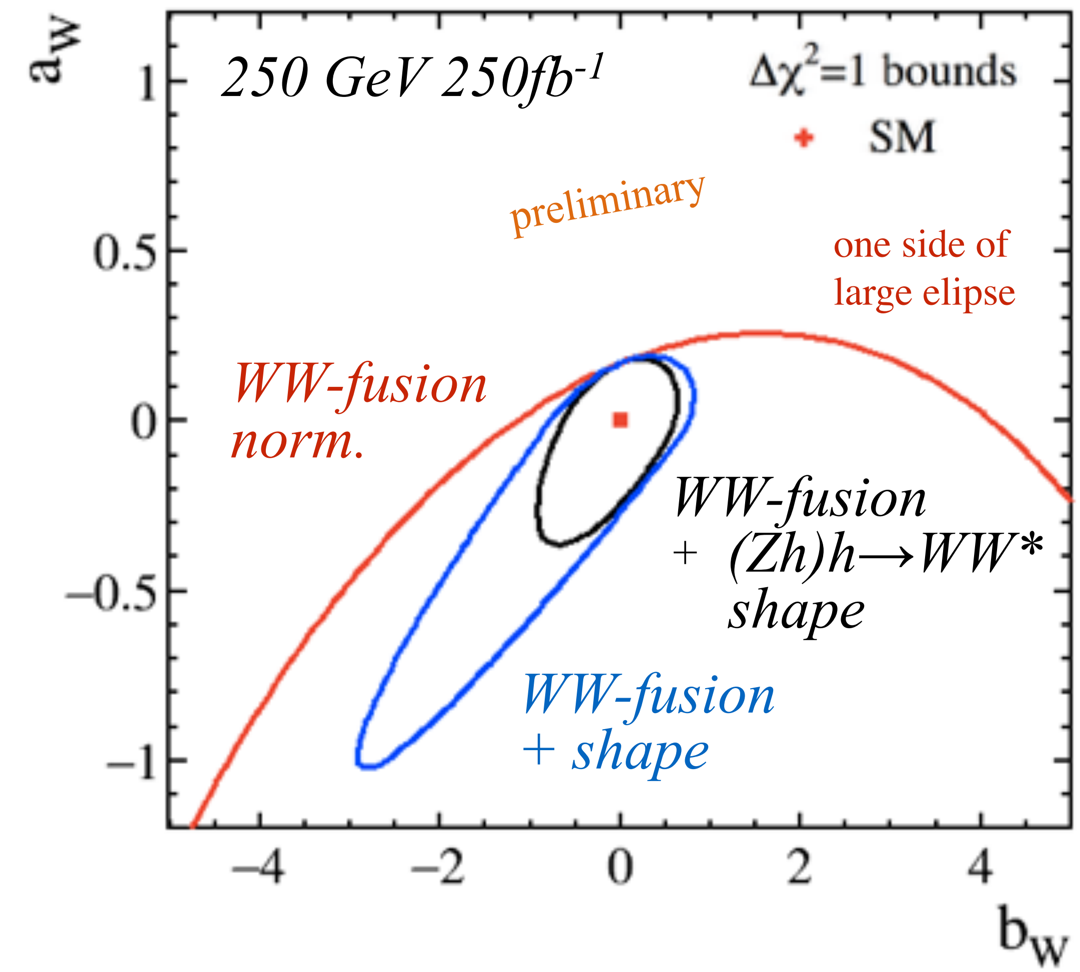
interference

WW-fusion





ZH w/ anomalous
Same final state → contaminate WWH
due to variation shape & norm.



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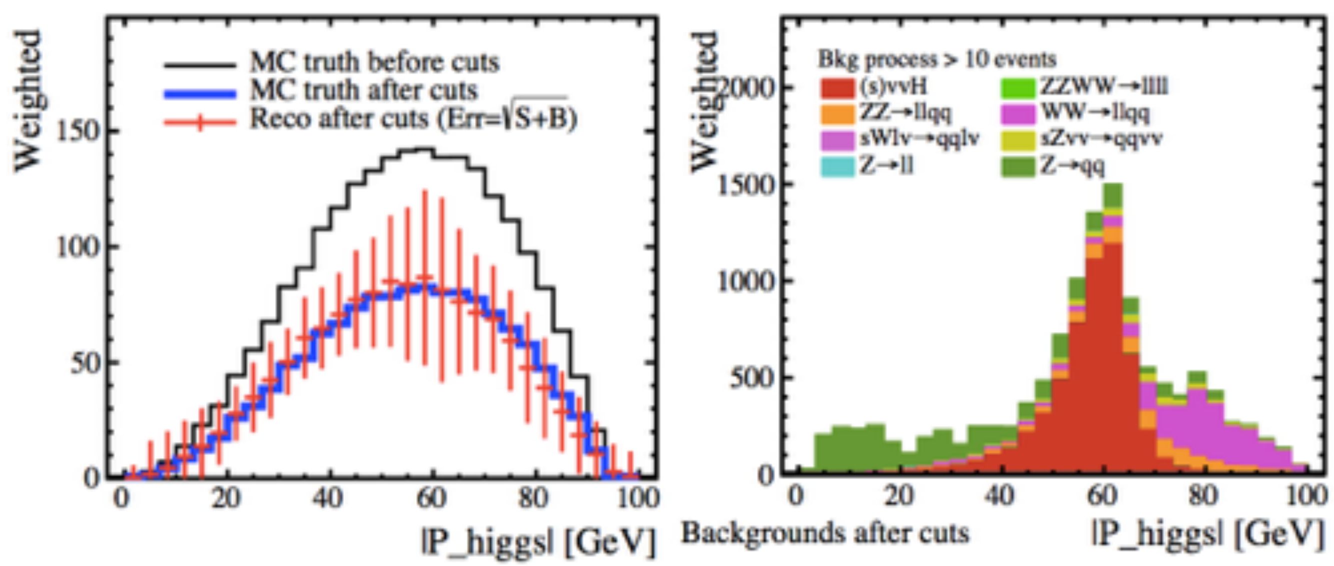

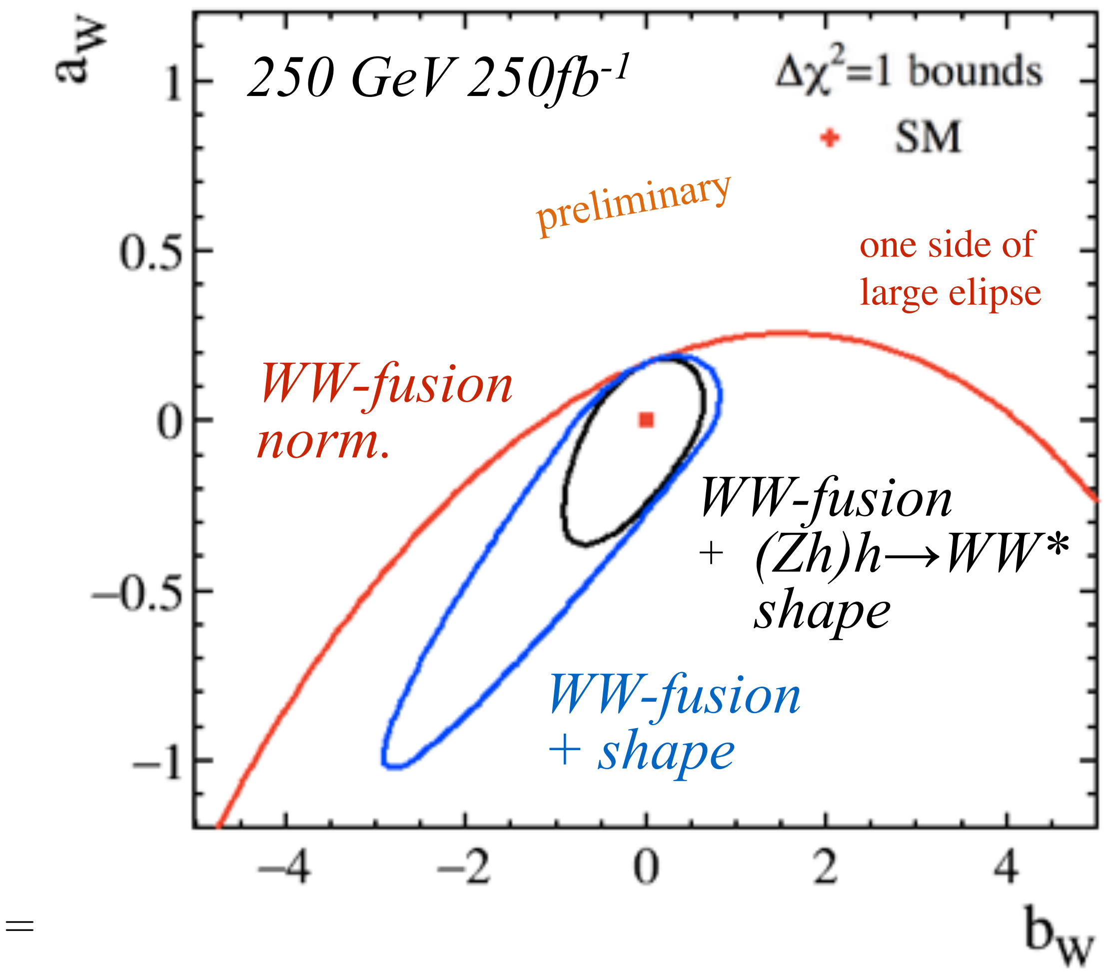

Six parameters fit

1σ bounds
including 500GeV operation

SM-like structure
can be measured ~2%
New structures a few %
Need to improve for bt

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

$\sqrt{s} = 250 + 500$ GeV with $\mathrm{L_{int}} =$
w/ ZZH contributions
w/ the shape $\nu\bar{\nu}h$ + w/ the shape $Zh, h \to WW^*$

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

The sensitivities to anomalous VVH

- ILC full operation (including 500GeV studies)

$$\Delta\mathcal{L}_h = -\eta_h\lambda_0 v_0 h^3 + \frac{\theta_h}{v_0} h\partial_\mu h\partial^\mu h + \eta_Z \frac{m_Z^2}{v_0} Z_\mu Z^\mu h +$$ **~0.5% (az~2%)**

$$+\eta_W \frac{2m_W^2}{v_0} W^+_\mu W^{-\mu} h +$$ **~0.5% (aw~2%)**

< 0.3%(bz~1%) $$+\frac{1}{2}\left(\zeta_Z \frac{h}{v_0} + \frac{1}{2}\zeta_{2Z}\frac{h^2}{v_0^2}\right)\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} + \left(\zeta_W\frac{h}{v_0} + \frac{1}{2}\zeta_{2W}\frac{h^2}{v_0^2}\right)\hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu}$$ **~1~2% (bw=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%**

< 0.3%(btz~1%) $$+\frac{1}{2}\left(\tilde{\zeta}_Z \frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2Z}\frac{h^2}{v_0^2}\right)\hat{Z}_{\mu\nu}\hat{\tilde{Z}}^{\mu\nu} + \left(\tilde{\zeta}_W\frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2W}\frac{h^2}{v_0^2}\right)\hat{W}^+_{\mu\nu}\hat{\tilde{W}}^{-\,\mu\nu}$$ **~5% (btw=17%)**

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common *notation difference*

$$\zeta_{ZZ} = \frac{v}{\Lambda} b_Z,$$

must convert them with factor of 4 .07

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

The values given above are direct measurement without any assumption.

When performing the global fitting by using the other channels the results could be improved more.

The sensitivities to anomalous VVH

- ILC full operation (including 500GeV studies)

common *notation difference*

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must convert them with factor of 4 .07

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

- LHC ATLAS : EFT analysis

JHEP 03 (2018) 095
DOI: 10.1007/JHEP03(2018)095

$$\mathcal{L}_0^V = \Big\{ \kappa_{SM}\left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\right]$$
$$-\frac{1}{4}\left[\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tan\alpha\, \kappa_{Agg} g_{Agg} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right]$$
$$-\frac{1}{4}\frac{1}{\Lambda}\left[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha\, \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right]$$
$$-\frac{1}{2}\frac{1}{\Lambda}\left[\kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + \tan\alpha\, \kappa_{AWW} W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\} \chi_0 .$$

(given inverse power is Λ)

Expected and observed confidence intervals at 95% CL with 36.1 fb^{-1} of data at $\sqrt{s}$ = 13 TeV.

BSM coupling κ_{BSM}	Fit configuration	Expected conf. inter.	Observed conf. inter.	Best-fit $\hat{\kappa}_{BSM}$	Best-fit $\hat{\kappa}_{SM}$	Deviation from SM
κ_{HVV}	(κ_{Hgg} = 1, κ_{SM} = 1)	[−2.9, 3.2]	[0.8, 4.5]	2.9	-	2.3σ
κ_{HVV}	(κ_{Hgg} = 1, κ_{SM} free)	[−3.1, 4.0]	[−0.6, 4.2]	2.2	1.2	1.7σ
κ_{AVV}	(κ_{Hgg} = 1, κ_{SM} = 1)	[−3.5, 3.5]	[−5.2, 5.2]	±2.9	-	1.4σ
κ_{AVV}	(κ_{Hgg} = 1, κ_{SM} free)	[−4.0, 4.0]	[−4.4, 4.4]	±1.5	1.2	0.5σ

ZZH b_z [-30%, 200%] (HL-LHC *1/√10)
bt_z [-200%, 200%]

WWH b_w, bt_w are not still evaluated using data.

1). An overview of the anomalous VVH study
ZZH/γZH and WWH induced with dim-6 operators

2). An application of a Matrix Element method
toward further improvement of the sensitivity

Matrix Element Method

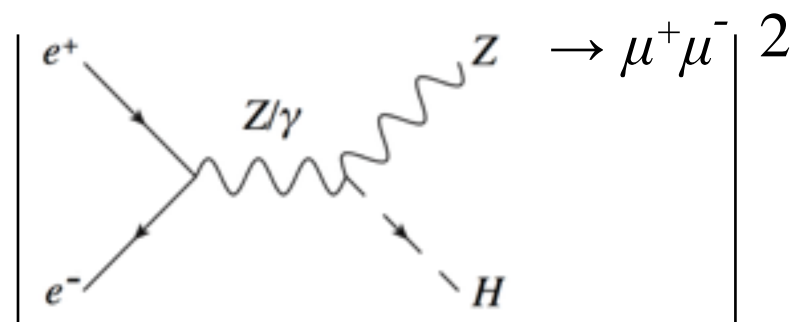
- An objective is clear

Try to encode all available kinematical information
on an event into a single observable . LHC, Tevatron … have used it !

Observation in an event
in terms of differential σ

LO

$$P(\vec{p}^{\mu}) = \frac{|\mathcal{M}(\vec{p}^{\mu})|^2}{\sigma} d\Phi$$

Probability = 

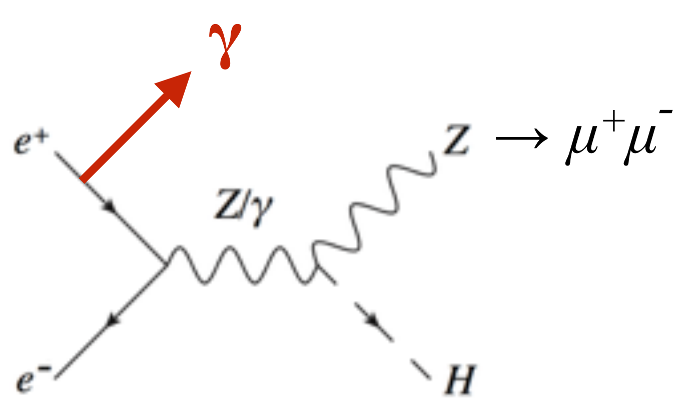
dΦ

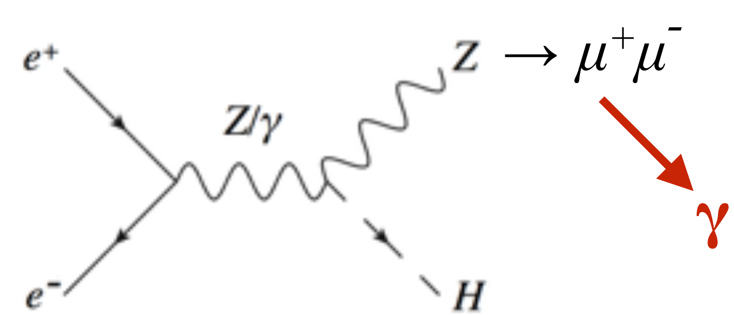
Matrix Element

- However, ISR, beam-strahlung, and FSR

NLO effects

Matrix Element doesn't fit reaction anymore





- ILCSoft framework : Marlin-PHYSSIM

The development is on going by Junping, Keisuke

Matrix Element Calculation
based on PHYSSIM , Junping Tian
https://agenda.linearcollider.org/event/6301/contributions/29469/attachments/24440/37804/MatrixElement_AWLC14.pdf

Application : constructing probability

- General expression

Event probability based on diff. cross-section

$$P_{\rm shape}(\vec{p}^{\,\mu};\vec{a}_V) = \frac{1}{A_{cc}(\vec{a}_V)\ \sigma(\vec{a}_V)} \int d\bar{\Phi}\ |\mathcal{M}(\vec{\bar{p}}^{\,\mu};\vec{a}_V)|^2\ T(\vec{p}^{\,\mu} \to \vec{\bar{p}}^{\,\mu}) A_{cc}(\vec{p}^{\,\mu})$$

Integration over phase-space for four momenta

Acceptance function

Overall acceptance

Normalization

Matrix Element

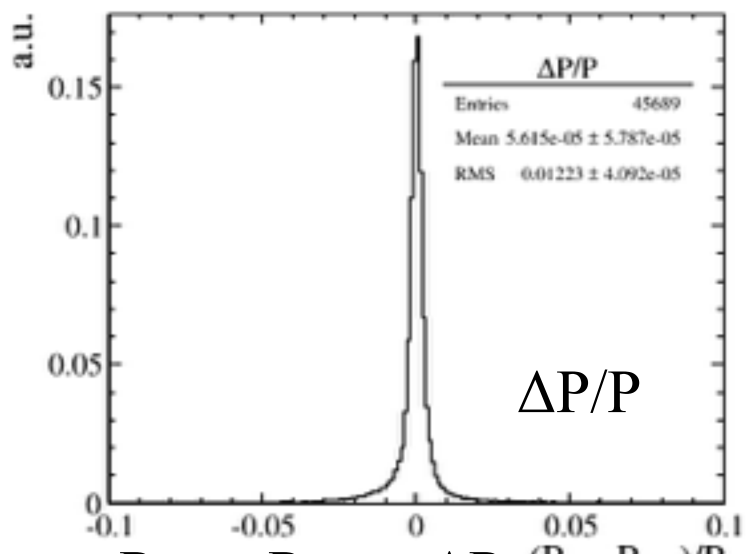
Transfer function (detector resolution)

Assuming momenta are precisely measurable

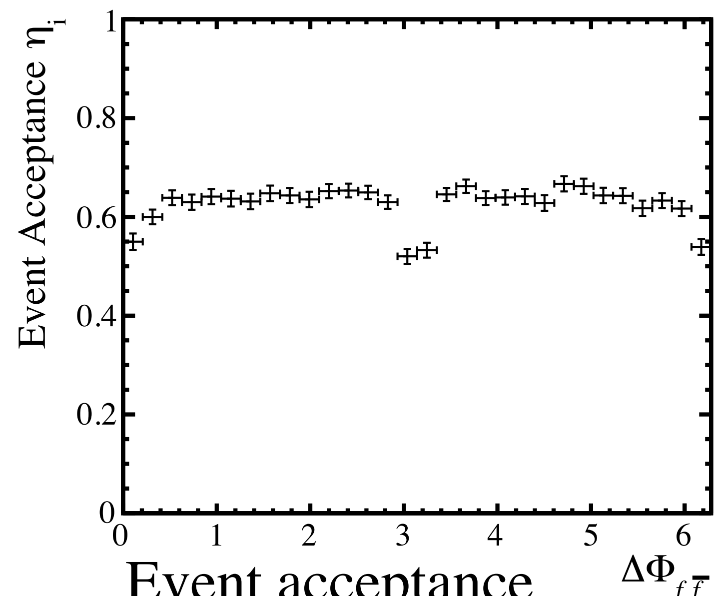
Transfer is replaced with δ

$$T(\vec{p}^{\,\mu} \to \vec{\bar{p}}^{\,\mu}) = \delta(\vec{p}^{\,\mu} - \vec{\bar{p}}^{\,\mu})$$

function is just extracted



P_{MC} - P_{reco} = ΔP



Event acceptance

$$P_{\rm shape}(\vec{p}^{\,\mu};\vec{a}_V) = \frac{A_{cc}^{\mu\mu H}(\vec{p}^{\,\mu})|\mathcal{M}_{ZH\to\mu\mu H}(\vec{p}^{\,\mu};\vec{a}_V)|^2}{A_{cc}^{\mu\mu H}(\vec{a}_V)\sigma_{ZH\to\mu\mu H}(\vec{a}_V)}$$

Denominator : integration is done including an acceptance function using PHYSSIM generator

Application : trial for the signal

- Chi-squared $\chi^2 \quad = -2\log\Delta\mathcal{L} = -2w(\log\mathcal{L}(\vec{a}_V) - \log\mathcal{L}_{SM})$

w : a factor for scaling the norm. to #expected ~1623
(after bkg suppression in the **shape analysis**)

- Likelihood function (unbinned estimation)

$$\mathcal{L}(\vec{a}_V) = \mathcal{L}_{\text{shape}}(\vec{a}_V)\cdot\mathcal{L}_{\text{norm}}(\vec{a}_V)$$
$$= \prod_{i=1}^{\text{MCevents}} P_{\text{shape}}(\vec{p}_i^{\,\mu};\vec{a}_V)\cdot P_{\text{norm}}(\vec{a}_V)$$

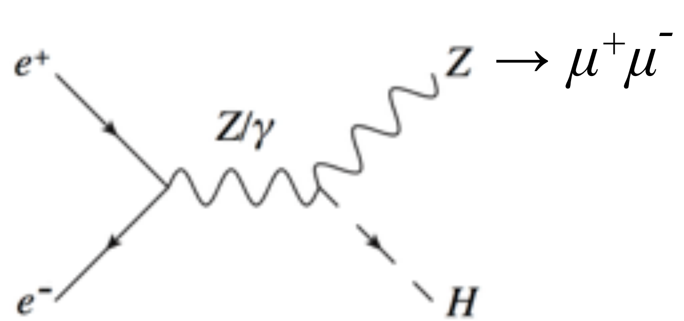
momenta: μ, μ, and it’s recoil info.

- Event probability

$$P_{\text{shape}}(\vec{p}^{\,\mu};\vec{a}_V) = \frac{A_{cc}^{\mu\mu H}(\vec{p}^{\,\mu})|\mathcal{M}_{ZH\to\mu\mu H}(\vec{p}^{\,\mu};\vec{a}_V)|^2}{A_{cc}^{\mu\mu H}(\vec{a}_V)\sigma_{ZH\to\mu\mu H}(\vec{a}_V)}$$

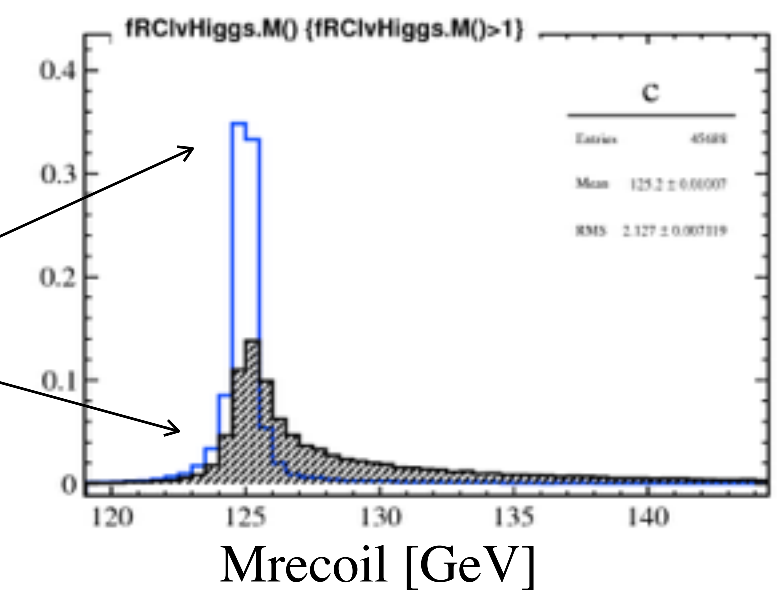
Denominator :
integration is done including Acc
is also calculated without ISR, BSL, FSR

- MarlinPhyssim : Calculator is LO



250GeV

Sample :
1). no ISR, no BSL, and no FSR
2). with ISR, BSL and FSR

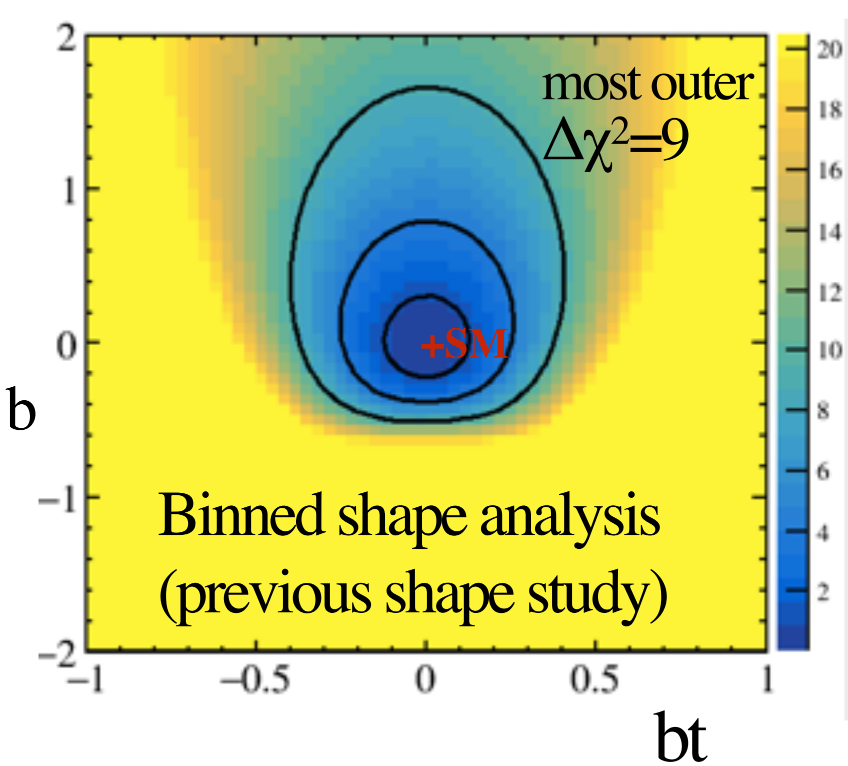


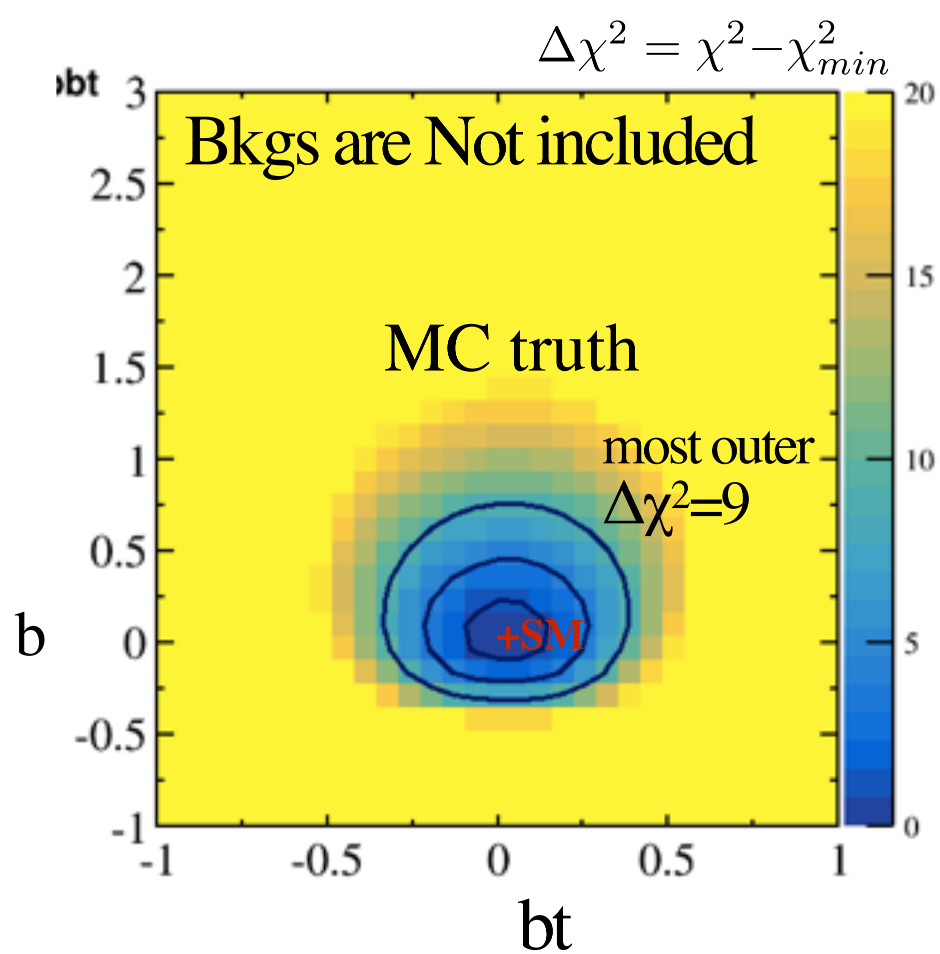
Application : trial for the signal

- b bs bt contours in the 2-parameter space
  - A consistent situation: LO, hopefully it's perspective improvement

- ZH→ $\mu^+\mu^- H$ *(signal only)*
  250GeV 250fb^{-1} [b vs bt]

ME : is LO
Sample : no ISR, BSL, and FSR
Denomi. : is calculated based on LO

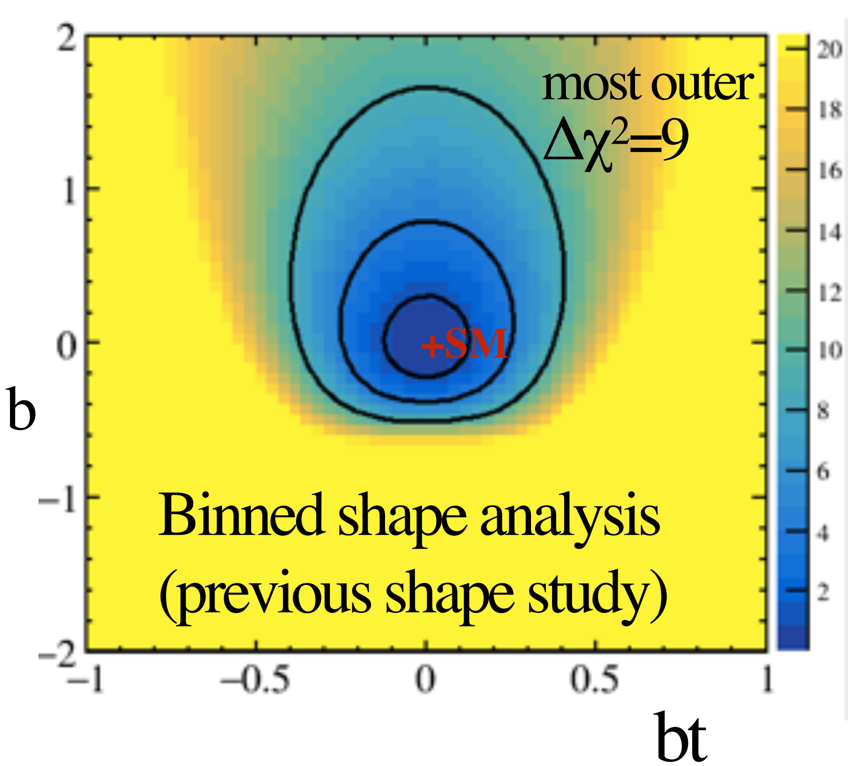




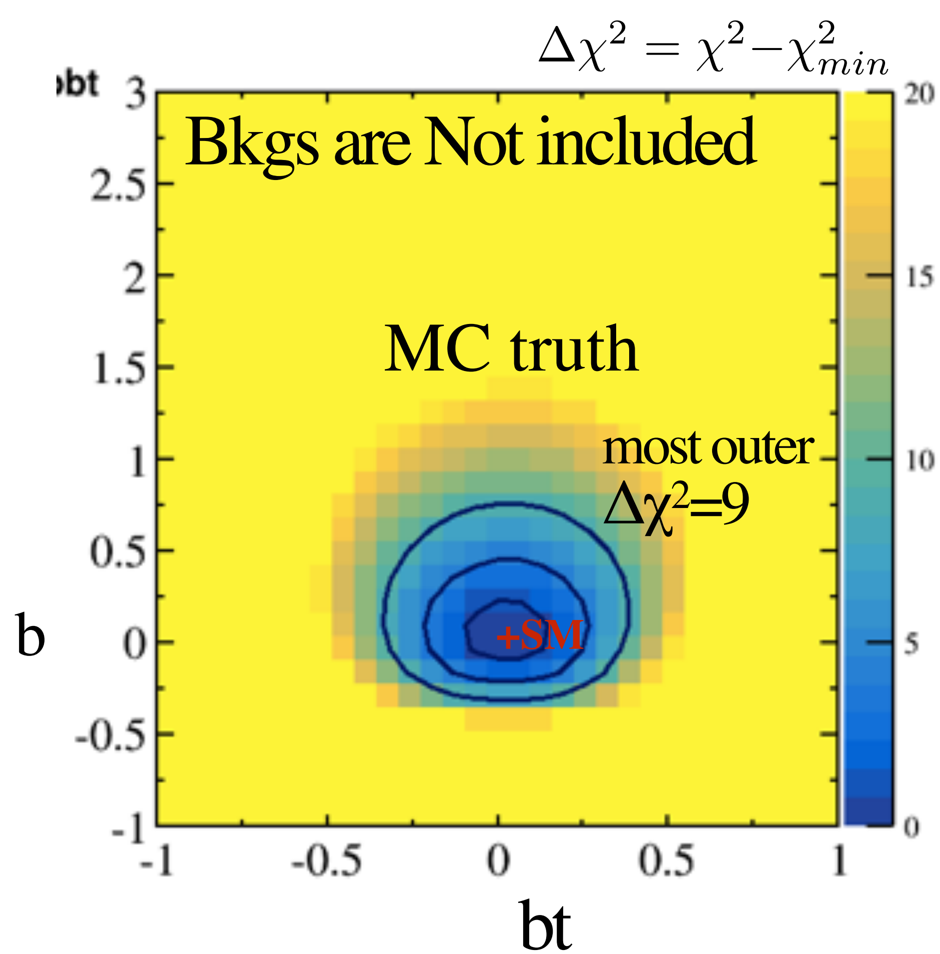
Application : trial for the signal

- b bs bt contours in the 2-parameter space
  - A consistent situation: LO, hopefully it's perspective improvement
  - NLO effects, → change shape, direct usage of momenta give large impact
    → shift minimum, falsehood sensitivity
    - Need to handle NLO effects correctly if wants to exceed 1% sensitivity

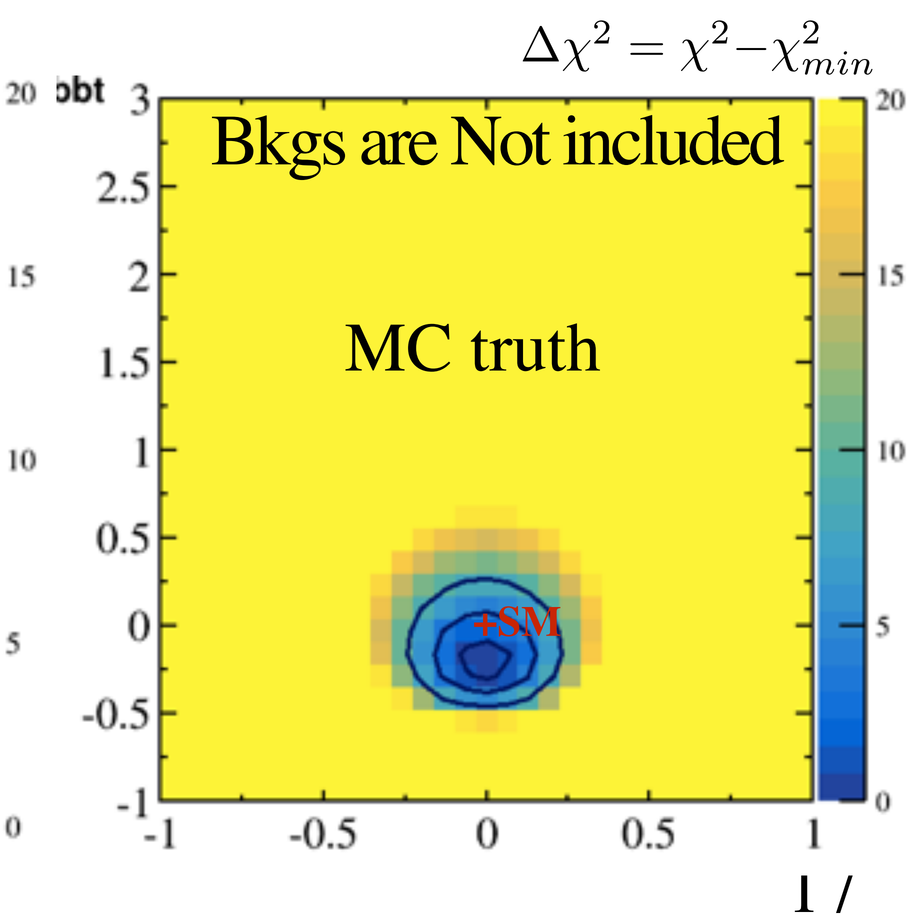
- ZH→ $\mu^+\mu^- H$ *(signal only)*
  250GeV 250fb[-1] [b vs bt]



ME : is LO
<u>Sample : no ISR, BSL, and FSR</u>
Denomi. : is calculated based on LO



ME : is LO
<u>Sample : with ISR, BSL, and FSR</u>
Denomi. : is calculated based on LO



Summary

1). An overview of the anomalous VVH study
ZZH/γZH and WWH induced with dim-6 operators

- Model independently the sensitivities to the structures were evaluated.
  (including 500GeV operation)
  - SM-like ZZH/WWH structures ~2%
  - new ZZH/γZH structures < 1%
  - new WWH structures 3~7 % and ~17%

2). An application of a Matrix Element method
toward further improvement of the sensitivity

- Try to encode all information into a single observable

  Intrinsically the improvement could be given,
  however, it turns out that NLO effects (ISR, BSL)
  affect to results largely when discussing the sensitivity ~1%

  Need to handle carefully, we will start to develop it to include ISR & BSL

Back up

Observables (anom-ZZ)

Focusing on ZZH

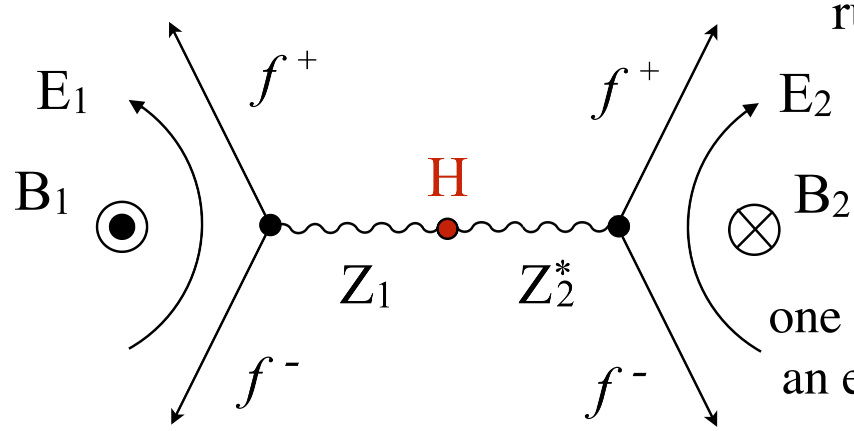
SM-like coupling

- a different CP-even structure

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

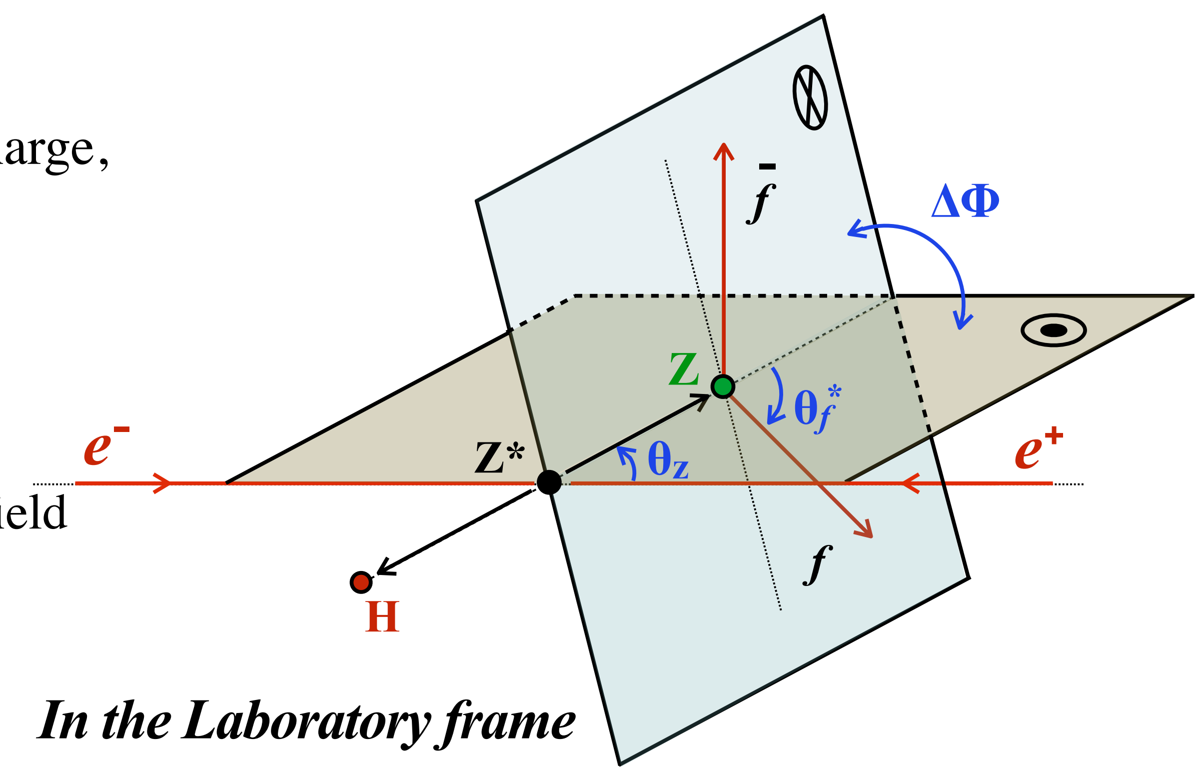
- a CP-violating structure

Structures vary kinematics



running weak/hyper charge,

one like an electroweak magnetic field could be generated



In the Laboratory frame

Result in EM dynamics

would give peculiar kinematical distributions

$$\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} \quad \propto \quad \boldsymbol{B}_1\cdot\boldsymbol{B}_2-\boldsymbol{E}_1\cdot\boldsymbol{E}_2$$

$$\hat{F}_{\mu\nu}\tilde{\hat{F}}^{\mu\nu} \quad \propto \quad \boldsymbol{E}_1\cdot\boldsymbol{B}_2$$

take a parallel state

makes both planes tend to take a perpendicular state

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

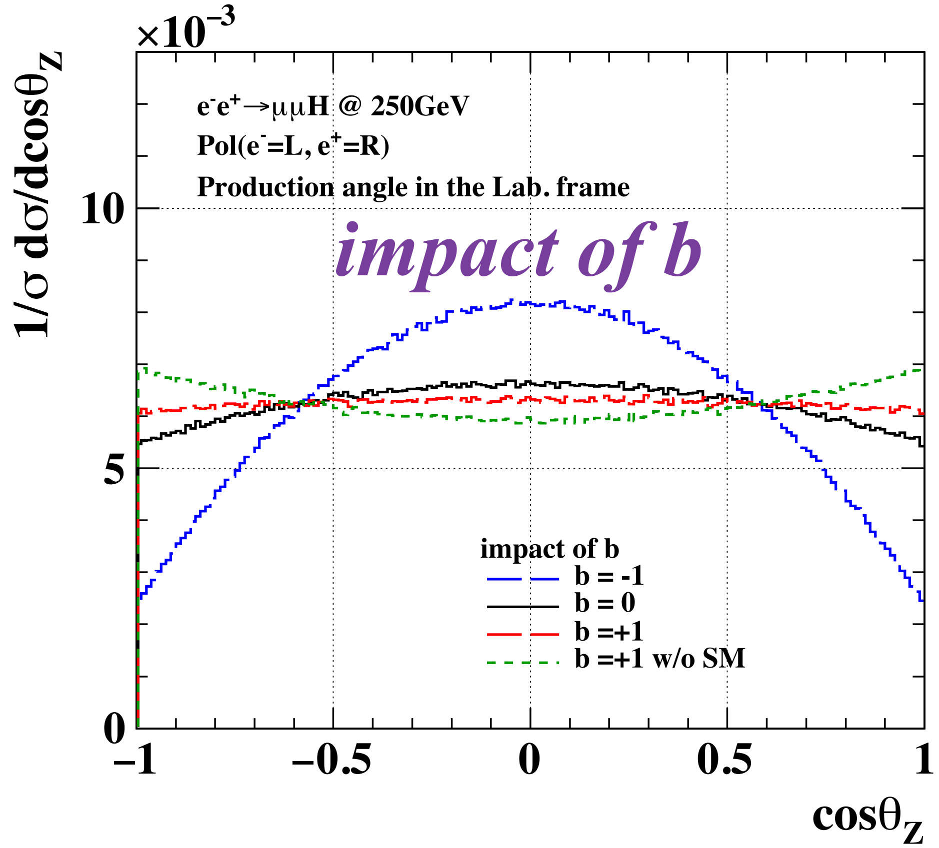
cosθz : a production of the Z.

cosθf*: a helicity angle of a Z's daughter.

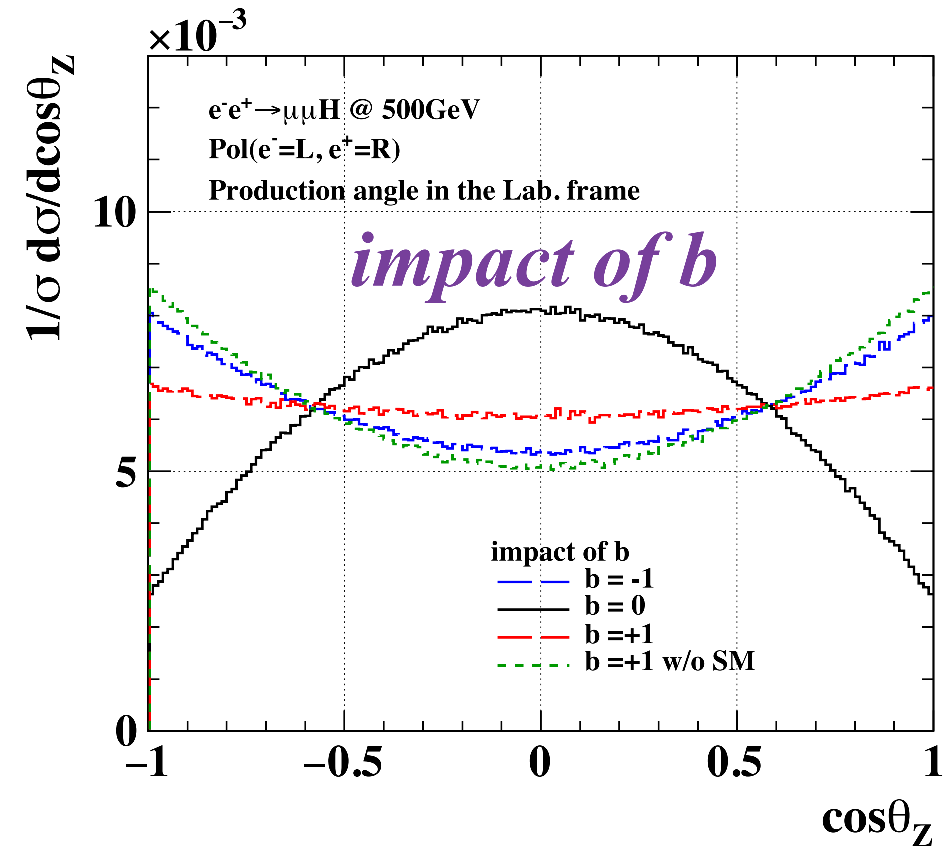
ΔΦ : an angle b/w two production plane.

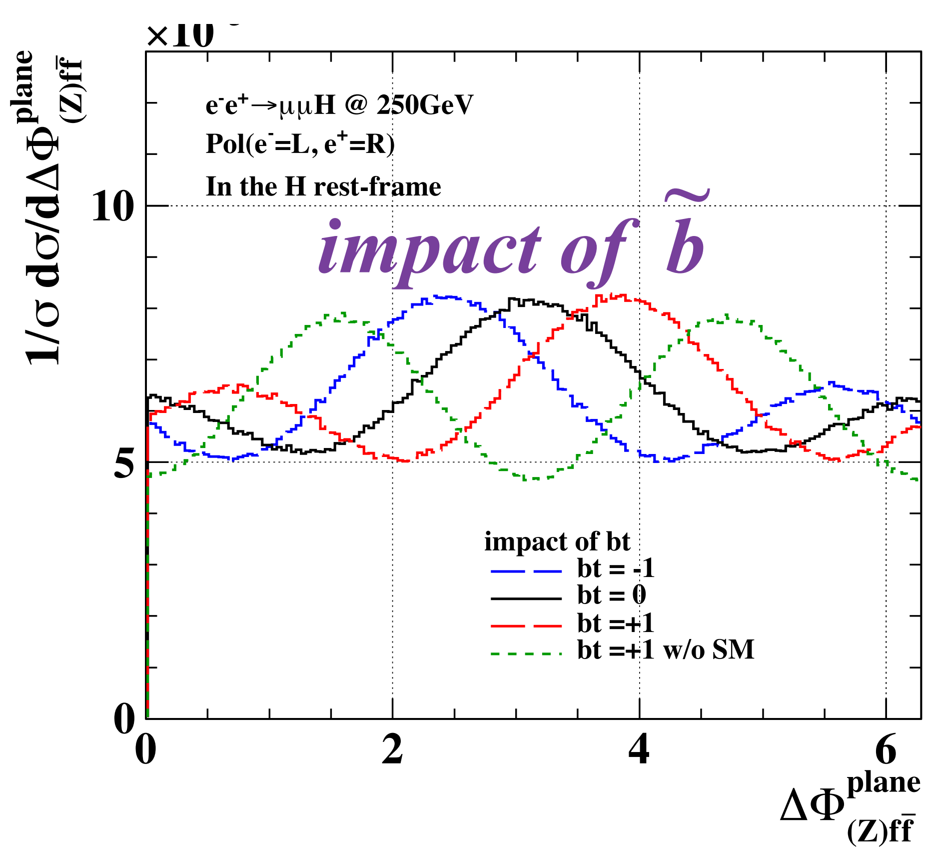
Observables (anom-ZZ)

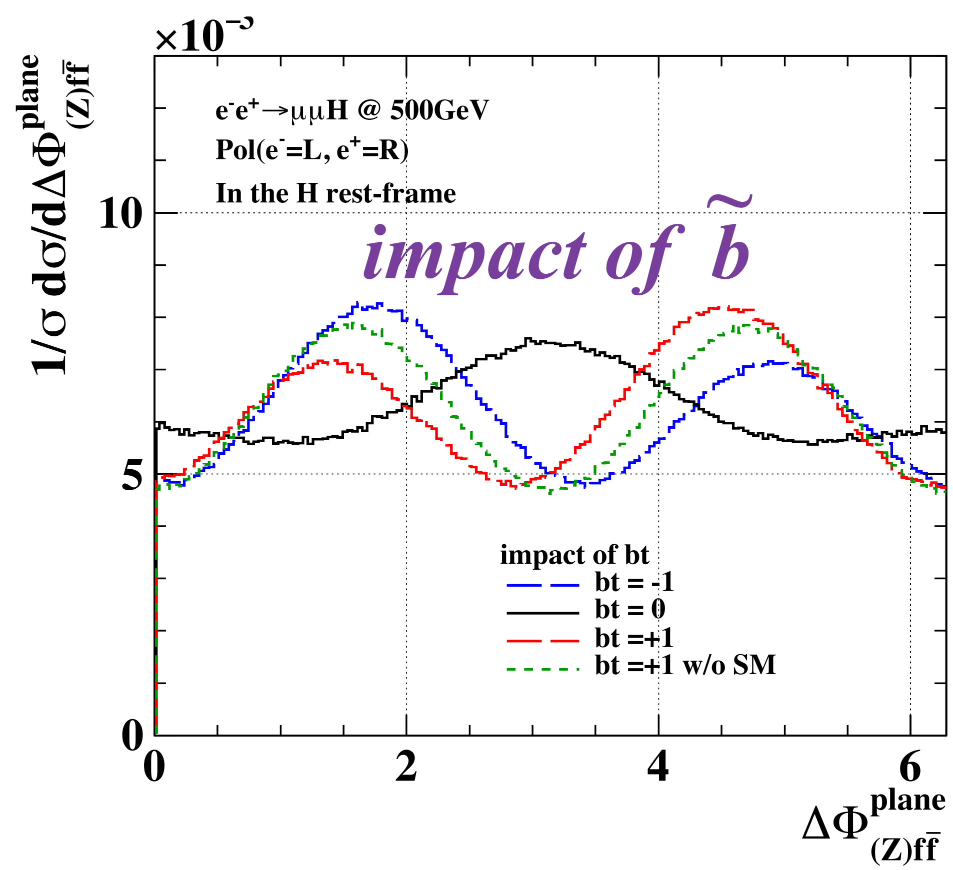
$ZH \to l^+l^-H$, $\sqrt{s} = 250GeV$



$\sqrt{s} = 500GeV$





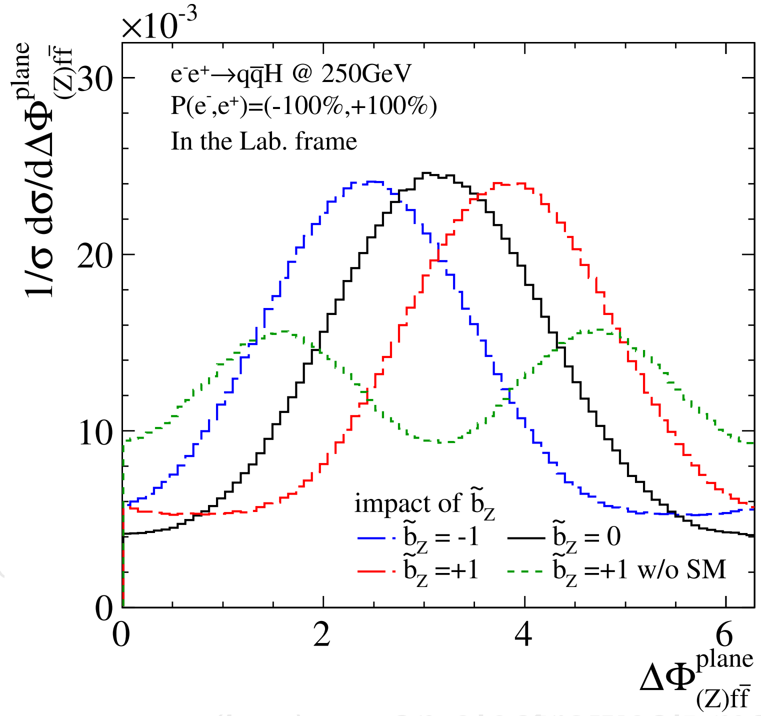


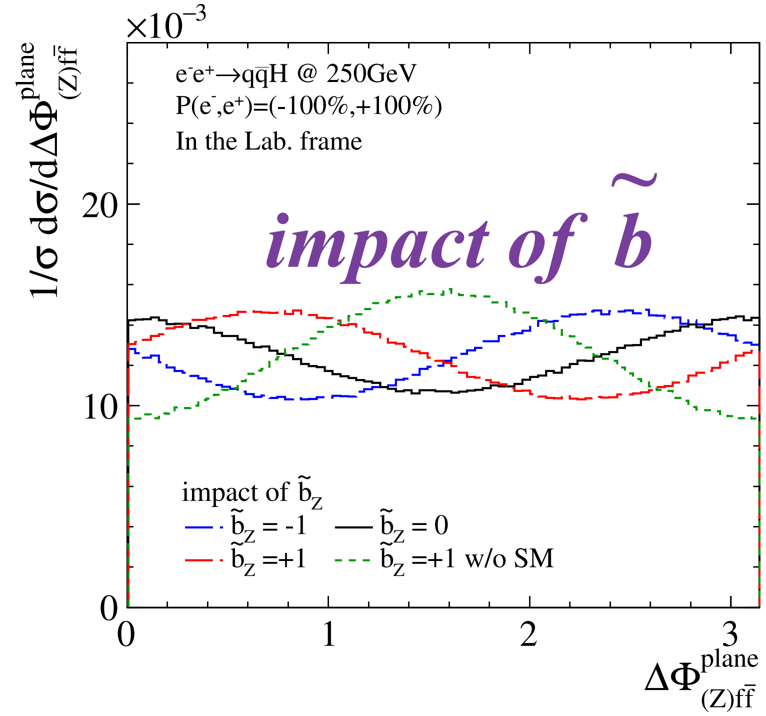
Observables (anom-ZZ)

$ZH \rightarrow q\,q\,H$, $\sqrt{s} = 250GeV$

$I_3\text{-}Q\sin^2\theta_W$

[0 , 2π]

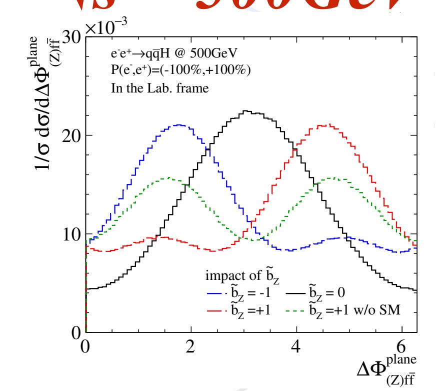




w/o jet charge ID

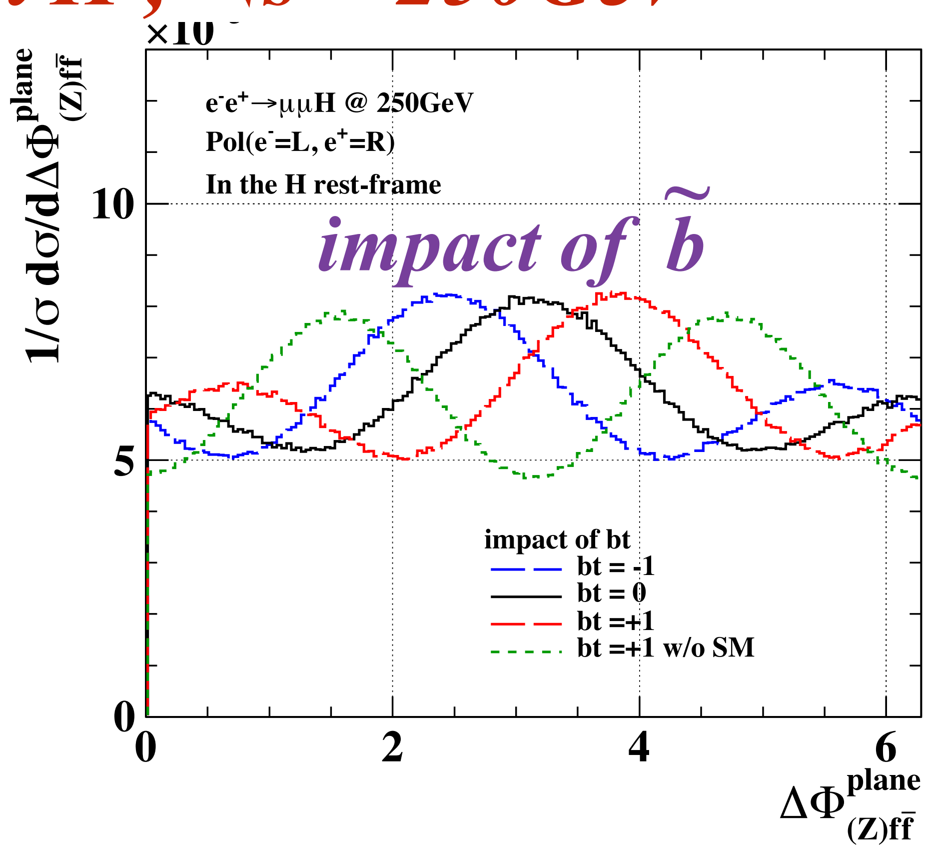
[0 , π]

$\sqrt{s} = 500GeV$

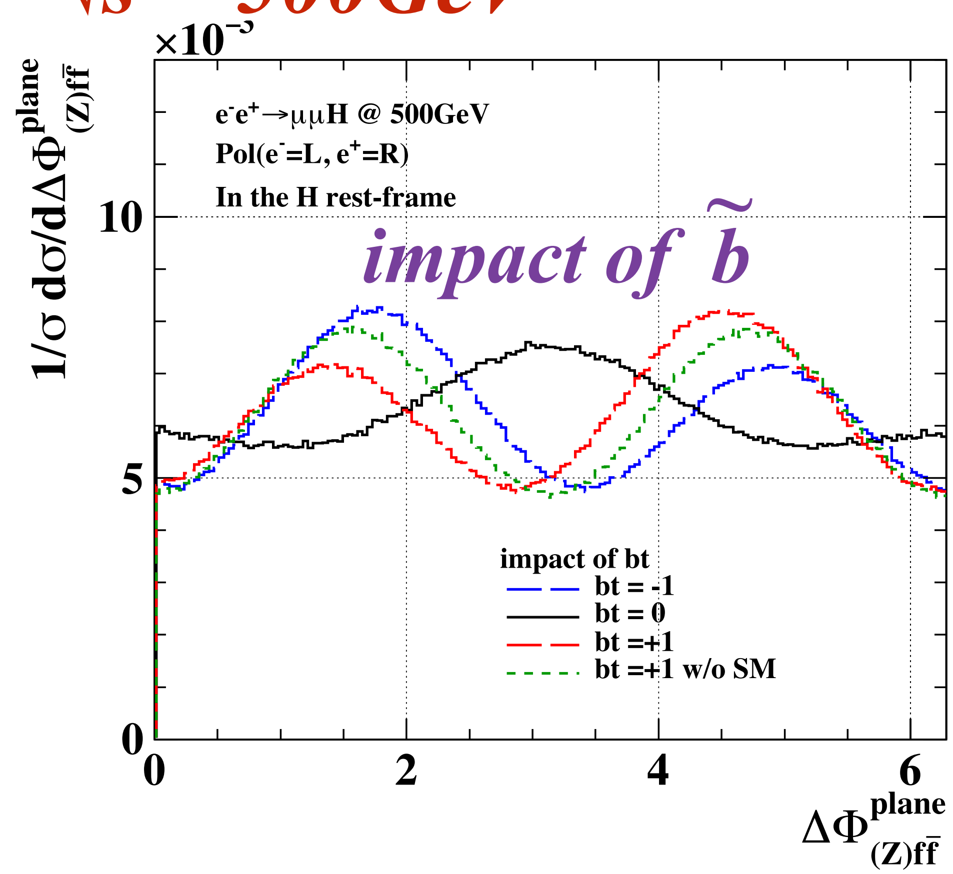


$e^+e^- \rightarrow ZH \rightarrow llH$

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



$\sqrt{s} = 500GeV$



Observables (anom-ZZ)

Focusing on ZZH

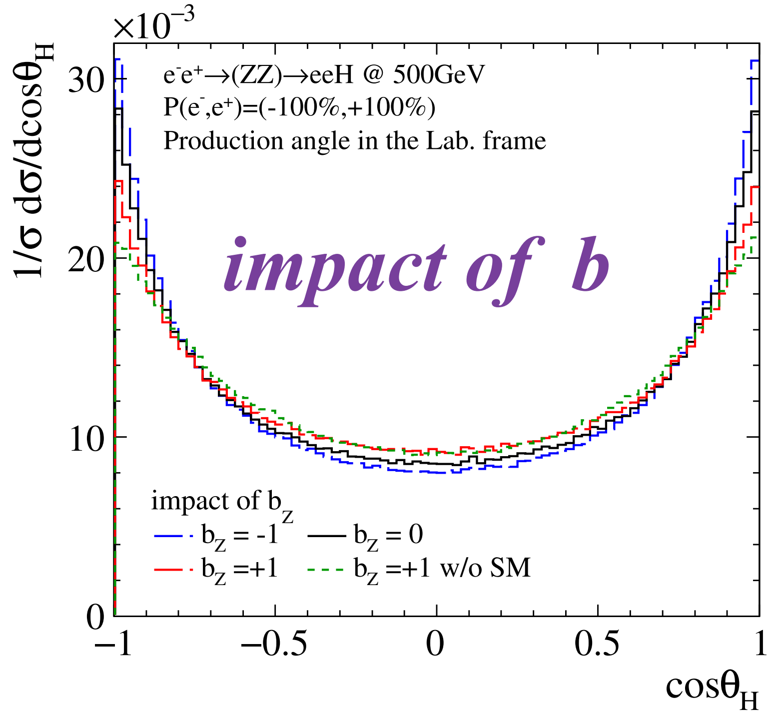
SM-like coupling

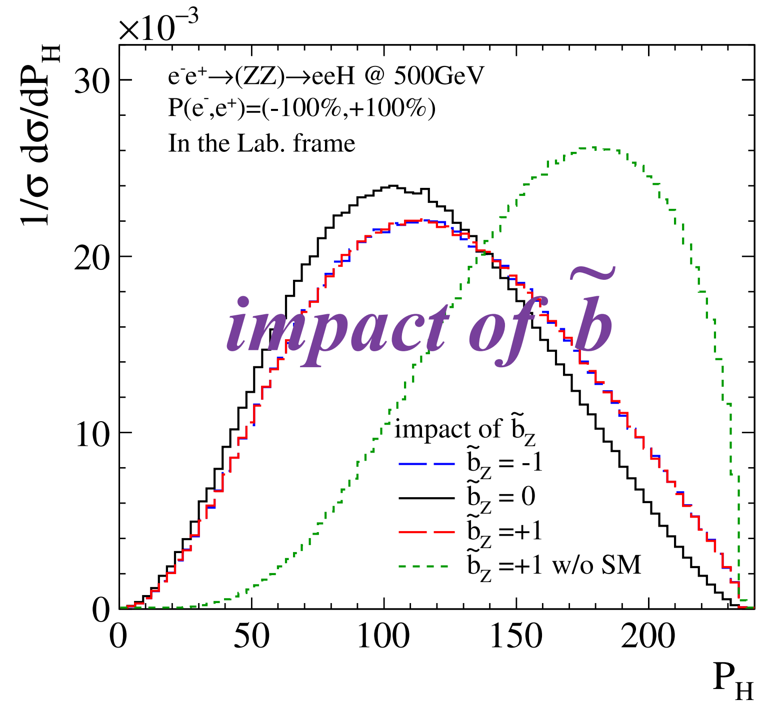
- a different CP-even structure

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

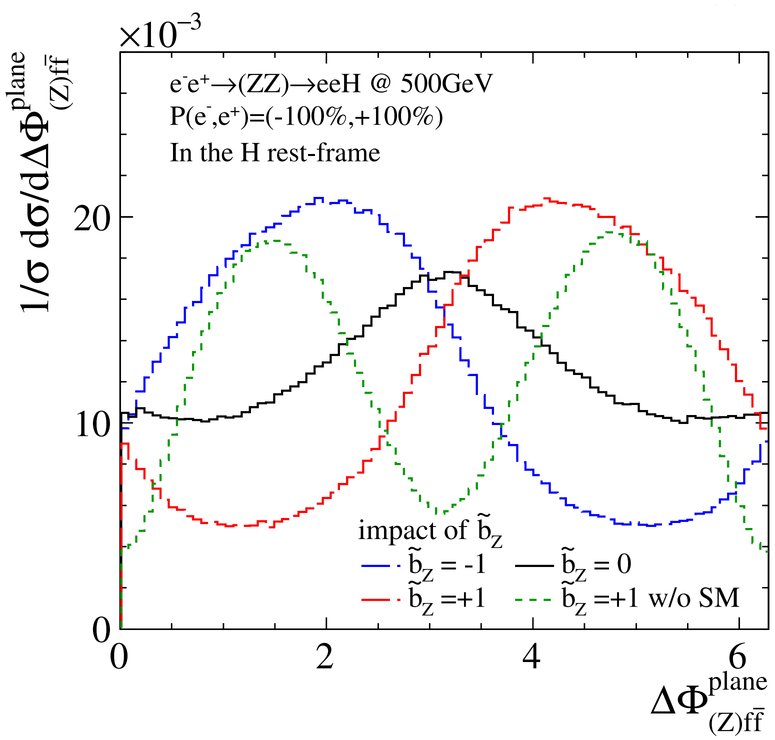
- a CP-violating structure

ZZfusion → eeH , √s = 500GeV



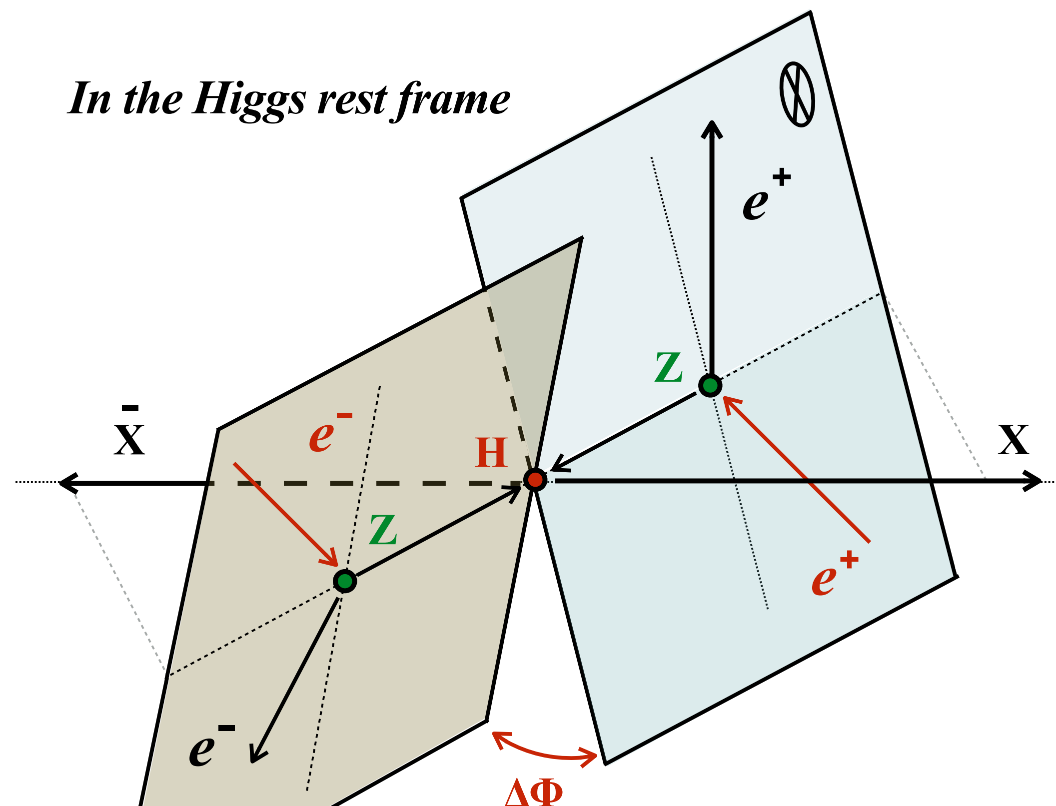


impact of $\tilde{b}$



[0 , 2π]

In the Higgs rest frame



Observables (anom-WW)

Focusing on WWH

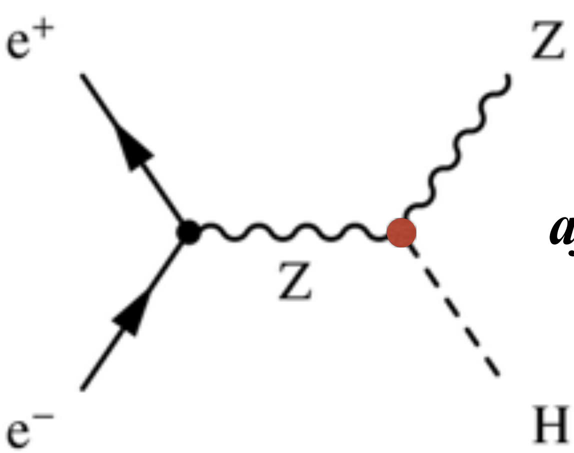
SM-like coupling

- a different CP-even structure

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

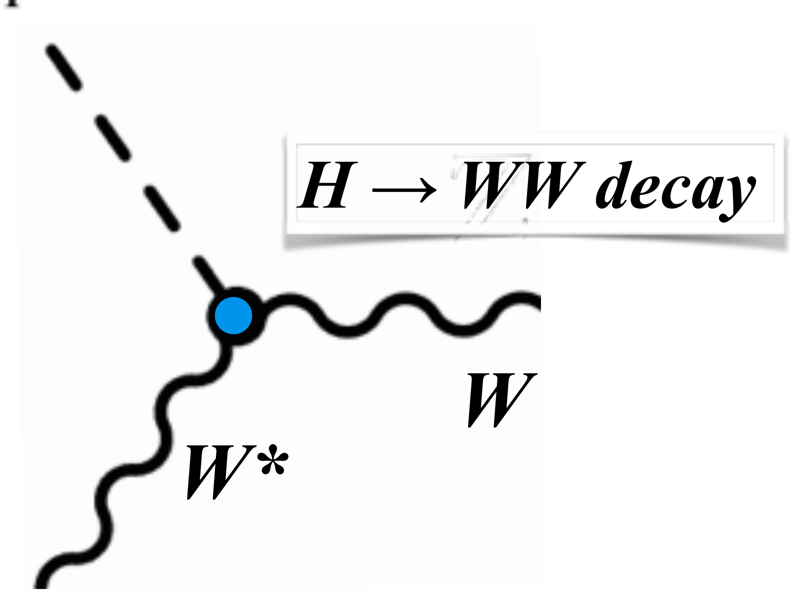
- a CP-violating structure

The Higgs-straulung

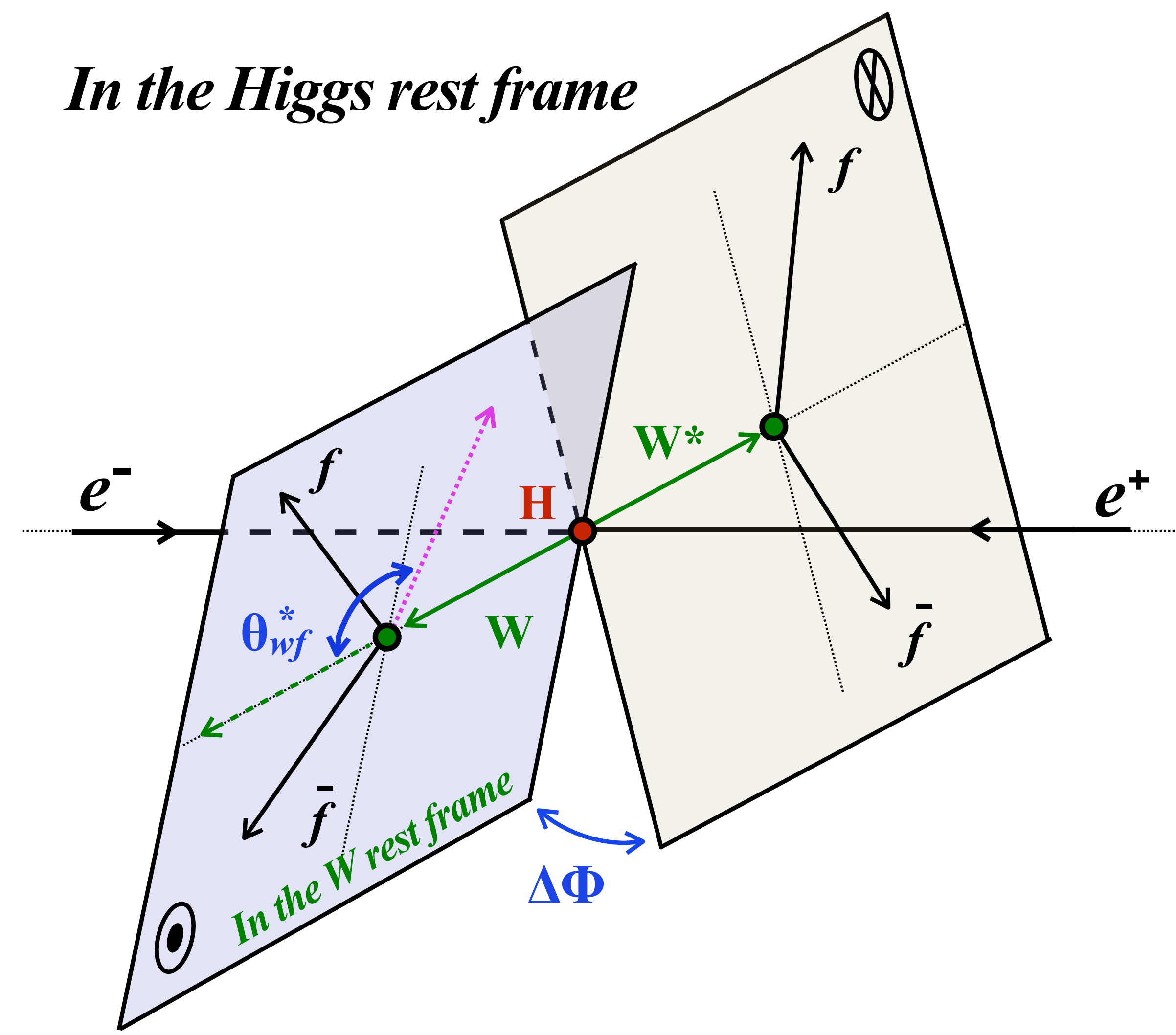


affects ZH production

H *rest-frame is not affected*



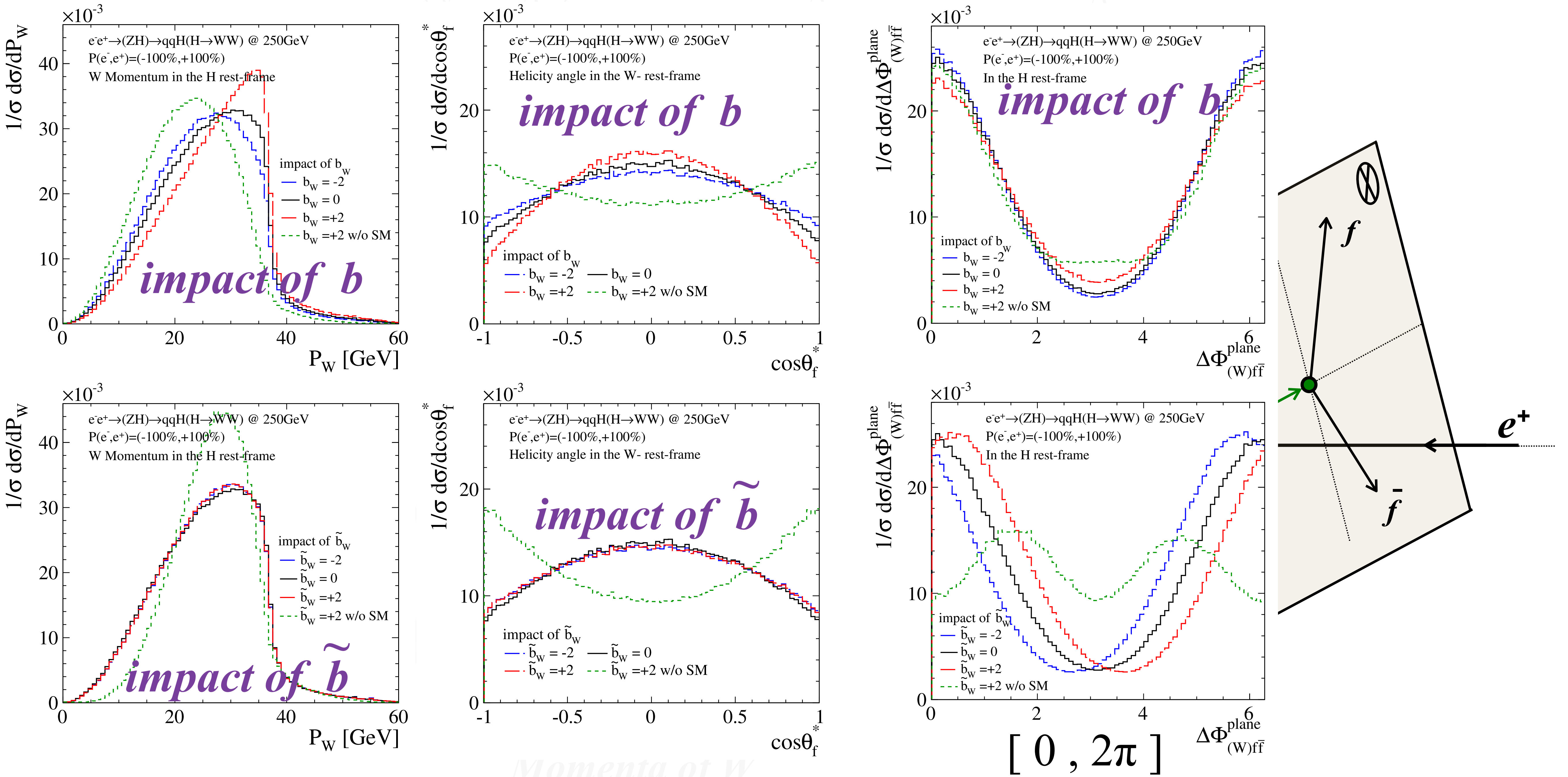
In the Higgs rest frame



Observable
Momenta of W
helicity angle of a W's daughter
angle b/w decay palnes

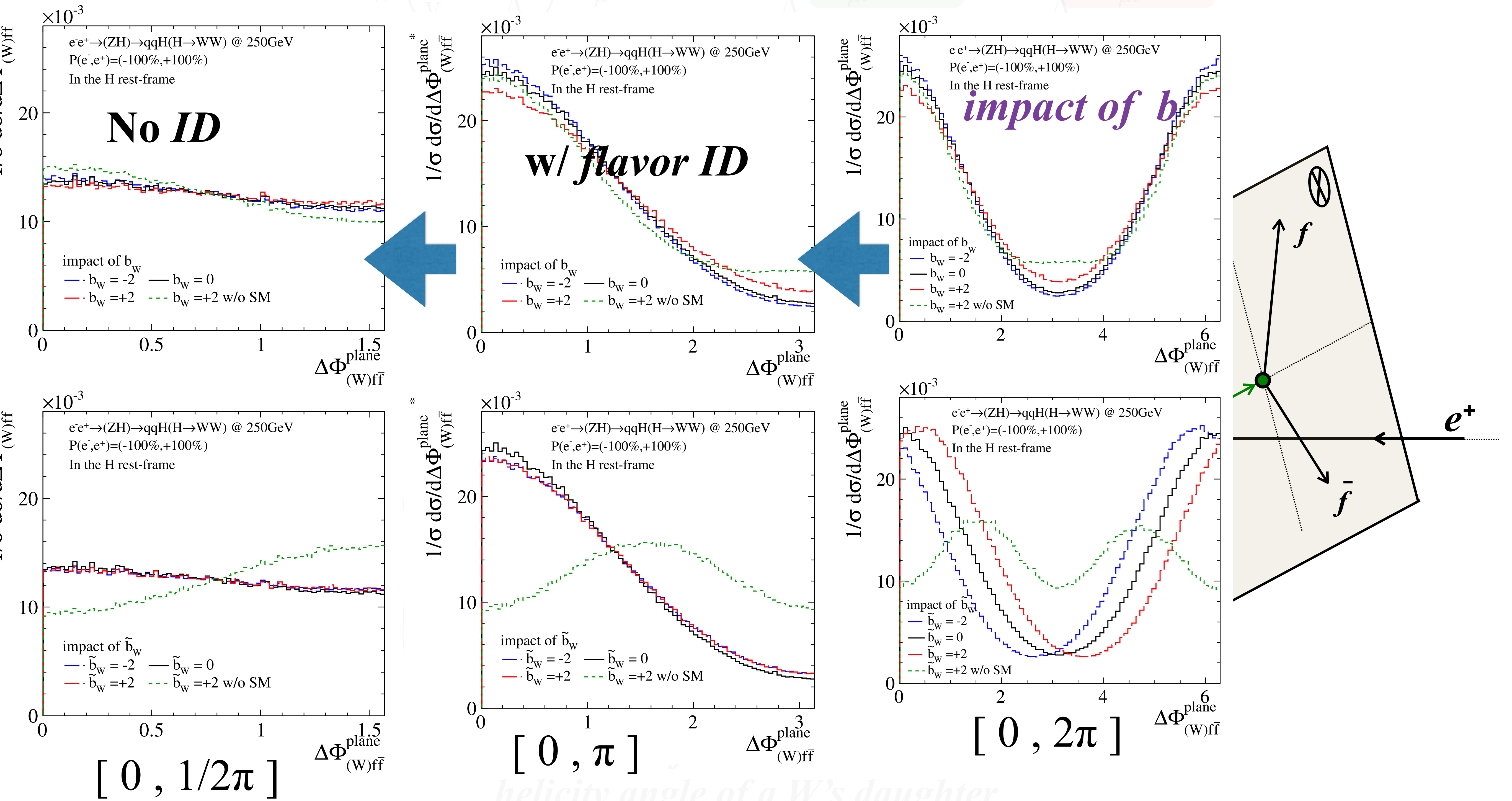
Observables (anom-WW)

ZH → *H → WW* decay*



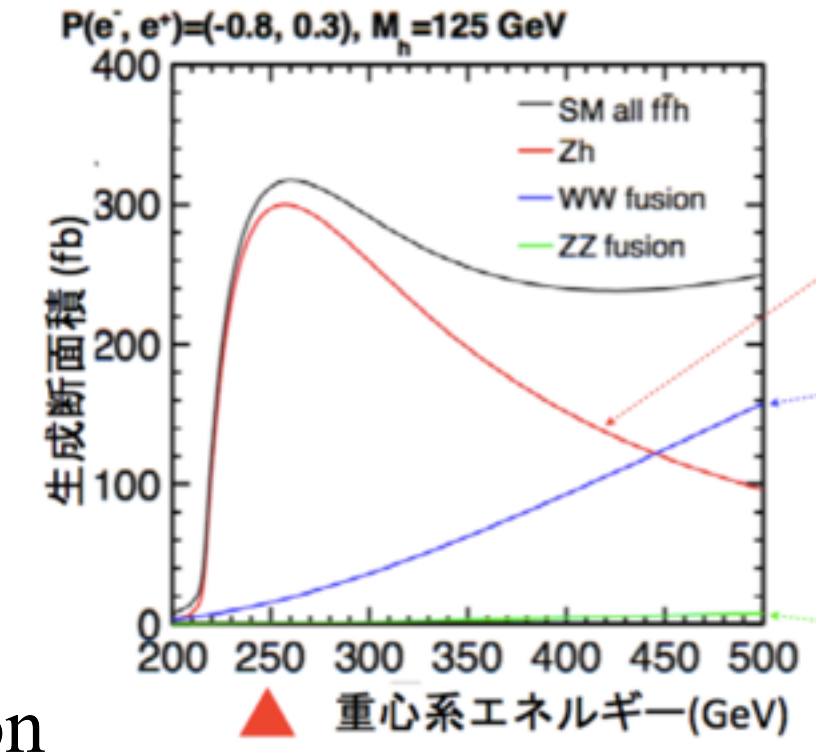
Observables (anom-WW)

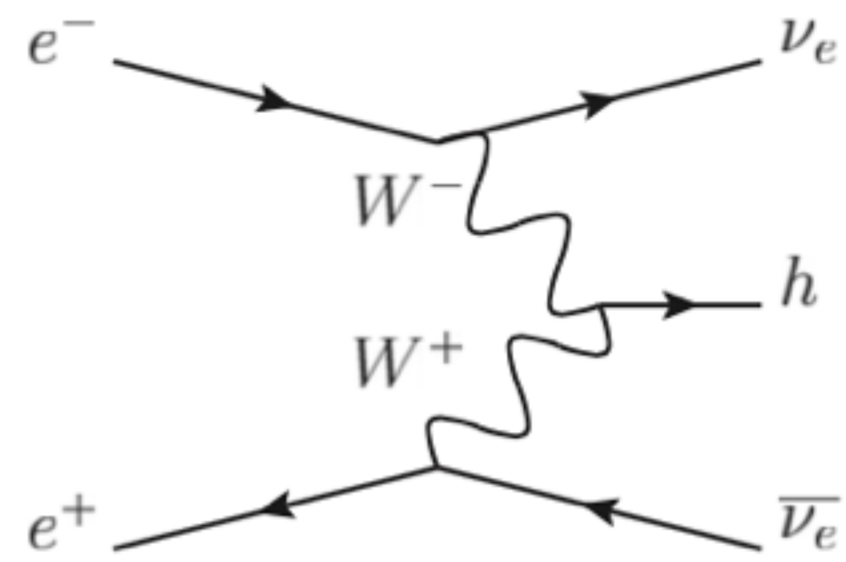
ZH → *H → WW* decay* *w/o Jet charge & w/o flavor ID*



Observables (anom-WW)

250, 500GeV
WW-fusion Production
is possible



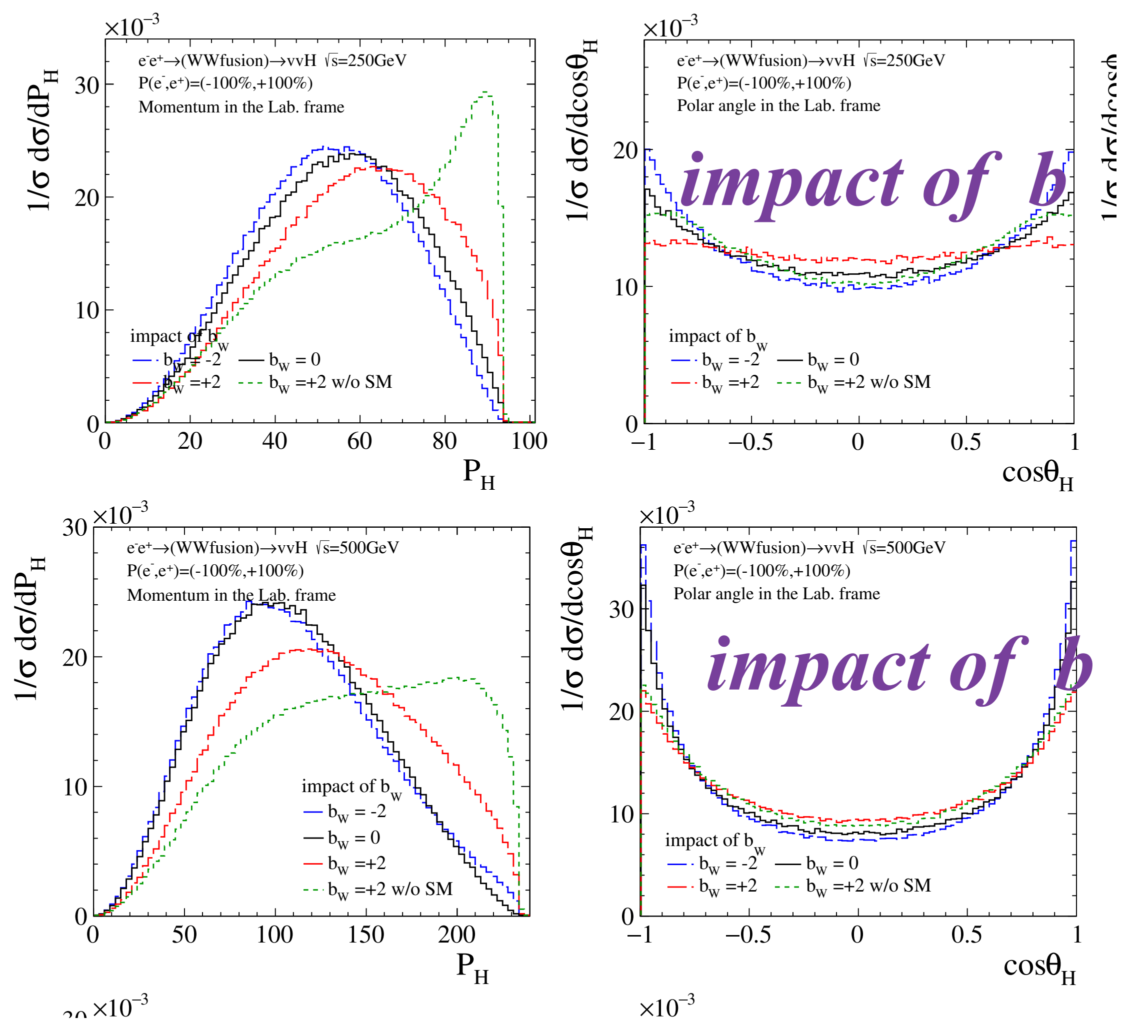


Higgs related observables

momentum & production

250GeV

500GeV



Observables (Production Cross-section)

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

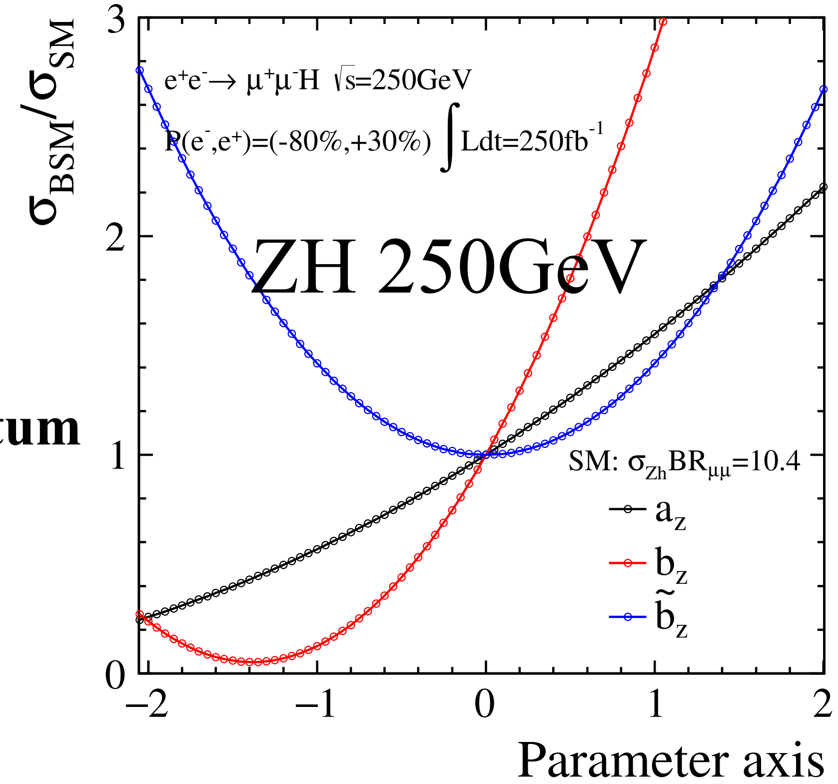
No energy dependence on a

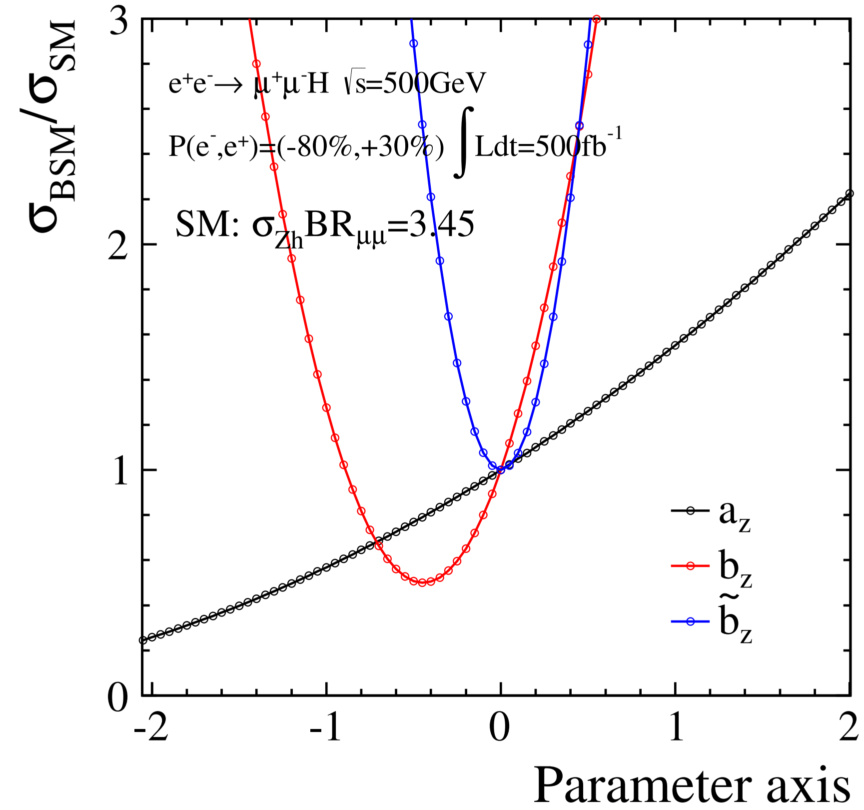
Recover the SM with - Λ/v

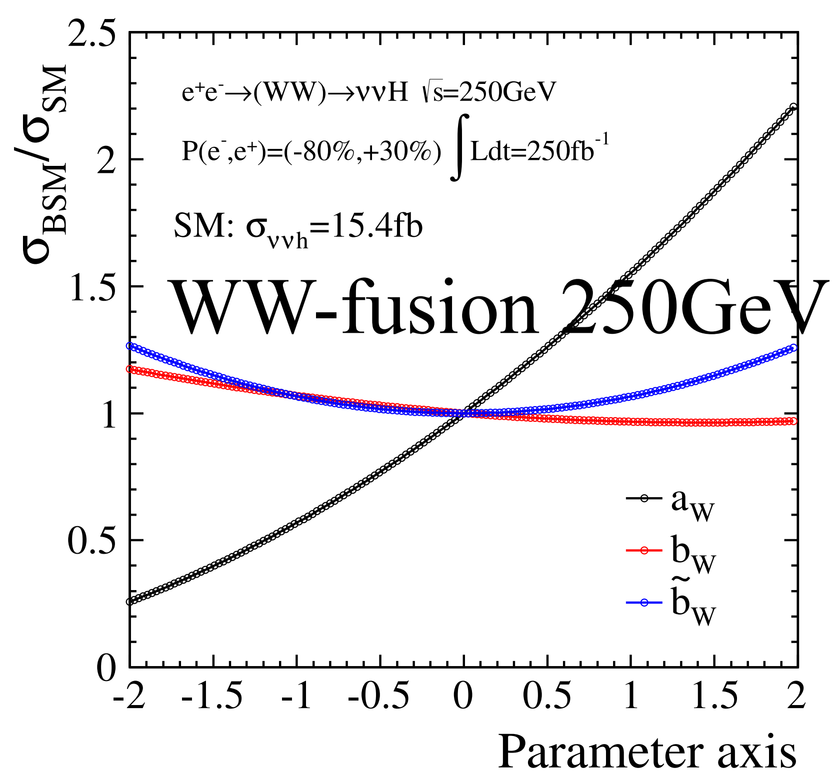
b bt vary depending on momentum

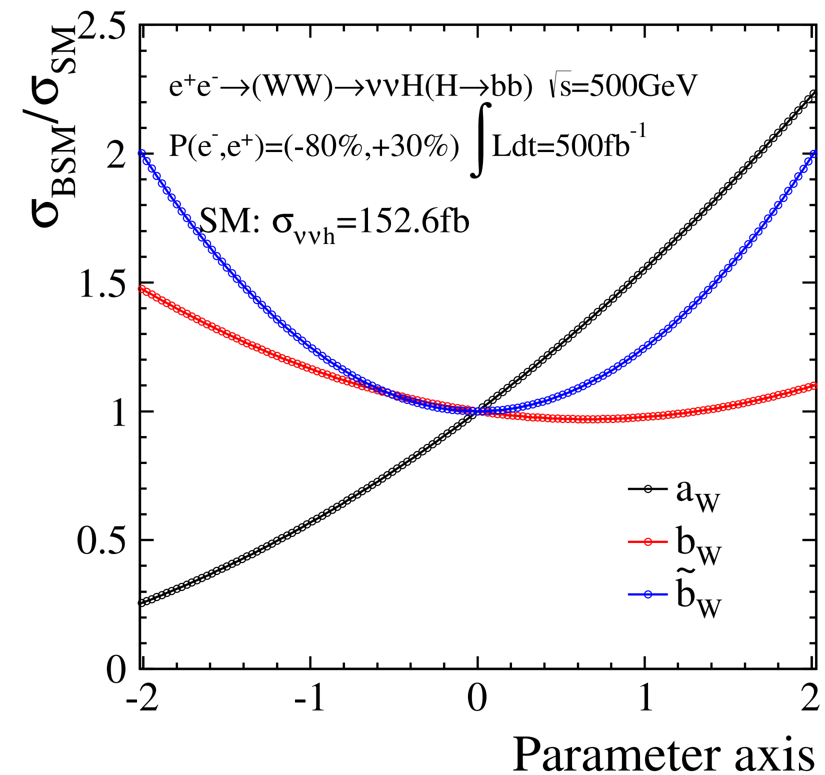
bt change symmetric

$(F_{\mu\nu}\tilde{F}^{\mu\nu})^2$ gives one term with positive sign.







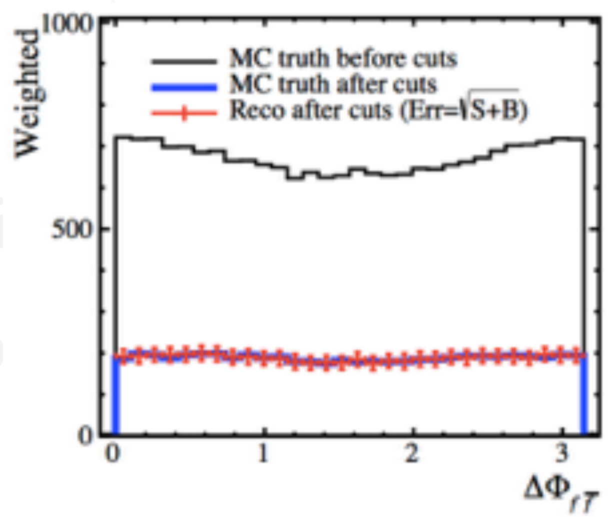


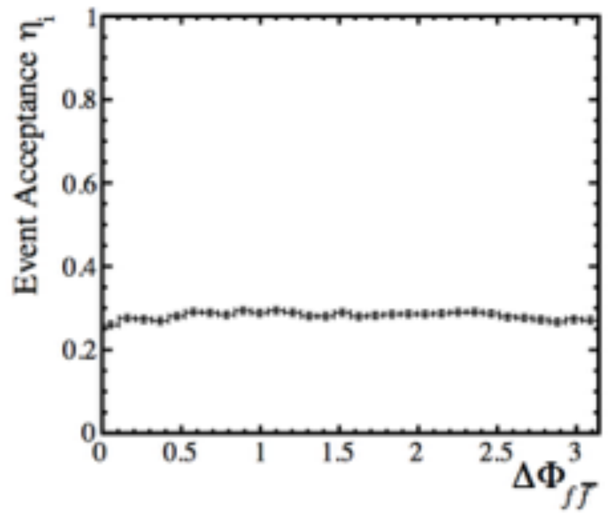
Analysis Strategy Detector Responce function

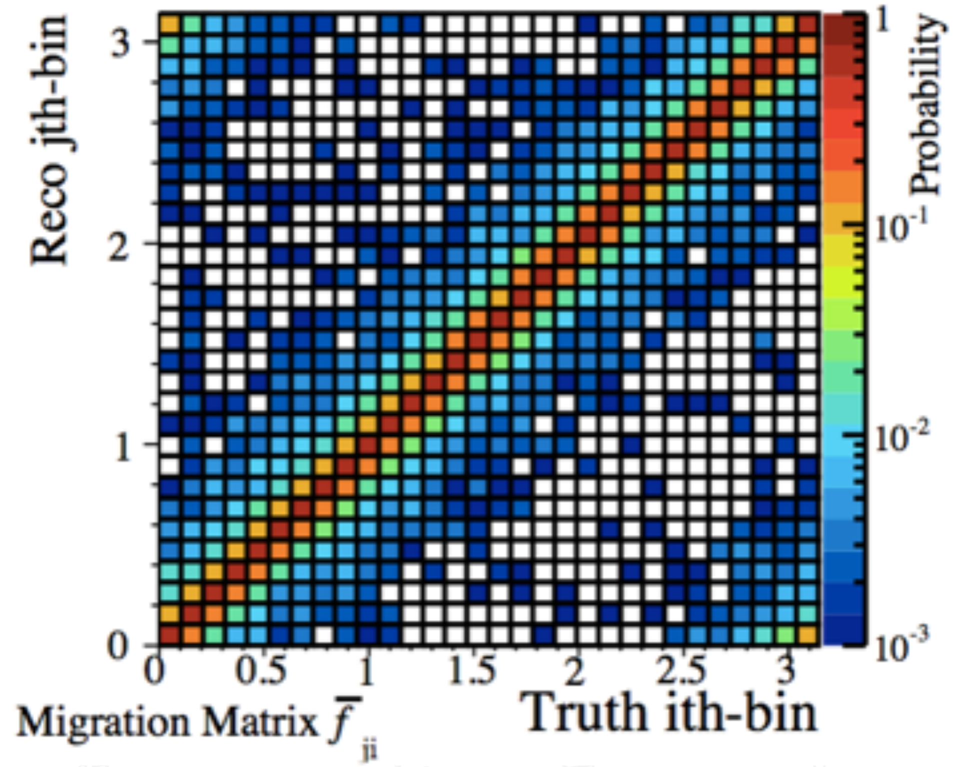
Constructing an event acceptance η and a migration matrix $\bar{f}$

(theoretical distributions => realistic distributions observed in reality)

1-dim observable $\Delta\Phi$ production







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

Observed

generated

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

Two probabilities

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

Evaluation of the sensitivity

Binned info. derived form **shape**

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

Normalized to Nsm

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

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

Detector response function
→ Transfer the theory to
"Detector level" distribution

Normalization (Cross-section)

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

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

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

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

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

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

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

WW-fusion 250 GeV

production cross-section
8.1% and 1.0%.

t-channel variation
due to WWH

s-channel variation
due to ZZH

$$\chi^2_{tot} = \left(\frac{N^{t\text{-}\nu\nu h}_{SM} - N^{t\text{-}\nu\nu h}_{BSM}(\vec{a}_W) + N^{s\text{-}\nu\nu h}_{SM} - N^{s\text{-}\nu\nu h}_{BSM}(\vec{a}_Z)}{\delta\sigma_{\nu\nu h}\cdot N^{t\text{-}\nu\nu h}_{SM}}\right)^2$$

Normalization

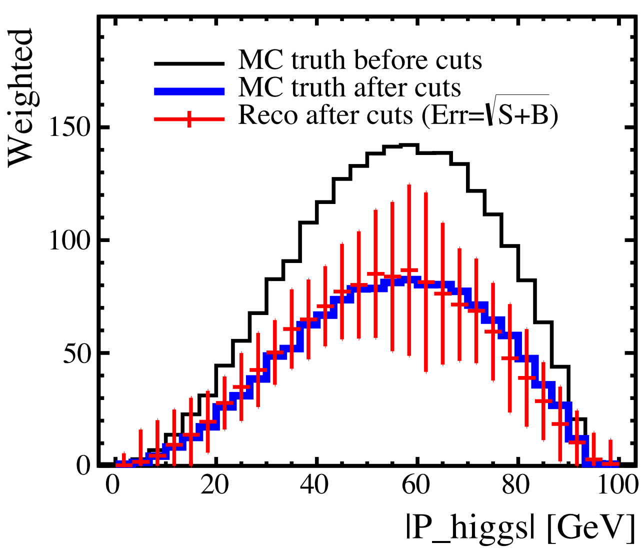
$$+ \sum_j^n \left(\frac{S^{t\text{-}\nu\nu h}_{SM}(x_j) - S^{t\text{-}\nu\nu h}_{BSM}(x_j;\vec{a}_W) + S^{s\text{-}\nu\nu h}_{SM}(x_j) - S^{s\text{-}\nu\nu h}_{BSM}(x_j;\vec{a}_Z)}{\Delta n^{obs}_{SM}(x_j)}\right)^2$$

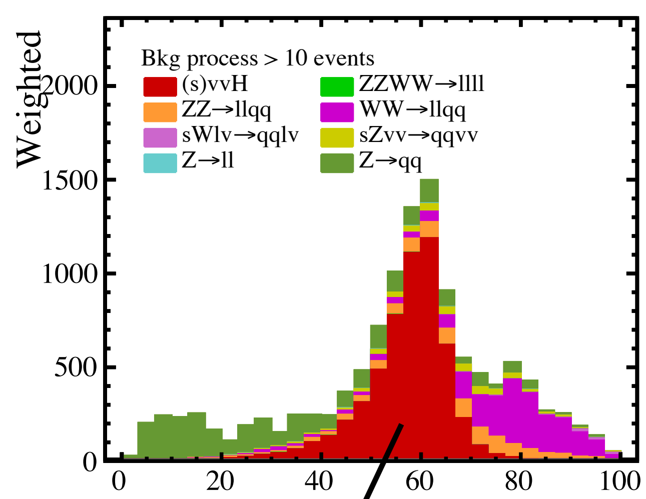
Shape

$$+ \vec{a}_Z^{\,\mathrm{T}}\, \boldsymbol{C}^{-1}_{ZZH}\, \vec{a}_Z$$

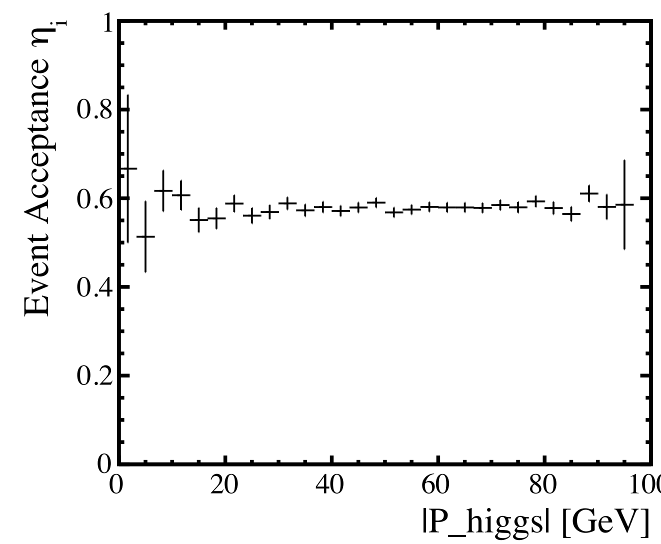
Evaluated Responce function
individually

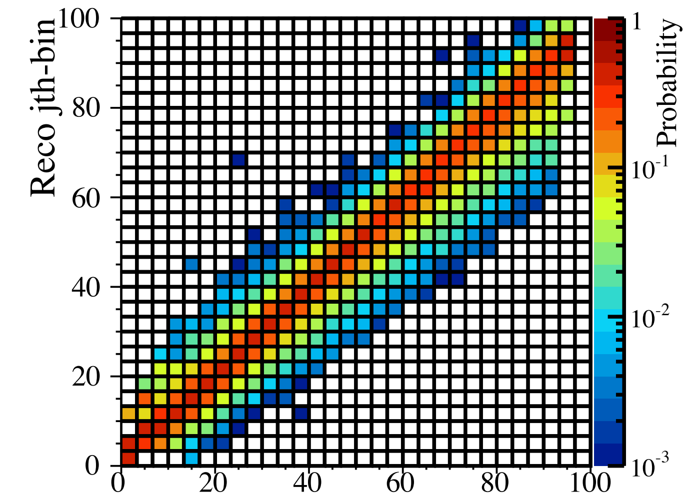
Constraints and correlation for ZZH
C_{ZZH}: variance-covariance



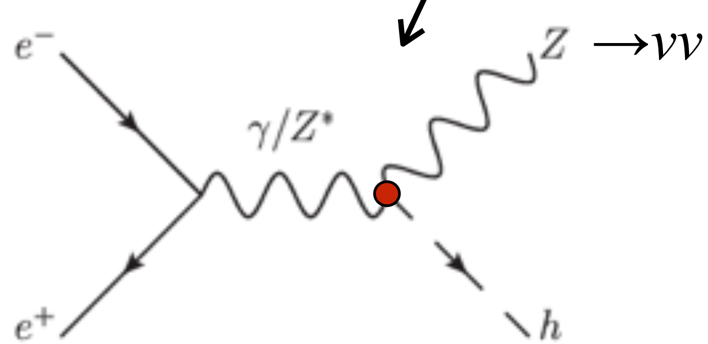


Backgrounds after cuts





Migration Matrix $\overline{f}_{ji}$



anomalous ZZH varies the shape

ZZH a-b

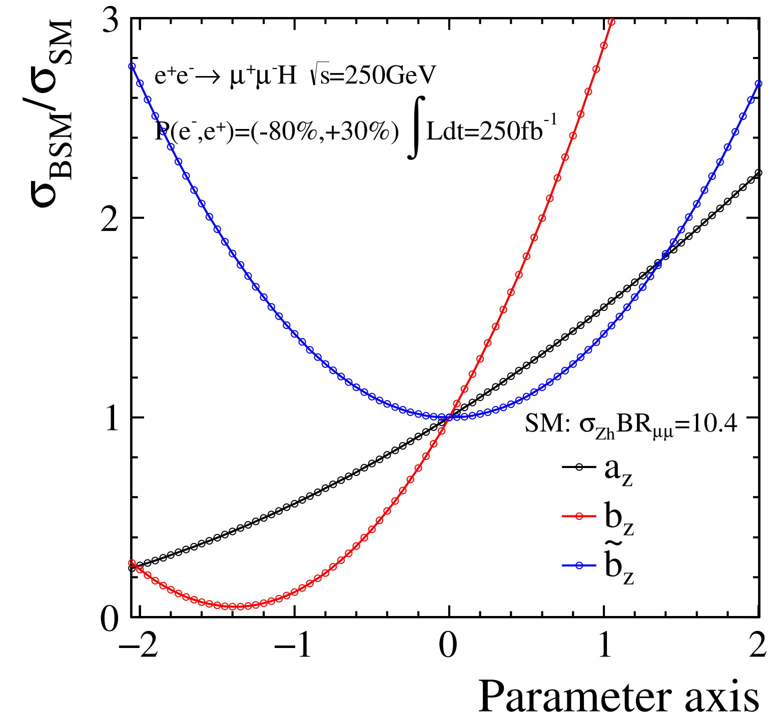
Normalization from ZH and ZZ

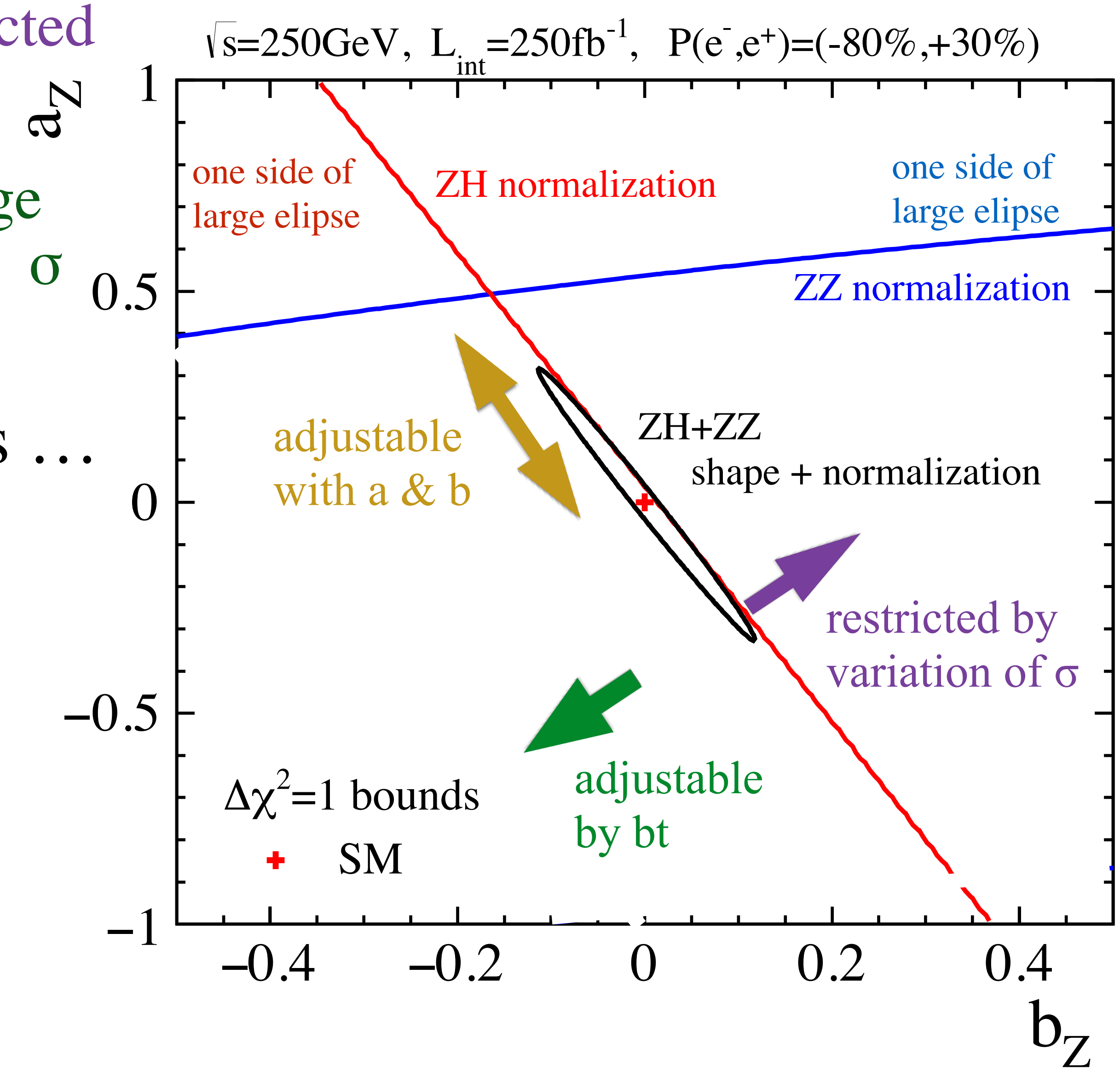
Both az & bz can adjust each other
by making σ increase & decrease

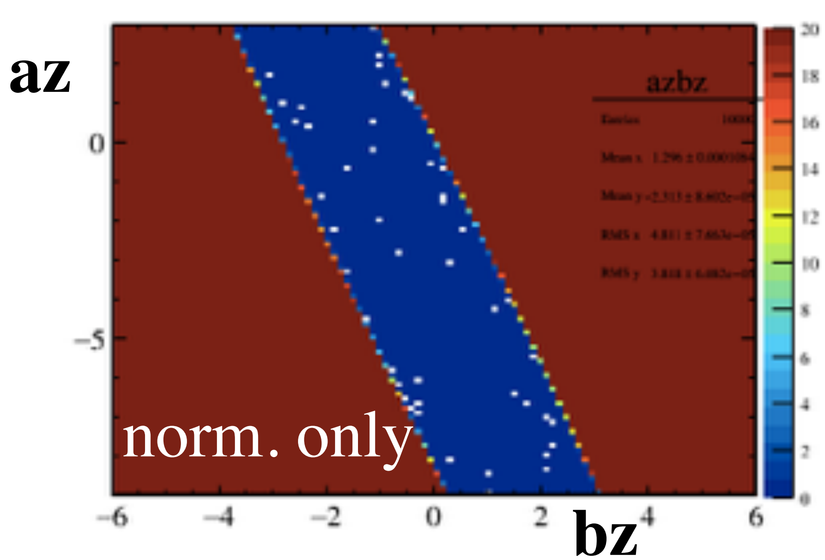
Both az & bz make σ increase, and
any btz can not adjust since any btz can
increase σ. Thus, the bound is quickly restricted

For this direction
both az & bz make σ decrease, and btz has huge
room to recover the SM value by increasing σ

Once the shape is included in the analysis …
the bound is strongly constrained.

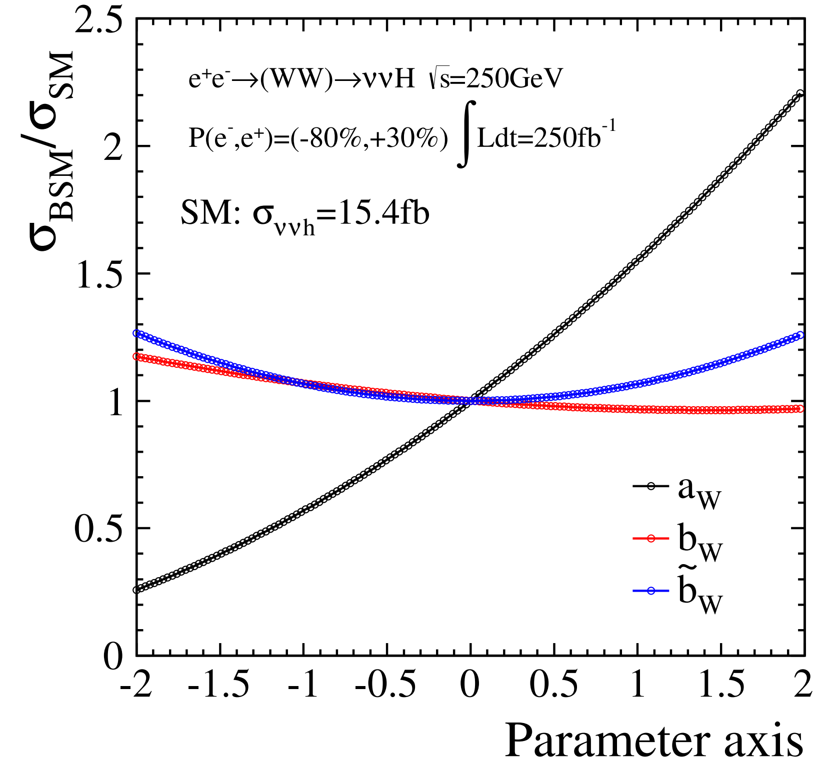






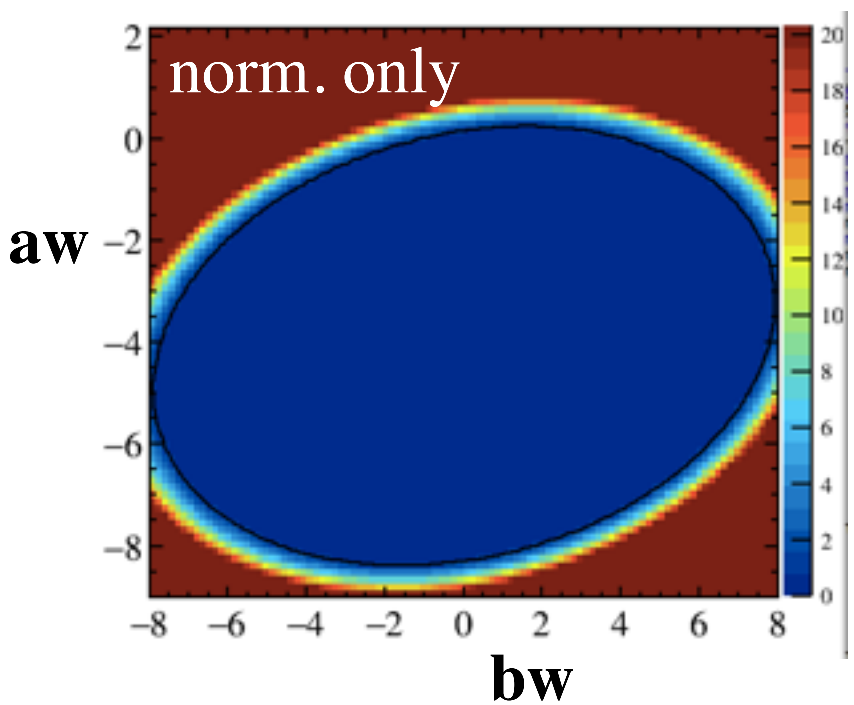
WWH a-b

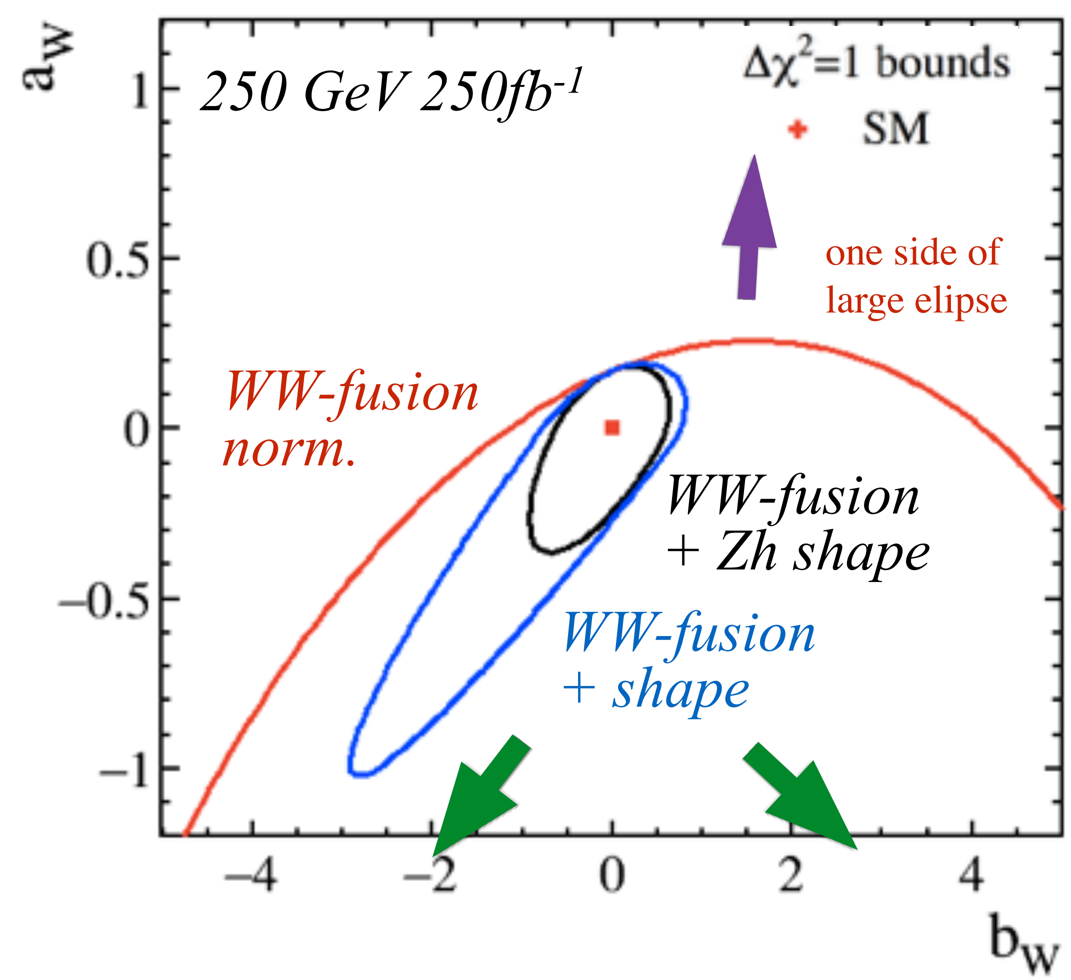
Normalization from **WW-fusion**



az make σ increase, but, this time,
bz can not change it largely
any btz can not adjust since any btz can
increase σ. Thus, the bound is quickly restricted

For this direction
both az make σ decrease. Both bz & btz
has huge room to recover the SM value
by increasing σ





WWH a-b 250 & 500 GeV