Probing anomalous ZZH/WWH couplings at the ILC

21th, October, 2021, T.Ogawa
on behalf of the ILD collaboration and ILC-IDT-WG3

Outline

-. EFT and Lagrangian at the ILC

-. Impact of the anomalous ZZH/WWH couplings on kinematical shape

-. Estimation of the sensitivity to the anomalous ZZH/WWH couplings

-. Comparison of the sensitivity between LHC and ILC

-. Summary

Motivations for Effective Field Theory (EFT)

-. Several phenomena are not allowed by the SM.

-. Supersymmetry provides solutions for them.

-. No conclusive evidence of SUSY/BSM at the LHC.

-. BSM could exist at an energy scale to be high enough (>TeV) compared to the scale of EW symmetry breaking.

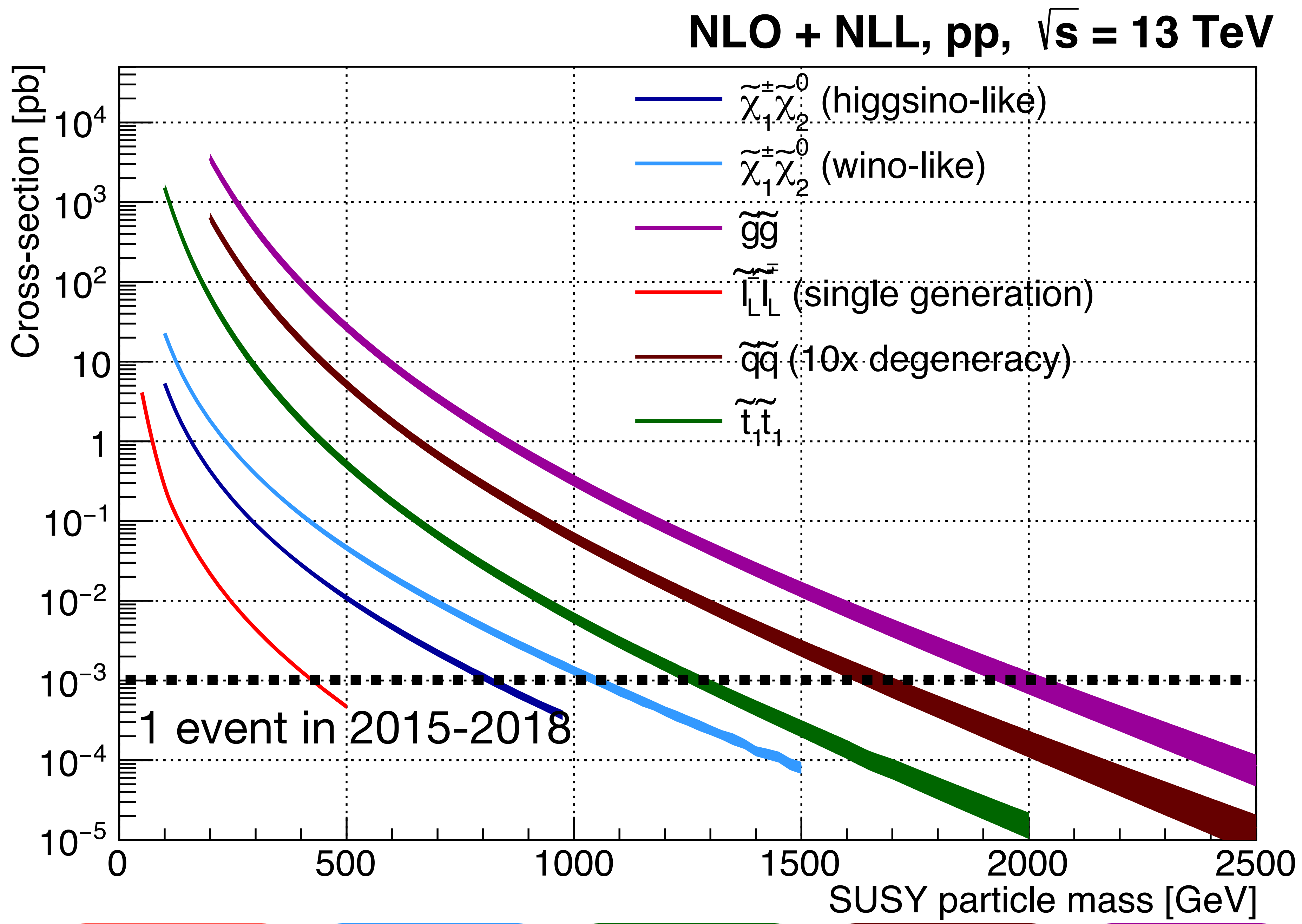
-. Now, EFT is valid given that BSM may exists at high energy.

-. A strong phenomenological approach is EFT as analogous to Fermi's theory of the beta decay.

-. Instantaneous appearance of a high-energy field is renormalized into the coupling constants at lower energy. It modifies the constant from the SM expectation.

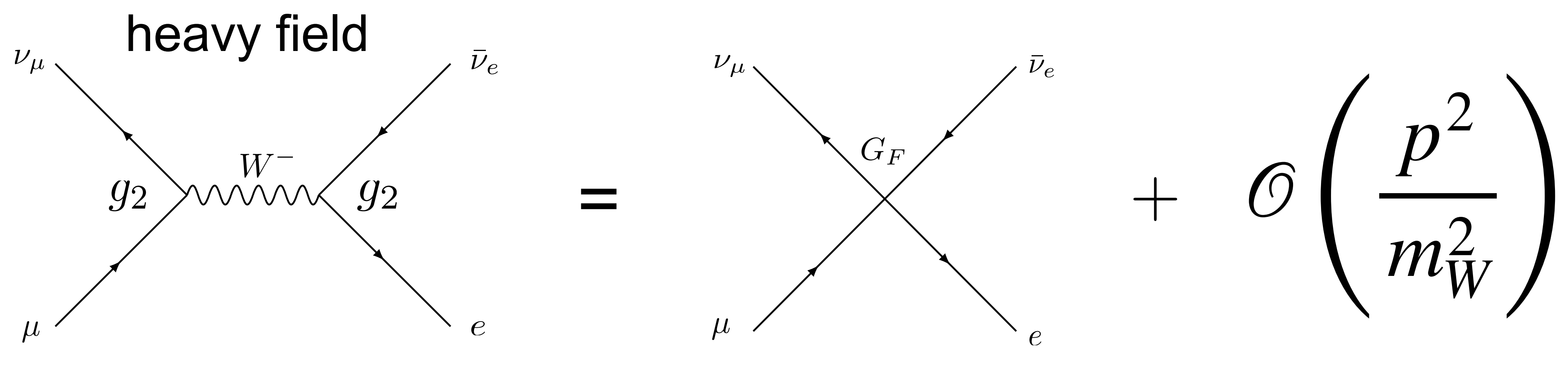
LHCP 2021 : SUSY search at LHC

https://indico.cern.ch/event/905399/sessions/373072/#20210608



slepton: 0.7 TeV	EWK: 0.95 TeV	stop: 1.3 Tev	squarks: 1.85 Tev	gluinos: 2.2 Tev

Current limits at the end of 2015-2018 data taking



phenomena at high E | at low E | Once our E gets higher

Anomalous VVH couplings in SMEFT at the ILC

-. Model independent test for the gauge-Higgs sector.

-. Model-independent Lagrangian is defined by taking all possible dim-6 combinations consisting of the SM fields.

-. The SU2xU1 gauge invariance, Lorentz invariance.
Define the acronym “SMEFT”: Higgs-strahlung, Weak Boson Fusion

-. After SSB, several terms relevant to the gauge-Higgs sector:

$$\Delta\mathscr{L}_h = -\eta_h\lambda_0 v_0 h^3 + \frac{\theta_h}{v_0} h\partial_\mu h\partial^\mu h \quad \longleftarrow \text{(Higgs)}$$

T. Barklow et al., PRD 97, 053004 (2018)

$$+\eta_Z\frac{m_Z^2}{v_0}Z_\mu Z^\mu h + \frac{1}{2}\eta_{2Z}\frac{m_Z^2}{v_0^2}Z_\mu Z^\mu h^2 \quad \longleftarrow \text{(same structure with the SM)}$$

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

(new tensor structures)

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

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

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

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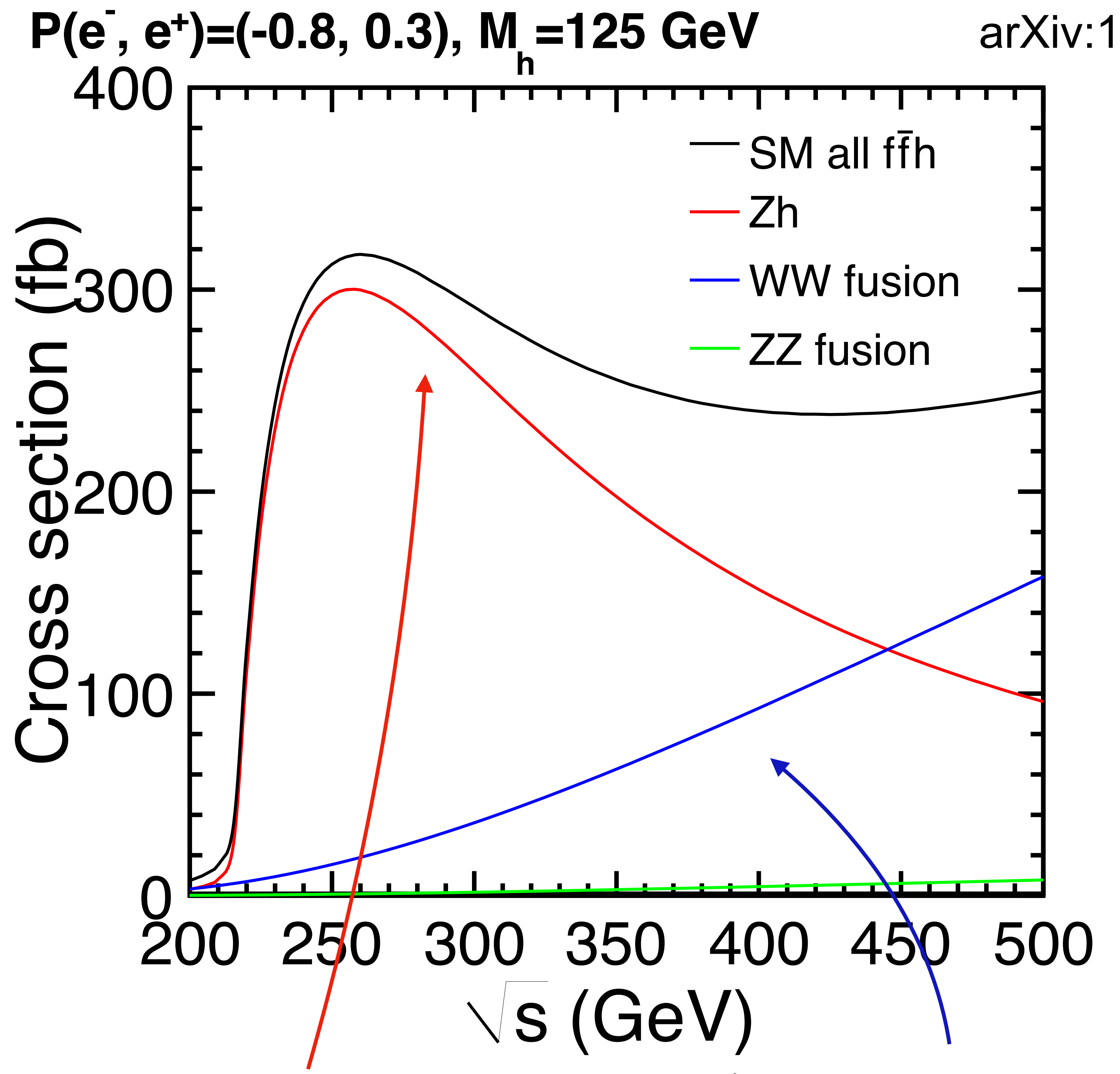
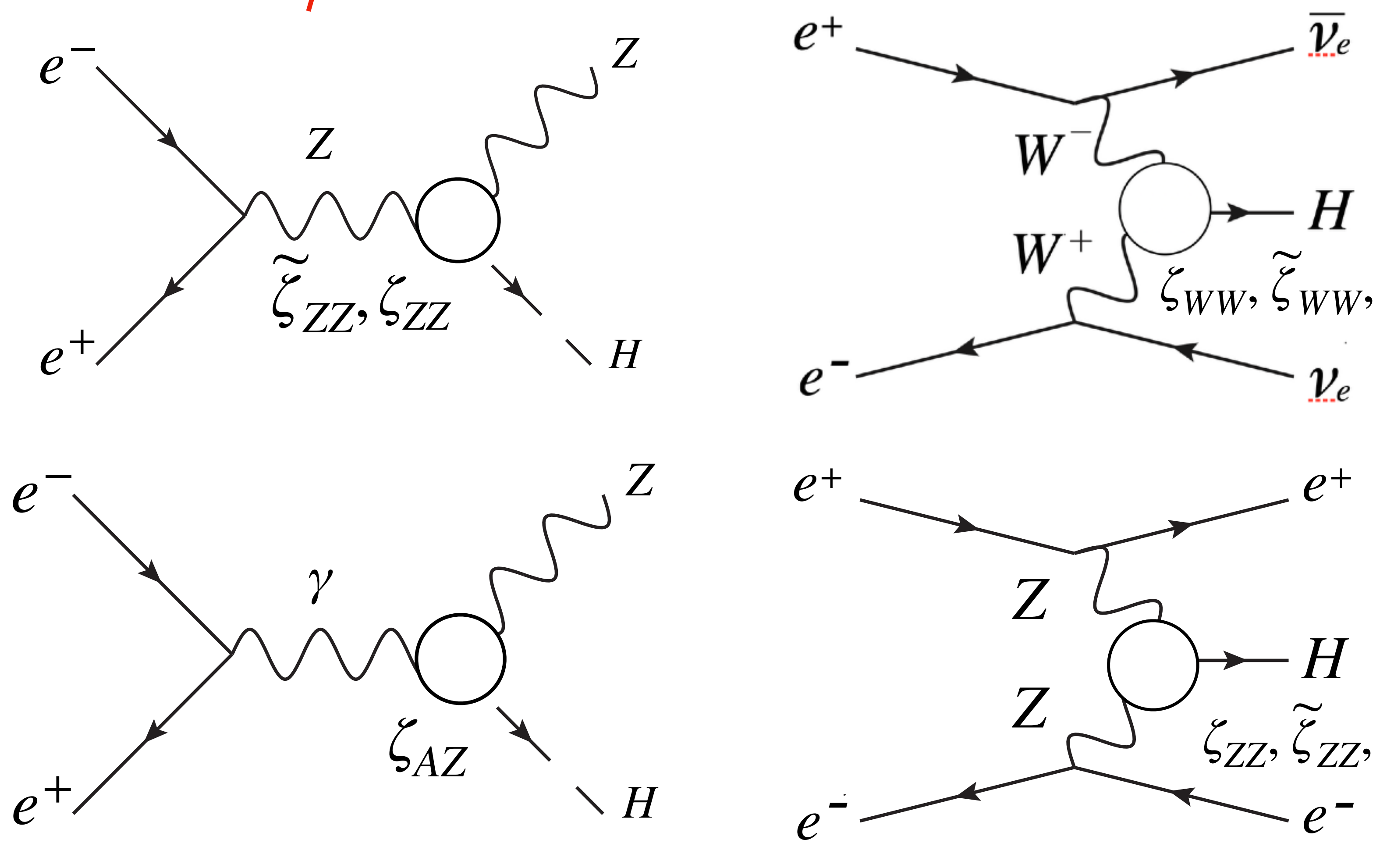
Higgs production in the SM





Framework and Software for the study

-. The study was done based on International Large Detector (ILD) for the ILC. Reconstruction tools developed by 2018 are used in the study.

https://arxiv.org/abs/1306.6329 Volume 4: Detectors

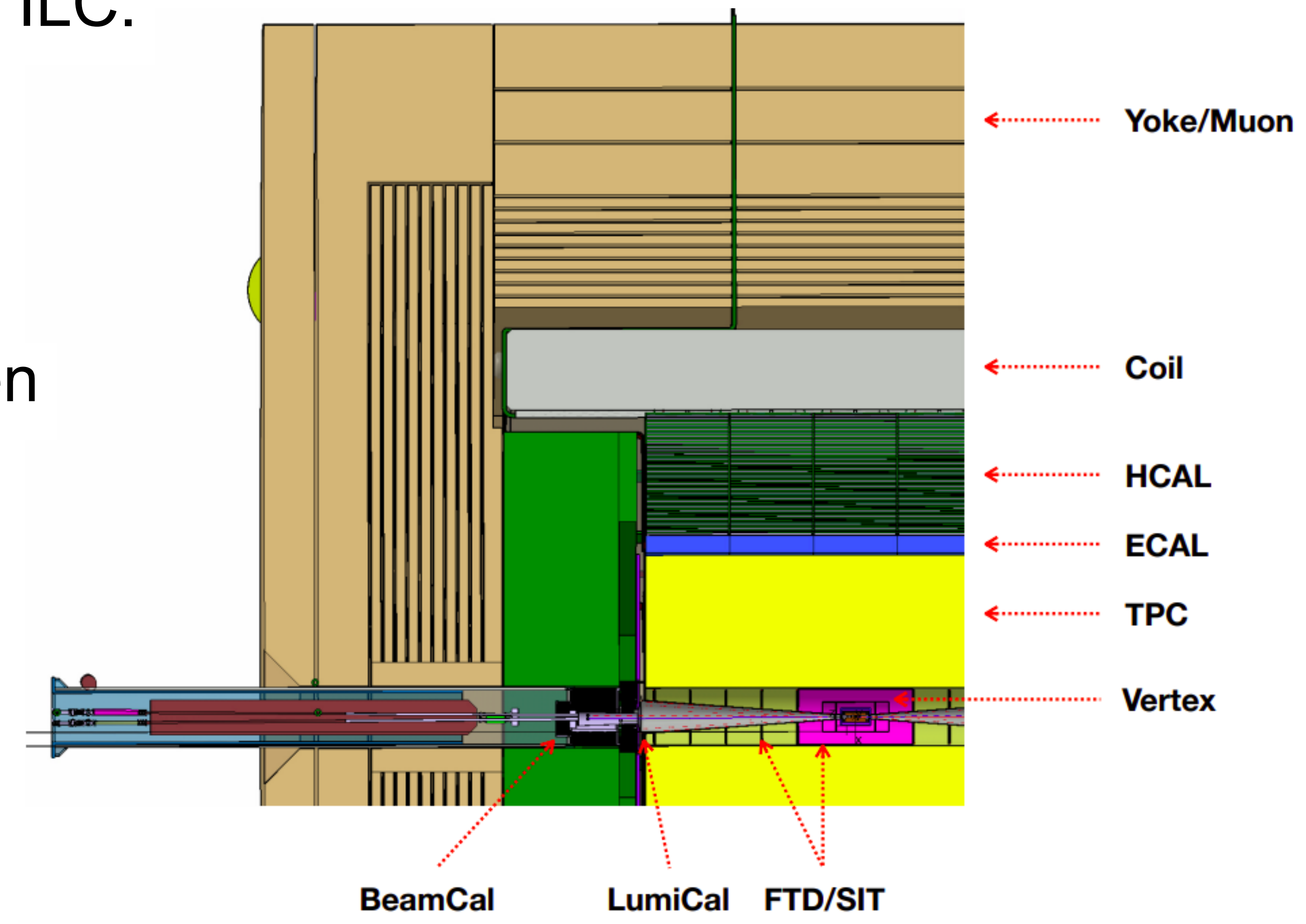
-. After 2018 the design was updated and reconstruction tools have been developed based on ToF and DNN, which could improve the results.

https://arxiv.org/abs/1912.04601 The ILD detector at the ILC

-. Physics generator for predicting the shape of kinematics including the anomalous VVH is PHYSSIM, which has been developed for LC physics studies as of today. https://www-jlc.kek.jp/subg/offl/physsim/

-. All MC event samples used in the study was originally generated for ILC physics studies. https://arxiv.org/abs/1306.6352 Volume 2: Physics

https://arxiv.org/abs/1912.04601



A magnetic filed of 3.5 [T]

Resolutions as the key detector performance

Impact parameter	$\sigma_{r\phi} = 5 \oplus 10/p \cdot \sin^{3/2}\theta$ [μm]
Momentum	$\sigma_{1/p_T} \sim 2 \times 10^{-5}$ [GeV^{-1}]
Jet energy	$\sigma_{E_{\rm jet}}/E_{\rm jet} \sim 3\,\%$ ($E_{\rm jet} < 100$GeV)

Impact on the shape in ZZH

-. Focus on ZZH:

Rescaling
the normalization.

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

parity-conserving interaction
scalar : CP-even interaction

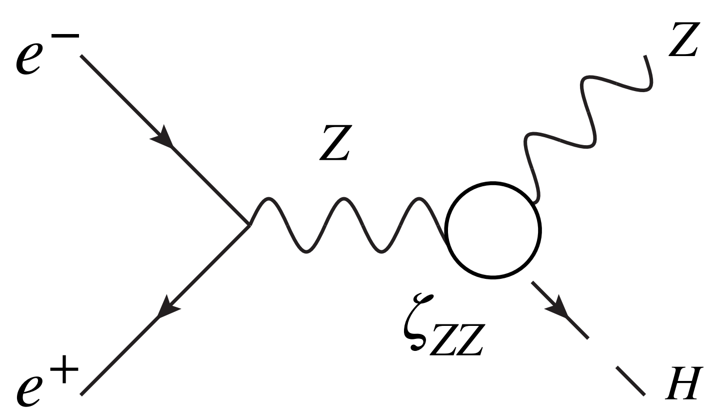
parity-conserving interaction
pseudo-scalar : CP-odd interaction

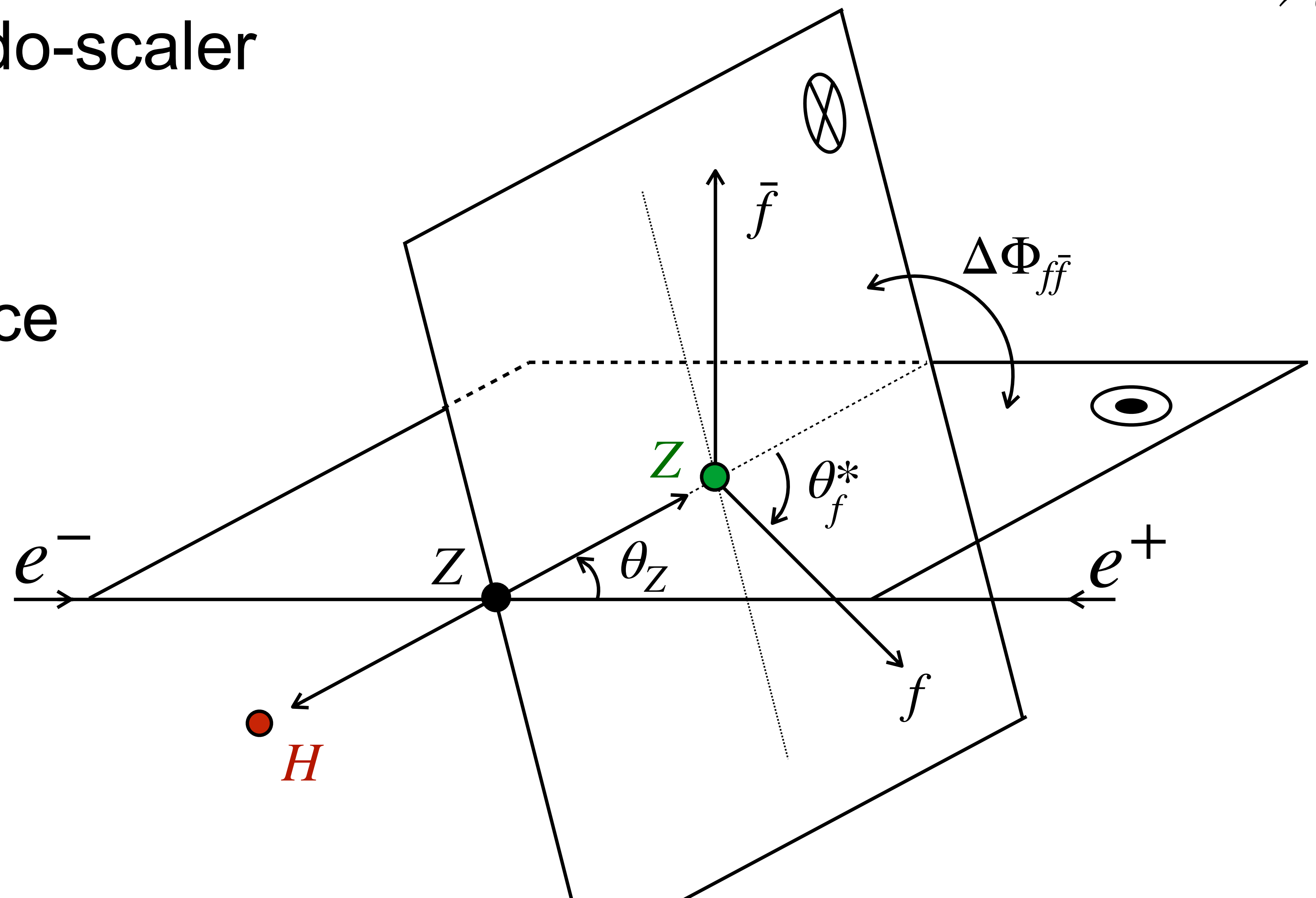
-. a term is the same structure with the SM.

-. b term is a new scalar (Parity=+1) structure

-. bt term is a new pseudo-scaler (Parity= −1) structure

-. Field strength has momentum dependence



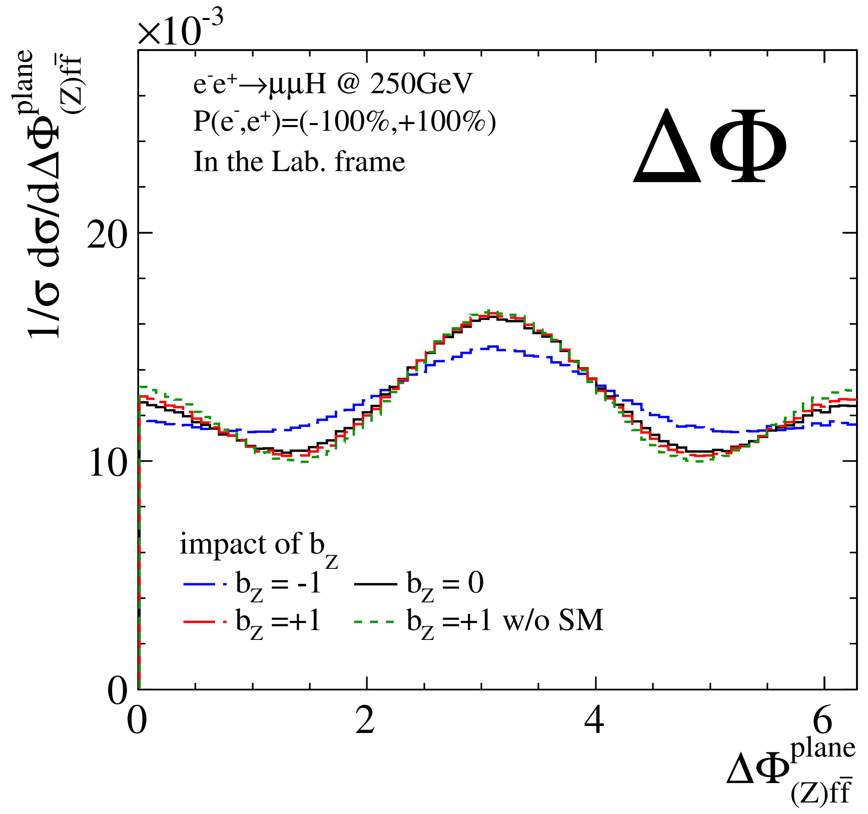


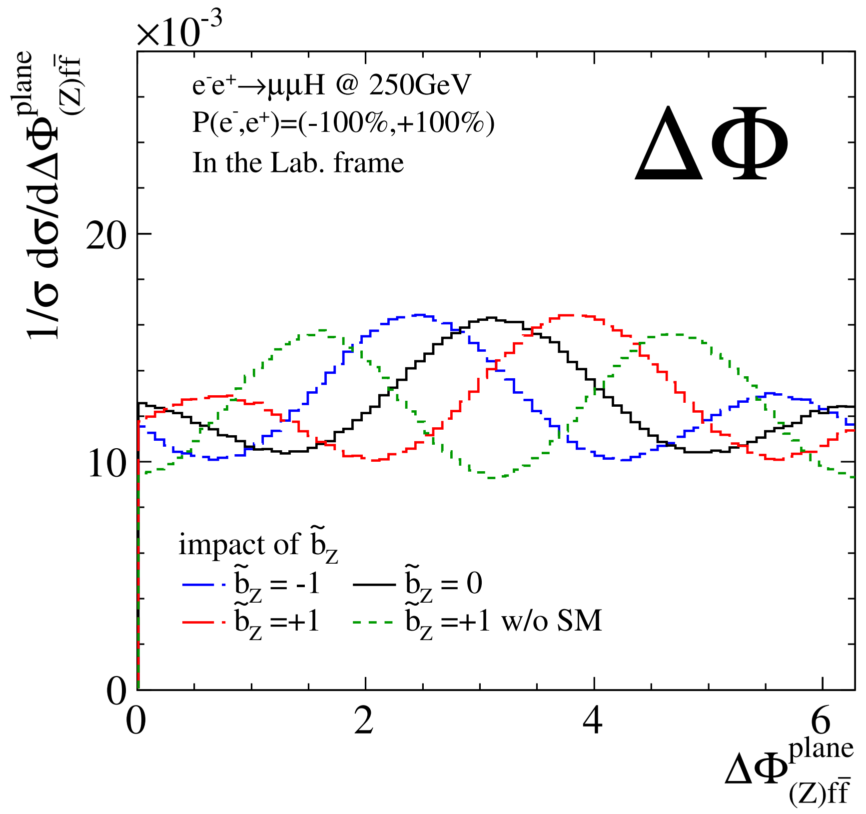
the laboratory frame

b term

bt term

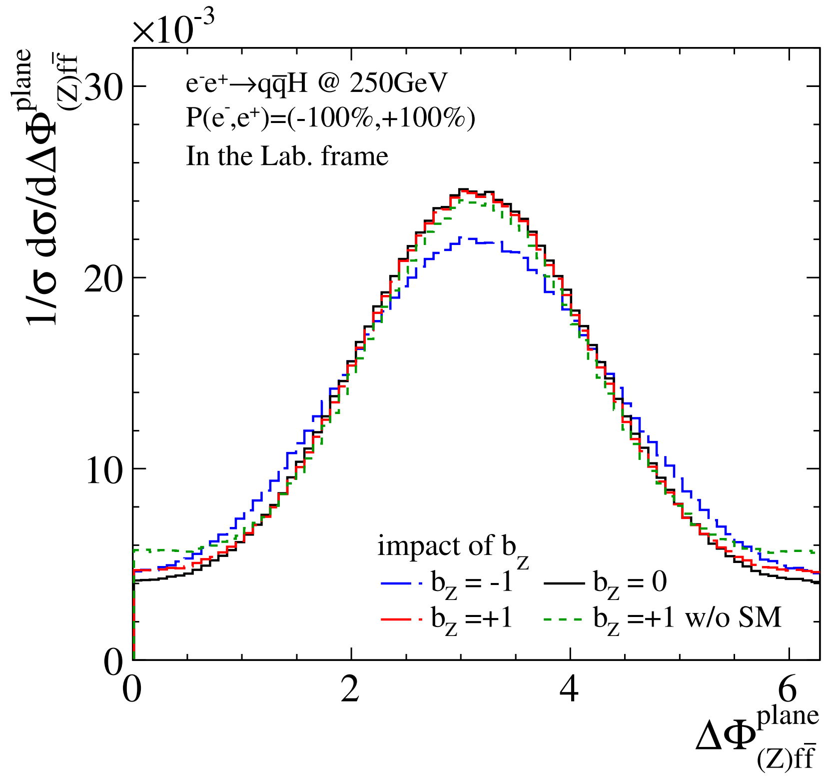
$e^+e^- \to Zh \to l^+l^-h$

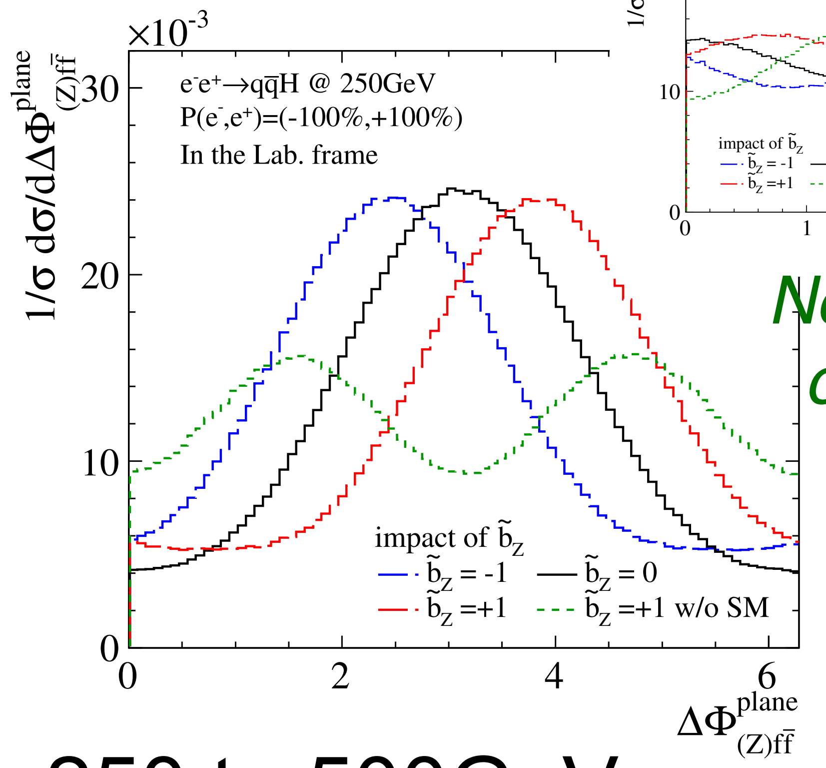


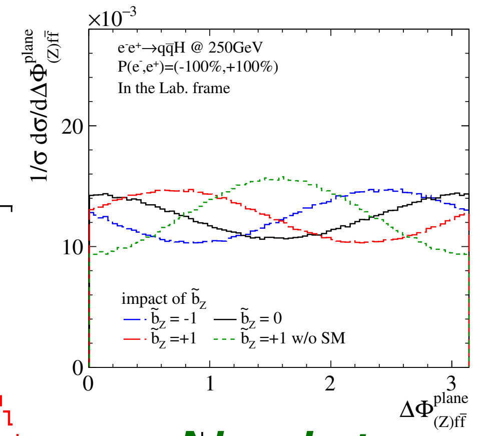


Because of the V-A structure
the coupling of q to Z is different from the lepton, thus, the shape varies

$e^+e^- \to Zh \to q\bar{q}h$

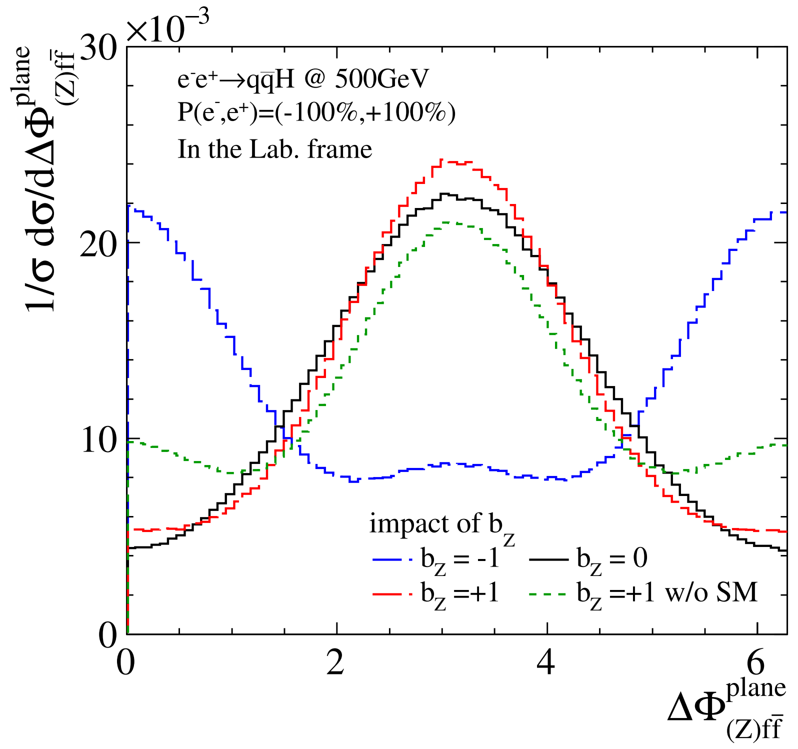


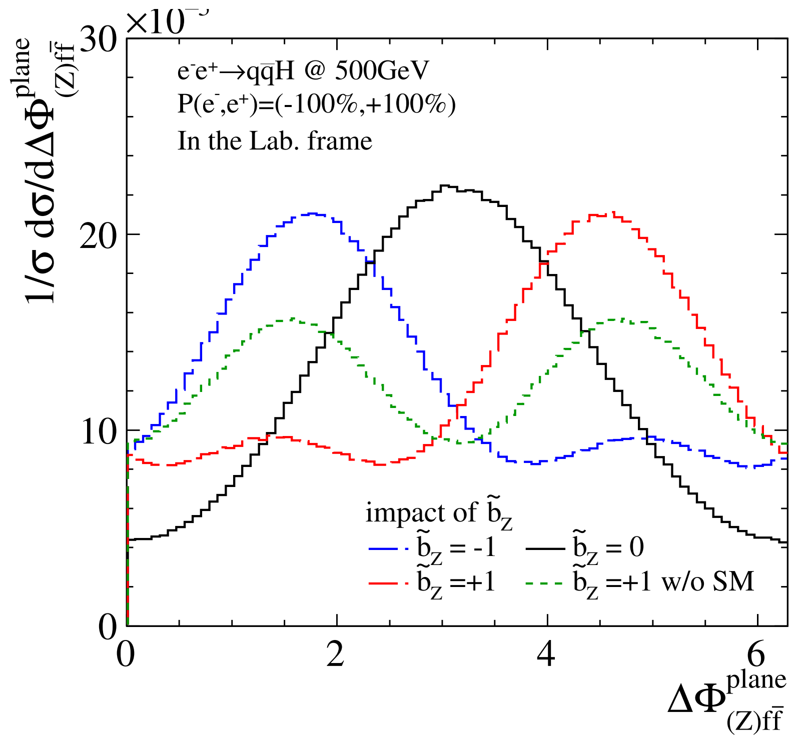




No Jet
charge ID

250 to 500GeV





Impact on the shape in WWH

-. Focus on WWH:

$$\mathcal{L}_{\mathrm{WWH}} = 2M_{\mathrm{W}}^2\left(\frac{1}{v}+\frac{a_{\mathrm{W}}}{\Lambda}\right)W_\mu W^\mu H + \frac{b_{\mathrm{W}}}{\Lambda}\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}H + \frac{\tilde{b}_{\mathrm{W}}}{\Lambda}\hat{W}_{\mu\nu}\widetilde{\hat{W}}^{\mu\nu}H$$

Rescaling the normalization.

parity-conserving interaction
scalar : CP-even interaction

parity-conserving interaction
pseudo-scalar : CP-odd interaction

-. a term is the same structure with the SM.

-. b term is a new scalar (Parity=+1) structure

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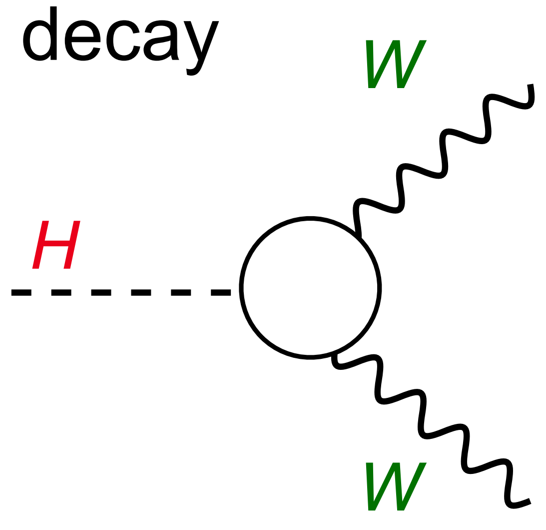
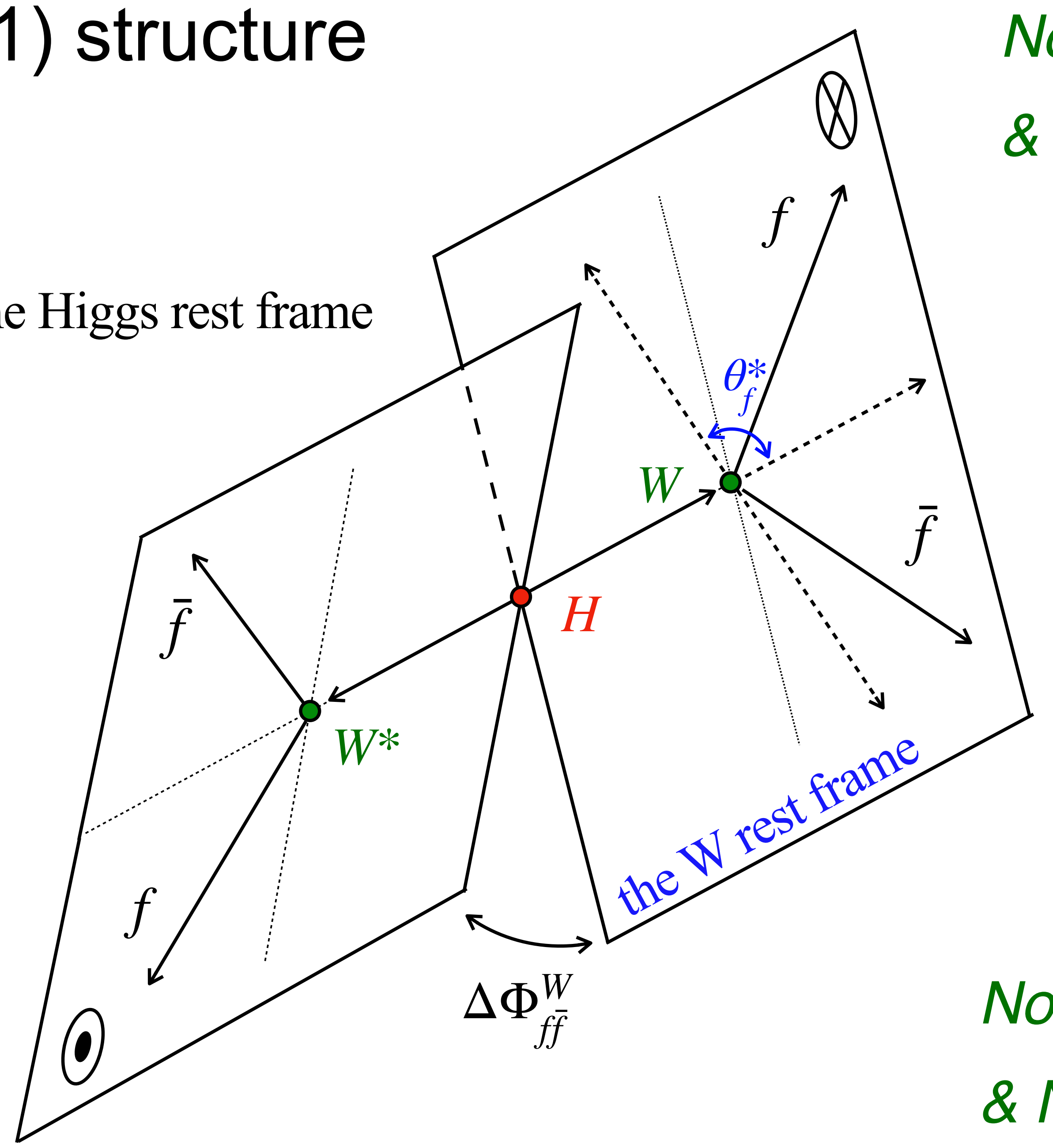
-. Field strength has momentum dependence

the Higgs decay



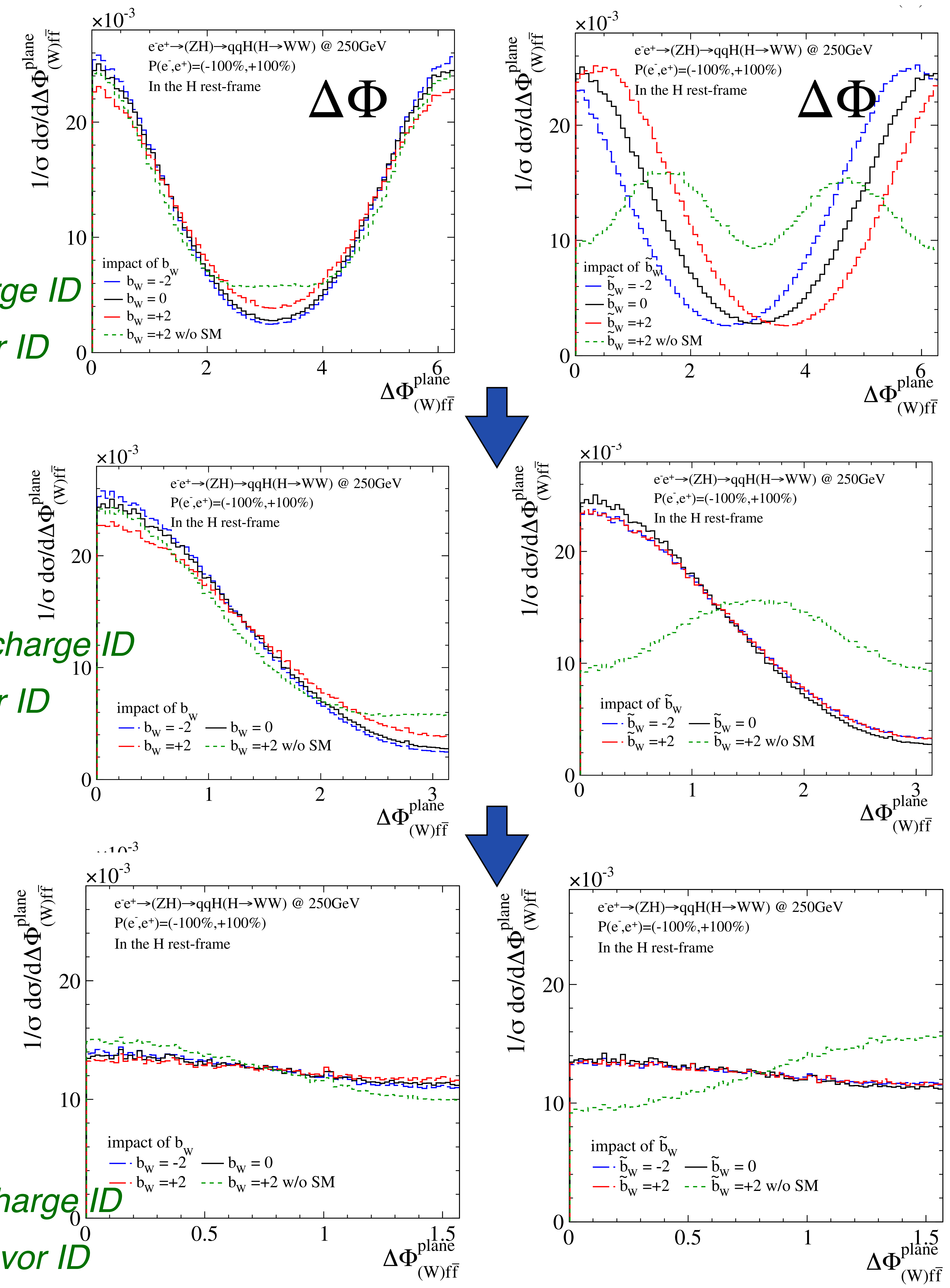


b term | bt term

Jet charge ID & Flavor ID

No Jet charge ID & Flavor ID

No Jet charge ID & No Flavor ID

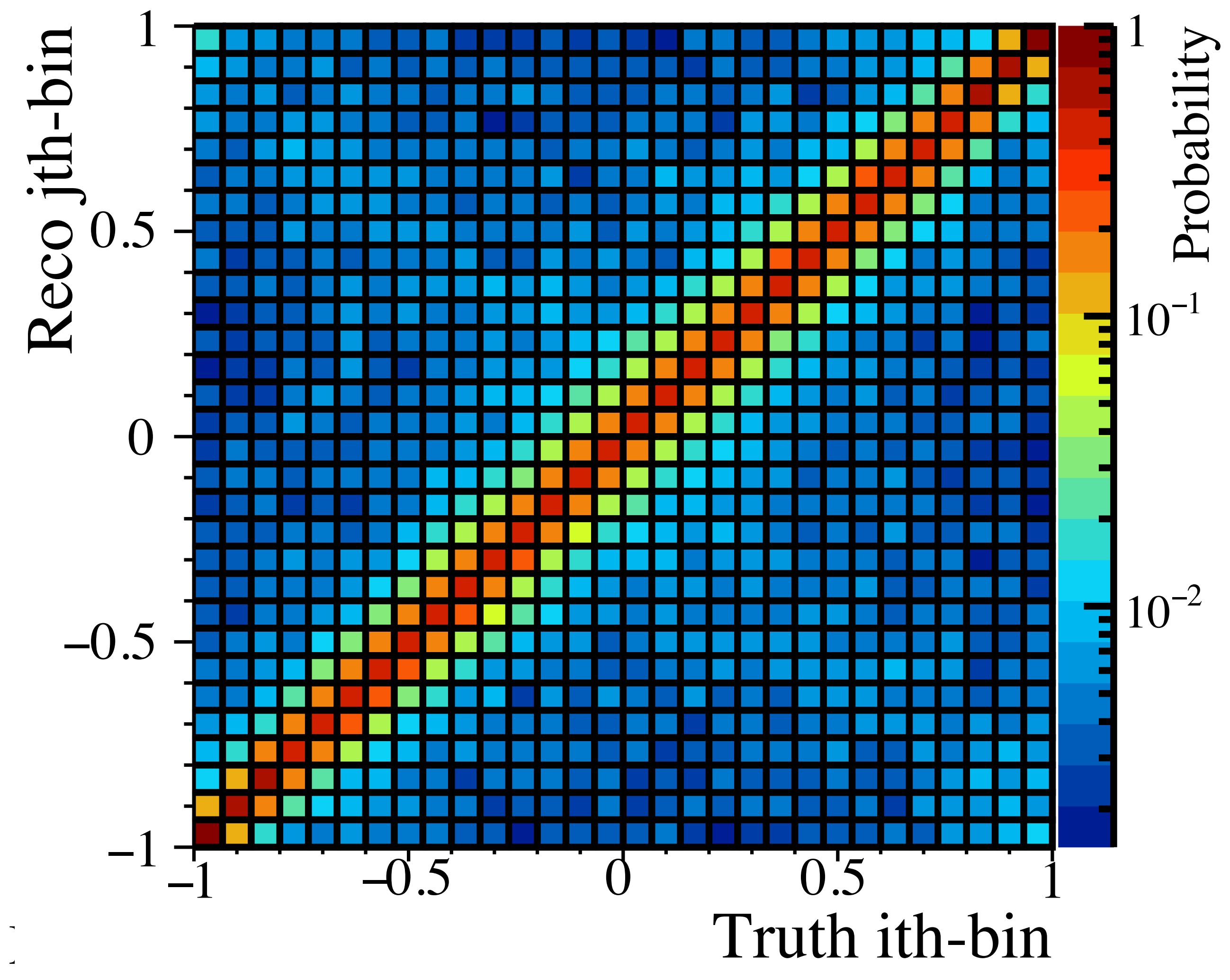


Analysis strategy

-. Clarification of the impact of shape and normalization on the sensitivity

$$\chi^2_{\rm shape} = \sum_{j=1}^{n} \left[\frac{N_{\rm SM} \sum_{i=1}^{n} (S_i^{\rm SM} \cdot f_{ji}^{\rm Det} - S_i^{\rm BSM} \cdot f_{ji}^{\rm Det})}{\Delta n^{\rm obs}_{\rm SM}(x_j)} \right]^2$$

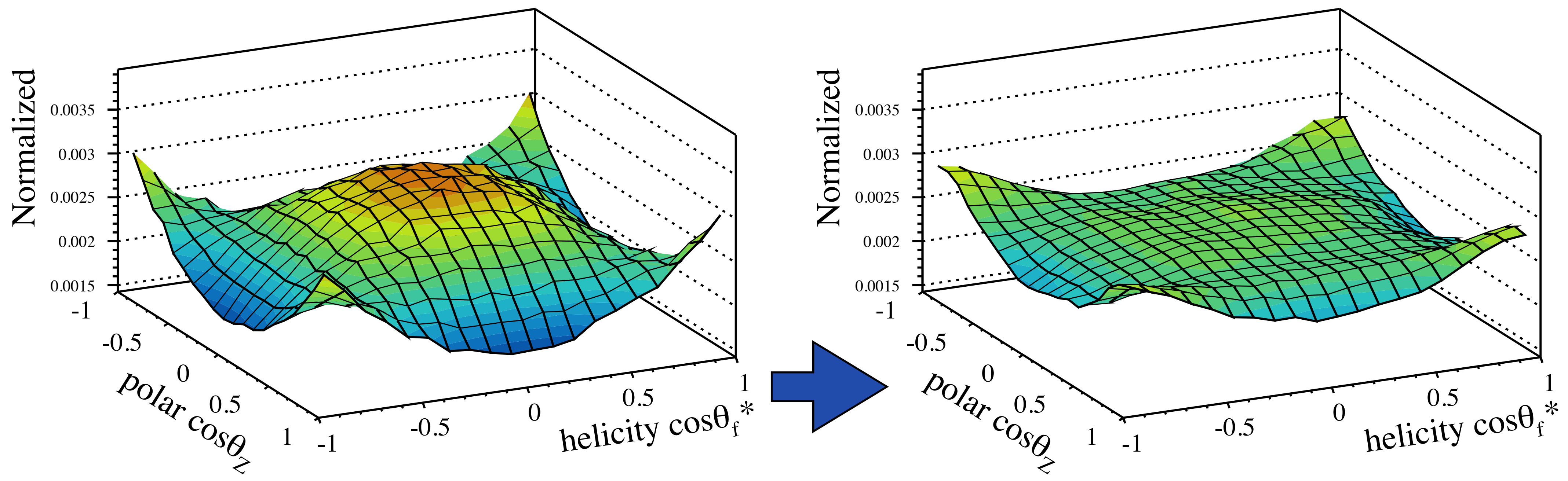
= Detector acceptance × Detector migration matrix



Normalized shape $S_i^{\rm BSM} = \frac{1}{\sigma_{\rm BSM}} \frac{d\sigma_{\rm BSM}}{dx}(x_i; \vec{a}_{\rm Z})$

-. Prepared a multi dimensional distribution in each process, which is sensitive to the anomalous VVH couplings.

e.g. 2-dim



Smear following the detector effects

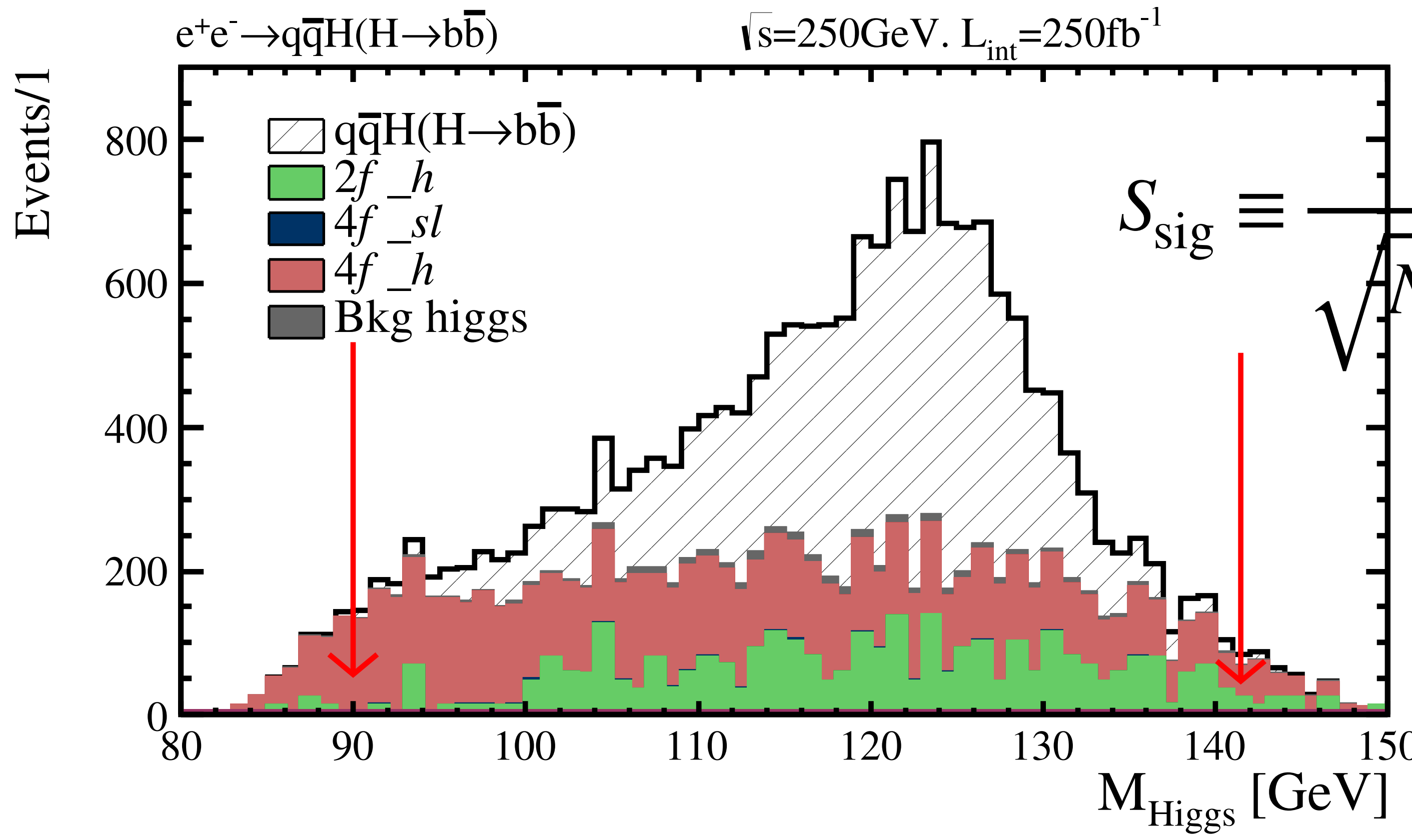
$$\chi^2_{\rm norm} = \left[\frac{N_{\rm SM} - N_{\rm BSM}(\vec{a}_Z)}{\delta\sigma_{ZH} \cdot N_{\rm SM}} \right]^2$$

↪ Inputs from the past full simulation studies.
δσzh = 2%, 3% for 250GeV, 500GeV (e.g. arXiv:1604.07524)

-. The variation of partial widths due to anomalous VVH is not considered.
Thus, normalization of the decay is not included in this study.
Consideration of variation of partial widths will be a next step.

Constraints on ZZH

$e^+e^- \to q\bar{q}h\ (h \to b\bar{b})$ has large statistics.



$$S_{\rm sig} \equiv \frac{N_{\rm sig}}{\sqrt{N_{\rm sig}+N_{\rm bkg}}} = 72.4$$

-. Analyzed dominant processes for E_{cm} of 250 & 500GeV.

$$\begin{cases} e^+e^- \to Zh \to \mu^+\mu^- h,\ \ e^+e^- h \\ e^+e^- \to Zh \to q\bar{q}h\ (h \to b\bar{b}) \\ e^+e^- \to ZZ \to e^+e^- h\ (h \to b\bar{b}) \end{cases}$$

Fit in three parameters.

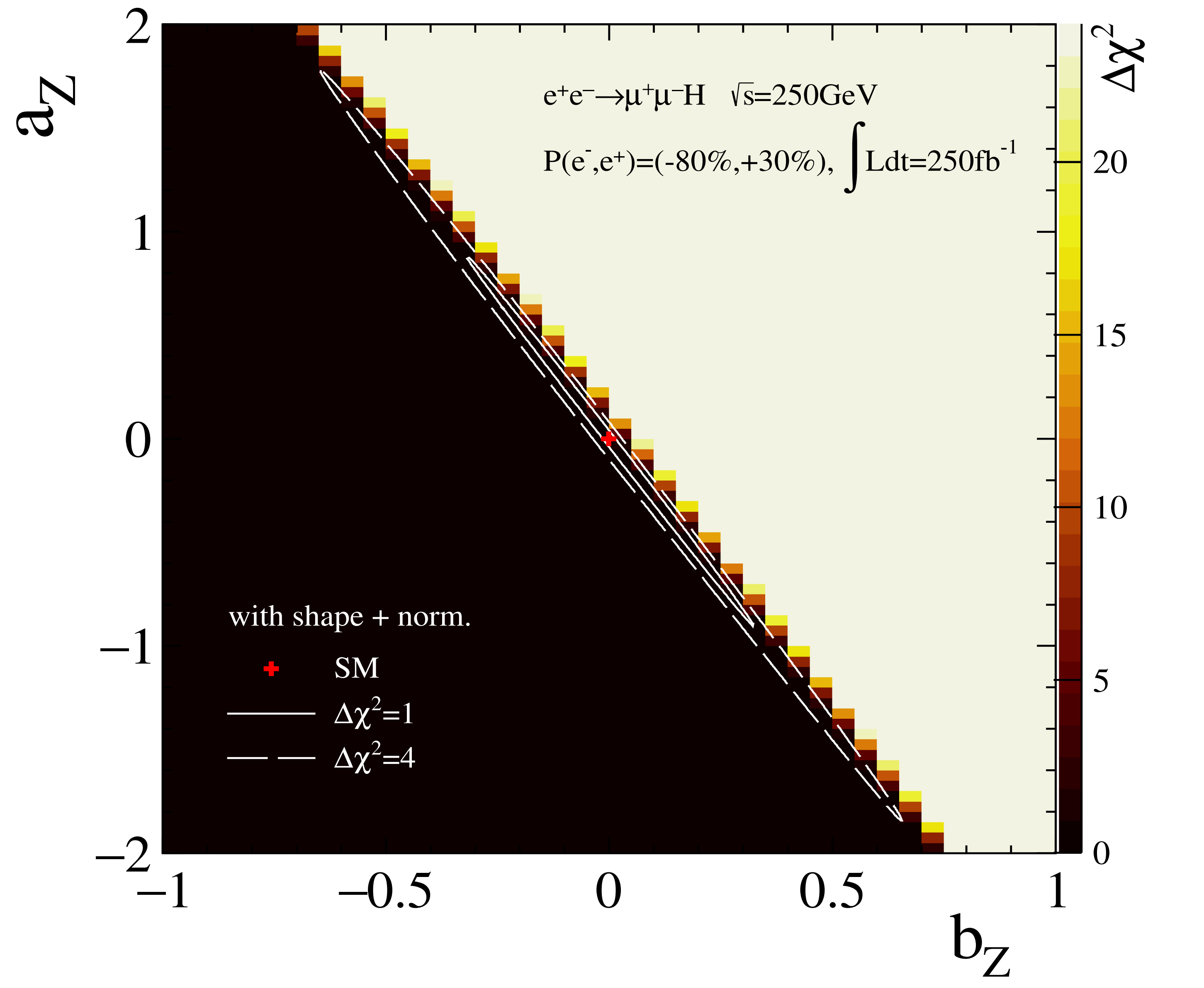
-. Inclusion of the norm. only is color.

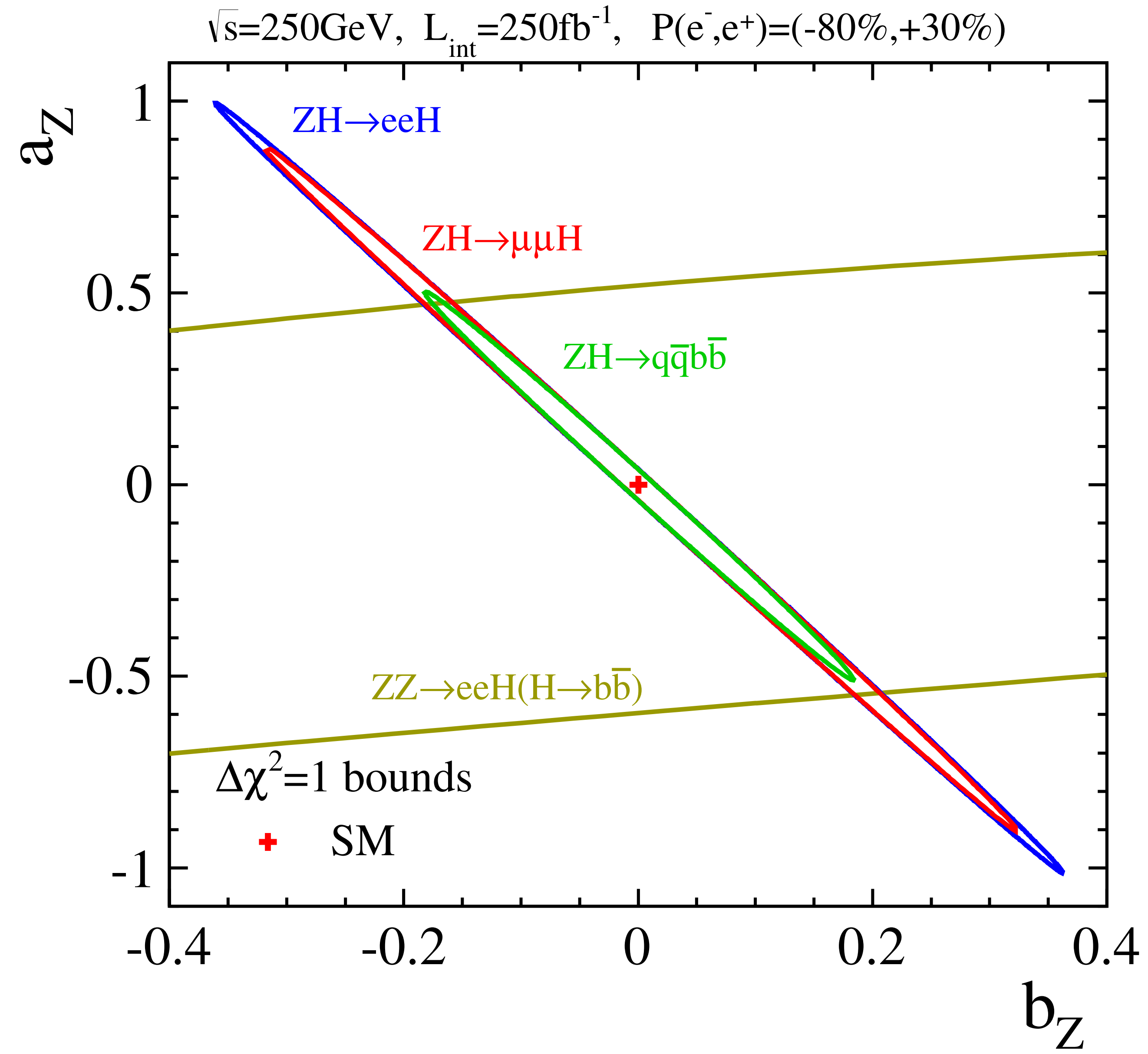
-. Contours include the shape.

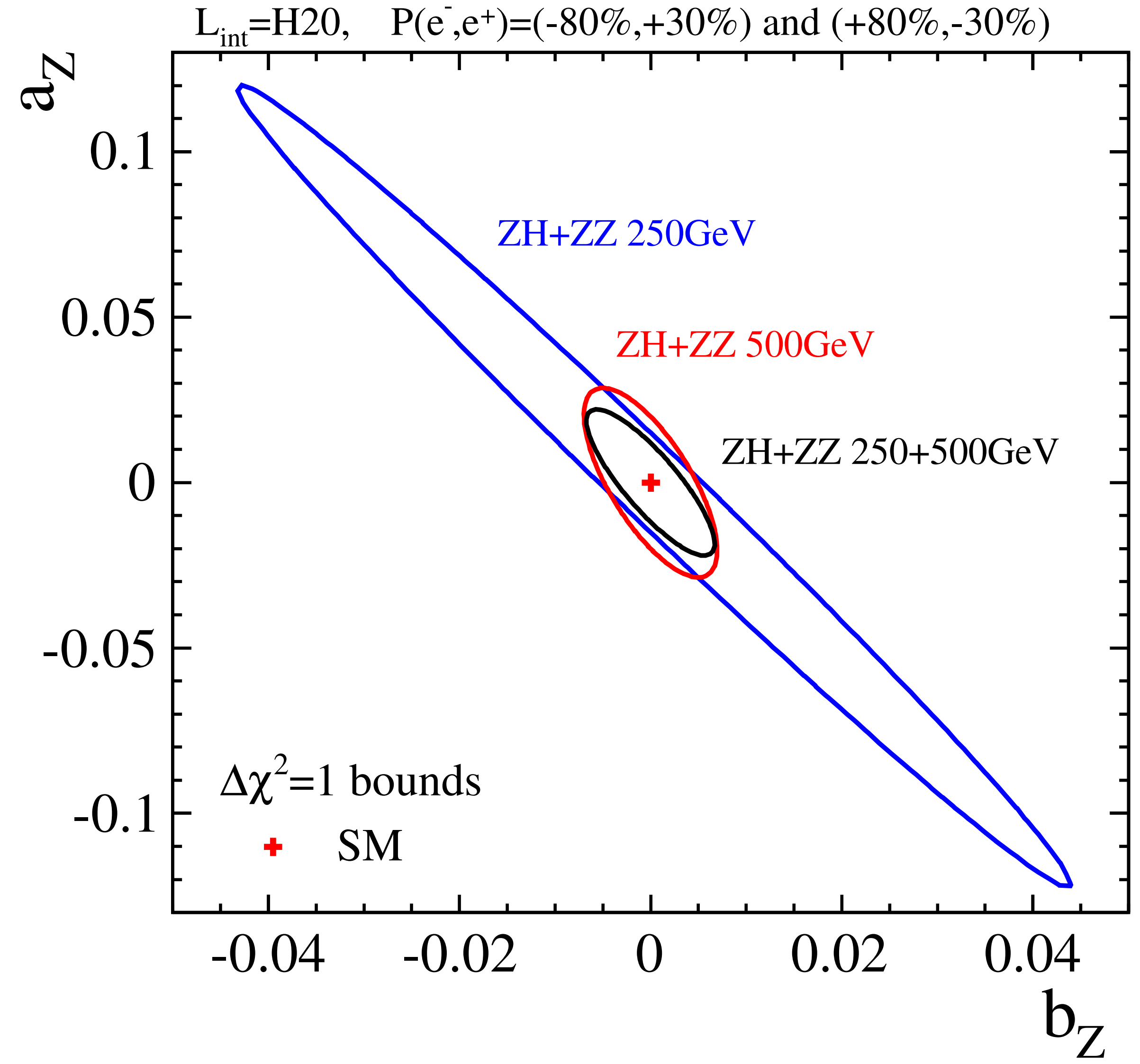
-. qqH has significant sensitivity even w/o jet charge identification.

-. The ZZ-fusion can disentangle the correlation → it gets significant more at 500GeV.

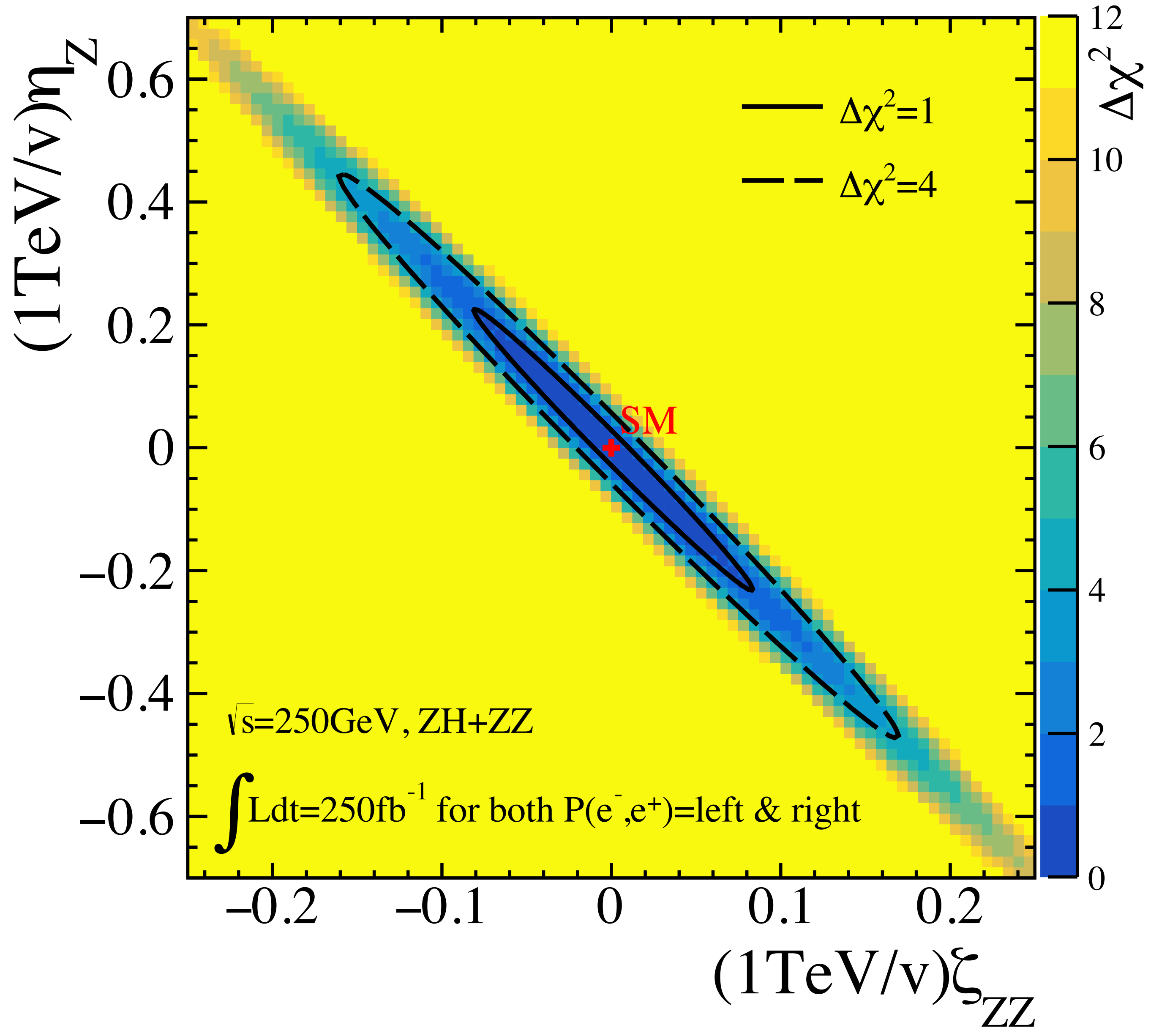
-. The sensitive in ILC full operation 500GeV gives better sensitivities w/250 GeV squeezes the area more.



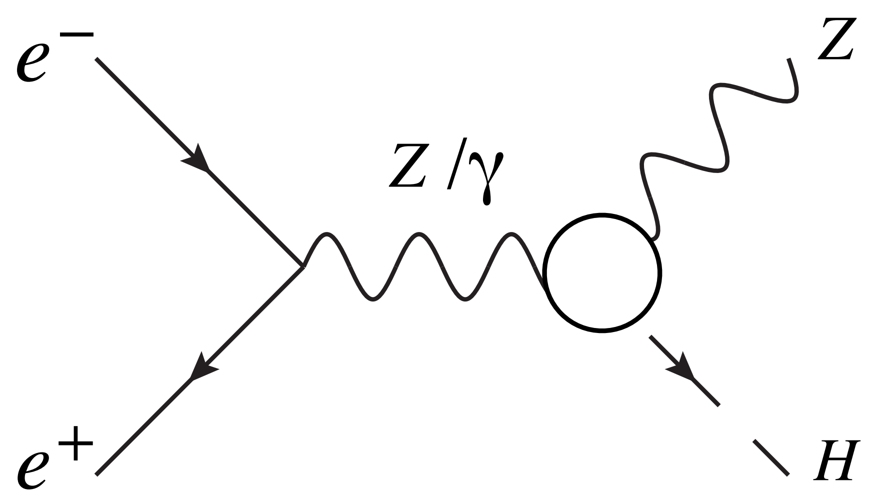




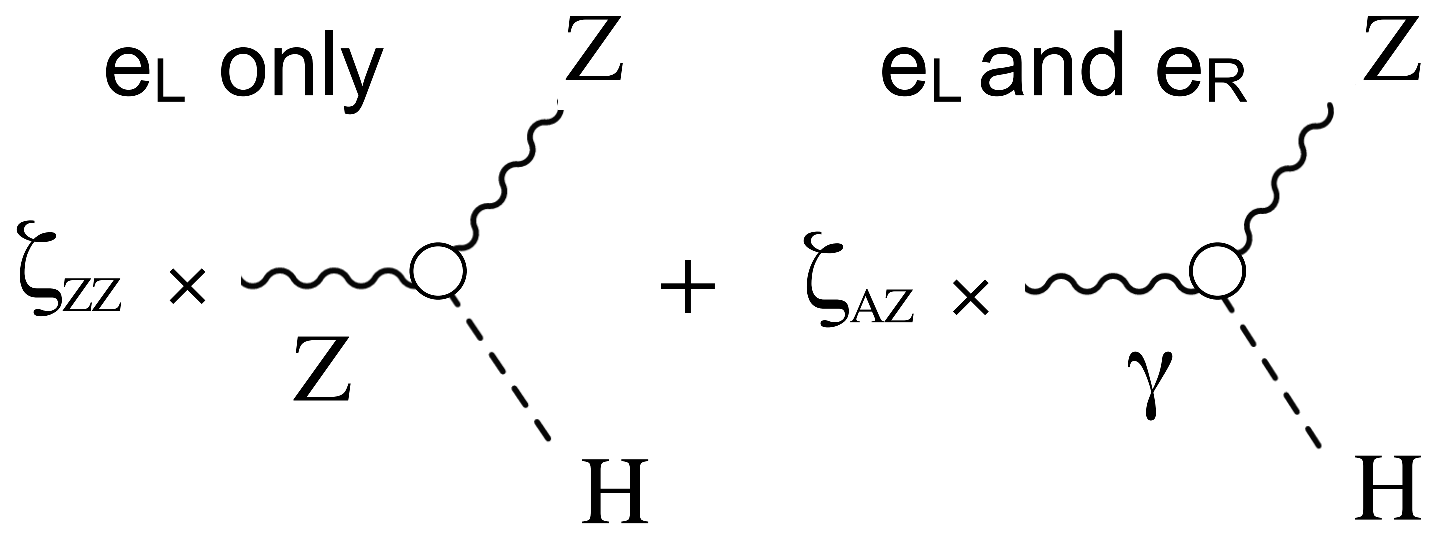
Constraints on ZZH and ZγH



A and Z are mixing through SU2xU1 gauge symmetry.



→ Beam polarization can disentangle ZZH and ZγH by employing the characteristic of B and W^3



To connect both parametrizations, the different beam polarization state LR and RL are connected based on the cross section calculation. (Based on PHYSSIM)

250GeV case

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

$$\begin{cases} \zeta_{ZZ} = 0.54\, b_Z^{e_L^- e_R^+} + 0.46\, b_Z^{e_R^- e_L^+} \\ \zeta_{AZ} = 0.34\, b_Z^{e_L^- e_R^+} - 0.34\, b_Z^{e_R^- e_L^+} \end{cases}$$

$$\eta_Z = \frac{v}{\Lambda}a_Z, \quad \zeta_{ZZ} = \frac{v}{\Lambda}b_Z, \quad \widetilde{\zeta}_{ZZ} = \frac{v}{\Lambda}\widetilde{b}_Z$$

$$\mathcal{L}_{ZZH+\gamma ZH} = M_Z^2\frac{1}{v}\left(1+\eta_Z\right)Z_\mu Z^\mu H + \frac{\zeta_{ZZ}}{2v}Z_{\mu\nu}Z^{\mu\nu}H + \frac{\zeta_{AZ}}{v}A_{\mu\nu}Z^{\mu\nu}H + \frac{\widetilde{\zeta}_{ZZ}}{2v}Z_{\mu\nu}\widetilde{Z}^{\mu\nu}H + \frac{\widetilde{\zeta}_{AZ}}{v}A_{\mu\nu}\widetilde{Z}^{\mu\nu}H$$

Constraints on WWH

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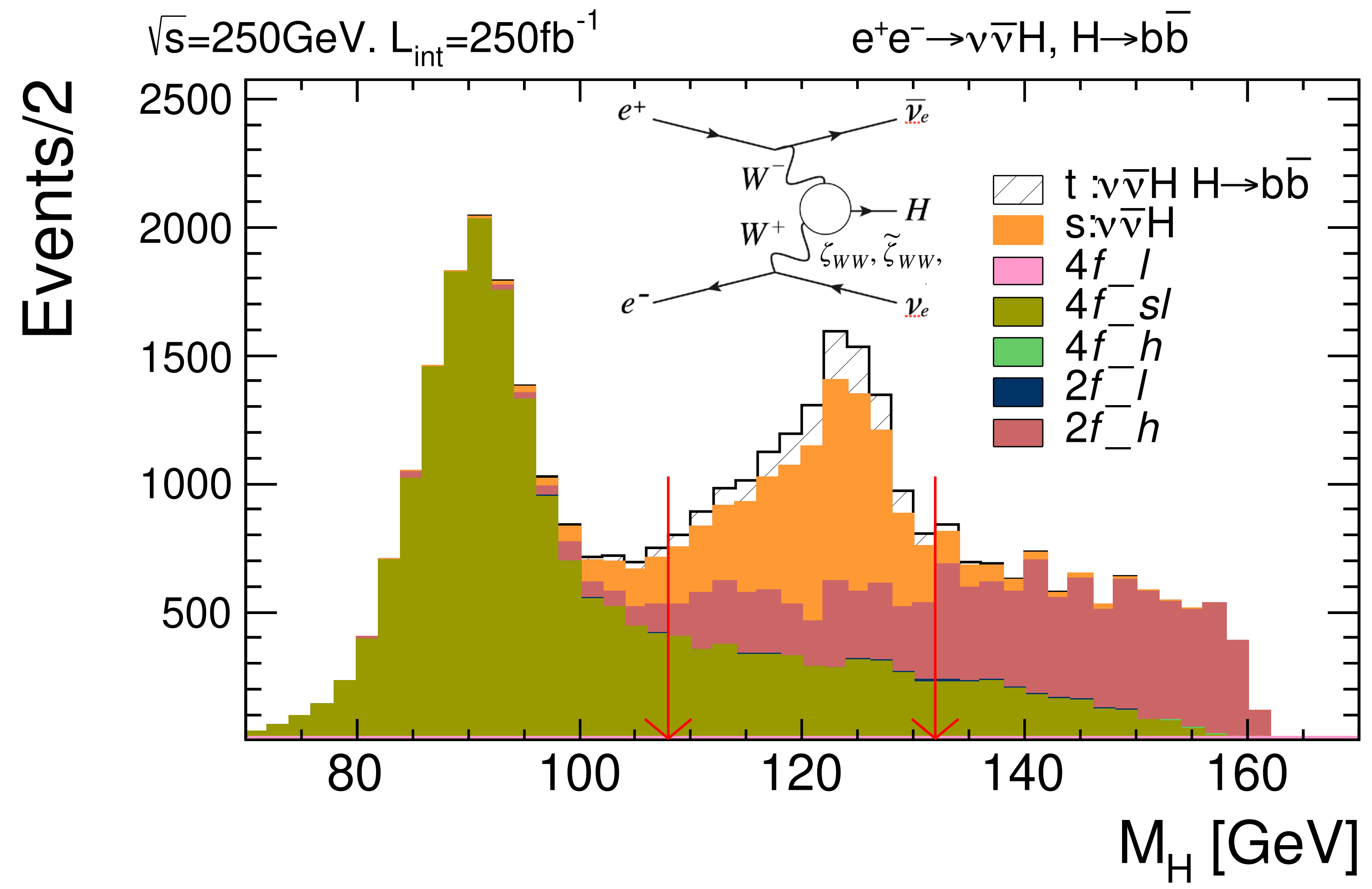


-. Analyzed dominant processes for E_{cm} of 250 & 500GeV.

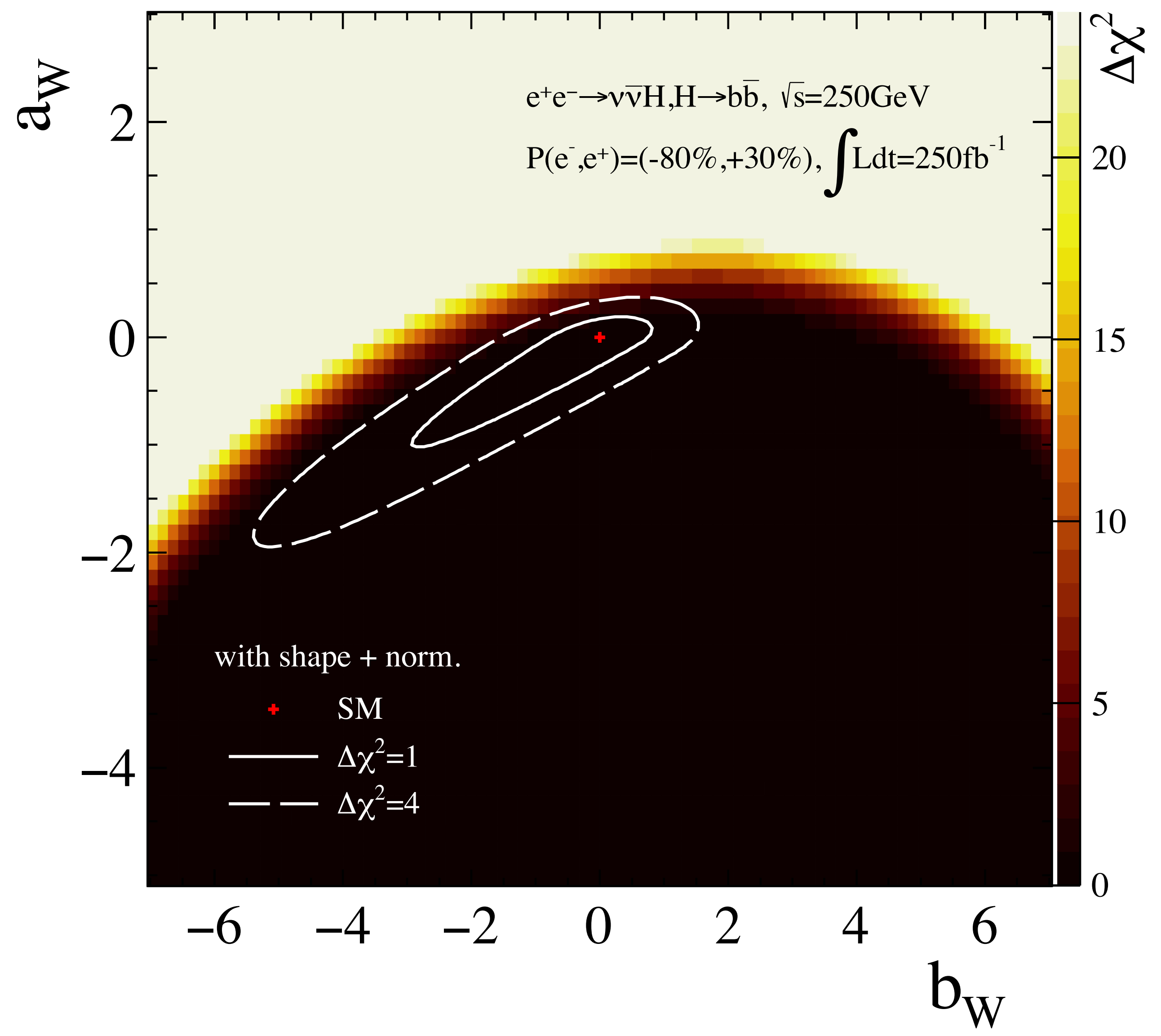
$$\begin{cases} e^+e^- \to WW \to \nu_e\bar{\nu}_e h \quad (h \to b\bar{b}) \\ e^+e^- \to WW \to \nu_e\bar{\nu}_e h \ (h \to WW \to 4q) \\ e^+e^- \to Zh \to q\bar{q}h \ (h \to WW^* \to q\bar{q}l\bar{\nu}/4q) \\ e^+e^- \to Zh \to \nu\bar{\nu}h \ (h \to WW^* \to 4q) \end{cases}$$

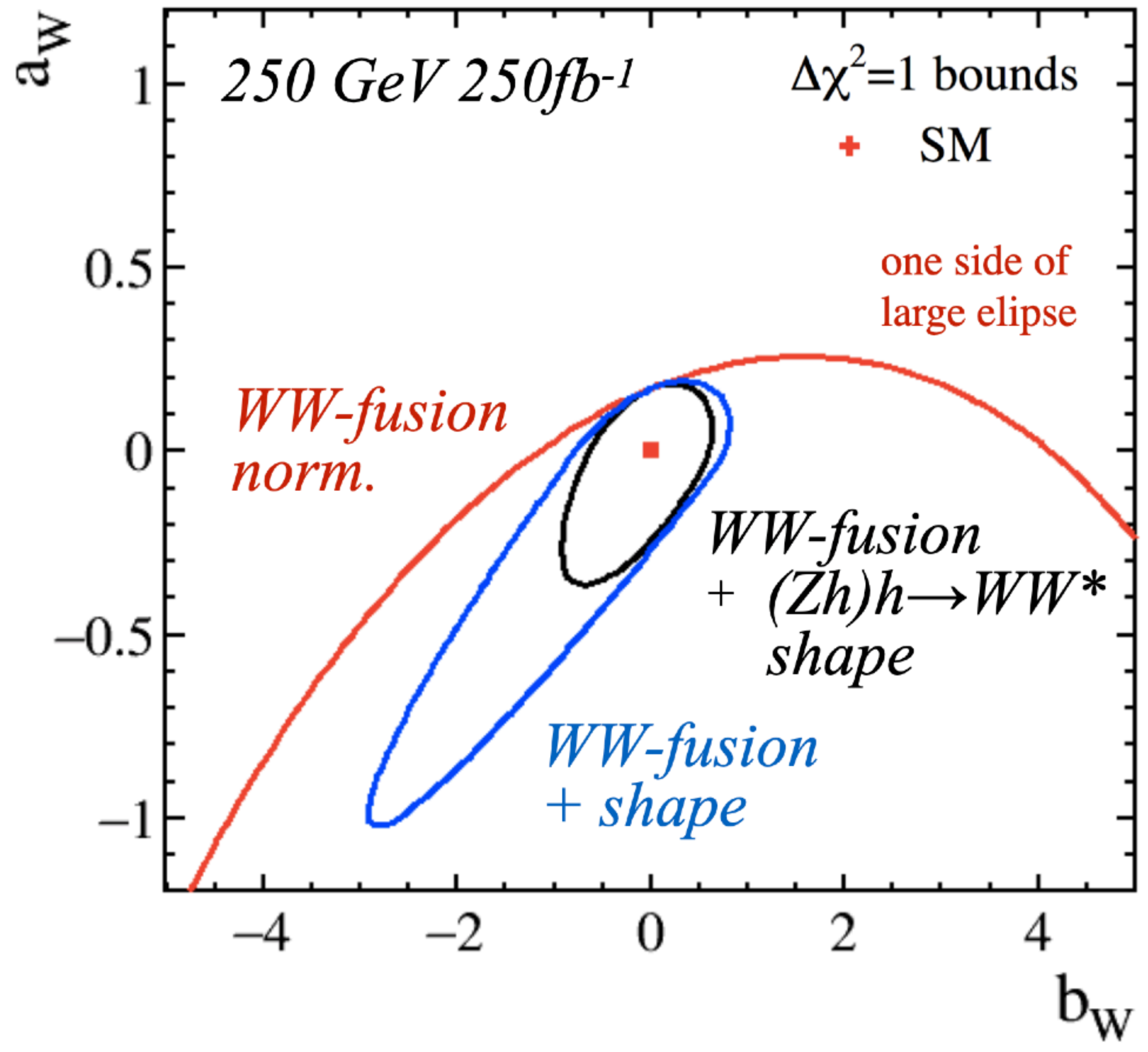
Fit in three parameters.

-. Inclusion of the norm. only is color.

-. Contours include the shape.

the shape from Zh (dominated by qqlv) can squeeze the parameter space.





Constraints on WWH

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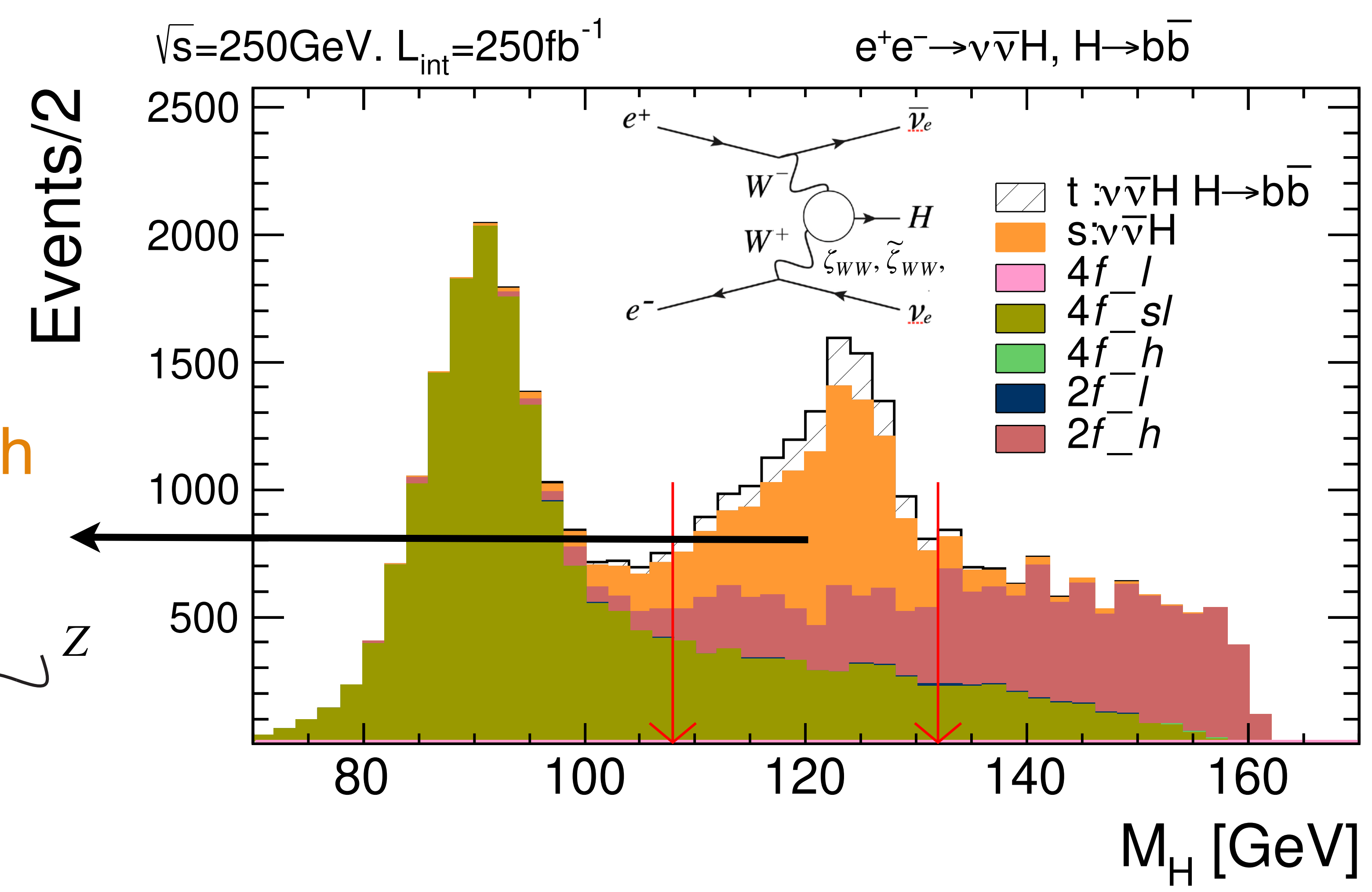
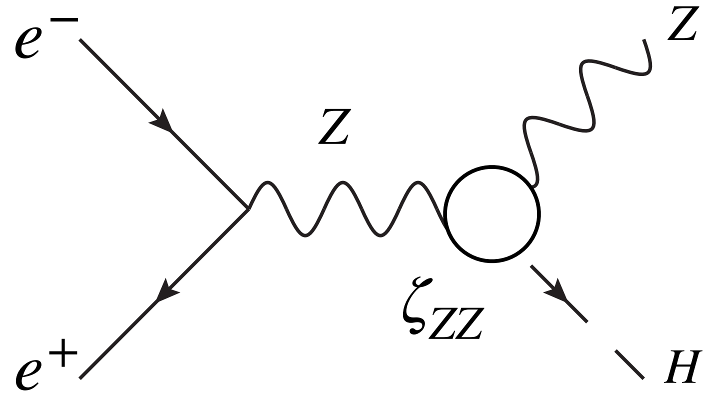
$$e^+e^- \to WW \to \nu_e\bar{\nu}_e h \ \ (h \to b\bar{b})$$



Remains the large num. of s-ch ZH (ZZH vertex) that changes the shape



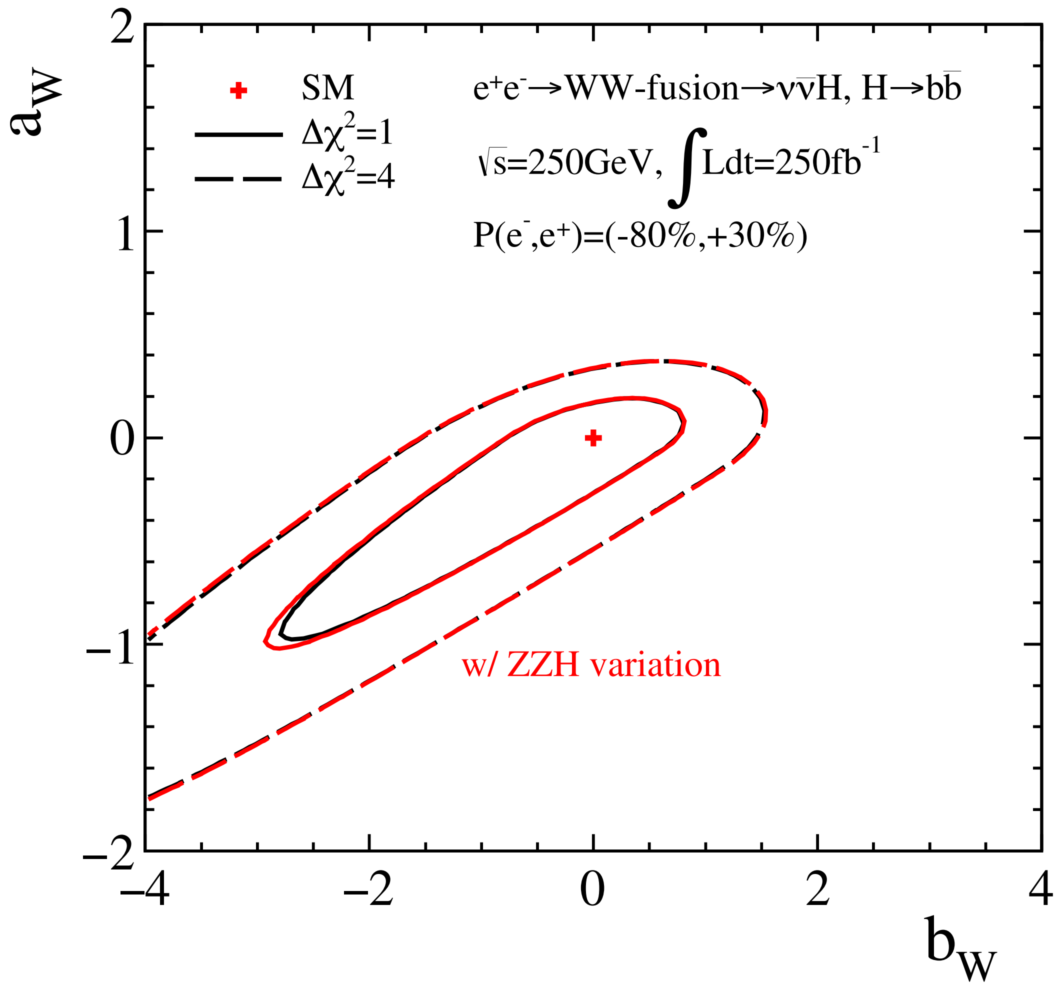
$$\chi^2_{\rm total} = \sum_j^n \left[\frac{S^{(t)}_{\rm SM}(x_i)\cdot f^{(t){\rm Det}}_{ji} - S^{(t)}_{\rm BSM}(x_i;\vec{a}_{\rm W})\cdot f^{(t){\rm Det}}_{ji} + S^{(s)}_{\rm SM}(x_i)\cdot f^{(s){\rm Det}}_{ji} - S^{(s)}_{\rm BSM}(x_i;\vec{a}_{\rm Z})\cdot f^{(s){\rm Det}}_{ji}}{\Delta n^{\rm obs}_{\rm SM}(x_j)} \right]^2$$

t-ch   s-ch

$$+ \left[\frac{N^{(t)}_{\rm SM} - N^{(t)}_{\rm BSM}(\vec{a}_{\rm W}) + N^{(s)}_{\rm SM} - N^{(s)}_{\rm BSM}(\vec{a}_{\rm Z})}{\delta\sigma^{(t)}_{\nu\bar{\nu}H}\cdot N^{(t)}_{\rm SM}} \right]^2$$

$$+ \ \vec{a}^{\,\rm T}_{\rm Z} \left(C^{\rm 25GeV}_{\rm ZZH}\right)^{-1} \vec{a}_{\rm Z}$$

ZZH constraints



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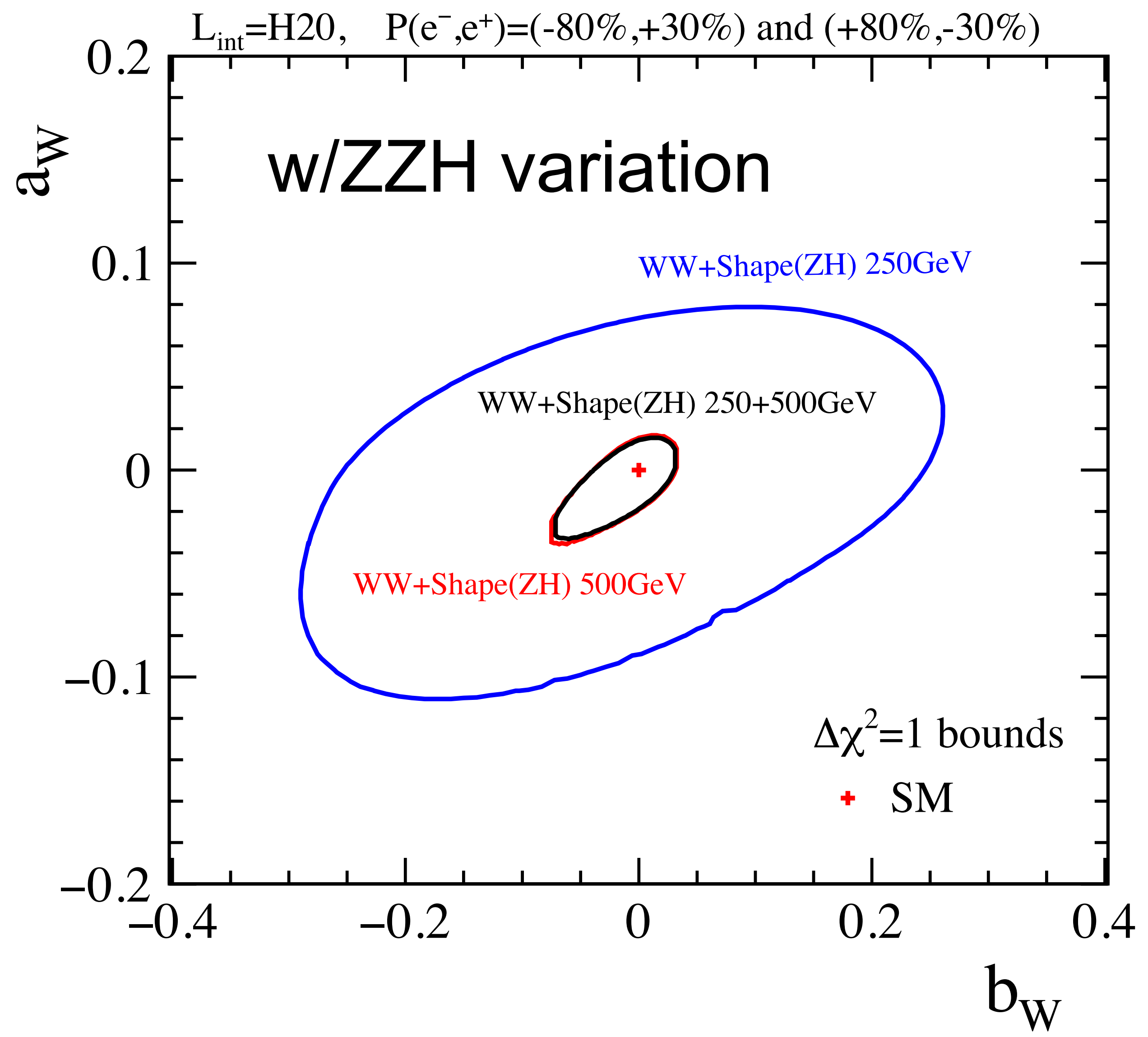


Constraints on VVH

-. The constraints for each VVH structure at the ILC are given.

$$\Delta\mathscr{L}_h = -\eta_h\lambda_0 v_0 h^3 + \frac{\theta_h}{v_0} h\partial_\mu h\partial^\mu h \quad \longleftarrow \text{(Higgs)}$$

T. Barklow et al., PRD 97, 053004 (2018)

$$+\eta_Z \frac{m_Z^2}{v_0} Z_\mu Z^\mu h + \frac{1}{2}\eta_{2Z}\frac{m_Z^2}{v_0^2} Z_\mu Z^\mu h^2 \quad \longleftarrow \text{(same structure with the SM)}$$

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

(new tensor structures)

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

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

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

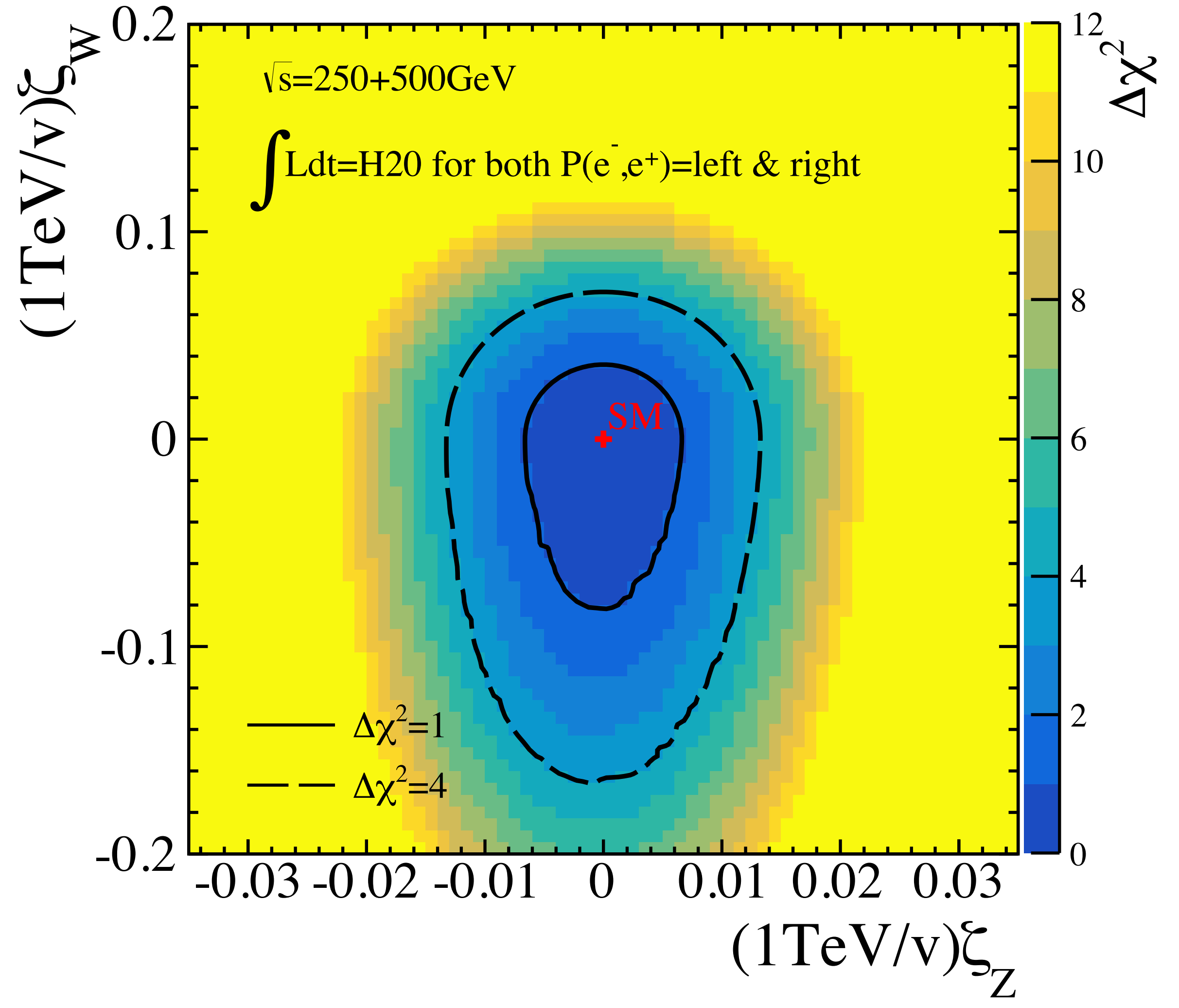
ILC operation scenario of 20 years

$$\sqrt{s} = 250 + 500\ \mathrm{GeV\ with} \int \mathrm{Ldt} = \mathrm{H20}$$

$$\left(\eta_Z = \frac{v}{\Lambda}a_Z,\ \zeta_{ZZ} = \frac{v}{\Lambda}b_Z\ :\ \Lambda/v = 4.065\right)$$

1 sigma bounds based on the study

$$\begin{cases} \eta_W &= [-0.0080, 0.0045] \\ \zeta_{WW} &= [-0.0172, 0.0088] \\ \tilde{\zeta}_{WW} &= [-0.0429, 0.0438] \\ \eta_Z &= \pm 0.0054 \\ \zeta_{ZZ} &= \pm 0.0016 \\ \zeta_{AZ} &= \pm 0.0010 \\ \tilde{\zeta}_{ZZ} &= \pm 0.0027 \\ \tilde{\zeta}_{AZ} &= \pm 0.0003 \end{cases},$$



Constraints on VVH, and comparison with HL-LHC

ILC operation scenario of 20 years

$\sqrt{s} = 250 + 500$ GeV with $\int Ldt = H20$

$(\eta_Z = \frac{v}{\Lambda} a_Z, \zeta_{ZZ} = \frac{v}{\Lambda} b_Z \; : \Lambda / v = 4.065)$

-. ATLAS and CMS report the sensitivity to the VVH couplings.

ATLAS (arXiv:1712.02304v2) **VVH using 36.1 fb-1**
ATLAS-CONF-2019-029 VVH in SMEFT with 139 fb-1
CMS (arXiv:2104.12152v1) VVH in SMEFT with 137 fb-1
The latest one provides constraints for C:Wilson coefficients.
Interpretation of C to C at the ILC is ongoing.

$$\mathscr{L}_0^V = \left\{ \kappa_{SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] - \frac{1}{4} \left[\kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + \tan\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right] - \frac{1}{4} \frac{1}{\Lambda} \left[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \frac{1}{2} \frac{1}{\Lambda} \left[\kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + \tan\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \right\} X_0$$

$\kappa_{HZZ} = \kappa_{HWW}$

BSM coupling κ_{BSM}	Fit configuration	Expected conf. inter.	Observed conf. inter.
κ_{Agg}	$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$	[−0.47, 0.47]	[−0.68, 0.68]
κ_{HVV}	$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$	[−2.9, 3.2]	[0.8, 4.5]
κ_{HVV}	$(\kappa_{Hgg} = 1, \kappa_{SM}$ free)	[−3.1, 4.0]	[−0.6, 4.2]
κ_{AVV}	$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$	[−3.5, 3.5]	[−5.2, 5.2]
κ_{AVV}	$(\kappa_{Hgg} = 1, \kappa_{SM}$ free)	[−4.0, 4.0]	[−4.4, 4.4]

κ_{HVV} assumes [-0.6, 4.2] → (3000 fb-1) = [−0.06, 0.46]
κ_{AVV} assumes [-4.4, 4.4] → (3000 fb-1) = [−0.48, 0.48]

1 sigma bounds based on the study

$$\begin{cases} \eta_W = [-0.0080, 0.0045] \\ \zeta_{WW} = [-0.0172, 0.0088] \\ \tilde{\zeta}_{WW} = [-0.0429, 0.0438] \\ \eta_Z = \pm 0.0054 \\ \zeta_{ZZ} = \pm 0.0016 \\ \zeta_{AZ} = \pm 0.0010 \\ \tilde{\zeta}_{ZZ} = \pm 0.0027 \\ \tilde{\zeta}_{AZ} = \pm 0.0003 \end{cases},$$

$\kappa_{HZZ} = 8.1 \zeta_{ZZ}$

κ_{HVV} assumes ± 0.026 @ ILC H20
κ_{AVV} assumes ± 0.044 @ ILC H20

ILC can give good synergy to HL-LHC results.

Potential improvement: jet charge, flavor-tag, matrix element approach

-. To improve the sensitivity to ZZH, **jet charge ID is critical:**

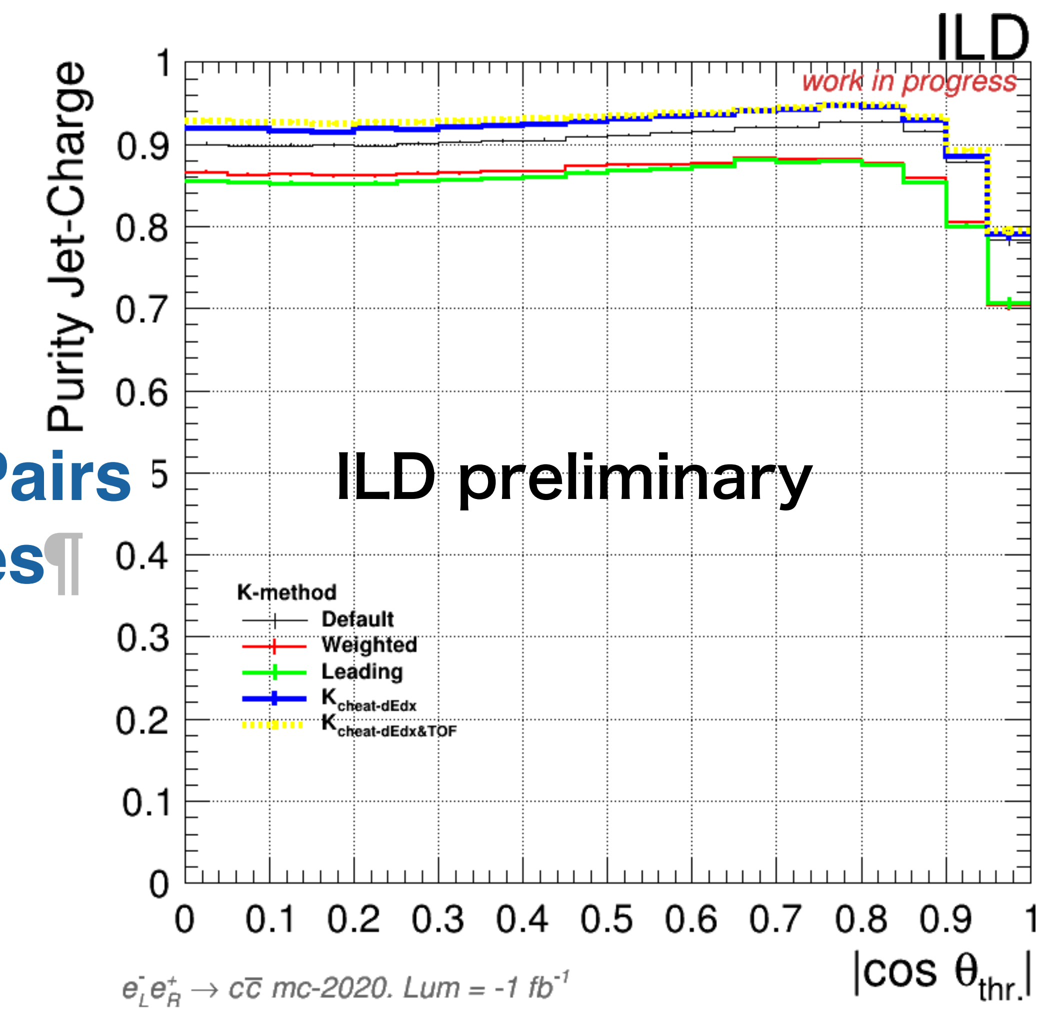
The current results to ZZH based on qqH uses $\Delta\Phi$ of [0-π] (no jet charge identification)

-. To improve the sensitivity to WWH, **flavor ID is critical**:

c-tag performance in the study is not good, $\Delta\Phi$ is almost no power to improve the sensitivity to WWH

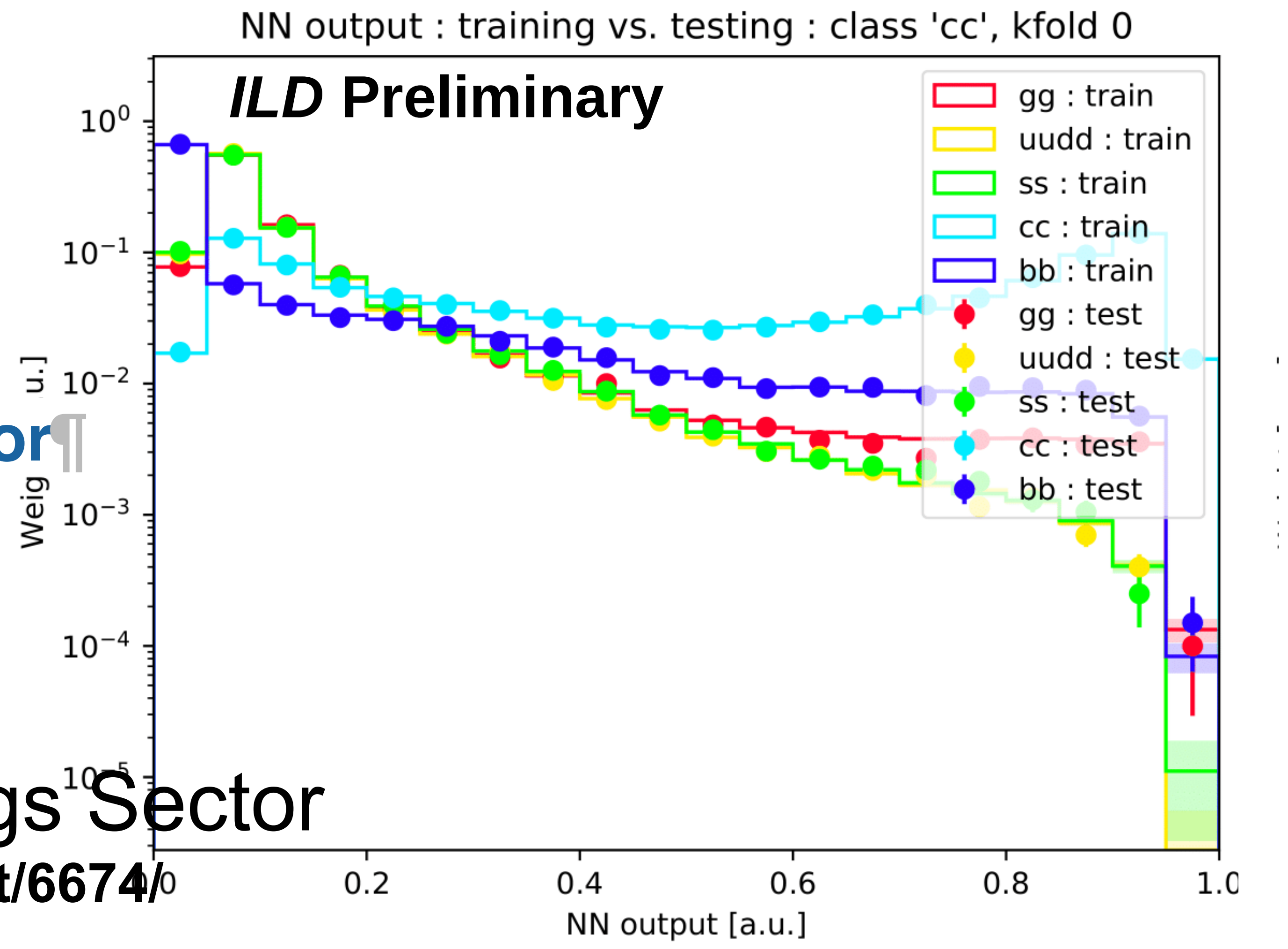
-. Jet charge Measurement has been developed aiming for identification of Kaon for new physics

Please refer to Flavor-Tagging of Quark Pairs at e+e- Higgs/Top Factories¶ @ Higgs2021 by A. Irles



-. c-flavor (even s) identification has been developed

Please refer to Strange Quark as a Probe for New Physics in the Higgs Sector¶ @ Higgs2021 M. Basso



Strange Quark as a probe for new physics in the Higgs Sector
https://indico.slac.stanford.edu/event/6674/

-. Matrix element approach has been also developed aiming for the ultimate sensitivity to the anomalous couplings as ATLAS/CMS does.

Summary

-. In the context of the LHC results as of today,
the energy scale of the BSM is expected to be much higher than the EW scale, where the EFT is valid.

-. Based on the SMEFT the model-independent Lagrangian at the ILC is defined, and the sensitivity to the anomalous VVH couplings was tested **based on the robust analysis technique.**

-. According to the analysis using all most all of t**he dominant Higgs production and decay processes, the sensitivity to anomalous VVH at the ILC could reach about 10 times better than that of the LHC.**

-. New analysis techniques, **jet charge and jet flavor identification**, have been developed for other physics motivations, which can lead the better sensitivity to the anomalous VVH couplings at the ILC s as well.

Backup: EFT parameters at the ILC

○ Dim-6 Effective Field Lagrangian at the ILC

General $SU(2) \times U(1)$ gauge invariant Lagrangian
with dimension-6 operators in addition to the SM.

$\mathcal{L}_{SM} + \mathcal{L}_{eff}^{dim6}$

- **10 EFT coefficients** (h,W,Z,γ): $C_H, C_T, C_6, C_{WW}, C_{WB}, C_{BB}, C_{3W}, C_{HL}, C'_{HL}, C_{HE}$
- **2 EFT coefficients** for contact interaction with quarks
- 5 EFT coefficients for couplings to b, c, τ, μ, g
- 4 SM parameters: g, g', v, λ
- 2 parameters for h→invisible and exotic

○ Retain model independence

○ Make Z, W and γ relate → Improve precision of Higgs couplings

○ Treatable 23 parameters → The LHC situation has > 50 EFT coefficients, it is not easy to determine them simultaneously.

○ ILC250 provides sufficient observables.

23 parameters can be determined simultaneously

1) Higgs-related observables

→ σ and σ×BR …

2) Observables from angular distributions

→ Test new Lorentz structures…

3) Triple Gauge Couplings from $e^+e^- \to W^+W^-$

4) Electroweak precision observables

→ Constrain SM parameters …

5) Beam polarizations double the number of observables

6) HL-LHC Higgs observables, BR(h→γγ, γZ)

Backup: EFT parameters at the ILC

T. Barklow et al.,
PRD 97, 053004 (2018)

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

After EWSB

$$\Delta\mathscr{L}_h = -\eta_h\lambda_0 v_0 h^3 + \frac{\theta_h}{v_0}h\partial_\mu h\partial^\mu h \quad +\eta_Z\frac{m_Z^2}{v_0}Z_\mu Z^\mu h + \frac{1}{2}\eta_{2Z}\frac{m_Z^2}{v_0^2}Z_\mu Z^\mu h^2 \quad +\eta_W\frac{2m_W^2}{v_0}W^+_\mu W^{-\mu}h + \eta_{2W}\frac{m_W^2}{v_0^2}W^+_\mu W^{-\mu}h^2$$
$$+\frac{1}{2}\left(\zeta_{ZZ}\frac{h}{v_0} + \frac{1}{2}\zeta_{2Z}\frac{h^2}{v_0^2}\right)\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} + \left(\zeta_{WW}\frac{h}{v_0} + \frac{1}{2}\zeta_{2W}\frac{h^2}{v_0^2}\right)\hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu} \quad +\frac{1}{2}\left(\zeta_{AA}\frac{h}{v_0} + \frac{1}{2}\zeta_{2A}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{A}^{\mu\nu} + \left(\zeta_{AZ}\frac{h}{v_0} + \zeta_{2AZ}\frac{h^2}{v_0^2}\right)\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}$$
$$+\frac{1}{2}\left(\tilde{\zeta}_{ZZ}\frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2Z}\frac{h^2}{v_0^2}\right)\hat{Z}_{\mu\nu}\hat{\tilde{Z}}^{\mu\nu} + \left(\tilde{\zeta}_{WW}\frac{h}{v_0} + \frac{1}{2}\tilde{\zeta}_{2W}\frac{h^2}{v_0^2}\right)\hat{W}^+_{\mu\nu}\hat{\tilde{W}}^{-\mu\nu}$$

+ $\Delta\mathscr{L}_{TGC}$ triple gauge couplings + $\Delta\mathscr{L}_{eeHZ}$ contact interactions

Backup: EFT parameters in $e^+e^- \to ZH$

PHYS. REV. D 97, 053004 (2018)

The complete set of Feynman diagrams

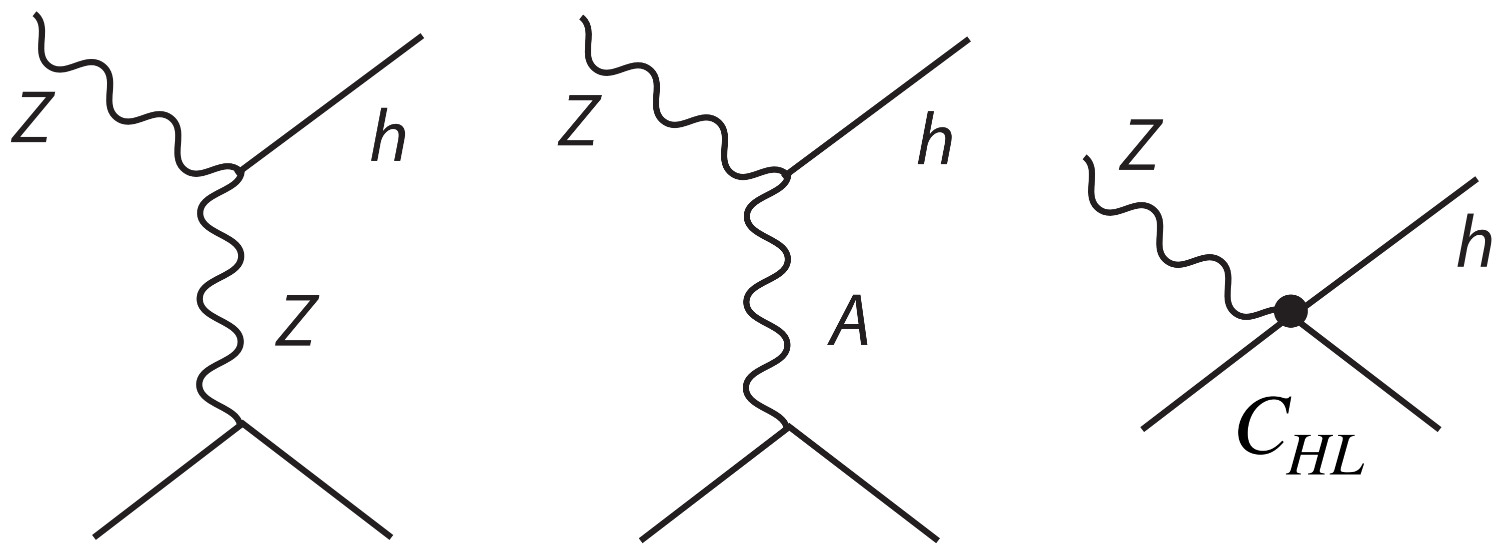


FIG. 4. Feynman diagrams contributing to the amplitudes for $e^+e^- \to Zh$.

$$\Delta\mathscr{L} = g_L \bar{\psi}_L \gamma_\mu \psi_L Z^\mu + g_{HZZ} H Z_\mu Z^\mu$$

$$\Delta\mathscr{L} = \frac{C_{HL}}{\Lambda^2} \bar{\psi}_L \gamma_\mu \psi_L Z^\mu H$$

$$i\mathscr{M} = \frac{g_L g_{HZZ}}{s - M_Z^2} \left\langle ZH \left| H Z^\mu \bar{\psi}_L \gamma_\mu \psi_L \right| e^+e^- \right\rangle$$

$$i\mathscr{M} = \frac{C_{HL}}{\Lambda^2} \left\langle ZH \left| \bar{\psi}_L \gamma_\mu \psi_L Z^\mu H \right| e^+e^- \right\rangle$$

Backup: ILC H20 operation senario

Higgs 2019

https://indico.cern.ch/event/796574/contributions/3521685/

ILC running modes - and Z production

ILC e^+e^- collider

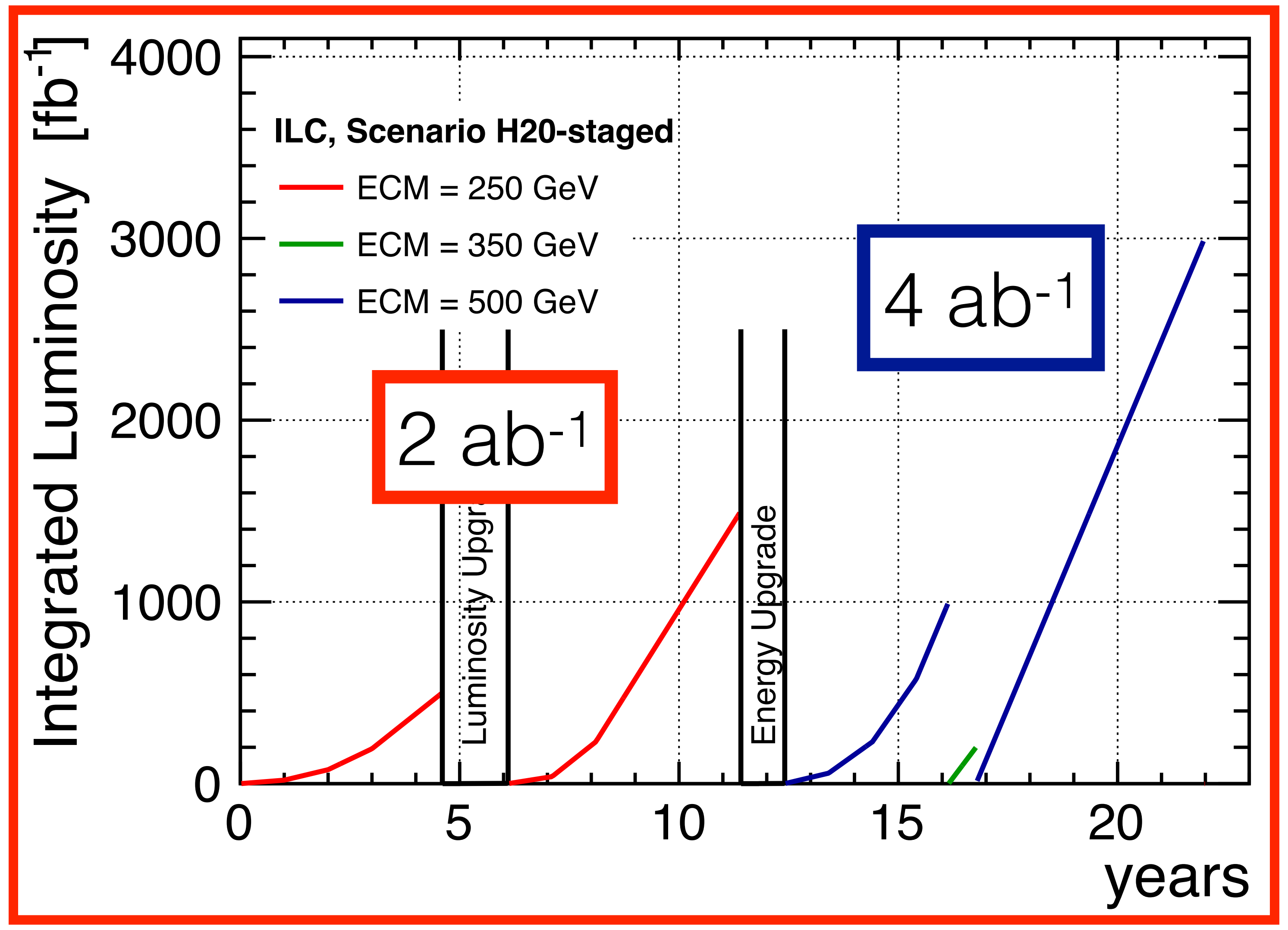
- first stage: 250 GeV
- GigaZ & WW threshold possible
- upgrades: 500 GeV, 1 TeV

polarised beams

- $P(e^-) \geq \pm 80\%$,
- $P(e^+) = \pm 30\%$, at 500 GeV upgradable to 60%

Since 2015 arXiv:1506.07830

$\sqrt{s}$	$\int \mathscr{L} dt$
250 GeV	2 ab^{-1}
350 GeV	0.2 ab^{-1}
500 GeV	4 ab^{-1}
1 TeV	8 ab^{-1}
91 GeV	0.1 ab^{-1}
161 GeV	0.5 ab^{-1}



(radiative) Z's in 2 ab^{-1} at **250 GeV**:

- ~77 10^6 Z->qq
- ~12 10^6 Z->ll

=> substantial increase over LEP,
....and polarised!

Z's in 0.1ab^{-1} at **91 GeV**:

- ~3.4 10^9 Z->qq
- ~0.5 10^9 Z->ll

~1-2 years of running (after lumi upgrade)

Accelerator implementation - arXiv:1908.08212

Backup: Impact on the shape in WWH

-. Focus on WWH:

$$\mathcal{L}_{\rm WWH} = 2M_{\rm W}^2\left(\frac{1}{v}+\frac{a_{\rm W}}{\Lambda}\right)W_\mu W^\mu H + \frac{b_{\rm W}}{\Lambda}\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}H + \frac{\tilde{b}_{\rm W}}{\Lambda}\hat{W}_{\mu\nu}\widetilde{\hat{W}}^{\mu\nu}H$$

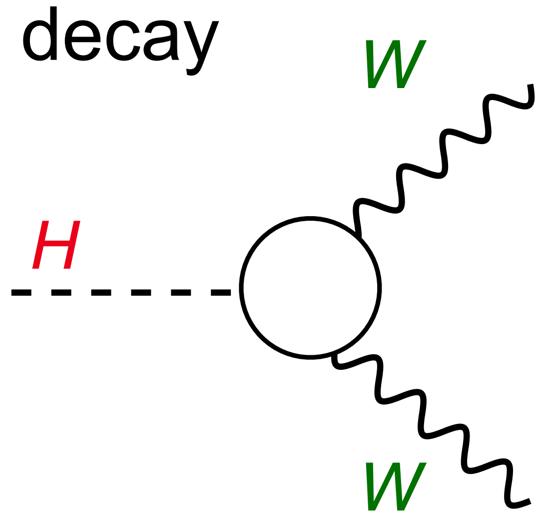
Rescaling the normalization.

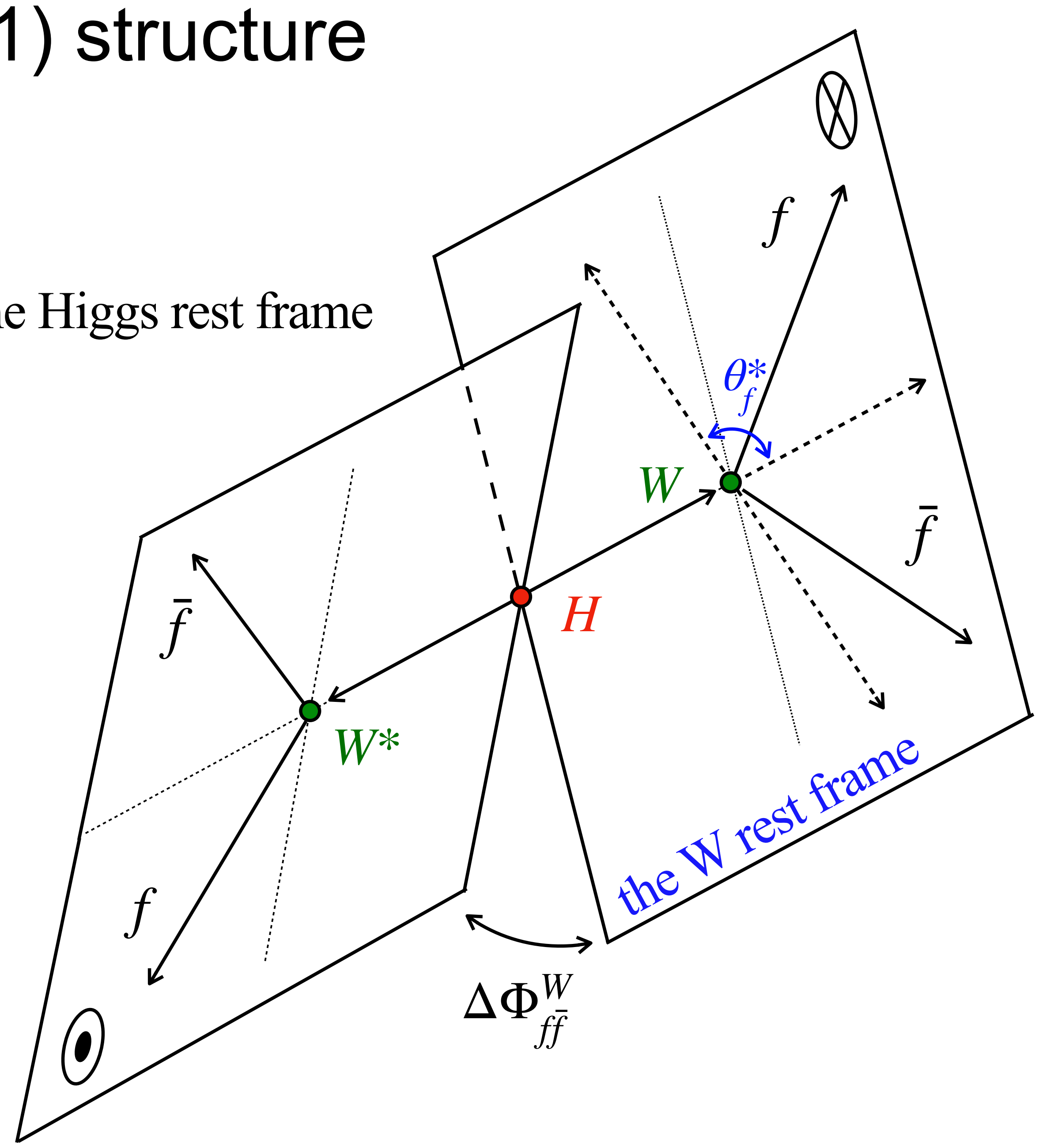
parity-conserving interaction
scalar : CP-even interaction

parity-conserving interaction
pseudo-scalar : CP-odd interaction

-. a term is the same structure with the SM.
-. b term is a new scalar (Parity=+1) structure
-. bt term is a new pseudo-scaler (Parity= −1) structure
-. Field strength has momentum dependence

the Higgs decay

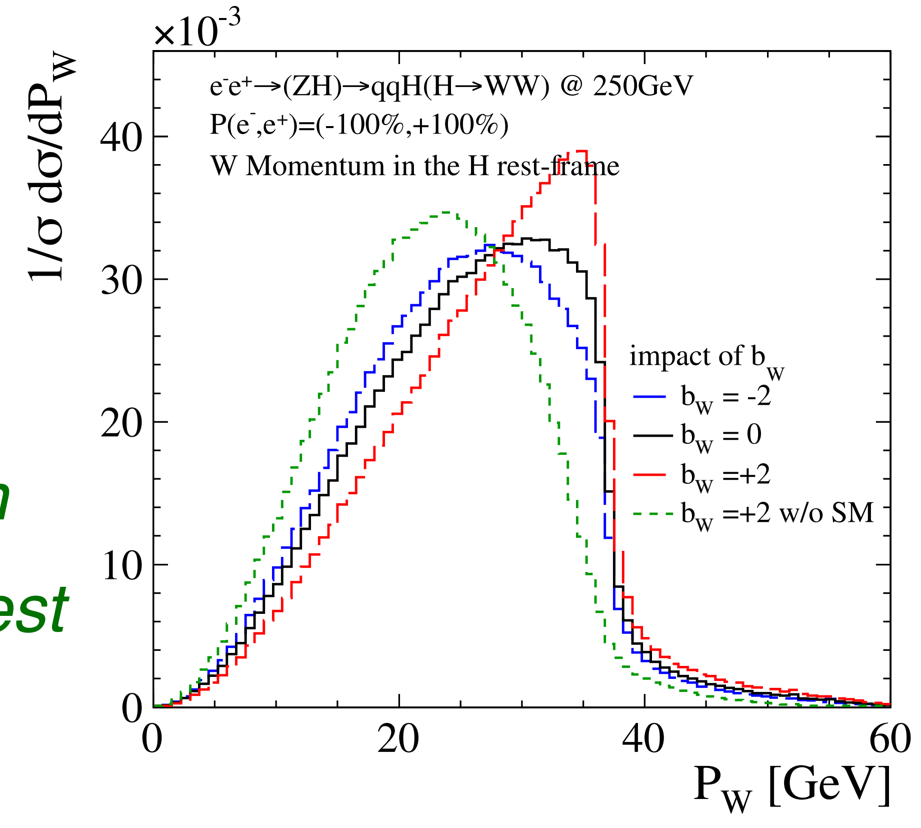


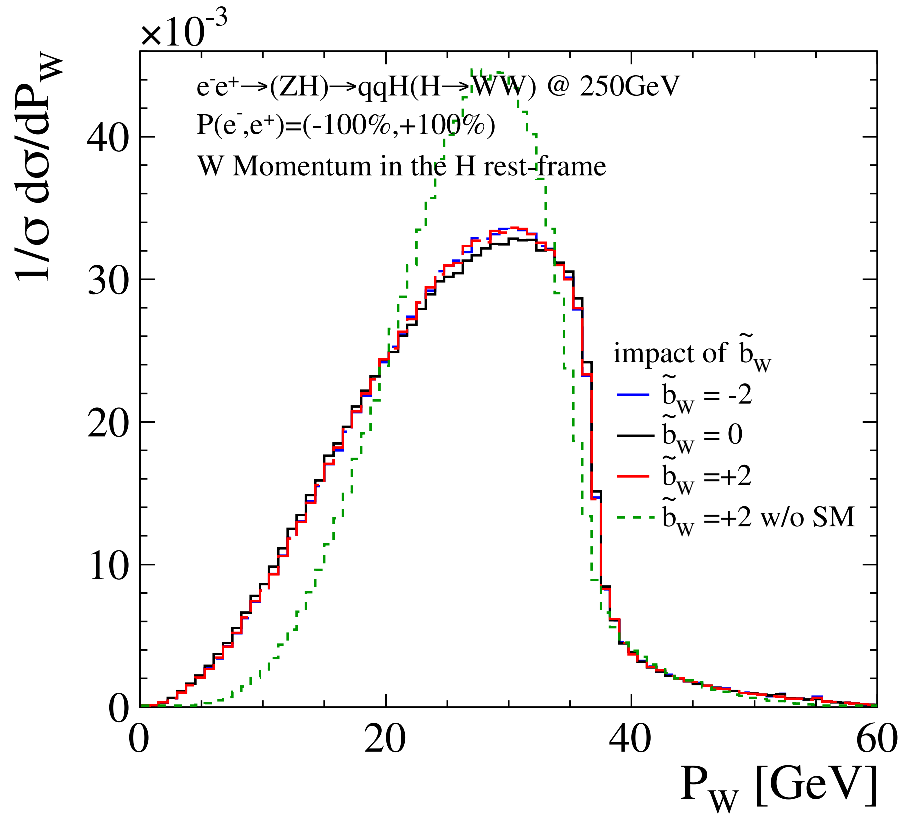


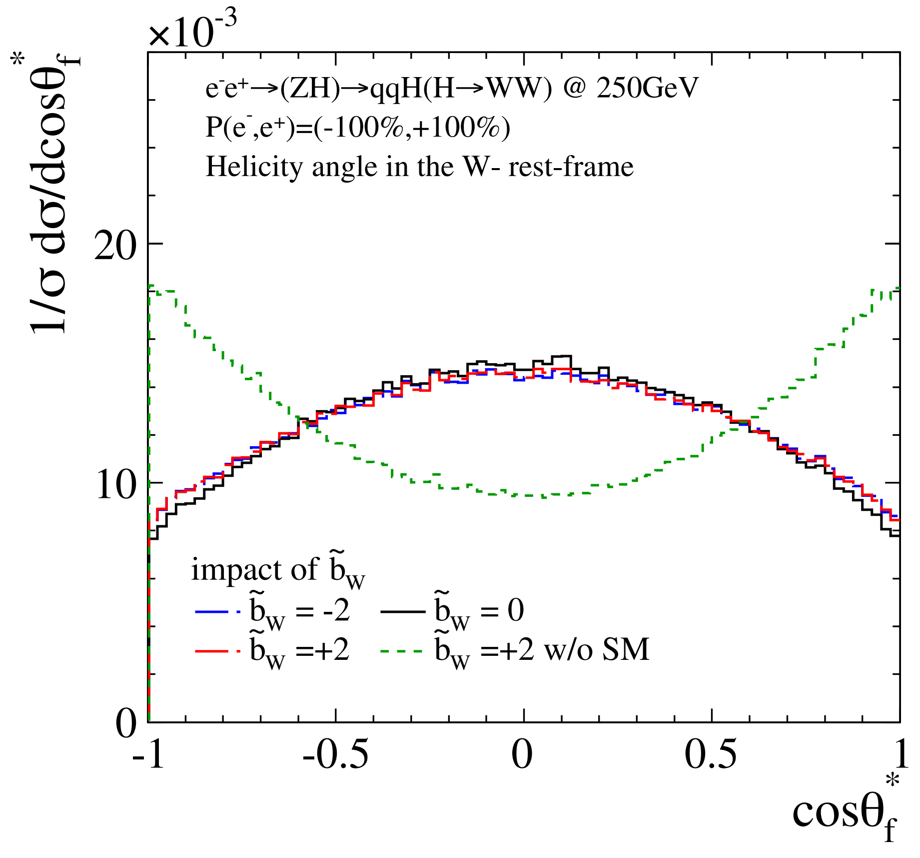
W momentum in the higgs rest

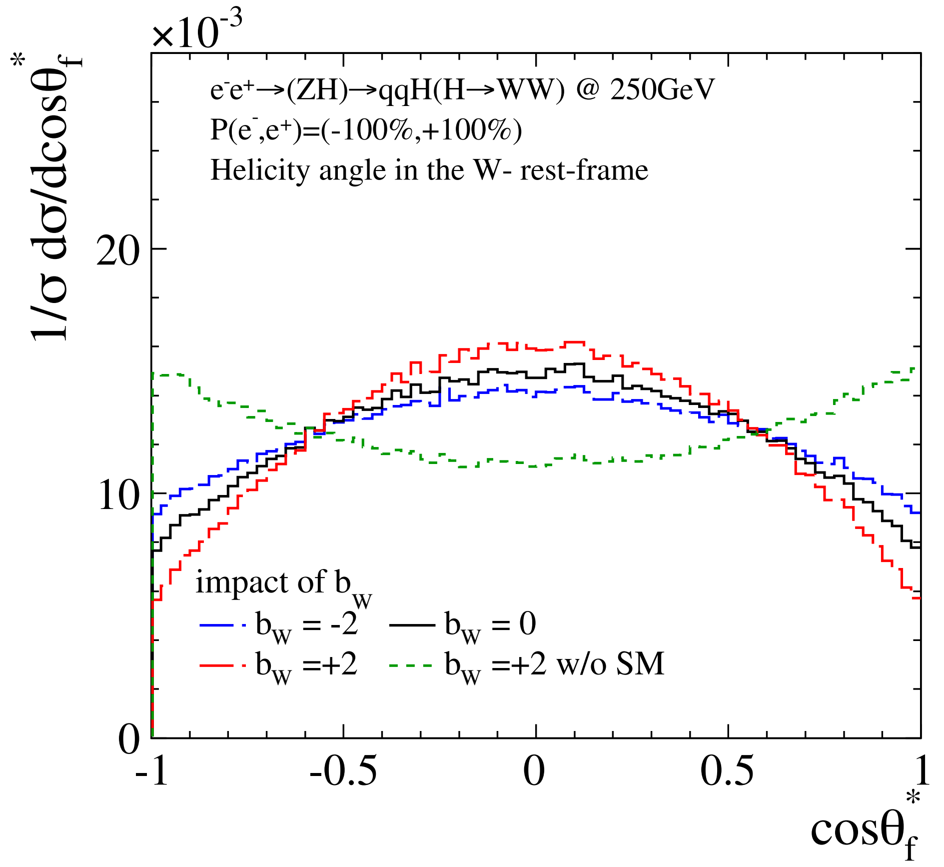
b term

bt term



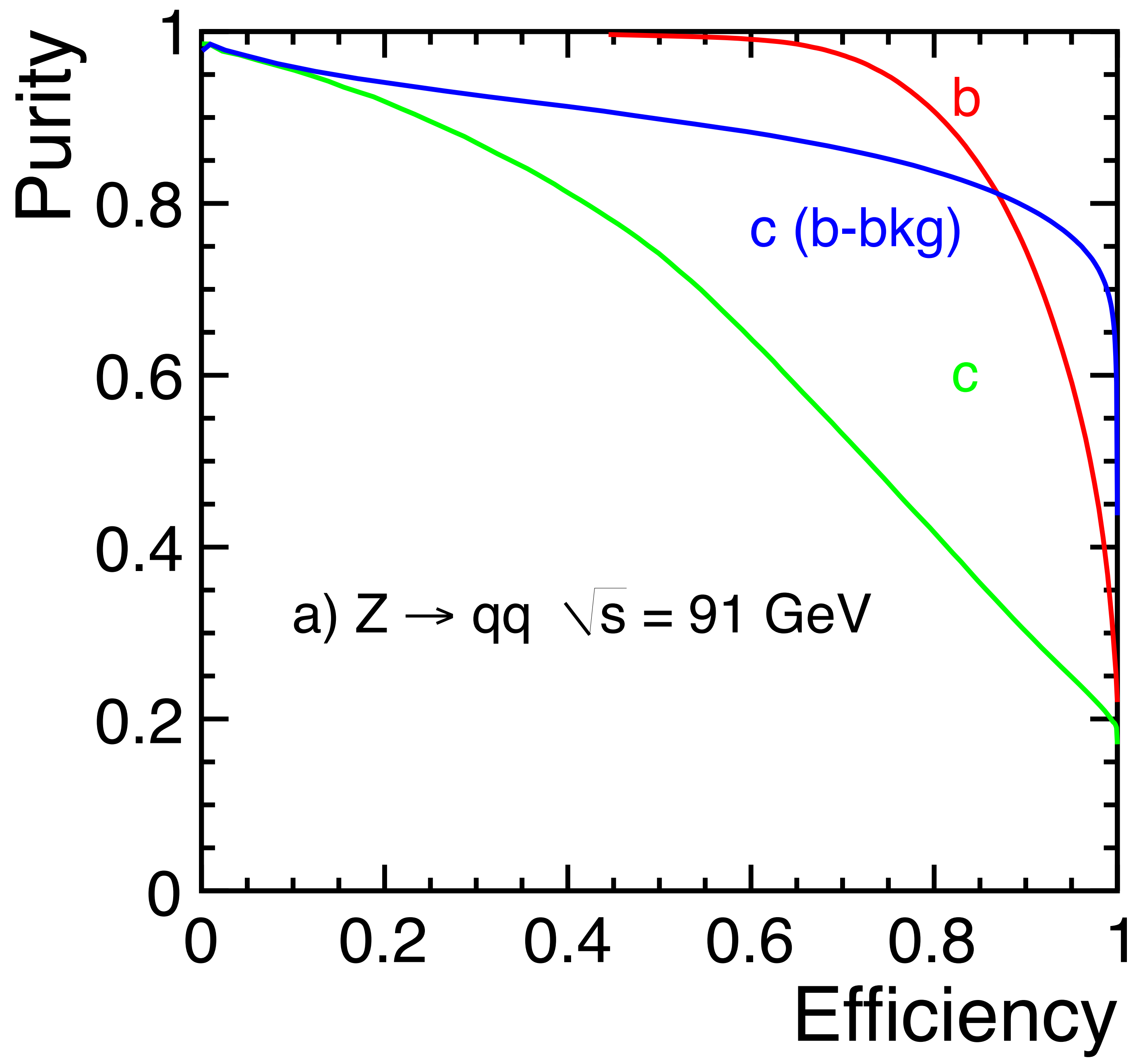






Backup: Flavor identification

arXiv 1306.6329
ILD



c-flavor ID in $H \to WW^* \to c\bar{x}x\bar{c}$ of the ZH process